Energy Research and Development Division
FINAL PROJECT REPORT

# ENERGY-EFFICIENT HIGH-TECH BUILDINGS

## Appendices A-K

Prepared for: California Energy Commission
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# PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

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For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

# ABSTRACT

This project focused on research and demonstrations of energy efficiency strategies for improving the energy performance of laboratories, cleanrooms, and data centers. Key results included proposed Leadership in Energy and Environmental Design criteria for use with cleanrooms or data centers; data center modular cooling system comparisons; cross-cutting efficiency strategies for high-tech buildings; collaboration on direct current power use; alternative cooling demonstrations for data centers; and collaboration with the Silicon Valley Leadership Group on data center demonstrations.

An industry committee assembled for each building type developed Proposed Leadership in Energy and Environmental Design criteria. The criteria emphasized energy and water use credits and deemphasized other sustainability credits.

Evaluations of modular cooling systems for data centers involved significant commitment from industry partners who supplied the systems for evaluation and hosted the installation in an operating data center. The study concluded that these systems perform better than standard practice.

Industry collaboration to promote the use of direct current power distribution in data centers continued following a demonstration in a prior California Energy Commission research project. This led to developing and commercializing standard direct current power connectors for use with information technology equipment and general agreement on distribution voltage.

An alternative cooling technology for use in data centers was demonstrated. This complex system involves spraying a di-electric fluid directly on components; however, significant energy savings were achieved compared to standard practice.

Lawrence Berkeley National Laboratory and the Silicon Valley Leadership Group jointly encouraged data center demonstration projects, which culminated in a data center "Summit" hosted by Silicon Valley Leadership Group where new or underutilized technologies were demonstrated.

One of the project's key recommendations is that the California Energy Commission Energy Research and Development program continues research on high-tech buildings and forms a high-tech center to continue research and development for high-tech buildings.

**Keywords:** California Energy Commission, high-tech buildings, data centers, DC Power, LEED criteria, modular cooling, SVLG, spray cooling, data center efficiency

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# APPENDIX A:
# Contract Task 2.1.1 Cleanroom/Laboratory Case Study

Draft report – Chilled water plant case study
Case Study: Sun Microsystems Chilled Water Plant

When Sun Microsystems built a new data center, it chose to build a chilled water plant to support the new data center and office space sharing the existing building.

Customer Case

In 2007, Sun Microsystems built 72,000 square feet of datacenter space in 14 rooms, all cooled by the same chilled water plant. This report focuses on the performance of the chiller plant and a room with a large installation of APC Hot Aisle Containment. This room is a 12,771 square foot data center in an existing building within Sun's Santa Clara campus and supports primary hardware and software research and development. Sun built the energy efficient data center with a chilled water plant serving chilled water to APC rack row units, which distribute chilled air via fans and a coil. Alternating hot rows are enclosed with roof and end of aisle doors to eliminate cold air mixture. The chilled water plant became operational in June of 2007 and commissioned six months later by a 3rd party.

Project Summary

From December 2007 through February 2008, electrical loads of the infrastructure and IT loads were measured by Sun personnel, and chiller plant data collected. Chiller plant loads were calculated by a Lawrence Berkeley National Labs' (LBNL) team with chiller, tower, pump and weather data collected from the Building Management System (BMS) every 15 minutes or daily from equipment control panels. Because the chilled water system serves 14 different data center rooms and also office areas, facility loads for this data center were calculated from usage data, equipment panel readings, equipment specifications and minor assumptions. Plant load varied little during this period, with 80% of the plant load measurements being at the average and the rest being within a range of about 10% higher or lower than the average. Average annual plant load was calculated using these measurements and extrapolated with nearby annual weather data. Electrical power for a sand gravel filter with pump was not measured, so these loads were calculated using known pump information, piping resistance and usage parameters. The calculated annual average efficiency of the plant is 0.52 kW/ton, or at code required efficiency.

Average IT load during this period was 750 kilowatts (kW) and remained fairly constant. Total IT load was calculated from PDU (Power Distribution Unit) panels, but because the PDUs also supply power to the in-row cooling units, IT and cooling loads were calculated based on an equation that predicted In-row cooling power loads based on measured cubic-feet per minute (CFM) use. Actual measured values were compared to the equation data and found to be very close, and thus, cooling loads were subtracted to derive IT loads.

Total infrastructure electrical power was derived using manufacturer's data to calculate losses of PDUs and other transformers as well as of the Uninterruptable Power Supplies (UPS). Lighting loads were calculated and electrical load of the APC In Row RC units measured. Electric power for the Information Technology (IT/servers) loads was obtained by reading measured load on the electrical panels that serve the above infrastructure and subtracting its total from the total on the electrical panels, which includes IT loads. Due to the focus of this study on the chilled-water plant, actual total measured losses of UPS and PDU loads will likely vary slightly from manufacturer's specified efficiency ratings, although spot measuring proved that the manufacturer's efficiency curves were accurate. Lighting loads were also calculated along with the Cubic Feet per Minute (CFM) proportional load of a building Air Handling Unit (AHU) providing make-up air to this data center space. Both of these loads are a small portion of the total data center's load and have a legible affect on total load and calculated Power Usage Effectiveness (PUE). The data center's annual Power Usage Effectiveness (PUE) is calculated to be 1.29.

Project Details

A combination of efficient chillers, oversized piping for the current load and Variable Speed Drives (VSDs) on all pumps and chillers along with good cooling tower operation create a total Heating, Ventilation, Air Conditioning (HVAC) system PUE of 0.22 and 0.69 kW/ton of cooling. The chilled water system itself has a PUE of 0.17 and 0.52 kW/ton. The efficient Trane chillers have an average PUE of 0.12 and 0.38 kW/ton with a range between 0.49 to 0.29 kW/ton.

| *Calculations* | **Data Center** | **Total HVAC** | **Chilled Water** | **Chillers** |
|---|---|---|---|---|
| **PUE** | 1.29 | 0.22 | 0.17 | 0.12 |
| **kW/ton** | n/a | 0.69 | 0.52 | 0.38 |

This chilled water plant is a primary only variable flow configuration, consisting of two variable speed centrifugal chillers (nominally 1,000 tons each), two draw through cooling towers and pairs of condenser water and chilled water pumps that are configured so that each pump can serve either chiller. The cooling towers and pumps are controlled with VSDs. The distribution piping is designed for future build out so it is oversized for the current load. The oversized piping coupled with the use of two-way valves and supply pressure reset control minimizes the energy used from the distribution pumps.

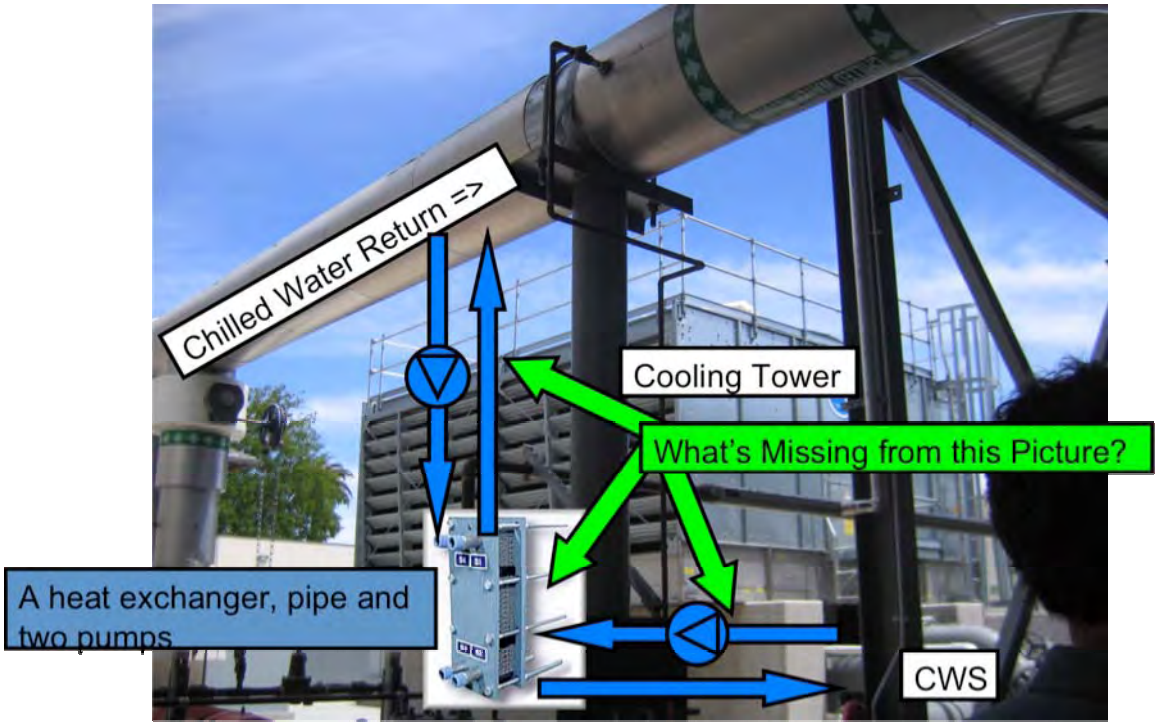
The plant provides 44°F chilled water and is currently operating at about 750 tons of total data center and office load with a 9-10°F delta-t. Both towers run in parallel to serve the chillers. The tower fans have VSDs which are controlled to maintain a condenser water supply of 70°F. The tower fans are cycled off when their speed drops below 20hz.

The PUE is calculated with the energy of a 15 horsepower Lycos filtration pump that operates 24x7 in addition to a shared central air-handling unit that provides about 5,000 CFM of ventilation air to the data center. Nearby annual weather bin data was used to calculate the annual efficiency of the chilled-water plant, as the measured data period was limited to three wintertime months. Actual performance of this chilled-water plant and the APC systems will vary as IT load increases, which might improve or or even decrease system efficiency.

In addition to the BMS upgrade and retro-commissioning already planned by Sun, the LBNL team recognized that more improvements can be made to improve the plant efficiency. Sun could:

- Raise chilled-water supply temperature to 70F reducing total plant kW/ton to 0.086. (Note that the existing tower can only keep supply at 74F. A 75F setpoint would yield 0.072 kW/ton.) These temperatures are within revised ASHRAE CL1 and 2 recommended ranges although likely outside of the operating range of the existing condenser coils in the AHUs that support the building's office space;

- Add an integrated waterside economizer to the chilled water return line upstream of the chillers. In simulations with the LBNL DC Pro tool, this addition reduces the plant PUE by 0.04 in ASHRAE 90.1 Climate Zone 3B (San Jose). A diagram of this arrangement is depicted here:




- Reset supply temperature by demand. A higher supply temperature would need to accommodate office space as well;
- Reset condenser water temperature with pump speed, which would yield an estimated 20-30% plant savings. Control sequence would be to slow pump speed while increasing tower fan speed, providing the effect of a larger tower, and;
- Reduce minimum speeds for the cooling tower fans to 6hz from 20hz.

With this upgrade and these minor programming changes, the PUE can be improved to create a more energy efficient chilled water plant and data center.

Summary by KC Mares and Calculations by Mark Hydeman (Contractors) Nov 2008

# APPENDIX B:
# Contract Task 2.1.2 Low Grade Heat Recovery

This task was terminated.

# APPENDIX C:
# Contract Task 2.1.3 LEED™ type Criteria for Cleanrooms

LEED-NC for Fabs
DRAFT – September 12, 2007

Edited credits are highlighted in yellow. New credits are highlighted in pink. Credits directly included from Labs 21 are highlighted in green.

| | |
|---|---|
| **Sustainable Sites** | **14 Possible** |
| Prereq 1 **Construction Activity Pollution Prevention** | **Required** |
| Credit 1 **Site Selection** | **1** |
| Credit 2 **Development Density and Community Connectivity** | **1** |
| Credit 3 **Brownfield Redevelopment** | **1** |
| Credit 4.1 **Alternative Transportation**, Public Transportation Access | **1** |
| Credit 4.2 **Alternative Transportation**, Bicycle Storage & Changing Rooms | **1** |
| Credit 4.3 **Alternative Transportation**, Low Emitting & Fuel Efficient Vehicles | **1** |
| Credit 4.4 **Alternative Transportation**, Parking Capacity | **1** |
| Credit 5.1 **Site Development**, Protect or Restore Habitat | **1** |
| Credit 5.2 **Site Development**, Maximize Open Space | **1** |
| Credit 6.1 **Stormwater Management**, Quantity Control | **1** |
| Credit 6.2 **Stormwater Management**, Quality Control | **1** |
| Credit 7.1 **Heat Island Effect**, Non-Roof | **1** |
| Credit 7.2 **Heat Island Effect**, Roof | **1** |
| Credit 8 **Light Pollution Reduction** | **1** |
| **Water Efficiency** | **6+ Possible** |
| Credit 1.1 **Water Efficient Landscaping**, Reduce by 50% | **1** |
| Credit 1.2 **Water Efficient Landscaping**, No Potable Use or No Irrigation | **1** |
| Credit 2 **Innovative Wastewater Technologies** | **1** |
| Credit 3.1 **Water Use Reduction**, 20% Reduction | **1** |
| Credit 3.2 **Water Use Reduction**, 30% Reduction | **1** |
| Credit 4 **Water Recycle & Reuse** | **TBD** |
| **Energy & Atmosphere** | **22 Possible** |
| Prereq 1 **Fundamental Commissioning of the Building Energy Systems** | **Required** |
| Prereq 2 **Minimum Energy Performance** | **Required** |
| Prereq 3 **Fundamental Refrigerant Management** | **Required** |
| Credit 1 **Optimize Energy Performance** | **10** |
| Credit 2 **On-Site Renewable Energy** | **3** |
| Credit 3 **Enhanced Commissioning** | **1** |
| Credit 4 **Enhanced Refrigerant Management** | **1** |
| Credit 5 **Measurement & Verification** | **1** |
| Credit 6 **Green Power** | **1** |
| Credit 7 **Energy Supply Efficiency** | **5** |
| **Materials & Resources** | **15+ Possible** |
| Prereq 1 **Storage & Collection of Recyclables** | **Required** |
| Prereq 3 **Tool Purchasing** | **Required** |
| Credit 1.1 **Building Reuse**, Maintain 75% of Walls, Floor, and Roof | **1** |
| Credit 1.2 **Building Reuse**, Maintain 95% of Walls, Floor, and Roof | **1** |
| Credit 1.3 **Building Reuse**, Maintain 50% of Interior Non-Structural Elements | **1** |
| Credit 2.1 **Construction Waste Management**, Divert 50% from Disposal | **1** |
| Credit 2.2 **Construction Waste Management**, Divert 75% from Disposal | **1** |
| Credit 3.1 **Materials Reuse**, 5% | **1** |

| | |
|---|---|
| Credit 3.2 **Materials Reuse**, 10% | 1 |
| Credit 4.1 **Recycled Content**, 10% (post-consumer + 1/2 pre-consumer) | 1 |
| Credit 4.2 **Recycled Content**, 20% (post-consumer + 1/2 pre-consumer) | 1 |
| Credit 5.1 **Regional Materials**, 10% Extracted, Processed & Manufactured Regionally | 1 |
| Credit 5.2 **Regional Materials**, 20% Extracted, Processed & Manufactured Regionally | 1 |
| Credit 6 **Rapidly Renewable Materials** | 1 |
| Credit 7 **Certified Wood** | 1 |
| Credit 8 **Chemical Resource Management** | 1 |
| Credit 9 **Chemical Reuse and Recycle** | TBD |
| **Indoor Environmental Quality** | **18 Possible** |
| Prereq 1 **Minimum IAQ Performance** | **Required** |
| Prereq 2 **Environmental Tobacco Smoke** (ETS) **Control** | **Required** |
| Credit 1 **Outdoor Air Delivery Monitoring** | 1 |
| Credit 2 **Increase Ventilation** | 1 |
| Credit 3.1 **Construction IAQ Management Plan**, During Construction | 1 |
| Credit 3.2 **Construction IAQ Management Plan**, Before Occupancy | 1 |
| Credit 4.1 **Low-Emitting Materials**, Adhesives & Sealants | 1 |
| Credit 4.2 **Low-Emitting Materials**, Paints & Coatings | 1 |
| Credit 4.3 **Low-Emitting Materials**, Carpet Systems | 1 |
| Credit 4.4 **Low-Emitting Materials**, Composite Wood & Agrifiber Products | 1 |
| Credit 5 **Indoor Chemical & Pollutant Source Control** | 1 |
| Credit 6.1 **Controllability of Systems**, Lighting | 1 |
| Credit 6.2 **Controllability of Systems**, Thermal Comfort | 1 |
| Credit 7.1 **Thermal Comfort**, Design | 1 |
| Credit 7.2 **Thermal Comfort**, Verification | 1 |
| Credit 8.1 **Daylight & Views**, Daylight 75% of Spaces | 1 |
| Credit 8.2 **Daylight & Views**, Views for 90% of Spaces | 1 |
| Credit 9.1 **Indoor Environmental Safety**, Airflow Modeling | 1 |
| Credit 9.2 **Indoor Environmental Safety**, Fumehood Commissioning | 1 |
| Credit 9.3 **Indoor Environmental Safety**, Alarm Systems | 1 |
| **Innovation & Design Process** | **5 Possible** |
| Credit 1.1 **Innovation in Design**: | 1 |
| Credit 1.2 **Innovation in Design**: | 1 |
| Credit 1.3 **Innovation in Design**: | 1 |
| Credit 1.4 **Innovation in Design**: | 1 |
| Credit 2 **LEED™ Accredited Professional** | 1 |
| **Total** | **80+ Possible** |

# APPENDIX D:
# Contract Task 2.2.1 LEEDTM type Criteria for Data Centers

**Datacenter Environmental Performance Criteria**

EPC for New Construction v2.2 rev.6
Proposed Registered Project Checklist

| | | Before | After |
|---|---|---|---|
| **Total Available Points** | | **69 Points** | **100 Points** |
| **Sustainable Sites** | | **14 Points** | **14 Points** |
| | | 20% | 14% |
| **Eliminated** | | | |
| Credit 4.1 | **Alternative Transportation**, Public Transportation Access | | 1 |
| Credit 4.2 | **Alternative Transportation**, Bicycle Storage & Changing Rooms | | 1 |
| Credit 4.3 | **Alternative Transportation**, Low-Emitting & Fuel-Efficient Vehicles | | 1 |
| Credit 4.4 | **Alternative Transportation**, Parking Capacity | | 1 |
| **Added** | | | |
| Prereg 2 | **Fuel Storage and Handling**, Storm water discharge protection | | |
| Credit 5.3 | **Site Development**, Impacts to Local Infrastructure (Power Grid), Sewage (Cooling Tower) | | 1 |
| Credit 5.4 | **Site Development**, Noise Impacts (Generators), (Cooling Towers) | | 1 |
| Credit 5.5 | **Site Development**, Air Quality & Emissions Impacts | | 1 |
| **Water Efficiency** | | **5 Points** | **9 Points** |
| | | 7% | 9% |
| **Added** | | | |
| Credit 3.3 | **Water Use Reduction**, 20%-40% Reduction in Cooling Tower Make-up, Condensate Re-use | | 3 |
| **Energy Efficiency** | | **17 Points** | **60 Points** |
| | | 25% | 50% |
| **Added** | | | |
| Prereg 4 | **Minimum Energy Sub-metering & Reporting of DCiE Metric** | | Required |
| Credit 1 | **Enhanced Energy Sub-metering & Automated Reporting of Metrics of Performance** | | 3 |
| **Changed** | | | |
| Credit 2 | **Optimize Infrastructure Energy Performance -( Above new ASHRAE 90.1 Minimum by Tier)** | | 10 to 24 |
| | 10.5% New Buildings or 3.5% Existing Building Renovations | | 10 |
| | 14% New Buildings or 7% Existing Building Renovations | | 12 |
| | 17.5% New Buildings or 10.5% Existing Building Renovations | | 14 |
| | 21% New Buildings or 14% Existing Building Renovations | | 16 |
| | 24.5% New Buildings or 17.5% Existing Building Renovations | | 18 |
| | 28% New Buildings or 21% Existing Building Renovations | | 20 |
| | 31.5% New Buildings or 24.5% Existing Building Renovations | | 22 |
| | 35% New Buildings or 28% Existing Building Renovations | | 24 |
| Credit 3 | **On-Site Renewable Energy** | | 5 to 10 |
| | 2.5% Renewable Energy | | 5 |
| | 5.0% Renewable Energy | | 6 |
| | 7.5% Renewable Energy | | 7 |
| | 12.5% Renewable Energy | | 8 |
| | 15.0% Renewable Energy | | 9 |
| | 20.0% Renewable Energy | | 10 |
| Credit 4 | **On-Site Generation (Based upon % Reduction in Source Energy)** | | 1 to 3 |
| | 7.5% On-Site Energy Generation | | 1 |
| | 12.5% On-Site Energy Generation | | 2 |
| | 15.0% On-Site Energy Generation | | 3 |
| Credit 5 | **Enhanced Commissioning** | | 2 |
| Credit 7 | **Enhanced Measurement & Verification** | | 2 |
| Credit 8 | **Renewable Source (Green) Energy** | | 1 to 4 |
| | 7.5% Renewable Source Energy | | 1 |
| | 12.5% Renewable Source Energy | | 2 |
| | 15.0% Renewable Source Energy | | 3 |
| | 17.5% Renewable Source Energy | | 4 |

| Materials & Resources | | 13 Points | 10 Points |
|---|---|---|---|
| | | 19% | 10% |
| **Eliminated** | | | |
| Credit 6 | **Rapidly Renewable Materials** | | 1 |
| Credit 7 | **Certified Wood** | | 1 |

| Indoor Environmental Quality | | 13 Points | 7 Points |
|---|---|---|---|
| **Eliminated** | | 22% | 7% |
| Prereq 2 | **Environmental Tobacco Smoke** (ETS) **Control** | | Required |
| Credit 2.0 | **Increased Ventilation** | | 1 |
| Credit 4.3 | **Low Emitting Materials,** Carpet Systems | | 1 |
| Credit 4.4 | **Low Emitting Materials,** Composite Wood & Agrifiber Products | | 1 |
| Credit 5 | **Indoor Chemical & Pollutant Source Control** | | 1 |
| Credit 6.2 | **Controllability of Systems,** Thermal Comfort | | 1 |
| Credit 7.1 | **Thermal Comfort,** Design | | 1 |
| Credit 7.2 | **Thermal Comfort,** Verification | | 1 |
| Credit 8.1 | **Daylight & Views,** Daylight 75% of Spaces | | 1 |
| Credit 8.2 | **Daylight & Views,** Daylight 90% of Spaces | | 1 |
| **Added** | | | |
| Credit 6 | **Acoustic Environment** | | 1 |

| Innovation & Design Process | | 5 Points | 10 Points |
|---|---|---|---|
| | **Changed** | 7% | 10% |
| Credit 1.1 | **Innovation in Design** | | 1 |
| Credit 1.2 | **Innovation in Design** | | 1 |
| Credit 1.3 | **Innovation in IT Design** | | 1 |
| Credit 1.4 | **Innovation in IT Design** | | 1 |
| Credit 1.5 | **Innovation in Design** | | 1 |
| Credit 1.6 | **Innovation in Design** | | 1 |
| Credit 1.7 | **Innovation in Design** | | 1 |
| Credit 1.8 | **Innovation in Design** | | 1 |
| Credit 1.9 | **Innovation in Design** | | 1 |
| Credit 1.10 | **Innovation in Design** | | 1 |

**Certified:** 38-46 points, **Silver:** 47-55 points, **Gold:** 56-74 points, **Platinum:** 75-100 points

# Environmental Performance Criteria

# Guide for New Data Centers

**DRAFT based on LEED NC 2.2**
23 December 2008

## FOREWORD

The project to develop this Environmental Performance Criteria (EPC) Guide for Data Centers is a Lawrence Berkeley National Labs (LBNL) project funded by the California Energy Commission (CEC) program. The goal of the project was similar to a previous LBNL/CEC project to develop an EPC for laboratories for subsequent submission to the US Green Building Council (USGBC) for consideration and adoption.

The CEC commissioned LBNL to customize a data center specific Environmental Performance Criteria because data centers present both a challenge and an opportunity in the development and implementation of sustainable design, construction and operation practices. Issues such as mission critical 24/7 operations; energy and water use intensity in data centers; are not addressed adequately in the current USGBC, LEED NC 2.2 Guideline to adequately meet the data center sector's requirements for quantifiable sustainable and energy efficient design.

The project goal is to build flexibility into this Guide to allow users to consider the whole building life cycle, regional climatic issues, partial and full-load design and specific innovation and design concepts applicable to data centers. The document is not intended to establish regulatory requirements, but is designed to serve as a voluntary guide for early adopters of sustainable data center design, construction and operation practices, to encourage continuous improvement in the data center sector, and to provide the industry's collective knowledge and guidance to the USGBC in their development of a data center specific LEED NC standard. Although this guide is intended for new data center design and construction, many of the ideas are directly applicable to existing data centers.

The application intent of this EPC is for both purpose-built stand alone buildings and a new or data center renovation within a larger overall building. If is also envisioned that this EPC will apply to different types of data centers, including enterprise, co-location, Telco, web-hosting, etc. When applying the EPC to a new construction data center within a larger overall building, the intent would be to apply the EPC checklist and ASHRAE 90.1 model to the only the data center and the direct mechanical and electrical support systems as described in the EPC based upon its percent of energy use.

LEED NC 2.2 as currently written would be used for the office or commercial space in the building, including the existing LEED credits related to occupant comfort and environmental impact due to higher occupancy per square foot such as alternative transportation, etc. which are not applicable to the data center space. In mixed-use buildings where the non data center space is <10% of the total building space, at the Owner's discretion, the Data Center EPC may be used for the entire building.

Where the non data center space is >10%, than the prorate methodology using both the EPC and LEED NC 2.2 shall be used. Where both share a common facilities infrastructure such as a central cooling system, the central cooling energy would be allocated based upon their respective energy use.

By requesting the USGBC to apply building use specific checklists and standards to mixed-use buildings in this way enables the credits to be specific to the energy and environmental impact of the building type. The level of LEED certification that the overall building would achieve would be determined by the score achieved for both the data center and the rest of the building based upon the ratio of overall building energy use.

In keeping with the both the California Energy Commission's goal to enlist industry involvement and collaboration in the development of the EPC, LBNL reached out to the key data center industry organizations, including ASHRAE TC9.9, The Green Grid, The Uptime Institute, 24x7, the European Commission, the Critical Facilities Roundtable, and the Silicon Valley Leadership Group.

Each of these organizations assigned key members of these technical committees to contribute to the core EPC draft development team and following completion of the draft, submit it for formal review and comments. Each organization has agreed to complete their formal review by January 31, 2009. Following the review process by the sponsoring organizations, LBNL will complete a final consensus draft for formal adoption by each of the member organizations for submission to the USGBC.

Following adoption of the final draft standard, each organization has also agreed to encourage their member companies to voluntarily trial-run this standard as a guideline in the design and development of new data centers, including comparing and where applicable, publically releasing the building's score against both the LEED and EPC checklists. This industry information will be extremely valuable in the final drafting of a LEED standard for data centers.

By working together collaboratively, the key stakeholders in the data center industry will provide a common voice to encourage the USGBC to move forward with a data center specific LEED NC standard in 2009.

The California Energy Commission has expressed their interest in continuing their support of this collaborative industry effort by sponsoring a follow-on effort to develop a similar EPC for existing data centers.

**NOTES:**

- This DRAFT is in development and is available for informational purposes only. It is not an official release of the United States Green Building Council, (USGBC).
- This draft only contains credits and prerequisites that are being modified or added to LEED NC Version 2.2. All other credits and prerequisites will remain the same.
- This draft does not contain submittals.
- This draft was developed by the drafting committee by reviewing the current LEED design criteria for new commercial buildings and deleting credits considered not applicable to data centers; accepting credits deemed applicable as currently written; modifying credits as required to make them applicable; or by adding new credits applicable specifically to data centers. This draft includes a "rationale" for deletion, modification and additions of credits and prerequisites. The rationale will be included in the final document submitted to the USGBC for review and consideration for informational purposes only.

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# List of New and Modified Credits

### *Sustainable Sites*

Credit 4.1 Alternative Transportation, Public Transportation Access *(deleted)*
Credit 4.2 Alternative Transportation, Bicycle Storage and Changing Rooms *(deleted)*
Credit 4.3 Alternative Transportation, Low-emitting and Fuel-Efficient Vehicles *(deleted)*
Credit 4.4 Alternative Transportation, Parking Capacity *(deleted)*
Prerequisite 2 Fuel Storage and Handling, Storm Water Discharge Protection *(added)*
Credit 5.3 Site Development, Impacts to Local Infrastructure
(Power Grid), Sewage (Cooling Tower) *(added)*
Credit 5.4 Site Development, Noise Impacts (Generators, Cooling Towers) *(added)*
Credit 5.5 Site Development, Air Quality & Emissions Impacts *(added)*

### *Water Efficiency*

Credit 2.0 Innovative Wastewater Technologies *(changed)*
Credit 3.3 Water Use Reduction, 20%> Total Building Water Use *(added)*

### *Energy & Atmosphere*

Prerequisite 1 Fundamental Commissioning & Energy Efficiency Validation *(changed)*
Prerequisite 4 Minimum Energy Metering & Reporting of DCiE Metric *(added)*
Credit 1 Enhanced Energy Sub-Metering & Automated Reporting
of Metrics of Performance *(added)*
Credit 2 Optimize Infrastructure Energy Performance, Above ASHRAE 90.1 *(changed)*
Credit 3 On-Site Renewable Energy *(changed)*
Credit 4 On-Site Generation, Based upon Reduction in Source Energy *(added)*
Credit 5 Enhanced Commissioning *(changed)*
Credit 7, Enhanced Environmental Measurement & Verification *(changed)*
Credit 8, Green Power *(changed)*

### *Materials and Resources*

Credit 6 Rapidly Renewable Materials *(deleted)*
Credit 7 Certified Wood *(deleted)*

### *Indoor Environmental Quality*

Prerequisite 2 Environmental Tobacco Smoke (ETS) Control *(deleted)*
Credit 2.0 Increased Ventilation *(deleted)*
Credit 4.3 Low-Emitting Materials: Carpet Systems *(deleted)*
Credit 4.4 Low-Emitting Materials: Composite Wood & Agrifiber Products *(deleted)*
Credit 5 Indoor Chemical and Pollution Source Control *(deleted)*
Credit 6.2 Controllability of Systems: Thermal Comfort *(deleted)*
Credit 7.0 Acoustic Environment *(added)*
Credit 7.1 Thermal Comfort, Design *(deleted)*
Credit 7.2 Thermal Comfort, Verification *(deleted)*
Credit 8.1 Daylighting and Views: Daylight for 75% of Spaces *(deleted)*
Credit 8.2 Daylighting and Views: Views for 90% of Spaces *(deleted)*

### *Innovation in Design*

Credit 1.1 Innovation in Design *(Changed)*
Credit 1.2 through 1.8 Innovation in Design *(Changed)*

# Sustainable Sites

## Credits 4.1 – 4.4 Alternative Transportation *(deleted credits)*

### Rationale for Deletion

Data centers are designed to house computing equipment and have a very small number of building occupants per square foot as compared to commercial buildings. Therefore, the transportation impact of the occupants is not significant when compared to the data center building energy usage, hence the reason for deleting these commuting impact credits.

## Credits 4.1 – 4.4 Alternative Transportation *(deleted credits)*

### Rationale for Deletion

Data centers are designed to house computing equipment and have a very small number of building occupants per square foot

## Prerequisite 2 Fuel Storage & Handling, Storm Water Discharge Protection *(new prerequisite)*

### Intent

Prevent the release of hydrocarbons and other pollutants from oil spills or leaks that may occur during re-fueling of all on-site storage into the soil, ground water and storm system.

### Requirements

Means to prevent leaks or spills of all oils from being released into the storm drain system or back into the environment. Oils are as defined by the US EPA CFR Title 40 Parts 110 and 112.

### Potential Technologies & Strategies

Consider the installation of shut-off valves and filter media inserts in storm water catch basins that require storm events to be filtered to capture hydrocarbons and other fine pollutants, oil/water separators and designs to capture vent pipe overflows during filling or running operations.

## Credit 5.3 Site Development, Impacts to Local Infrastructure *(new credit)*

### Intent

To incent the consideration of the impact to local infrastructure during the data center center site selection and development process. As a minimum, impacts to be considered shall include site source energy generation emissions and transmission losses; municipal water supply, sewage and waste water treatment systems.

### Requirements

As part of the site selection process, the data center design team shall assess the potential sites and compare the impact to local infrastructure including the need for additional utility sub-station and transmission capacity, water and waste water storage and pumping stations and waste water treatment capacity.

In addition, the design team shall calculate the equivalent GHG emissions for each site based upon the data center's proposed total source energy requirement, using the ENERGY STAR CO2e emission factor, Table 8.1.1 –A for each fuel in the data center's total annual energy fuel mix. The data center may use up to 25% of off-site renewable electricity; (renewable energy certificates or "green power") and may subtract the associated CO2e emissions from the total CO2e emissions for the building, provided the contracts have duration of at least 2 years.

To apply for this point, the data center developer shall include this comparison in their application along with a justification of how the site selected provided the least impact to local infrastructure and the environment, based upon total source GHG emissions from energy generation and transmission.

### Potential Technologies & Strategies

Consider sites with higher percentages of energy generated from renewable sources, including solar and wind power; hydroelectric; and geo-thermal. Also consider sites with existing local infrastructure, such as the ability to use waste heat and adequate electric sub-stations and power transmission, water and sewage lines.

### Rationale for Addition

Data centers consume up to 100 times more energy per square foot than commercial buildings and may create a significant impact to both local infrastructure and the resulting GHG emissions depending upon where they are sited. Reducing the need for construction of power and water infrastructure and selecting a site where the source energy is generated and delivered at the lowest GHG emissions should be encouraged.

## Credit 5.4 Site Development, Noise Impacts *(new credit)*

### Intent

To incent the consideration of the noise impact of the data center in the site development process. As a minimum, impacts to be considered shall include the site noise from stand-by generators, exhaust fans, air-cooled chillers, cooling towers or evaporative coolers. One point each is available for normal and emergency operations of the data center for reducing the sound level below the locally mandated requirement by a minimum of 10%.

### Requirements

As part of the site development process, the data center design team shall assess the potential noise impact to neighbors including evaluating alternatives for equipment

placement on the building or site, sound barriers, etc. to not increase the noise levels adjacent to the site from current levels before development.

To apply for these points, the data center developer shall include calculations by the designer which show sound levels at the property line are less than required by the local planning authority. Where the existing sound levels at the property line already exceed the level required by the local planning authority, the design team needs to demonstrate that no additional noise is added to the surrounding environment either during normal and emergency operation of the facility at its full connected load design capacity. In addition where the sound level from offsite noise is above the level required by the local planning authority at the site boundary, the building itself should be sited and the spaces within the building acoustically located to provide isolation from outside noise.

### Potential Technologies & Strategies

Consider locating engine generators, cooling towers or evaporative coolers inside the facility and/or the use of sound barriers or retaining walls, attenuators, or other means to reduce the noise impact of the equipment to the environment from engine exhaust systems, as well as the radiator fans on the engine and the fans in cooling towers or evaporative coolers. Consider the use of slower speed or more sound efficient fans. Consider ground source well water to cool engine generators which eliminate the radiator fans. Consider alternative sources of engine generator power such as fuel cells or energy storage systems.

### Rationale for Addition

Data centers, especially during emergency operations where they are running large diesel generators for extended periods of time, or those that utilize combined heat and power generation systems may create a significant noise impact to the surrounding environment, depending upon where they are sited and how the equipment is selected or attenuated. Cooling tower or evaporative cooler fans can be extremely noisy, especially on the hottest days when the fans run at their highest speed. Reducing the noise impact beyond the site property line should be encouraged.

## Credit 5.5 Site Development, Air Quality and Emissions Impacts *(new credit)*

### Intent

To incent the consideration of the air quality and emissions impacts of the data center in the site development process. As a minimum, impacts to be considered shall include the emissions from engine generators and on-site power generation systems. Consideration of alternative low emission impact power systems such as solar and fuel cells should be encouraged.

### Requirements

As part of the site development process, the data center design team shall assess the potential air quality impact to the environment including evaluating alternatives for equipment selection, emissions reduction, on-going maintenance and testing, etc. to minimize the air quality and emissions impact of the facility.

To apply for this point, the data center developer shall include calculations by the designer that show that the Nitrogen Oxide (NOx) or Carbon Monoxide (CO) emissions are a minimum of 10% better than the local code requirement, unless the local code requirement is equal to the Bay Area Air Quality Management District emission limits, effective 1/12/2012 for all stationary internal combustion engines, Regulation 9, Rule 8. In these locations, the designer need only demonstrate that the proposed emissions will meet this level vs. exceeding the local code in order to apply for this credit. The designer shall also assure that the emissions of the equipment selected meets or exceeds EPA Tier 2 standards.

### Potential Technologies & Strategies

Consider selecting standby generators and power generation systems and emissions reduction systems that exceed the current requirements or use other means to improve the air quality and reduce the emissions impact of the data center to the environment.

Institute a management operation procedure to only perform monthly testing of generators during morning hours and on good air days, including verification methodology such as generator run log and/or owners written operating procedures.

### Rationale for Addition

Data centers, especially during emergency operations where they are running large diesel generators for extended periods of time, or those that utilize on-site power generation systems may create a significant air quality or emissions impact to the surrounding environment, depending upon where they are sited and how the equipment is selected or the emissions are treated. Reducing the air quality and emissions impact to the environment should be encouraged.

12-23-08

## Water Efficiency

### WE Credit 2: Innovative Wastewater Technologies *(changed credit)*

### Intent

Reduce generation of wastewater and potable water demand, while increasing the local aquifer recharge.

### Requirements

Options 1 or 2 may be used when applying for this credit, but the following change to the calculation of total building use to include other than potable water is required. Calculate and document baseline of annual total building water and wastewater use and on-site irrigation water use. The baseline for the proposed facility must include the total building water usage excluding evaporated water if utilized in calculations of wastewater and

potable water demand for credit. The method used to develop the baseline must be included with documentation of this credit.

### Rationale for Change

Central cooling systems in data centers, especially those using cooling towers utilize a significant amount of water for blow-down and should be included in the total building water calculations.

## WE Credit 3.3: Water Use Reduction: 20% or Greater Reduction *(new credit)*

### Intent

Maximize water efficiency within the data center to reduce the burden on municipal water supply and wastewater systems.

### Requirements

Calculate and document baseline of annual total building water use wastewater. The baseline for the proposed facility must include the total building water usage including evaporated cooling system water usage, including cooling tower blow down, if utilized in calculations of wastewater and potable water demand for credit. The method used to develop the baseline must be included with documentation of this credit and the base and proposed building design must maintain the same level of minimum water solubility.

Employ strategies that in aggregate use less water than the total building water use baseline calculated for the building (not including irrigation).

| % Reduction | Water Efficiency Points |
|---|---|
| 20% | 2 |
| 30% | 4 |
| 40% | 6 |

### Potential Technologies & Strategies

Consider reuse of storm water and grey water for non-potable applications such as cooling tower makeup, emergency storage, etc. Consider condensate re-use and rainwater reclamation. Consider equipping cooling tower(s) with drift eliminators. Design cooling tower systems to limit the amount of water used for blow down by using other means other than chemical treatment to prevent equipment scaling while achieving higher number of cycles of concentration for makeup water or discharge conductivity. Consider airside free cooling technologies which reduce water consumption where climatic conditions are favorable. Also consider ground source cooling technologies such as wells, buried ground loops, lake and river cooling where appropriate.

Assure that the building water systems provide for turn down of water use as energy efficiency of the mechanical systems is improved. Design the central water cooling system to use less water than the standard design by selection and integration of the equipment, controls and piping.

Consider alternative heat rejection systems such as dry-coolers, glycol, etc. that eliminate the requirement for cooling towers.

### Rationale for Addition

Cooling system water use can be very significant in data centers depending upon location and climate. Reducing water use and the resulting pumping energy and the energy, chemicals and resources required to treat the resulting wastewater discharge should be encouraged. Combining this credit with the domestic water efficiency credit did not seem feasible because:

- There is no way to document the baseline usage in a similar manner to domestic water fixtures (which uses the minimum specifications in the 1992 Energy Policy Act).
- The two points available for the domestic water credit does not sufficiently reward the effort to reduce cooling system water use in data centers. Data centers are very technical facilities that have a variety of possible options to design a sustainable project that this credit rewards.
- The methods, strategies and technologies for domestic and process water use are different.

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## Energy & Atmosphere

### Prerequisite 1: Commissioning & EPC Validation of the Building Energy Systems *(Modification of the existing LEED prerequisite)*

### Intent

Verify that the data center's energy related systems are installed, calibrated and perform according to the owner's project requirements, basis of design, construction documents and that they meet the minimum ASHRAE 90.1, 2007 standards for cooling system energy coefficient of performance (COP); adjusted sensible coefficient of performance (ASCOP) requirements and minimum requirements for electrical systems including but not limited to the primary and distribution transformers, Uninterruptible Backup Power Systems and batteries or other energy storage system, Power Distribution Units (PDU) equipment. Commissioning and energy efficiency validation will also address all mechanical equipment including chillers or air conditioning compressors, heat rejection equipment including dry coolers or cooling towers, thermal storage systems, computer room air conditioning units, and all associated pumps, heat exchangers, air or water economizers, make-up air handlers or humidification systems, control air compressors and automation and control systems required for building and computer room heating, ventilation and air conditioning. Fundamental commissioning will also address lighting and all other energy consuming systems required for building operation.

### Benefits of Commissioning & Energy Efficiency Validation

Benefits of commissioning and energy efficiency validation include reduced energy use, lower operating costs, and verification that the systems perform in accordance with the

owner's project requirements and that the energy efficiency design objectives have been met.

### Requirements

The following commissioning and energy efficiency validation process activities shall be completed by the commissioning/validation team, in accordance with the Data Center EPC for New Construction 2.2 application guide.

1. Designate an individual as the Commissioning/Validation Authority (CVxA) to lead, review and oversee the commissioning/validation process activities.
    a. The CVxA shall have documented commissioning and energy efficiency validation authority expertise in at least two data center projects of comparable scale or larger.
    b. The individual serving as the CVxA shall be independent of the project's design and construction management though they may be employees of the firms providing those services. The CVxA may be a qualified employee or consultant to the Owner.
    c. The CVxA shall report results, findings and recommendations directly to the Owner.
2. The Owner shall document the Owner's Project Requirements (OPR). The design team shall develop the Basis of Design (BOD). The CVxA shall review these documents for clarity and completeness. The Owner and design team shall be responsible for updates to their respective documents.
3. Develop and incorporate commissioning and validation requirements into the construction documents using the current ASHRAE/NIBS Guideline 0-05: Article 5,6 and 7 for the following systems at a minimum:
    a. The mechanical plant, including chillers, heat rejection, thermal storage, pumps, air handlers, make-up air and humidification system, and cooling units for the computer and data processing room; mechanical and electrical support rooms and any other general administrative spaces
    b. The electrical power transformation and distribution systems including on site utility sub-station equipment, building transformers, engine generators, uninterruptible backup power systems, and PDUs.
    c. The building lighting system.
    d. Renewable energy systems (solar, wind, etc.)
    e. On-site power generation systems (cogeneration, fuel-cell)
4. Develop and implement a commissioning and validation plan.
5. Verify the installation and performance of the systems to be commissioned and validated at multiple load points to verify energy efficiency performance to design criteria during normal utility operations, maintenance operations and failure conditions.

6. Include in the final commissioning/validation report the data centers DCiE (including all energy sources) at partial (25%, 50%, and 75%) and full design load conditions. Use artificial loads to simulate computer equipment load. For each load point, allow environmental conditions to stabilize for at least one hour before moving to the next partial load point. Identify computer room temperature and relative humidity conditions at representative cold aisle inlet at the top of the planned IT equipment racks for at least two points in each cold aisle in the data center, supply and return temperature and humidity if applicable at each computer room air handling unit. If measured conditions are different than design assumptions, project the energy required to achieve design conditions. Identify outside weather conditions during commissioning and the effect of any free-cooling benefit.
7. Project the anticipated annual DCiE based on historical average weather conditions for the site, including component DCiE data for the mechanical and electrical systems components, including as a minimum: central cooling plant; including all chillers, heat rejection system (cooling towers or dry coolers), heat exchangers, and pumps); computer room or air handler fans; electrical transformation, storage and distribution losses; and on-site energy and power generation systems if applicable. The DCiE and its component constituents will be used for verification and acceptance by the Owner that the design and construction of the building's energy systems meets the project requirements.
8. Prior to commissioning and validation, the CVxA shall review the operations and maintenance manuals provided by the Construction Manager for all mechanical, electrical, energy and power generation systems and following commissioning and validation provide written comments where systems operating conditions were found to be different than designed or documented in the manuals.

### Rationale for Modification

Data centers are very technical facilities that have complex and interacting mechanical and electrical systems that are unique to the building type and that need to be commissioned and validated for sustainable projects that this credit rewards.

### Prerequisite 2: Minimum Energy Performance Required *(Modification of the existing LEED prerequisite)*

### Intent

Establish the minimum level of energy efficiency for the proposed building and systems.

### Requirement 1:

Design the building project to comply with —

(a) The mandatory provisions (Sections 5.4, 6.4, 7.4, 8.4, 9.4 and 10.4) of ASHRAE/IESNA Standard 90.1-2007 (without amendments); and

(b) The prescriptive requirements (Sections 5.5, 6.5, 7.5 and 9.5) or performance requirements (Section 11) of ASHRAE/IESNA Standard 90.1-2007 (without amendments).

### Requirement 2:

A team shall be formed and shall meet regularly as required over the planning, design, construction and commissioning of the data center project. The team shall be comprised of the following functions:

- Owner's representative responsible for site selection and development for the project.
- Owner's representative responsible for source and site energy utilization and green house gas emissions for the project.
- Owner's representative responsible for the design and construction of the project.
- Owner's facilities engineering and operations representative who will be responsible for operation of the mechanical and electrical plant for the project.
- Owner's IT end-user group(s) and data center IT operations team who will own and operate the IT equipment in the data center.
- One or more members of the Architectural/Engineering (A/E) and Construction Management team who will design and build the project.
- Commissioning and Energy Efficiency Validation Authority who will independently evaluate the operational performance of the building, mechanical and electrical systems to the design.

Each function shall be represented by an individual who independently and conscientiously represents the availability, performance, cost, schedule and environmental impact interests of their function.

The team shall, at a minimum, do the following:

- Determine and document the initial (1 year), near term (3 year) and ultimate required power and cooling requirements of the IT equipment to be housed in the data center. Because name plate data for IT equipment heat load is typically based upon the peak power requirement for the maximum available equipment configuration, where possible bench test the equipment the data center intends to house and use the measured power data at 100% utilization when calculating the total initial load requirements for computing and storage equipment power.
- Because name plate or published efficiency data for mechanical and electrical systems is typically based upon full and not partial load, where possible measured data from a similar data center for the type of equipment the data center is intended to house, should be used for estimating system efficiency at the initial, near term and ultimately planned design load.
- Document proposed future expansion plans for the data center including the planned IT and support power load for each addition or phase until the data center reaches the full design capacity.
- Document allowances for IT growth for the first year following completion of the facility with separate categories for existing application growth, new applications and acquisitions and consolidations. The objective is to identify compounding

safety factors that could result in future over capacity to eliminate inefficient operation at part load.

- Document that the basis of design for the data center environmental conditions: (temperature, relative humidity and air quality) are based upon ASHRAE TC 9.9. Document the rationale for requiring environmental conditions at the inlet to the equipment outside the recommended ranges in applicable standards or equipment specifications, if operation outside the recommended ranges decreases energy efficiency of the data center.
- Determine the necessary level of redundancy required in the data center electrical and mechanical building systems required for the planned business use of the data center over its intended life-cycle, based upon the Uptime Institute's Tier Classification system designation and current specifications provided by the IT manufacturers.

### Technologies and Strategies

Design the building envelope, mechanical and electrical plant (including uninterruptible backup power systems, and critical load distribution, mechanical systems for the computer rooms, building HVAC, lighting, and other building systems to maximize energy performance. The ASHRAE 90.1-2007 User's Manual contains worksheets that can be used to document compliance with this prerequisite. For projects pursuing points under EA Credit 1, the computer simulation model may be used to confirm satisfaction of this prerequisite.

If a local code has demonstrated quantitative and textual equivalence following, at a minimum, the U.S. Department of Energy standard process for commercial energy code determination, then it may be used to satisfy this prerequisite in lieu of ASHRAE 90.1-2007. Details on the DOE process for commercial energy code determination can be found at www.energycodes.gov/implement/determinations_com.stm.

### Rationale for modifying this prerequisite

Requirement 2: The utilization level of data center's mechanical and electrical systems is affected by the required level of redundancy in data center's cooling and IT power conditioning systems. Within the energy efficiency community, and less so within the user community, there is a wide range of and debate over required levels of redundancy and environmental conditions necessary for data centers. While the EPC cannot prescribe a particular level of equipment redundancy; utilization or environmental conditions that a data center should operate at, the intent of this prerequisite is to ensure that owner's IT, critical facilities infrastructure and design team do not use excessively conservative requirements without due analysis and consideration of alternatives.

Experience has shown that new projects often start out with assuming high levels of IT load that in practice take years to develop. Until this load develops, the data center operates at low utilization and is typically energy inefficient. The Team should demonstrate that they discussed initial and future load assumptions and investigated options for making mechanical and electrical capacity increases correspond with IT load

increases to achieve a higher operating point by balancing load and capacity for optimal energy efficiency. Another option to be considered would be specifying a significantly higher level of part load efficiency, (i.e. 15 to 40 percent loads) for uninterruptible backup power systems and chillers than would be typical, so that if the IT load did not develop as planned, the planned energy efficiency of the data center would still be high. This plan should also require turning off other installed equipment, such as computer room cooling units to balance load with capacity.

## Prerequisite 4: Minimum Energy Metering *(Added)*

### Intent

By requiring that the data center DCiE from all energy sources be measured and trended over time; the building owner and/or operator will be able to verify that the building's energy related systems are performing according to the basis of design.

### Requirements

The data center shall be equipped at a minimum with energy metering to provide total facility power and energy usage and total IT Equipment power and energy usage on a historical basis. The number and type of meters that are required to be installed shall be determined by the data center design, but at the minimum shall be one percent accuracy, full-scale and provided to meter all forms of energy to the data center, (electricity, natural gas, steam, chilled water, one-pass cooling, etc.) and at the output of the uninterruptible backup power systems or power distribution units (PDUs) that serve the IT equipment. If the data center uses on-site renewable energy or on-site energy generation, the data center shall be equipped at a minimum with power and energy metering to total power and energy input and output and net power and energy to the utility and the building.

### Rationale for Addition

Data center energy use can be very significant depending upon size and design of the facility, the location and climate. Measuring power and energy use on a historical basis provides a data center owner with the information necessary to determine opportunities to improve their data center's operational efficiency and how their data center compares with similarly designed data centers.

Verify that the data center's energy related systems are installed, calibrated and perform according to the owner's project requirements, basis of design, construction documents and to enable the data center operator to understand how the data center performs as IT equipment is installed. The addition of these meters will also enable the data center operator to participate in the Energy Star program and to benchmark the data center's performance with similar data centers.

## Credit 1: Enhanced Energy Sub-metering & Automated Reporting of Metrics of Performance *(Added)*

### Intent

By permanently installing enhanced energy sub-metering and automating the ongoing reporting of its component constituents and performance metrics, the building owner and/or operator will be able to verify that the building's energy related systems are performing according to the basis of design and manufacturer's specifications for efficiency performance at both partial load and full-load conditions.

### Requirements

The data center shall be equipped with energy metering to provide power and energy usage for the facility's power transformation and distribution systems, cooling systems and any on-site generation and trending of these metrics on a historical basis. The number and type of meters that are required to be installed shall be determined by the data center design, but at the minimum shall be one percent accuracy, full-scale and provided to sub-meter the electrical and mechanical systems as follows:

1. Lighting and lighting controls: power (kW) and consumption (kWh) by data center room.
2. Electrical power (kW) and consumption (kWh) or other energy sources for all mechanical cooling systems including (chillers, cooling towers, chilled water and condenser water pumps, cooling tower sump heaters or equivalent mechanical equipment for DX systems.)
3. Chilled water generation or equivalent for DX systems: tons, (based upon chilled water flow, supply and return temperature), and kW/ton or equivalent if other energy sources are used.
4. Heating water or steam generation: energy kBTU/per energy unit input.
5. Computer room cooling systems: power (kW) and consumption (kWH).
6. Uninterruptible backup power systems: power (kW) input and power output (kW) and consumption (kWH) input and output for each uninterruptible backup power systems.
7. Engine generator power equipment: power (kW) output and consumption (kWh) for each generator. Fuel consumption (diesel or natural gas) for all generators.
8. On-site renewable energy power generation: production power (kW) and production (kWH), and site specific weather characteristics (irradiance, wind, and temperature)
9. On-site power generation: production power (kW) and production (kWh).

The points shall be awarded on a sliding scale for sub-metering the electrical and mechanical systems as follows:

**Data Center with no on-site renewable or power generation:**

Requirement 1: 1 Point

Requirements 2-5: 3 Points

Requirement 6-7: 2 Points

**Data Center with on-site renewable and/or power generation:**

Requirement 1: 1 Point

Requirements 2-5: 2 Points

Requirements 6-7: 2 Point

Requirements 8-9: 1 Point

### Rationale for Addition

Data center energy use can vary significantly depending upon size and design of the facility, the location and local weather conditions. Measuring energy use and reporting these metrics provides a data center owner with the baseline information necessary to determine opportunities to improve their data center's operational efficiency and how their data center compares with similarly designed data centers in their climate zone.

## EA Credit 2: Optimize Energy Performance *(Modification of the existing credit)*

### Intent

Achieve increasing levels of energy performance above the baseline in the prerequisite standard to reduce environmental and economic impacts associated with excessive energy use.

### Requirements

Achieve increasing levels of energy performance above the baseline in the prerequisite standard to reduce environmental and economic impacts associated with excessive energy use.

The 90.1 baseline requirements for a new Data Center (Class 1 as defined in the ASHRAE Thermal Guidelines for Data Processing Environment) shall have a DCiE Equal to or less than the DCIE specified in Table 1 depending upon Climate Zone and Data Center Type (Tier I thru Tier IV as defined in the Uptime Institute Tier Classifications Define Site Infrastructure Performance). The DCiE shall be based upon full build out or design DCiE and not startup DCiE which will generally be higher and unable to the requirements of Table 1.

| DCiE by Climate Zone & Data Center Type | | | | |
|---|---|---|---|---|
| | **Tier I** | **Tier II** | **Tier III** | **Tier IV** |
| **1A** | 0.56 | 0.53 | 0.52 | 0.50 |
| **2A** | 0.57 | 0.55 | 0.53 | 0.52 |
| **3A** | 0.59 | 0.57 | 0.55 | 0.53 |
| **4A** | 0.61 | 0.59 | 0.57 | 0.55 |
| **5A** | 0.64 | 0.61 | 0.59 | 0.56 |
| **6A** | 0.66 | 0.63 | 0.61 | 0.58 |
| **7A** | 0.68 | 0.66 | 0.63 | 0.60 |
| **8A** | 0.71 | 0.68 | 0.65 | 0.63 |

| | **Tier I** | **Tier II** | **Tier III** | **Tier IV** |
|---|---|---|---|---|
| **1B** | 0.59 | 0.56 | 0.55 | 0.53 |
| **2B** | 0.61 | 0.58 | 0.56 | 0.54 |
| **3B** | 0.63 | 0.61 | 0.58 | 0.56 |
| **4B** | 0.65 | 0.63 | 0.60 | 0.58 |
| **5B** | 0.68 | 0.65 | 0.63 | 0.60 |
| **6B** | 0.71 | 0.68 | 0.65 | 0.62 |
| **7B** | 0.74 | 0.70 | 0.67 | 0.64 |
| **8B** | 0.77 | 0.73 | 0.70 | 0.67 |

| | **Tier I** | **Tier II** | **Tier III** | **Tier IV** |
|---|---|---|---|---|
| **1C** | 0.57 | 0.55 | 0.53 | 0.51 |
| **2C** | 0.59 | 0.57 | 0.55 | 0.53 |
| **3C** | 0.61 | 0.59 | 0.56 | 0.54 |
| **4C** | 0.63 | 0.61 | 0.58 | 0.56 |
| **5C** | 0.66 | 0.63 | 0.61 | 0.58 |
| **6C** | 0.68 | 0.65 | 0.63 | 0.60 |
| **7C** | 0.71 | 0.68 | 0.65 | 0.62 |
| **8C** | 0.74 | 0.70 | 0.68 | 0.65 |

Table 1: DCIE by Climate Zone & Data Center Type, ASHRAE TC9.9 Committee, 4/28/08

Project teams documenting achievement using a whole building energy simulation are assumed to be in compliance with EA Prerequisite 2. The Project Team shall perform a whole building energy simulation including technology systems at both 100% design load and at the partial load conditions of the data center as determined in Prerequisite 2, Rule 2 at the end of the first year's operation.

If the demonstrated percentage improvement in the proposed building performance rating compared to the baseline building performance rating at partial data center design power load is less than 75% of the percentage improvement at full data center design power load, then the points achieved shall be reduced by a factor of 2.

NOTE: EPC for New Construction projects are required to achieve at least ten (10) points under EAc2.

WHOLE BUILDING ENERGY SIMULATION INCLUDING TECHNOLOGY SYSTEMS (10–34 Points)

Demonstrate a percentage improvement in the proposed building performance rating compared to the baseline building performance rating per ASHRAE/IESNA Standard 90.1-2007 (without amendments) by a whole building project simulation using the Building Performance Rating Method in Appendix G of the Standard (with changes as indicated below).

The minimum energy cost savings percentage for each point threshold is as follows:

| New Buildings | Existing Building Renovations | Points |
|---|---|---|
| 5.0% | 2.0% | 10 |
| 7.0% | 3.5% | 14 |
| 9.0% | 5.0% | 18 |
| 10.5% | 7.0% | 24 |
| 12.0% | 8.0% | 28 |
| 14% | 10.5% | 30 |
| 16.0% | 12.0% | 32 |
| 17.5% | 14.0% | 34 |

Appendix G of Standard 90.1-2007 requires that the energy analysis done for the Building Performance Rating Method include ALL of the energy costs within and associated with the building project, including the IT equipment load. To achieve points using this credit, the proposed design—

- must comply with the mandatory provisions (Sections 5.4, 6.4, 7.4, 8.4, 9.4 and 10.4) in Standard 90.1-2007 (without amendments);
- must include all the energy costs within and associated with the building project; and must be compared against a baseline building that complies with Appendix G to Standard 90.1-2007 (without amendments). The baseline building rating shall include the electrical requirements and corresponding cooling loads for the technology systems.

For EA Credit 2, technology system electrical loads shall be identical for both the baseline building performance rating and for the proposed building performance rating. However, project teams may follow the Exceptional Calculation Method (ASHRAE 90.1-2007 G2.5) to document measures that reduce technology system electrical requirements. Documentation of technology system electrical requirements energy savings shall include a list of the assumptions made for both the base and proposed design, and theoretical or empirical information supporting these assumptions.

## Potential Technologies & Strategies

Design the building envelope and systems to maximize energy performance. Use a computer simulation model to assess the energy performance and identify the most cost-effective energy efficiency measures. Quantify energy performance as compared to a baseline building.

If a local code has demonstrated quantitative and textual equivalence following, at a minimum, the U.S. Department of Energy standard process for commercial energy code determination, then the results of that analysis may be used to correlate local code performance with ASHRAE 90.1-2007. Details on the DOE process for commercial energy code determination can be found at www.energycodes.gov/implement/determinations_com.stm.

Changes to Appendix G of Standard 90.1-2007 to be used for data center projects:

G1,4 c. – The input and output reports must include the energy breakdown of the following component (where applicable):

| Component | Notes |
|---|---|
| **IT Equipment** | Include the full design kW/rack power for all compute and storage servers, networking equipment and any other technology equipment that will be located in the computer and data processing rooms. |
| **Mechanical Systems** | |
| Computer and Computer Hardware Process (formerly called mainframe water cooling) | Include all mechanical systems (heating, cooling, dehumidification, humidification, ventilation and exhaust systems that directly support computer equipment or indirectly support the computer equipment (like uninterruptible backup power systems and battery room make-up and exhaust and other mechanical and electrical support spaces) |
| CRAC – Air Cooled | Include both the computer room unit with internal refrigeration compressor and external condensing unit |
| CRAH – Water Cooled | Include indoor unit and heat rejection equipment but not pumping |
| CDPR – Water Cooled with Economizer Coil | Include indoor unit and heat rejection equipment but not pumping |
| CDPR – Glycol Cooled | Include indoor unit and dry cooler but not pumping |

| | |
|---|---|
| CDPR – Glycol Cooled with Economizer Coil | Include indoor unit and dry cooler but not pumping |
| CPPR – Chilled Water | Include only indoor unit |
| Heat Rejection | Only use for chilled water systems |
| Open Cooling Towers | Use for indoor packaged water cooled chillers |
| Fluid Coolers | Use for indoor packaged water cooled chillers |
| Evaporative-cooled Condensers | Use for indoor water chiller with remote condenser |
| Air-cooled Condensers | Use for indoor water chiller with remote condenser |
| Fans | |
| CDPR Air Conditioning Units | |
| Other indirect support equipment | e.g. chiller room, mechanical substation room, uninterruptible backup power systems room, battery rooms, load bank substation room |
| Pumping | |
| Chilled Water | |
| Condenser Water<br>Glycol | |
| Heating Hot Water | |
| Spray Pumps | For evaporative cooled rejection equipment |
| Heating | |
| Humidification and Dehumidification | |
| **Electrical Systems** | |
| Lighting | For CDPR and support areas only |
| Primary MV to LV Transformer | $=kW_{in} – kW_{out}$ |
| Uninterruptible backup power systems | $=kW_{in} – kW_{out}$ |
| Power Distribution Units | $=kW_{in} – kW_{out}$ |

### Rationale for Modification

Because data centers are from 10-100 times as energy intensive as an office building it is very difficult and expensive to attain the percentage thresholds for commercial buildings. Accordingly, we have decreased the thresholds while substantially increasing the energy points to reflect that the energy systems are the most significant environmental impact of data centers.

## EA Credit 3: On-site Renewable Energy *(Modification of the existing LEED credit)*

### Intent

Encourage and recognize increasing levels of on-site renewable energy self-supply in order to reduce environmental and economic impacts associated with fossil fuel energy use and transmission distribution losses.

### Requirements

Use on-site renewable energy systems to offset building energy cost. Calculate project performance by expressing the energy produced by the renewable systems as a percentage of the average peak power (kW) of the data center using the table below to determine the number of points achieved.

Use the building annual energy cost calculated in EA Credit 2.

| % Renewable | Energy Points |
|---|---|
| 2.5% | 2 |
| 5.0% | 4 |
| 7.5% | 6 |
| 12.5% | 8 |
| 15.0% | 10 |
| 20.0% | 12 |

### Technologies and Strategies

Assess the project for non-polluting and renewable energy potential including solar, wind, geothermal, low-impact hydro, bio-mass and bio-gas strategies. When applying these strategies, take advantage of net metering with the local utility.

### Rationale for modification

Because Data Centers are from 10-100 times as energy intensive as an office building, the current availability and technology for on-site renewable energy makes it possible, although difficult and expensive to exceed the percentage thresholds for commercial buildings. Accordingly, we have increased the thresholds while substantially increasing the energy points.

## EA Credit 4: On-site Generation *(New credit)*

### Intent

Encourage and recognize increasing levels of on-site power generation in order to reduce environmental and economic impacts associated with fossil fuel energy use and transmission losses from utility power plants.

### Requirements

Use on-site generation energy systems to offset building energy cost. Calculate project performance by expressing the energy produced by the on-site systems as a percentage of reduction in source energy use and using the table below to determine the number of points achieved.

Use the building annual source energy use calculated in EA Credit 2.

| % On-Site Generation | Energy Points |
|---|---|
| 7.5.0% | 1 |
| 12.5% | 2 |
| 15.0% | 3 |

### Technologies and Strategies

Assess the project for on-site energy generation potential including fuel cell strategies. When applying these strategies, take advantage of net metering with the local utility.

### Rationale for addition

Because data Centers are anywhere from 10-100 times as energy intensive as an office building, the current availability and technology for on-site generation of energy makes it economically possible to reduce source energy use by on-site energy generation in a data center. Accordingly, we have added this strategy and energy points for achieving certain levels of source energy reduction.

## EA 5: Enhanced Measurement and Verification *(Modification of the existing LEED credit)*

### Intent

Provide for the ongoing environmental operating conditions and accountability of building energy consumption over time.

### Requirements

Develop and implement an enhanced Measurement & Verification (M&V) Plan consistent with Option D: Calibrated Simulation (Savings Estimation Method 2), or Option B: Energy Conservation Measure Isolation, as specified in the *International Performance Measurement & Verification Protocol (IPMVP) Volume III: Concepts and Options for Determining Energy Savings in New Construction, April, 2003.*

The M&V period shall cover a period of no less than one year of post-construction occupancy and provide a report of the environmental operating conditions of the data center and the data center energy performance metrics, DCiE. Hourly average DCiE shall be provided to enable M&V of the data center energy efficiency performance over the first year of operation.

### Technologies and Strategies

Develop an M&V Plan to evaluate data center environmental operating conditions and energy system performance. Characterize the building and/or data center energy systems through energy simulation or engineering analysis. Install the necessary measurement and metering equipment to validate the data center environmental conditions and measure energy use. Track performance by comparing performance at the closest predicted partial load point (25%, 50%, 75% and 100%) to actual performance at a specific load point, broken down by temperature differential across computer room cooling systems, average cold aisle and hot aisle temperature differential by room zone where each zone is pre-assigned a computer hardware load density, air flow or pressure differential across the computer room, and temperature differential across the central chilled water plant. Evaluate energy efficiency by comparing actual performance to baseline performance.

While the IPMVP describes specific actions for verifying savings associated with energy conservation measures (ECMs) and strategies, this LEED credit expands upon typical IPMVP M&V objectives. M&V activities should not necessarily be confined to energy systems where ECMs or energy conservation strategies have been implemented. The IPMVP provides guidance on M&V strategies and their appropriate applications for various situations. These strategies should be used in conjunction with monitoring and trend logging of significant energy systems to provide for the ongoing accountability of building energy performance and the establishment of seasonal profiles to assist operator predictability of the use of free and partial free-cooling opportunity.

### Rationale for modification

The purpose of including measurement of the data center environmental conditions and the temperature differentials across the cooling systems, along with total power and electrical consumption for the data center and the IT equipment is to inform users of how utilization levels and climatic changes affect the data center efficiency. Continuous measurement of these data center environmental conditions and energy efficiency metrics keeps real time information in front of the user to show the effect of their actions. The measuring device can also serve as an additional indicator of proper mechanical and electrical support systems operation and maintenance.

## EA Credit 8: Renewable Source Power *(Modification of the existing LEED credit)*

### Intent

Encourage the development and use of grid-source, renewable energy technologies on a net zero pollution basis.

## Requirements

Provide at least 7.5% of the building's electricity from renewable sources by engaging in at least a two year renewable energy contract with a Green-e certified REC provider. Renewable sources are as defined by the Center for Resource Solutions (CRS) Green-e products certification requirements.

Use the building annual energy use (kWh) calculated in EA Credit 2.

| % Renewable | Energy Points |
|---|---|
| 7.5% | 1 |
| 12.5% | 2 |
| 15.0% | 3 |
| 17.5% | 4 |

DETERMINE THE BASELINE ELECTRICITY USE

Use the annual electricity consumption from the results of EA Credit 2.

## Technologies and Strategies

Determine the energy needs of the building and investigate opportunities to engage in a renewable source power contract. Green power is derived from solar, wind, geothermal, biomass or low-impact hydro sources. Visit www.green-e.org for details about the Green-e program. The power product purchased to comply with credit requirements need not be Green-e certified. Other sources of renewable power are eligible if they satisfy the Green-e program's technical requirements. Renewable energy certificates (RECs), tradable renewable certificates (TRCs), green tags and other forms of green power that comply with Green-e's technical requirements can be used to document compliance with EA Credit 6 requirements.

## Rationale for modification

Data centers are from 10-100 times as energy intensive as an office building. Thus it is much more difficult and expensive to achieve the same percentage thresholds as commercial buildings. Accordingly, we conservatively reduce the thresholds by dividing current LEED thresholds by 2.

# Materials & Resources

## Default Project Materials Cost
## Used in credit calculations for EPC MRc3 and MRc4

### Proposed modification:

The LEED NC Default Project Materials Cost is currently 45% of the project's total Construction Cost. The proposed EPC default project materials cost is 21%, which is 24% less than the LEED NC Default Project Materials Cost.

### Rationale:

LEED NC allows projects to use 45% of the project's total construction cost as a default value for the architectural trades' Material Cost –the denominator for credits MRc3, MRc4 and MRc5. This default is based on the construction cost of a commercial building, for which the EPC committee determined MEP and equipment costs make up about 24% of the total construction cost, (based upon an analysis done by the Labs 21 committee of 7 random projects.)

By comparison, MEP and equipment costs make up about 75% of a data center project's construction cost; based on the EPC committee's analysis of several data center projects. To account for the lower percentage of architectural trade costs in a data center project, the EPC committee multiplied 25% (the remainder of a data center's construction cost after 75% for MEP and equipment is deducted) by the LEED NC's assumption that 60% of the architectural trades construction cost is material cost. (This LEED NC assumption was figured backwards by the EPC committee based on the analysis that 76% of a commercial building's construction cost is architectural (i.e. not MEP and equipment): 45% * 76% = 60%.) The outcome of this multiplication was a revised architectural trades' material cost default of 15% for data center projects.

The LEED AGL architectural trades' Material Cost default is tied to the LEED NC default. If the LEED steering committee reduces the LEED NC default, the LEED AGL default shall be proportionally reduced.

## MR Credit 3.1: Materials Reuse: 5% *(modification to existing credit)*

### Intent

Reuse building materials and products in order to reduce demand for virgin materials and to reduce waste, thereby reducing impacts associated with the extraction and processing of virgin resources.

### Requirements

Use salvaged, refurbished or reused materials such that the sum of these materials constitutes at least 5%, based on cost, of the total value of all materials including the MEP trades.

Mechanical and electrical equipment and materials such as computer room cooling conditioning units, chillers, pipe and fittings, IT equipment racks, floor tiles, transformers,

paralleling switchgear, engine generators, uninterruptible backup power systems and PDU equipment, loadbanks, general electrical switchgear, electrical wire and cable may be included in this calculation. Only include materials permanently installed in the project.

### Technologies and Strategies

Identify opportunities to incorporate salvaged materials into building design and research potential material suppliers. Consider salvaged materials such as raised floor supports and floor tiles, IT equipment racks, electrical and mechanical equipment and components, etc.

## MR Credit 3.2: Materials Reuse: 10% *(modification to existing credit)*

### Intent

Reuse building materials and products in order to reduce demand for virgin materials and to reduce waste, thereby reducing impacts associated with the extraction and processing of virgin resources.

### Requirements

Use salvaged, refurbished or reused materials such that the sum of these materials constitutes at least 5%, based on cost, of the total value of all materials on the project, including the MEP trades.

Mechanical and electrical equipment and materials such as computer room cooling conditioning units, chillers, pipe and fittings, IT equipment racks, floor tiles, transformers, paralleling switchgear, engine generators, uninterruptible backup power systems and PDU equipment, loadbanks, general electrical switchgear, electrical wire and cable may be included in this calculation. Only include materials permanently installed in the project.

### Technologies and Strategies

Identify opportunities to incorporate salvaged materials into building design and research potential material suppliers. Consider salvaged materials such as raised floor supports and floor tiles, IT equipment racks, electrical and mechanical equipment and components, etc.

12-23-08

# Indoor Environmental Quality

## EQ Credit 7: Data Center Acoustic Environment (*New credit)*

### Intent

Demonstrate that the acoustic design targets are 10% lower than industry regulated levels.

### Requirement

Establish acoustic design targets and implement acoustic design strategies as required to exceed industry regulated levels for the following specific interior sound control performance targets including:

- Noise Criterion (NC)
- Room Criterion (RC)
- Building assembly Sound Transmission Class (STC)
- Outdoor-Indoor Transmission Class (OITC)

### Technologies and Strategies

Specify building assemblies including interior partitions, ceilings/floors, and exterior wall configurations to achieve specific acoustic design targets.

### Rationale for Addition

Attention to the acoustic environment of a data center is essential to protect the health and safety of data center workers from sustained noise levels that exceed 90 dB. The comfort of the data center users remains important but must be secondary to their protection. Unlike offices and other general purpose workspace, where ventilation air is provided for occupant comfort, in data center's high air flow rates may be required to cool the IT equipment; which may lead to a significantly workplace noise levels.

The EPC cannot prescribe a particular acoustic environment, because operational needs vary widely. The intent of this credit is to encourage data center owners to ensure that noise levels

12-23-08

# Innovation & Design Process

## ID Credit 1 – 1.8: Innovation in Design *(Modification of the existing credits)*

### Intent

To provide design teams and projects the opportunity to be awarded points for performance above the requirements set by the EPC for New Construction Green Data Center Rating System and/or innovative performance in Green Data Center categories not specifically addressed by the EPC.

### Requirements

Credit 1.1 ( 1 point) In writing, identify the intent of the proposed innovation credit, the proposed requirement for compliance, and the design approach (strategies) that might be used to meet the requirements.

Credit 1.2 through 1.8 (1 point each) Same as Credit 1.1

### Potential Technologies & Strategies

The following is a list of suggested areas for data center innovation credits. It is not meant to be an exhaustive or restrictive list, and innovations not on the list may also be candidates for innovation credits, provided that the strategies or measures demonstrate quantifiable energy efficiency or environmental benefits.

- Air Flow Management: Minimize the amount of recirculation of hot air and minimize by-pass air of cold air in the data center by designing physical separation or containment of either the hot or cold air streams. Successfully implemented, both measures result in energy savings and better thermal operating conditions.

  The recommended submittal to qualify for this measure is submission of the DOE DC Pro Air mixing metrics: Rack Cooling Index (RCI); Return Temperature Index (RTI) for the data center. RCI is a measure of how effectively the equipment is cooled and maintained within an intake temperature specification and should be ≥96%. RTI is a measure of the level of by-pass air or recirculation air in data centers and should be 100%, ±5%.

- Implement and utilize “free cooling” techniques, such as airside economizing, waterside economizing, indirect evaporative cooling, and heat wheel cooling – where applicable and to the maximum extent possible

- Passive cooling systems that eliminate the requirement for additional air distribution fan power

- Hot Water Heating using Heat Recovery from Data Center to serve adjacent spaces or facilities

- Reduction of Hazardous Materials on-site: Reduction of on-site hazardous materials, such as fuel storage, lead-acid batteries, etc.

- Energy Star IT Equipment: Greater than 75% of all servers, storage and networking equipment to be procured for the data center shall be ENERGY STAR qualified, under its Tier 1 specification and have power management enabled.
- Energy Use Sub-Metering by User: The data center is designed to enable sub-metering of IT electrical power (kW) and consumption (kWh) to specific internal business unit or external customers based upon utilization. In addition a mechanism to include either metered or allocated energy use for the additional data center cooling and electrical power losses is recommended.
- IT Asset Utilization Capability: The data center is designed to automatically track and report IT equipment utilization, power usage and IT productivity output metrics for IT server, storage and network equipment installed in the data center to enable full life cycle tracking, including end-of-life and decommissioning of obsolete or under utilized equipment.
- IT Asset e-Waste Recycling Program: Agreement by the data center owner to abide by the EPEAT™ and WEEE Directives and put in place a purchasing and e-waste recycling program for IT equipment used in the data center.
- Adaptive IT & Cooling Load Optimization: The data center cooling systems are capable of automatically increasing or decreasing their capacity to match the IT heat load to optimize the energy consumption of the support infrastructure at varying IT work loads.
- Enroll in the EPA ENERGY STAR program for buildings: Agreement by the data center owner to enroll the data center in the ENERGY STAR program for data centers.
- Perform a DOE assessment of the data center annually and report the resulting DCiE metrics and track the on-going continuous improvement in energy efficiency in the DOE on-line tool, DCPro.
- Enroll facility technicians in ongoing educational programs annually to enhance and demonstrate their growing competence in operating the complex and interacting mechanical and electrical systems in the data center at higher levels of energy efficiency performance than in the assumptions used in the original basis of design.
- Owner's Project Requirements Document: Assign a senior member of the design team the responsibility for development and justification of environmental and energy efficiency improvements are funded and justified for inclusion in the design. In addition this individual shall be responsible for assurance that life cycle costing, total cost of ownership and the environmental impact of the original design are considered if these design improvements are re-considered during the value engineering and construction phase of the data center.

# APPENDIX E:
# Contract Task 2.2.2 Evaluate Modular Cooling

## Evaluation for Modular, Scalable Overhead Cooling Systems

## In Data Centers

## Final Report

## To

## The California Energy Commission

**Issued:** **December 21, 2008**

**Prepared By:**

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# 1 Evaluation for Modular, Scalable Overhead Cooling System in Data Centers

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## 1.1 Problem Statement

Enterprise data centers and IT equipment product development and research data center labs require continuous cooling to maintain inlet air temperatures within recommended operating levels for the IT equipment. The consolidation and higher density aggregation of slim compute, storage and networking hardware has resulted in higher power density/ft² than the commonly used raised floor, CRAC design was originally conceived to handle.

The result is that in many existing data centers and in the majority of newly constructed data centers, the performance of the ventilation and cooling systems is less than optimal. Current IT computing trends indicate that IT equipment manufacturers are designing their equipment to operate in “conventional” data center environments by providing alternative cooling solutions to either their equipment or relying on supplemental cooling in rack or row systems.

This trend to higher power density resulting from current and future generations of servers has created significant opportunities for precision cooling suppliers to engineer and manufacture packaged modular and scalable systems that will significantly improve efficiency while solving the thermal challenges, improving reliability, and allowing for future needs and growth.

Such pre-engineered and manufactured systems may be a significant improvement over current design; however, without an energy efficiency focus, they could also lead to even lower energy efficiencies in the overall data center support infrastructure

The research objective of the project was to evaluate several commercially available, modular localized cooling systems to test the research thesis that these types of close coupled cooling solutions will be more energy efficient than traditional legacy data center cooling systems.

## 1.2 Technical objectives

This report is the result of a test plan that was developed with the participants’ input to include specific design characteristics of the selected modular localized cooling solution provided by vendor 1 for a data center located in Sun Microsystems, Inc. The evaluation included monitoring and measurement of selected parameters, and establishing and calculating energy efficiency metrics for the selected product, which is a modular, scalable overhead cooling system that was tested in a hot/cold aisle environment without separation, or containment or the hot or cold aisles. The scope is to quantify energy

performance of the modular cooling unit as it corresponds to server load and inlet air temperature.

The information generated from this testing when combined with a concurrent research study to document the energy efficiency of the host data center's central chilled water cooling plant can be used to estimate potential energy savings from implementing modular cooling compared to conventional cooling in data centers.

## *1.3 Technical information on the characteristics of modular, scalable cooling systems and servers*

### 1.3.1 Modular, scalable, overhead cooling system

Cooling system. The cooling system in this study is a pumped refrigerant cooling system designed for cooling data center IT equipment racks. This system was configured for a total cooling capacity of 80 kW, and consisted of one pump unit and eight cooling modules. A typical system consists of one pump unit and up to 16 cooling modules, and can provide up to 160 kW of cooling. Multiple cooling systems may be used for higher cooling demands.

Pump unit. The pump unit includes a pump that circulates the refrigerant and a refrigerant-to-water heat exchanger. This heat exchanger transfers heat from the pumped refrigerant into the chilled water that circulates through the pump unit and back to the central chilled water source.

Cooling module. Each cooling module contains two fans and an air-to-refrigerant heat exchanger. Hot air from the hot aisle was pulled into the cooling module and heat was transferred into the pumped refrigerant through the air-to-refrigerant heat exchanger. Cool air is then provided to the cold aisle in front of the computer racks.

The water flow rates in the pump unit as well as the airflow rates in the cooling modules were controlled with constant-speed pump and fans. Regardless of the cooling load, the power consumption of the cooling system was largely fixed. For the servers with varying loads in this study, some experiments were included with only one single fan running under partial load.

### 1.3.2 Servers

The IT or heat load in each server rack was provided by 40 standard Sun V20 1U servers, each with a size of 28"x17"x1.75". Due to data center space availability constraints for the study, and the high capital cost for servers, 320 servers were selected to be stacked in eight server racks. As a result, the maximum nominal load per server rack was designed to be 10 kW. Details of the servers provided in this study are publicly available [1].

### 1.3.3 Server power management

Using a commercially available software program as the "control program", the load within each rack was effectively controlled at desired levels by dynamically turning on and off servers and running the program [2] at various CPU loads to achieve the desired

power consumption and resulting heat load to test the energy efficiency of the modular cooling system. Prior to the test, reference measurements on each type of server that was being used in the racks were performed to measure idle and loaded power consumption.

To achieve the desired partial or full power load level (kW/rack) to be tested, the number of servers needed to run at 100% load was calculated and the program turned the rest off. For example to achieve the desired heat load levels in the test plan, the number of servers running at full load per rack were as follows: 10kW - 33 servers; 7.5kW - 25 servers; 5kW - 17 servers; 2.5kW - 9 servers.

Although all of the servers used in the test configuration were the same, the initial reference measurements identified that they had significantly different power consumption due to different memory or computing configurations installed.

Therefore, to achieve and maintain the desired full or partial power load per rack during each test sequence, the monitoring system collected real time measurements of server power from the rack power strips and the program used this information to turn on or off additional servers as necessary to maintain the desired power load levels.

To monitor the inlet air temperature being delivered to the test racks by the modular cooling system, air temperature probes were installed at the top, middle and bottom of each rack. To improve the response time of these sensors, the power to the servers installed at these rack elevations were maintained on during each testing sequence. Prior to starting a specific modular cooling system test sequence, the total power consumption at each rack was verified against the readings of the power strip and adjusted as needed until the power consumption was stable.

### 1.3.4 Equipment location

The server racks and cooling modules in this study were located in the northwest corner of the data center. Due to the space constraints, the space containing all server racks and cooling modules has floor dimensions of 8’6”x22’, and was separated from the rest of data center by an array of transparent curtains surrounding the server racks and eight cooling modules. Eight 42U server cabinets, each with the size of 29.5”by 42” by 78,” were oriented in a single row, with a common cold aisle (42” wide) on the inlet side of the servers, and a common hot aisle (18” wide) on the outlet side of the servers. Air from the surrounding CRAC units in the vicinity was intended to be blocked off using the curtains. The asymmetric arrangement between cold- and hot-aisles allowed sufficient cold-aisle space for normal air movement.

One overhead cooling module (sizing 14 inches high X 24 inches wide X 39 inches long) was positioned at 4.5 inches above the top of each of the eight server cabinets. The overhead cooling modules are designed to draw air from the hot aisle, pass it through the air-refrigerant heat exchanger and direct cold air to the cold aisle. The cold air delivered overhead to the cold aisle is then moved from the inlet of the servers through the rack to the hot aisle where the process repeats itself. Figure 1 and Figure 2 illustrate the general equipment layout in this study.

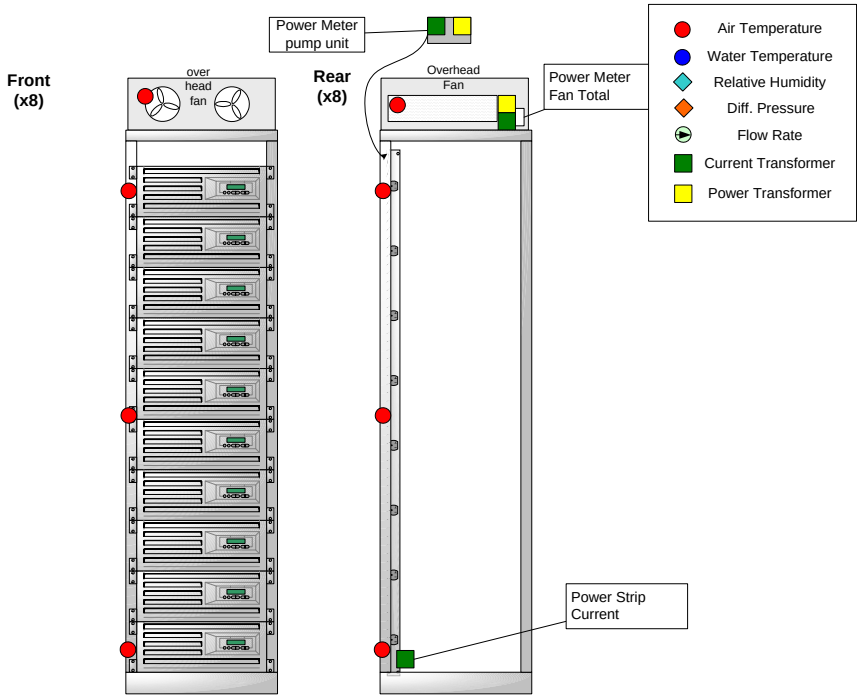


Figure 1 Equipment layout – Front view

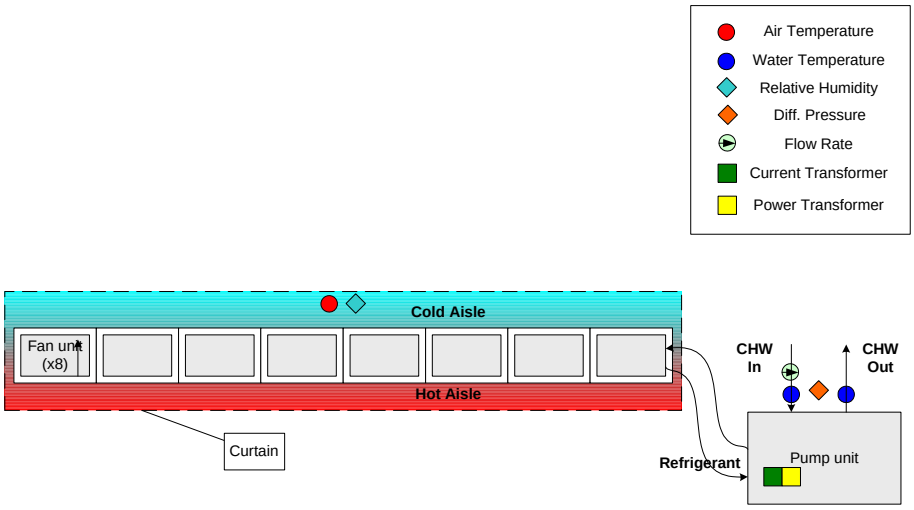


Figure 2  Equipment layout – Top view

## *1.4 Measured parameters*

The following parameters were monitored or measured during the evaluation

- Power demand of servers and cooling modules
  - o Actual power demand for servers used in this study.
  - o Actual power demand for the cooling modules

    Electric power demand for the pump unit and eight cooling modules was monitored separately.
- Air temperature
  - o Cold inlet air temperature to the front of server racks

    There were three temperature sensors (RTDs) installed at the bottom, middle, and top positions (0.65”, 37.5”, and 69”, respectively) at the front inlet of each of the server racks. These heights corresponded to servers 2U, 20U, and 38U, respectively.
  - o Hot outlet air temperature from the back of server racks

    There were three temperature sensors (RTDs) installed at the bottom, middle, and top positions (0.65.”, 37.5”, and 69”, respectively) at the rear outlet of for each of the server racks.
  - o Data center air temperatures (outside the enclosed test area): from building energy management system
- Pump unit entering and leaving chilled water temperatures

  Chilled water temperatures in the supply and return pipes were measured by installing two surface mounted temperature sensors on the supply and return chilled water lines. Insulation was wrapped around the pipes to eliminate the influence of the surrounding environment to the pipe sensors.
- Pump unit chilled water flow rate
  - o The flow rate was calculated to be within ± 5% accuracy using the pressure drop monitored and a vendor supplied conversion equation. Pressure drop was monitored across a balancing valve on the supply side of the chilled water connected to the refrigerant-water heat exchanger.

In addition to the real-time measurements taken of the test environment, the following parameters were recorded manually to quantify the power demand in the data center and the energy use of the central chilled water plant: total IT equipment power; total central chilled water plant power; primary chilled water flow and chilled water temperatures (supply and return); chilled water supply/return differential pressure. This data was used to perform an engineering analysis to determine the central chilled water plant energy efficiency to estimate the potential energy savings versus using a conventional raised, CRAH cooling system and the modular, scalable cooling system in this study.

## 1.5 Data acquisition system

Data collection for the test environment was performed using a commercially available data acquisition system [3]. Data collection for the central chilled water plant was collected from both the site energy management system and from field measurements taken were continuous monitoring data points were not available. Data points were measured over the duration of the study, gathered from the manufacturer's modular cooling equipment (where available), the Sun servers, the rack power strips, and an array of power meters, flow meters, pressure transducers, and RTD temperature sensors.

Data was gathered by local network appliances via a variety of network and serial communication protocols from the meters, the servers, and various analog sensors through I/O modules. After initial local processing and alarm checking, data was reported to a remote server and stored in a relational database. Similar data points were measured for each rack cooling technology, and stored in a shared relational database at a remote server. The real-time data was available through a web application, allowing users to monitor and manage the study remotely in real time. Access controls ensured that each manufacturer could see only its own data, while the designated host had access to all data.

Three power meters measured the energy use of the pumping system, the fans, and one rack of servers. Smart power strips reported current for each rack. RTDs were placed at three heights on each rack, front and back, as well as at the inlet and outlet of the fan units. Ambient temperature and humidity were measured on the cold-aisle. Various internal server temperatures were gathered from selected servers, as reported by the servers themselves. Supply and return chilled water conditions were measured using an ultrasonic flow meter, pressure transducers, and RTDs. The cooling hardware itself did not have communication capabilities.

## 1.6 Test procedures and operating conditions

The supply water temperature to the pump unit used in this evaluation was the data centers 45°F design chilled water temperature from the central cooling system which was maintained constantly and was continuously monitored.

Selected operating conditions were designed by combining various server loads (25% to 100%) and various inlet air temperatures in this study, and are presented in the following table.

Table 1 Set Points for Test Conditions

| Inlet air temperature set point (F) | Targeted total server load (kW) for 8 servers racks | Various server loads (kW) per rack | | | |
|---|---|---|---|---|---|
| | | 100% | 75% | 50% | 25% |
| 68 | 80 | 10.0 | 7.5 | 5.0 | 2.5 |
| 72 | 80 | 10.0 | 7.5 | 5.0 | 2.5 |
| 76 | 80 | 10.0 | 7.5 | 5.0 | 2.5 |
| 80 | 80 | 10.0 | 7.5 | 5.0 | 2.5 |

- For each desired rack power load, temperature control measures were taken to adjust inlet air temperatures at discrete set points, i.e., 68°F, 72°F, 76°F, and 80°F, respectively. The Cooling System 1 overhead cooling units used in this study are on designed to maintain a Minimum Room Temperature and are not specifically designed to provide direct set point control over inlet air temperature. Therefore, the inlet air temperature being delivered to the cold aisle is designed to float based upon the rack power or heat load of the rack. For this reason, it was difficult to achieve the exact set points for inlet air temperatures as contemplated in the test plan, especially during part load since the heat rise across the severs in the rack was not high enough to reach the low end of the lower inlet air temperature set points since the units are not designed to heat the air. Although initial trial tests followed the rule-of-thumb provided by the vendor that it took about 30 minutes to achieve steady-state air temperature. During the testing, we typically allowed from 45 minutes to up to two hour duration to enable the system to reach steady state for each operating condition in this study.
- Change the server load from full to 75%, 50%, and 25% of the defined nominal capacity per rack (i.e., approximately 10 kW/rack). Repeat and record the measurements for each operating condition.

## 1.7 Performance metrics for modular cooling

In order to characterize thermal performance of the cooling system, we used the ratio of cooling (in kW) transported by the cooling module to the total power demand for the operation of the module (refrigerant pump and fan), defined as "coefficient of performance (COP)." The COP is unitless, with a higher value representing higher efficiency for the cooling module. The COP can be calculated under applicable operating conditions (a range determined by inlet air temperature and server load).

In this evaluation, the total power demand is the pump and fan power required to transport the required refrigerant and airflow from the cooling system, while the heat removed is equivalent to the cooling provided by the cooling system.

$$COP = \frac{Cooling}{P_{total}}$$

Where *Cooling* is the amount of cooling power removed from the data center by the cooling system, and $P_{total}$ is defined as the total power demand for the cooling system to do so. Because there were fans and refrigerant pumps in the Cooling System 1, the total power demand was for pumping and air-circulating requirement in this study.

Total power demand for the module can be measured as follows:

$$P_{total} = P_{fan\ power} + P_{pump\ power}$$

Where

$P_{fan\ power}$ is the total measured fan power demand of the cooling modules

$P_{pump\ power}$ is the measured pump power demand of the pump unit

The actual cooling provided by the refrigerant-based cooling system can be calculated from the secondary-loop chilled water temperature rise and chilled water flow rate, using the following formula:

Where

$$Cooling = \frac{60 \rho Q C_p \Delta T_w}{3412.1}$$

*Cooling* is the heat transfer (in kW) from the chilled water plant via the heat exchanger in the pumping module.

$\rho$: Water density in lb/gal, assuming water density ρ of 8.34 lbm/gal (or 62.4 lbm/ft$^3$)

*Q*: Averaged chilled water flow rate measured in gallon per minute
The pressure difference between supply and return across the valve was used to estimate the actual water flow rate across the valve. The pressure-to-flowrate conversion formula was based upon the calibration provided by the balancing valve vendor, with an error bar of ±5%.

$$Q = 40.2\sqrt{\Delta \mathrm{P}}$$

where ΔP is the pressure difference of the chilled water flow in psi.

*Cp*: Specific thermal conductivity of water, 1 BTU/F-lbm

$\Delta T_w$ : Measured water temperatures rise, in °F

Therefore,

$$Cooling = 0.1467 Q\ \Delta T_w$$

$$COP = \frac{Cooling}{P_{total}} = \frac{0.1467 Q\ \Delta T_w}{P_{total}}$$

The portion of chiller pumping power required to deliver the chilled water volume in the primary-loop was ignored for this evaluation.

Another performance metric we calculated is the ratio of total power divided by the cooling transported by the modular system. This is similar to chiller efficiency defined as power demand per cooling transferred. Represented in kW per cooling ton, a lower value

of this ratio indicates a higher cooling energy efficiency at which the modular system is performing.

$$MSE = \frac{12000\mathrm{P}_{\mathrm{total}}}{Cooling} = \frac{12000\mathrm{P}_{\mathrm{total}}}{60\rho QC_p\Delta T_w} = 24\frac{\mathrm{P}_{\mathrm{total}}}{Q\Delta T_w}$$

$$MSE = \frac{3.52}{COP}$$

where

Module System Efficiency (*MSE*): ratio of total cooling power to the cooling transported by the module, in kW/ton
*Q*: Averaged water flow rate measured in gallon per minute
$\Delta T_w$ : Measured water temperatures rise, in °F

An alternative metric, defined as the module's power utilization index, *PI*, is the ratio of power demand for the cooling system to computer load under selected operating conditions. A higher value of the power index indicates higher cooling energy demand for the cooling system at a given server load.

$$PI = \frac{P_{total}}{P_{server}}$$

## 1.8 Summary of findings and conclusions

The measurement and data collection system deployed in this study was reliable and accurate, and provided continuous monitoring of a wide range of critical parameters. It also provided real-time data display during the course of the experimental study. Data analysis was further enabled by writing custom database queries to parse the raw data collected to provide the ability for effective analysis of the large amount of data collected during the testing.

The software program used in the study to measure and monitor the power to the test environment effectively created various load/power consumption scenarios (based on the reference measures) to make sure the necessary power draw was generated and maintained required for all the tests in this study. Each rack was capable of consuming over 10kW and depending on the server load set points, the program was used to set load levels (e.g., 2.5kW, 5kW, 7.5kW, 10kW or maximum) by turning on/off the necessary amount of servers and by running the server power benchmarking tool at full load.

Based upon the three temperature measurements at the server rack inlet and outlet, average top, middle and bottom temperatures were calculated for rack. These temperature measurements were used to calculate the average, maximum, minimum, and standard deviation among all eight racks. Table 2 shows the calculated statistical variation.

Table 2 Statistics for inlet air temperatures and average outlet air temperatures

| Average Inlet Air Temperature (F) | Maximum Inlet Air Temperature (F) | Minimum Inlet Air Temperature (F) | Standard Deviation of Inlet Air Temperature (F) | Average Outlet Air Temperature (F) | Range (difference of max and min) (F) |
|---|---|---|---|---|---|
| 74.6 | 75.9 | 72.4 | 1.0 | 102.4 | 3.5 |
| 73.1 | 75.8 | 68.5 | 3.0 | 100.6 | 7.4 |
| 74.1 | 78.1 | 64.3 | 5.2 | 100.4 | 13.8 |
| 76.4 | 81.2 | 64.9 | 6.9 | 103.4 | 16.3 |
| 73.3 | 76.4 | 67.1 | 3.6 | 99.9 | 9.3 |
| 71.9 | 73.3 | 69.1 | 1.4 | 94.8 | 4.2 |
| 72.1 | 75.2 | 65.1 | 4.1 | 96.7 | 10.0 |
| 79.7 | 80.9 | 77.7 | 1.2 | 105.1 | 3.1 |
| 71.5 | 73.2 | 69.9 | 1.2 | 95.0 | 3.2 |
| 65.6 | 66.4 | 65.1 | 0.5 | 86.4 | 1.4 |
| 65.3 | 66.5 | 64.8 | 0.6 | 86.6 | 1.7 |
| 65.3 | 66.5 | 64.9 | 0.6 | 86.6 | 1.6 |
| 74.7 | 76.2 | 73.7 | 1.0 | 98.7 | 2.5 |
| 68.5 | 69.4 | 68.0 | 0.5 | 82.4 | 1.4 |
| 66.0 | 66.8 | 65.5 | 0.6 | 84.0 | 1.4 |
| 68.3 | 69.0 | 67.8 | 0.4 | 85.1 | 1.3 |
| 71.1 | 72.0 | 69.7 | 0.8 | 86.9 | 2.3 |

The inlet air temperature distribution in this study appeared to be non-uniform, from the bottom to the top of the server racks, and from rack to rack. For example, the difference between maximum and minimum inlet temperatures ranged from less than 2°F up to 14°F, with the standard deviation ranging from less than 0.4°F up to 7°F. The non-uniformity among the eight racks tested was particularly evident when inlet air temperatures were intended to be controlled within the higher end of the set points shown in Table 1.

The actual operating conditions achieved in this evaluation are shown in Table 2. The overall coverage of operating conditions ranged from 65°F to 80°F for inlet air temperatures and the server loads ranged from 2.7 to 9.8 kW/rack.

Table 3 Actual Test Conditions and Results

| Server Load per Rack (kW/rack) | Average Inlet Air Temperature (F) | Average Outlet Air Temperature (F) | Chilled Water Flowrate (gpm) | Chilled water temperature difference (F) | Cooling from Chilled Water (kW) | Fan Power (kW) | Pump Power (kW) | Total Power for Cooling Module (kW) | Total Server Power (kW) | COP | MSE (kW/ton) | Power Index |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9.6 | 75 | 102 | 46.6 | 8.9 | 61.5 | 1.5 | 0.9 | 2.4 | 76.8 | 26.2 | 0.13 | 0.03 |
| 9.6 | 73 | 101 | 61.6 | 8.5 | 78.6 | 1.5 | 0.9 | 2.4 | 77.0 | 32.9 | 0.11 | 0.03 |
| 9.7 | 74 | 100 | 36.5 | 13.3 | 70.9 | 1.5 | 0.9 | 2.3 | 77.5 | 30.3 | 0.12 | 0.03 |
| 9.8 | 76 | 103 | 23.9 | 18.3 | 66.1 | 1.5 | 0.9 | 2.3 | 78.6 | 28.2 | 0.12 | 0.03 |
| 9.7 | 73 | 100 | 60.0 | 9.2 | 82.9 | 1.5 | 0.9 | 2.3 | 77.3 | 35.5 | 0.10 | 0.03 |
| 7.5 | 72 | 95 | 30.6 | 13.5 | 60.4 | 1.5 | 0.9 | 2.4 | 60.1 | 25.1 | 0.14 | 0.04 |
| 7.6 | 72 | 97 | 24.3 | 14.6 | 53.5 | 1.5 | 0.9 | 2.4 | 60.7 | 22.4 | 0.16 | 0.04 |
| 7.6 | 80 | 105 | 10.4 | 24.7 | 59.6 | 1.5 | 0.9 | 2.4 | 61.0 | 25.2 | 0.14 | 0.04 |
| 4.9 | 71 | 95 | 26.5 | 9.9 | 38.8 | 0.7 | 0.9 | 1.6 | 39.6 | 24.0 | 0.15 | 0.04 |
| 4.8 | 66 | 86 | 59.8 | 6.9 | 62.0 | 1.5 | 0.9 | 2.3 | 38.5 | 26.4 | 0.13 | 0.06 |
| 4.8 | 65 | 87 | 42.6 | 7.6 | 50.4 | 1.5 | 0.9 | 2.3 | 38.4 | 21.5 | 0.16 | 0.06 |
| 4.8 | 65 | 87 | 44.9 | 7.1 | 55.9 | 1.5 | 0.9 | 2.4 | 38.3 | 23.8 | 0.15 | 0.06 |
| 5.0 | 75 | 99 | 52.7 | 18.0 | 43.0 | 0.7 | 0.9 | 1.6 | 40.0 | 26.7 | 0.13 | 0.04 |
| 4.8 | 68 | 89 | 9.9 | 13.3 | 45.8 | 1.5 | 0.9 | 2.3 | 38.7 | 19.6 | 0.18 | 0.06 |
| 2.7 | 66 | 84 | 22.4 | - | - | 0.8 | 0.9 | 1.7 | 21.8 | - | - | 0.08 |
| 2.7 | 68 | 85 | 0.0 | - | - | 0.8 | 0.9 | 1.7 | 21.7 | - | - | 0.08 |
| 4.8 | 71 | 87 | 0.0 | - | - | 0.8 | 0.9 | 1.7 | 38.5 | - | - | 0.04 |

Table 3 shows the results from the tests performed at the facility including: server load; average inlet/outlet air temperatures monitored at three different heights for all eight server racks; cooling delivered by the modules; power demand of the cooling systems, and three performance metrics in this study: COP; module system efficiency; and PI.

The testing determined that different IT equipment and environmental operating conditions affected the cooling delivery efficiency of the modular cooling unit. Specifically, variations in server power load and inlet air temperature resulted in different COP, cooling efficiency (kW/ton), and power utilization index for modular Cooling System 1.

Generally, modular pump power demand remained stable (mostly around 0.9 kW), while fan power demand exhibited a slightly higher demand when both overhead unit fans were on (1.5 kW). Overall, the total power demand for the modular cooling was very constant for a given operation condition, i.e., 2.4 kW with dual fans on and 1.6-1.7 kW with one fan for each of the eight cooling modules.

Under similar server loads, the COP of cooling system 1 tended to increase with the decrease in inlet supply air temperature; while the cooling system's MSE (kW/ton value) tended to increase with the increase in inlet supply air temperature. The magnitude of this change, 0.1 to 0.2 kW/ton is lower than a normal computer room air handling (CRAH) unit. The PI value seemed to change little under similar server loads with various inlet air temperatures.

As expected for a system that consumes electric energy at a relatively constant rate, the COP values of the modular cooling system increased with the increase in server load;

indicating higher cooling system energy efficiency performance with higher rack power loads. Similarly, the PI values increased with the decrease in rack power load, indicating that higher cooling system power per unit of server heat demand was required under lower server loads.

The test results show that this cooling system was generally capable of providing cooling needed to achieve various inlet air temperatures under various server loads; however, there were challenges in the course of controlling and maintaining inlet air temperature within a desired range for some of the set points used in this evaluation. This condition was most evident at the high end of the selected set point temperatures.

Overall, the COP ranged from 20 up to 36; MSE (kW/ton) ranged from 0.11 up to 0.18kW/ton; and PI from 0.03 to 0.08. Cooling System 1 exhibited an energy efficiency level better than traditional CRAH units under the selected operating and environmental conditions (rack power and inlet air temperature) used in this study. The findings from this study indicate that by implementing overhead modular cooling in lieu of traditional CRAH units, the overall kW/Ton in the data center could be reduced. This type of modular cooling system also provides increased flexibility in data center configuration and layout.

The overall energy demand for cooling server racks in a data center is largely affected by the efficiency of the central cooling system. In this evaluation, the cooling system was operating at the central chilled water plant design operating temperature of 45°F.

In the future, we would recommend evaluating the cooling performance and energy efficiency of Cooling System 1 with higher supply water temperature up to the vendor's recommended maximum level.

In addition, due to testing constraints we were not able to test Cooling System 1 its design power load cooling capacity. Since the heat exchanger/pump system has constant power demand and is designed for a maximum of 160kW, we would recommend retesting the system at a more typical design operating cooling load of 80%, or 128kW. We would also like to test the system using the vendor's cold aisle containment system to better understand how the system performs both operationally and from an energy efficiency perspective.

In order to further save fan and pump energy and improve kW/Ton and COP values of the system, we recommend that the vendor consider variable flow rates on the heat exchanger/pump system and ability to operate the overhead units in a single or dual fan mode in future generations of the product.

This evaluation does not include the assessment of the potential energy savings possible if this cooling system technology was used for the entire data center. In addition, we did not test this system's cooling performance and energy efficiency in a redundant and/or failed operating condition. We also recommend that the reader of these individual reports, consider not only the energy efficiency performance of the modular scalable cooling system but the system's capability and effectiveness to maintain server inlet air temperature within ASHRAE recommended levels and the potential dependence on other cooling or humidification in the data center.

In closing, in order to quantify or estimate the impact of modular, scalable cooling systems on overall data center energy efficiency, one must also assess their integration with the rest of the data center eco-system, the temperature range of chilled water available from the plant, the local weather conditions where the datacenter is located, and the power density characteristics of the data center.

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## 1.9 Acknowledgements

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# Evaluation for Modular, Scalable Cooling Systems with Hot Aisle Containment in Data Centers

## Final Report

## To

## The California Energy Commission

**Issued:** **December 21, 2008**

**Prepared By:**

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# 2 Evaluation for Modular, Scalable Cooling Systems with Hot Aisle Containment in Data Centers

## 2.1 Problem Statement

Enterprise data centers and IT equipment product development and research data center labs require continuous cooling to maintain inlet air temperatures within recommended operating levels for the IT equipment. The consolidation and higher density aggregation of slim compute, storage and networking hardware has resulted in higher power density/ft² than the commonly used raised floor, CRAC design was originally conceived to handle.

The result is that in many existing data centers and in the majority of newly constructed data centers, the performance of the ventilation and cooling systems is less than optimal. Current IT computing trends indicate that IT equipment manufacturers are designing their equipment to operate in "conventional" data center environments by providing alternative cooling solutions to either their equipment or relying on supplemental cooling in rack or row systems.

This trend to higher power density resulting from current and future generations of servers has created significant opportunities for precision cooling suppliers to engineer and manufacture packaged modular and scalable systems that will significantly improve efficiency while solving the thermal challenges, improving reliability, and allowing for future needs and growth.

Such pre-engineered and manufactured systems may be a significant improvement over current design; however, without an energy efficiency focus, they could also lead to even lower energy efficiencies in the overall data center support infrastructure

The research objective of the project was to evaluate several commercially available, modular localized cooling systems to test the research thesis that these types of close coupled cooling solutions will be more energy efficient than traditional legacy data center cooling systems.

## 2.2 Technical objectives

### Technical objectives

This report is the result of a test plan that was developed with the participants' input to include specific design characteristics of the selected modular localized cooling solution provided by vendor 2 for a data center located in Sun Microsystems, Inc. The evaluation included monitoring and measurement of selected parameters, and establishing and calculating energy efficiency metrics for the selected product, which is a modular, scalable pair of chilled water cooling modules that were tested in a hot/cold aisle environment with hot aisle containment.

The scope is to quantify energy performance of the modular cooling unit as it corresponds to server load and inlet air temperature.

The information generated from this testing when combined with a concurrent research study to document the energy efficiency of the host data center's central chilled water cooling plant can be used to estimate potential energy savings from implementing modular cooling compared to conventional cooling in data centers.

## *2.3 Technical information on the characteristics of cooling systems and servers*

The evaluation tests were performed in a data center space located in Santa Clara, California. The datacenter area is approximately 12,800 square feet, with a ceiling height of 13 ft 6 inches and no raised floor. All server racks and support equipment are installed directly on the slab floor. There were various types of servers, rack sizes and shapes from various vendors. The data center was specifically designed to support racks with any type of IT equipment.

Power, chilled water, and communication cables to the server racks were provided through overhead cable trays. 700 tons of cooling is provided to the space from the central chilled water plant for cooling the IT equipment. The chilled water is supplied by a 2,000 ton central chilled water plant.

Power for thirty six 150kW PDUs was provided through a 480v AC bus way system. The 150kW power distribution units (PDUs) were located throughout the space. The PDUs transform the power from 480v AC to 208v AC for distribution to the server racks. The data center currently can support 190 watts/ft$^2$ of floor area. The design load per rack footprint was 5kW/rack with growth to 9kW/rack.

### 2.3.1 Modular, scalable cooling system with hot-aisle containment

The modular, scalable cooling system in this study was a chilled-water-based cooling solution combined with a hot aisle containment system. The cooling system consists of two parallel rows of IT Racks (sizing 42"x29x78") sharing a common hot aisle with a width of 36", with each row containing a chilled-water modular cooling module (42"x23"x78"). The common hot aisle was contained with modular clear ceiling panel along with access doors at the end of the aisle.

Each chilled-water cooling module contains a chilled water coil, chilled water flow control valve, multiple variable speed fans, DC power supply, instrumentation and controls needed to assure continuous automatic operation. The fans in the cooling module pull hot air from the hot aisle through the chilled water coil and transport the cooler supply air into the cold aisle.

The controls automatically regulate the airflow and chilled water flow rates as needed to achieve the desired operating conditions driven by specific set points. The primary control loop regulates chilled water to maintain the user selected supply air temperature. Additional controls regulate the fan speed as needed to provide airflow necessary to maintain the selected temperature differential across the servers (heat load). Figure 3 show a cooling module used within the hot aisle containment system

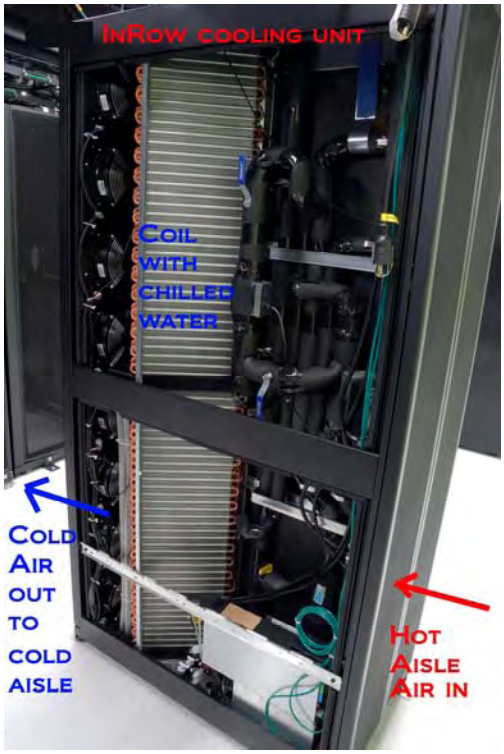


**Figure 3. Modular cooling unit**

### 2.3.2 Server equipment

The IT or heat load in each server rack was provided by 40 standard Sun V20 1U servers, each with a size of 28”x17”x1.75”. Due to data center space availability constraints for the study, and the high capital cost for servers, 240 servers were selected to be stacked in six server racks. As a result, the maximum nominal load per server rack was designed to be 10 kW. The maximum load per server rack tested ranged from 5kW to 10kW based upon the preset inlet air temperature of the cooling modules. Details of the servers provided in this study are publicly available [1].

### 2.3.3 Server power management

Using a commercially available software program as the “control program”, the load within each rack was effectively controlled at desired levels by dynamically turning on and off servers and running the program [2] at various CPU loads to achieve the desired power consumption and resulting heat load to test the energy efficiency of the modular cooling system. Prior to the test, reference measurements on each type of server that was being used in the racks were performed to measure idle and loaded power consumption.

To achieve the desired partial or full power load level (kW/rack) to be tested, the number of servers needed to run at 100% load was calculated and the program turned the rest off. For example to achieve the desired heat load levels in the test plan, the number of servers running at full load per rack were as follows: 10kW - 33 servers; 7.5kW - 25 servers; 5kW - 17 servers; 2.5kW - 9 servers.

Although all of the servers used in the test configuration were the same, the initial reference measurements identified that they had significantly different power consumption due to different memory or computing configurations installed.

Therefore, to achieve and maintain the desired full or partial power load per rack during each test sequence, the monitoring system collected real time measurements of server power from the rack power strips and the program used this information to turn on or off additional servers as necessary to maintain the desired power load levels.

To monitor the inlet air temperature being delivered to the test racks by the modular cooling system, air temperature probes were installed at the top, middle and bottom of each rack. To improve the response time of these sensors, the power to the servers installed at these rack elevations were maintained on during each testing sequence. Prior to starting a specific modular cooling system test sequence, the total power consumption at each rack was verified against the readings of the power strip and adjusted as needed until the power consumption was stable.

### 2.3.4 Equipment location

Two rows of server racks were positioned at the southwest corner of the data center for this study. They were separated from the rest of the data center by an array of curtains surrounding the six server racks and the two cooling modules. The space within the curtain has a floor area of 110” x 178” and a height of 86”. The in-row cooling modules are designed to draw air from the hot aisle, pass it through the chilled water heat exchanger and direct cold air to the cold aisle. The cold air is then moved from the inlet of the servers through the rack to the contained hot aisle where the process repeats itself.

Figure 4 and Figure 5 show the equipment layout in this study.

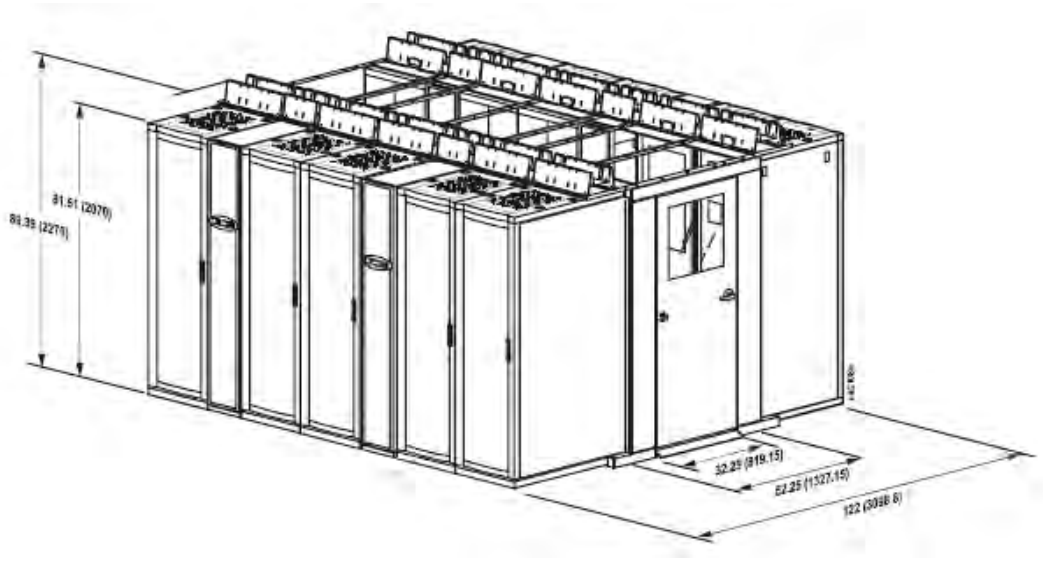


**Figure 4 Generic Layout of Equipment**

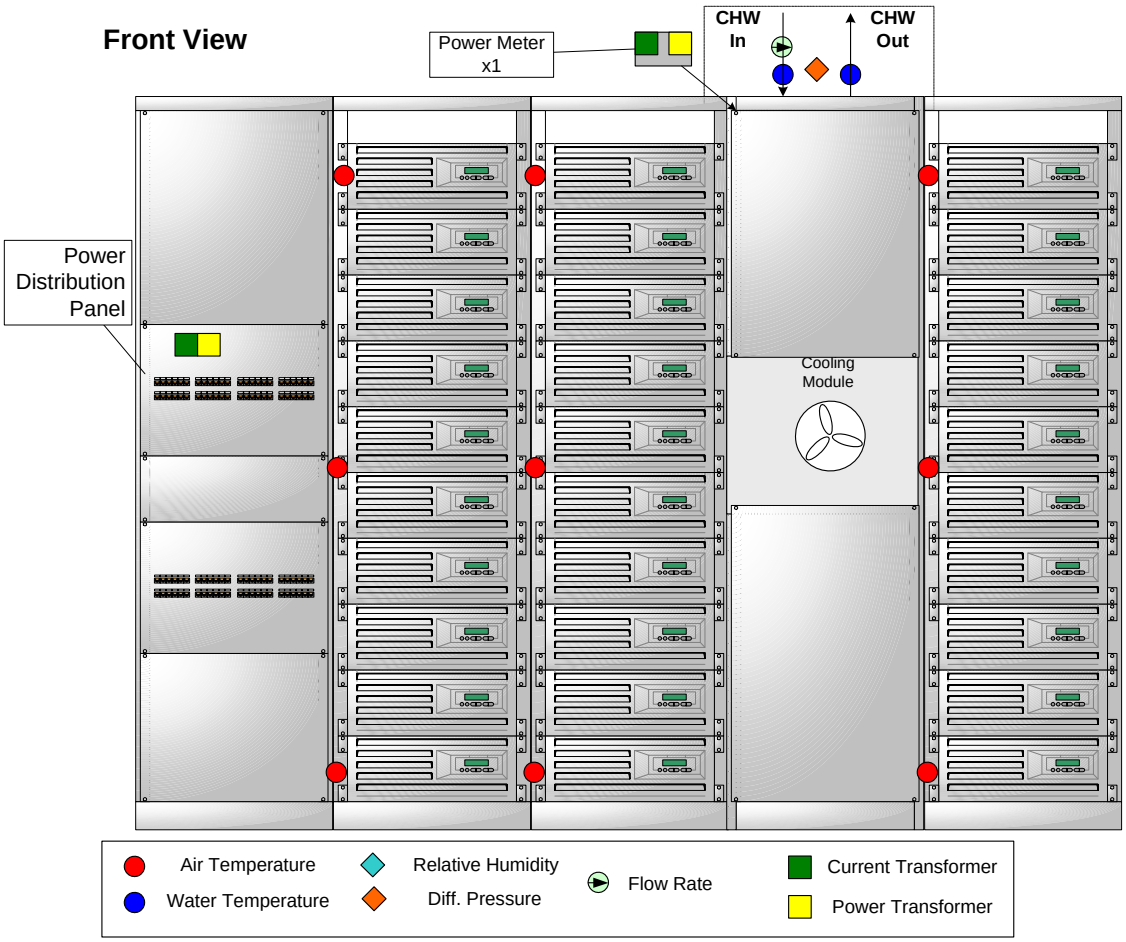


**Figure 5 Layout of Equipment – Front View**

## 2.4 Measured parameters

The following parameters were monitored or measured during the evaluation

- Power demand of servers and cooling modules
  - Actual power demand for servers used in this study.
  - Actual power demand for the cooling modules

    Electric power demand for the pump unit and eight cooling modules was monitored separately.
- Air temperature
  - Cold inlet air temperature to the front of server racks

    There were three temperature sensors (RTDs) installed at the bottom, middle, and top positions (0.65”, 37.5”, and 69”, respectively) at the front inlet of each of the server racks. These heights corresponded to servers 2U, 20U, and 38U, respectively.
  - Hot outlet air temperature from the back of server racks

    There were three temperature sensors (RTDs) installed at the bottom, middle, and top positions (0.65.”, 37.5”, and 69”, respectively) at the rear outlet of for each of the server racks.
  - Data center air temperatures (outside the enclosed test area): from building energy management system
  - Outdoor air temperatures (dry-bulb & relative humidity).
- Cooling module entering and leaving chilled water temperatures

  Chilled water temperatures in the supply and return pipes were measured by installing two temperature sensors on the surface of the water pipes, with insulation material wrapped around.
- Cooling module chilled water flow rates
- Cooling module entering and leaving chilled water pressure differential.

In addition to the real-time measurements taken of the test environment, the following parameters were recorded manually to quantify the power demand in the data center and the energy use of the central chilled water plant: total IT equipment power; total central chilled water plant power; primary chilled water flow and chilled water temperatures (supply and return); chilled water supply/return differential pressure. This data was used to perform an engineering analysis to determine the central chilled water plant energy efficiency to estimate the potential energy savings versus using a conventional raised, CRAH cooling system and the modular, scalable cooling system in this study.

## 2.5 Data acquisition system

Data collection for the test environment was performed using a commercially available data acquisition system [3]. Data collection for the central chilled water plant was collected from both the site energy management system and from field measurements taken were continuous monitoring data points were not available. Data points were measured over the duration of the study, gathered from the manufacturer's modular cooling equipment (where available), the Sun servers, the rack power strips, and an array of power meters, flow meters, pressure transducers, and RTD temperature sensors.

Data was gathered by local network appliances via a variety of network and serial communication protocols from the meters, the servers, and various analog sensors through I/O modules. After initial local processing and alarm checking, data was reported to a remote server and stored in a relational database. Similar data points were measured for each rack cooling technology, and stored in a shared relational database at a remote server. The real-time data was available through a web application, allowing users to monitor and manage the study remotely in real time. Access controls ensured that each manufacturer could see only its own data, while the designated host had access to all data.

Two power meters measured the energy use of the entire system and the in-row cooling modules alone. Smart power strips reported current for each rack. RTDs were placed at three heights on each rack, front and back, as well as at the inlet and outlet of the fan units. Ambient temperature and humidity were measured on the cold-aisle. Various internal server temperatures were gathered from selected servers, as reported by the servers themselves. Supply and return chilled water conditions were measured using a flow meter, pressure transducers, and RTDs. The cooling modules themselves also reported water conditions, fan speed, air temperatures, and cooling output power.

## 2.6 Test procedures and operating conditions

The supply water temperature to the cooling modules used in this evaluation was the data centers 45°F design chilled water temperature from the central cooling system which was maintained constantly and was continuously monitored.

Selected operating conditions were designed by combining various server loads (25% to 100%) with the full load level indentified by vendor input and are presented in the following table.

**Table 4 Set Points for Test Conditions**

| Inlet air temperature set point (F) | Targeted total server load (kW) for 6 servers racks | Various server loads (kW) per rack | | | |
|---|---|---|---|---|---|
| | | 100% | 75% | 50% | 25% |
| 68 | 40 | 6.7 | 5.0 | 3.3 | 1.7 |
| 72 | 56 | 9.3 | 7.0 | 4.7 | 2.3 |
| 76 | 60 | 10.0 | 7.5 | 5.0 | 2.5 |
| 80 | 60 | 10.0 | 7.5 | 5.0 | 2.5 |

During the testing we controlled the server load at full level (100%) for at least an hour or often longer. We then adjusted the cold aisle air temperatures (i.e., server inlet air temperature) at discrete set points from 80°F down to 68°F, in 4°F steps. Per the vendor's recommendation, we used a 30-minnute duration for the system to reach steady-state operation at each desired inlet air temperature level. A minimum of 30 minutes up to several hours of operation was observed (after adjusting the temperature set points) to perform testing. Similar steps and tests were repeated with the system operating at partial rack power loads, i.e., 75%, 50%, and 25% of the 10 kW/rack capacity.

## 2.7 Performance metrics for modular cooling

In order to characterize thermal performance of the module, we used the ratio of cooling provided from the cooling module to the total power demand for the operation of the module (water pump and fan), defined as the "coefficient of performance (COP)." Normally COP of a cooling module is the ratio of the heat removed by the module to the work supplied to the module. The COP is unit less, with a higher value representing higher efficiency for the cooling module. The COP can be calculated under applicable operating conditions (a range determined by inlet air temperature and server load).

In this evaluation, the work supplied is the pump and fan power required to produce the required water and air flow from the cooling module, while the heat removed is equivalent to the cooling provided by the module.

$$COP = \frac{Cooling}{P_{total}}$$

Where Cooling is the cooling provided by the cooling module and $P_{total}$ is defined as the total power demand for all components (e.g., fan, pump) in the two cooling modules in this evaluation. Because there are fans and water pumps in the cooling modules, the total power demand was for the pumping and air-circulation. The cooling module fans and pumps used in this study were 115 VAC, single-phase power.

Total power demand for the cooling modules can be calculated as follows:

$$P_{total} = P_{module1} + P_{module2}$$

The actual cooling provided by the water-cooling module can be calculated from the secondary-loop chilled water temperature rise and chilled water flow rate, using the following formula:

Where

$$Cooling = \frac{60 \rho Q C_p \Delta T_w}{3412.1}$$

Cooling is the cooling transported by the cooling module, in kW.

ρ: Water density in lb/gal, assuming water density ρ of 8.34 lbm/gal (or 62.4 lbm/$ft^3$)

Q: Averaged water flow rate measured in gallon per minute

Cp: Specific thermal conductivity of water, 1 BTU/F-lbm

$\Delta T_w$ : Measured water temperatures rise, in °F

Therefore, for each cooling module, the cooling can be calculated by the following formula.

$$Cooling = 0.1467 Q\ \Delta T_w$$

Because there were two cooling modules operating at the same time for the six server racks, the total cooling from the modules can be calculated by the following formula:

$$\sum Cooling = 0.1467 \sum_{i=1}^{2} Q_i \Delta T_{w,i}$$

$$COP = \frac{\sum Cooling}{P_{total}} = \frac{0.1467 \sum_{i=1}^{2} Q_i \Delta T_{w,i}}{P_{total}}$$

The portion of chiller pumping power required to deliver the chilled water volume in the primary-loop was ignored for this evaluation.

Another performance metric we calculated is the ratio of total power for the modular cooling units divided by the cooling provided. This is similar to chiller efficiency defined as power demand per cooling produced. Represented in kW per cooling ton, a lower value of this ratio indicates a higher cooling energy efficiency at which the cooling system is performing in terms of delivering cooling needed for rack cooling.

$$MSE = \frac{12000 P_{total}}{\sum Cooling} = \frac{12000 P_{total}}{\sum_{i=1}^{2} 60 \rho Q_i C_p \Delta T_{w,i}} = 24 \frac{P_{total}}{\sum_{i=1}^{2} Q_i \Delta T_{w,i}}$$

where

Module System Efficiency (MSE): ratio of total cooling power to cooling provided, in kW/ton

Q: Averaged water flow rate measured in gallon per minute

$\Delta T_w$ : Measured water temperatures rise, in °F

An alternative metric, defined as the module's power utilization index, *PI*, is the ratio of power demand for the cooling system to computer load under selected operating conditions. A higher value of the power index indicates higher cooling energy demand

$$PI = \frac{P_{total}}{P_{server}}$$

for the cooling system at a given server load.

Total server load was measured at the PDU supporting the server racks. The three-phase real power demand of the PDU was monitored and was considered to be the total server power load in this evaluation.

## 2.8 Summary of findings and conclusions

The measurement and data collection system deployed in this study was reliable and accurate, and provided continuous monitoring of a wide range of critical parameters. It also provided real-time data display during the course of the experimental study. Data analysis was further enabled by writing custom database queries to parse the raw data collected to provide the ability for effective analysis of the large amount of data collected during the testing.

The software program used in the study to measure and monitor the power to the test environment effectively created various load/power consumption scenarios (based on the reference measures) to make sure the necessary power draw was generated and maintained required for all the tests in this study. Each rack was capable of consuming over 10kW and depending on the server load set points, the program was used to set load levels (e.g., 2.5kW, 5kW, 7.5kW, 10kW or maximum) by turning on/off the necessary amount of servers and by running the server power benchmarking tool at full load.

The overall coverage of operating conditions ranged from 65°F to 80°F for inlet air temperatures, and the server loads ranging from 1.7 kW/rack up to 10.4 kW/rack

**The difference between maximum and minimum inlet temperatures ranged from less than 3F up to 6F, with the standard deviation ranging from less than 1°F to 2.5°F.**

Table 5 also shows the results from the tests performed at the facility, including server load, average inlet/outlet air temperatures monitored at three different heights for all six server racks, cooling delivered by the modules, power demand of the cooling modules, and three performance metrics in this study: COP, module system efficiency, and power index.

**Table 5 Actual Test Conditions and Results**

| Server Load per Rack (kW/rack) | Average Inlet Air Temperature (F) | Average Outlet Air Temperature (F) | Cooling from Module 1 (kW) | Cooling from Module 2 (kW) | Total Cooling (kW) | Total Power for Cooling Module (kW) | Total Power for Server (kW) | COP | Modular System Efficiency (kW/ton) | Power Index |
|---|---|---|---|---|---|---|---|---|---|---|
| 10.4 | 80 | 113 | 27.3 | 26.9 | 54.2 | 2.3 | 62.4 | 23.1 | 0.15 | 0.04 |
| 10.4 | 79 | 112 | 28.1 | 26.3 | 54.4 | 2.3 | 62.4 | 23.2 | 0.15 | 0.04 |
| 10.4 | 77 | 110 | 28.3 | 27.8 | 56.1 | 2.3 | 62.2 | 24.1 | 0.15 | 0.04 |
| 9.6 | 74 | 105 | 28.1 | 26.6 | 54.7 | 2.3 | 57.7 | 23.5 | 0.15 | 0.04 |
| 9.6 | 74 | 105 | 27.1 | 25.2 | 52.3 | 2.3 | 57.4 | 22.3 | 0.16 | 0.04 |
| 7.8 | 76 | 101 | 23.5 | 22.9 | 46.4 | 2.3 | 46.8 | 19.8 | 0.18 | 0.05 |
| 7.3 | 72 | 94 | 22.9 | 22.3 | 45.2 | 2.3 | 43.8 | 19.4 | 0.18 | 0.05 |
| 6.9 | 68 | 91 | 23.0 | 21.9 | 44.9 | 2.3 | 41.3 | 19.2 | 0.18 | 0.06 |
| 5.1 | 74 | 98 | 16.5 | 14.4 | 30.9 | 1.1 | 30.7 | 28.2 | 0.13 | 0.04 |
| 4.7 | 72 | 95 | 14.4 | 12.8 | 27.2 | 0.8 | 28.4 | 32.2 | 0.11 | 0.03 |
| 4.5 | 66 | 88 | 17.8 | 16.4 | 34.2 | 1.2 | 27.0 | 29.1 | 0.12 | 0.04 |
| 3.4 | 67 | 87 | 9.8 | 1.1 | 10.9 | 0.5 | 20.4 | 22.5 | 0.16 | 0.02 |
| 2.6 | 75 | 98 | 9.7 | 7.4 | 17.1 | 0.5 | 15.7 | 34.5 | 0.10 | 0.03 |
| 2.6 | 73 | 97 | 10.4 | 8.0 | 18.4 | 0.5 | 15.6 | 37.5 | 0.09 | 0.03 |
| 2.4 | 69 | 91 | 8.6 | 6.8 | 15.4 | 0.5 | 14.3 | 31.4 | 0.11 | 0.03 |
| 1.7 | 65 | 87 | 9.0 | 6.9 | 15.9 | 0.5 | 10.4 | 32.5 | 0.11 | 0.05 |

The testing determined that different IT equipment and environmental operating conditions affected the cooling delivery efficiency of the modular cooling units. Specifically, variations in server power load and inlet air temperature resulted in different COP, cooling efficiency (kW/ton), and power index for modular Cooling System 2.

Generally, total modular cooling power demand was somewhat stable (mostly around 2.3 kW) at higher server loads. The cooling power demand decreased when lower server loads were in operation which is a good characteristic. This is the intended behavior to reduce cooling power with reduced IT power to maintain better PI under lower load conditions.

Under a similar server load, the COP of cooling module 2 tended to be constant at various inlet supply air temperatures, as was the cooling module's cooling kW/ton value. In addition, the PI values seemed to change little under a similar server load with various inlet air temperatures. The COP values of the modular cooling increased with the decrease in server loads – indicating a higher energy efficiency of cooling module's performance in transporting cooling when coping with lower server loads in this study.

Overall, the COP ranged from 19 up to 38, MSE (kW/ton) values from 0.09 up to 0.18 kW/ton, and PI from 0.03 to 0.06. Cooling System 2 exhibited an energy efficiency level better than traditional CRAH units under the selected operating and environmental conditions (rack power and inlet air temperature) used in this study.

The dynamic nature of the fan control algorithms within this particular modular cooling system allowed the kW/ton to decrease in response to reductions of IT server loads, with a range from 0.09kW/ton to 0.18kW/ton. This power consumption compares favorably against conventional CRAH units that typically have higher kW/Ton values (lower efficiency).

The findings from this study indicate that by implementing in-row modular cooling in lieu of traditional CRAH units, the overall kW/Ton in the data center could be reduced. This type of modular cooling system also provides increased flexibility in data center configuration and layout.

The test results show that this cooling system was generally capable of providing cooling needed to achieve various inlet air temperatures under various server loads

The overall energy demand for cooling server racks in a data center is largely affected by the efficiency of the central cooling system. In this evaluation, the cooling system was operating at the central chilled water plant design operating temperature of 45°F.

In the future, we would recommend evaluating the cooling performance and energy efficiency of Cooling System 2 with higher supply water temperature up to the vendor's recommended maximum level.

This evaluation does not include the assessment of the potential energy savings possible if this cooling system technology was used for the entire data center. In addition, we did not test this system's cooling performance and energy efficiency in a redundant and/or failed operating condition. We also recommend that the reader of these individual reports, consider not only the energy efficiency performance of the modular scalable cooling system but the system's capability and effectiveness to maintain server inlet air temperature within ASHRAE recommended levels and the potential dependence on other cooling or humidification in the data center.

In closing, in order to quantify or estimate the impact of modular, scalable cooling systems on overall data center energy efficiency, one must also assess their integration with the rest of the data center eco-system, the temperature range of chilled water available from the plant, the local weather conditions where the datacenter is located, and the power density characteristics of the data center.

## 2.9 Acknowledgements

The author wishes to acknowledge Bill Tschudi of LBNL, Dean Nelson and his team from Sun Microsystems, especially Brian Day and Mike Ryan, Ray Pfeifer of the Silicon Valley Leadership Group and a number of anonymous industry participants for their assistance and review of this project report. The project is funded by the Industrial Section of the Public Interest Energy Research (PIER) Program of the California Energy Commission. This work was also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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3. V20z Servers provided by Sun Microsystems. http://www.sun.com/servers/entry/v20z/index.jsp
4. SPEC (Standard Performance Evaluation Corporation) Power, Power Assure, Inc.
5. Modius OpenData® Data Center infrastructure Manager, Modius Inc.

# Evaluation for a Modular, Scalable Liquid-Rack Cooling System In Data Centers

## Final Report

## To

## The California Energy Commission

**Issued:** **December 21, 2008**

**Prepared By:**

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# 3 Evaluation for a Modular, Scalable Liquid-Rack Cooling System in Data Centers

## 3.1 Problem Statement

Enterprise data centers and IT equipment product development and research data center labs require continuous cooling to maintain inlet air temperatures within recommended operating levels for the IT equipment. The consolidation and higher density aggregation of slim compute, storage and networking hardware has resulted in higher power density/ft² than the commonly used raised floor, CRAC design was originally conceived to handle.

The result is that in many existing data centers and in the majority of newly constructed data centers, the performance of the ventilation and cooling systems is less than optimal. Current IT computing trends indicate that IT equipment manufacturers are designing their equipment to operate in "conventional" data center environments by providing alternative cooling solutions to either their equipment or relying on supplemental cooling in rack or row systems.

This trend to higher power density resulting from current and future generations of servers has created significant opportunities for precision cooling suppliers to engineer and manufacture packaged modular and scalable systems that will significantly improve efficiency while solving the thermal challenges, improving reliability, and allowing for future needs and growth.

Such pre-engineered and manufactured systems may be a significant improvement over current design; however, without an energy efficiency focus, they could also lead to even lower energy efficiencies in the overall data center support infrastructure

The research objective of the project was to evaluate several commercially available, modular localized cooling systems to test the research thesis that these types of close coupled cooling solutions will be more energy efficient than traditional legacy data center cooling systems.

## 3.2 Technical objectives

This report is the result of a test plan that was developed with the participants' input to include specific design characteristics of the selected modular localized cooling solution provided by vendor 3 for a data center located in Sun Microsystems, Inc. The evaluation included monitoring and measurement of selected parameters, and establishing and calculating energy efficiency metrics for the selected product, which is a modular, scalable liquid-rack cooling system in this study.

The scope is to quantify energy performance of the modular cooling unit as it corresponds to server load and inlet air temperature.

The information generated from this testing when combined with a concurrent research study to document the energy efficiency of the host data center's central chilled water

cooling plant can be used to estimate potential energy savings from implementing modular cooling compared to conventional cooling in data centers.

## *3.3 Technical information on the characteristics of cooling systems, servers*

The evaluation tests were performed in a data center space located in Santa Clara, California. The datacenter area is approximately 12,800 square feet, with a ceiling height of 13 ft 6 inches and no raised floor. All server racks and support equipment are installed directly on the slab floor. There were various types of servers, rack sizes and shapes from various vendors. The data center was specifically designed to support racks with any type of IT equipment.

Power, chilled water, and communication cables to the server racks were provided through overhead cable trays. 700 tons of cooling is provided to the space from the central chilled water plant for cooling the IT equipment. The chilled water is supplied by a 2,000 ton central chilled water plant.

Power for thirty six 150kW PDUs was provided through a 480v AC bus way system. The 150kW power distribution units (PDUs) were located throughout the space. The PDUs transform the power from 480v AC to 208v AC for distribution to the server racks. The data center currently can support 190 watts/ft$^2$ of floor area. The design load per rack footprint was 5kW/rack with growth to 9kW/rack.

### 3.3.1 Modular liquid-rack cooling equipment

The liquid-rack cooling system studied consisted of a single modular system, sized 78”x12”x48” attached to two equipment racks that measured 78”x24”x48”. The modular system was powered via a single 208V single-phase 20A electrical circuit. Where redundant electrical service is available, two such circuits are available and provided. Water connections were made at the rear of the unit via two externally threaded 1” connections.

This modular, scalable cooling system is designed to provide rack cooling up to 35 kW cooling per enclosure depending upon the supplied chilled water temperature and desired server air inlet temperature set point. Using a local controller, the system ensures that all components are operating at preset levels (e.g., inlet air temperature) to support the removal of specific heat loads. Three main features comprise the control system:

- Three (3) independent temperature zones (top, middle, bottom) with each zone monitoring inlet and outlet air temperature, water inlet and outlet temperature, fan speed and water flow rate.
- Variable speed fans with four (4) speed set points. The fans have adjustable speeds for given heat loads.
- Cooling water flow control from 0 – 100% of maximum flow rate. As with the fans, cooling water flow rate is regulated to provide the appropriate heat removal capacity based on the heat load.

With control and monitoring of all parameters regulated by a local controller, an end user is able to establish a specific set point for server inlet air temperature. By constantly monitoring the various temperature and flow parameters the controller regulates water flow and fan speed to achieve a preset supply air temperature.

In order to test the cooling performance and energy efficiency of the modular liquid cooling system with varying supply water temperatures, an additional coolant distribution unit (CDU) was installed and connected to the system. The CDU consists of a water-to-water heat exchanger that provided isolation between the primary chilled water loop and secondary cool water loop that is connected to the modular system. The CDU contained its own pump and monitoring equipment to measure primary and secondary chilled water pressure, temperatures, and flow rate.

Airflow through the modular system is horizontal such that cool air is pushed to the front of the server equipment, drawn through the equipment and exhausted where it is drawn back into the modular cooling system and passed through the unit's air-to-water heat exchanger to cool the supply air to the desired temperature.

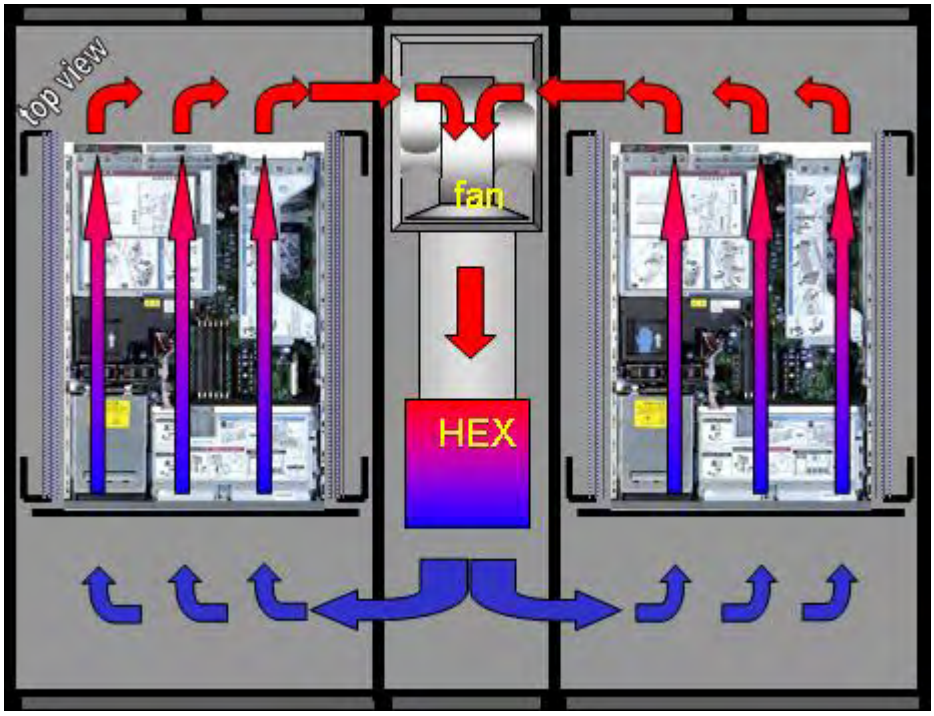


**Figure 6 Modular liquid cooling enclosure**

### 3.3.2 Server

The IT or heat load in each server rack was provided by 38 standard Sun V20 1U servers, each with a size of 28"x17"x1.75"each the two server racks tested. The maximum load per server rack was 9.75kW for all temperature setpoints tested. Details of the servers provided in this study are publicly available [1].

### 3.3.3 Server power management

Using a commercially available software program as the “control program”, the load within each rack was effectively controlled at desired levels by dynamically turning on and off servers and running the program [2] at various CPU loads to achieve the desired power consumption and resulting heat load to test the energy efficiency of the modular cooling system. Prior to the test, reference measurements on each type of server that was being used in the racks were performed to measure idle and loaded power consumption.

To achieve the desired partial or full power load level (kW/rack) to be tested, the number of servers needed to run at 100% load was calculated and the program turned the rest off. For example to achieve the desired heat load levels in the test plan, the number of servers running at full load per rack were as follows: 10kW - 33 servers; 7.5kW - 25 servers; 5kW - 17 servers; 2.5kW - 9 servers.

Although all of the servers used in the test configuration were the same, the initial reference measurements identified that they had significantly different power consumption due to different memory or computing configurations installed.

Therefore, to achieve and maintain the desired full or partial power load per rack during each test sequence, the monitoring system collected real time measurements of server power from the rack power strips and the program used this information to turn on or off additional servers as necessary to maintain the desired power load levels.

To monitor the inlet air temperature being delivered to the test racks by the modular cooling system, air temperature probes were installed at the top, middle and bottom of each rack. To improve the response time of these sensors, the power to the servers installed at these rack elevations were maintained on during each testing sequence. Prior to starting a specific modular cooling system test sequence, the total power consumption at each rack was verified against the readings of the power strip and adjusted as needed until the power consumption was stable.

### 3.3.4 Equipment location

The two server racks were positioned at the southwest corner of the data center in this study. The server racks together with the modular system and CDU were separated from the rest of the data center by an array of curtains surrounding them. The space within the curtain has a floor area of 110” x 178” and a height of 86”.

Figure 7 shows the front- and rear-view of the equipment layout in this study.

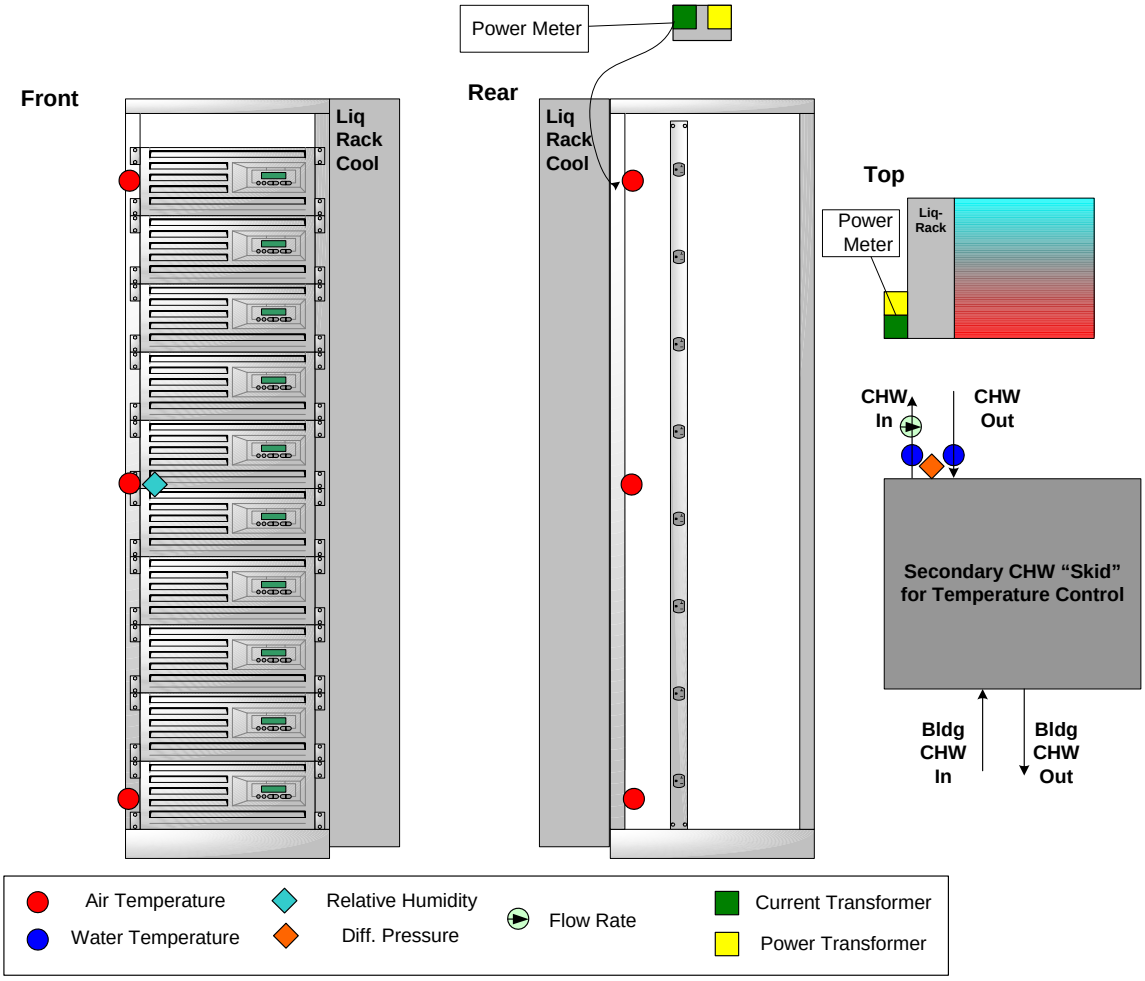


Figure 7 Liquid Rack Cooling Layout

## 3.4 Measured parameters

The following parameters were monitored or measured during the evaluation

- Power demand of servers and cooling modules
  - o Actual power demand for servers used in this study.
  - o Actual power demand for the cooling modules

    Electric power demand for the pump unit and eight cooling modules was monitored separately.
- Air temperature
  - o Cold inlet air temperature to the front of server racks

    There were three temperature sensors (RTDs) installed at the bottom, middle, and top positions (0.65”, 37.5”, and 69”, respectively) at the front inlet of each of the server racks. These heights corresponded to servers 2U, 20U, and 38U, respectively.
  - o Hot outlet air temperature from the back of server racks

    There were three temperature sensors (RTDs) installed at the bottom, middle, and top positions (0.65.”, 37.5”, and 69”, respectively) at the rear outlet of for each of the server racks.
  - o Data center air temperatures (outside the enclosed test area): from building energy management system
  - o Outdoor air temperatures (dry-bulb & relative humidity).
- Cooling module entering and leaving chilled water temperatures

  Chilled water temperatures in the supply and return pipes were measured by installing two temperature sensors on the surface of the water pipes, with insulation material wrapped around.
- Cooling module chilled water flow rates
- Cooling module entering and leaving chilled water pressure differential.
- In addition to the real-time measurements taken of the test environment, the following parameters were recorded manually to quantify the power demand in the data center and the energy use of the central chilled water plant: total IT equipment power; total central chilled water plant power; primary chilled water flow and chilled water temperatures (supply and return); chilled water supply/return differential pressure. This data was used to perform an engineering analysis to determine the central chilled water plant energy efficiency to estimate the potential energy savings versus using a conventional raised, CRAH cooling system and the modular, scalable cooling system in this Power demand of servers and modular system

## 3.5 Data acquisition system

Data collection for the test environment was performed using a commercially available data acquisition system [3]. Data collection for the central chilled water plant was collected from both the site energy management system and from field measurements taken were continuous monitoring data points were not available. Data points were measured over the duration of the study, gathered from the manufacturer's modular cooling equipment (where available), the Sun servers, the rack power strips, and an array of power meters, flow meters, pressure transducers, and RTD temperature sensors.

Data was gathered by local network appliances via a variety of network and serial communication protocols from the meters, the servers, and various analog sensors through I/O modules. After initial local processing and alarm checking, data was reported to a remote server and stored in a relational database. Similar data points were measured for each rack cooling technology, and stored in a shared relational database at a remote server. The real-time data was available through a web application, allowing users to monitor and manage the study remotely in real time. Access controls ensured that each manufacturer could see only its own data, while the designated host had access to all data.

Three power meters measured the energy use of the rack chiller and the two racks of servers. Smart power strips reported current for each rack. RTDs were placed at three heights on each rack, front and back, as well as at the inlet and outlet of the fan units. Ambient temperature and humidity were measured on the cold-aisle. Various internal server temperatures were gathered from selected servers, as reported by the servers themselves. Supply and return chilled water conditions were measured using a flow meter, pressure transducers, and RTDs. The cooling modules themselves also reported water conditions, fan speed, air temperatures, and cooling output power.

## 3.6 Test procedures and operating conditions

- Control and adjust the server inlet air temperature at discrete set points from 80°F down to 68°F, with steps of 4°F.
- For each desired inlet air temperature level identify the level of available and applicable full server load (e.g., 9.75kW per rack). Allow sufficient operating time, and perform steady-state testing and monitoring.
- Decrease the server load from full (100% available) to 50% of the defined capacity per rack (e.g., 9.75 kW/rack). Perform steady-state testing and monitoring for 50% load level.
- Vary chilled water supply temperature at three levels: 70°F, 60°F, and 50°F.

The matrix of various inlet air temperatures (from 68°F to 80°F) with various chilled water temperatures (from 50°F to 70°F) used for both full load and half load in this study is presented in the following table.

**Table 6 Set Points for Test Conditions**

| Supply water temperature (F) | Inlet air temperature set point (F) | Targeted total server load (kW) for one servers rack | Various server loads (kW) per rack | |
|---|---|---|---|---|
| | | | 100% | 50% |
| 50 | 68 | 10 | 9.8 | 4.9 |
| 50 | 72 | 10 | 9.8 | 4.9 |
| 50 | 76 | 10 | 9.8 | 4.9 |
| 50 | 80 | 10 | 9.8 | 4.9 |
| 60 | 68 | 10 | 9.8 | 4.9 |
| 60 | 72 | 10 | 9.8 | 4.9 |
| 60 | 76 | 10 | 9.8 | 4.9 |
| 60 | 80 | 10 | 9.8 | 4.9 |
| 70 | - | 10 | 9.8 | 4.9 |
| 70 | 72 | 10 | 9.8 | 4.9 |
| 70 | 76 | 10 | 9.8 | 4.9 |
| 70 | 80 | 10 | 9.8 | 4.9 |

## *3.7 Performance metrics for modular cooling*

In order to characterize the thermal performance of the modular liquid cooling system, we calculated the ratio of cooling produced by the modular system to the total power demand for the modular system, defined as "coefficient of performance (COP)." Normally COP of a modular system is the ratio of the heat removed by the modular system to the work supplied to the modular system. The COP is unit less, with a higher value representing higher efficiency for the modular system. The COP can be calculated under applicable operating and environmental conditions (a range determined by server power load and inlet air temperature).

In this evaluation, the work supplied is fan power required to produce the required airflow from the modular system, while the heat removed is equivalent to the cooling transferred by the modular system.

$$COP = \frac{Cooling}{P_{total}}$$

Where Cooling is the cooling provided by the modular system, and $P_{total}$ is generally defined as the total power demand for all components (e.g., fan, and pump if necessary) in the modular system. Because there are only fans in this modular system, the total power demand was for air-circulating requirement in this case.

Total power demand for the modular system can be measured as follows:

Ptotal = $P_{fan\ power}$

The actual cooling provided by the water-modular system can be calculated from the secondary-loop chilled water temperature rise and chilled water flow rate, using the following formula:

Where

$$Cooling = \frac{60\rho Q C_p \Delta T_w}{3412.1}$$

Cooling is produced from the modular system, in kW.

ρ: Water density in lb/gal, assuming water density ρ of 8.34 lbm/gal (or 62.4 lbm/$ft^3$)

Q: Averaged water flow rate measured in gallon per minute

Cp: Specific thermal conductivity of water, 1 BTU/F-lbm

$\Delta T_w$ : Measured water temperatures rise, in °F

Therefore,

$$Cooling = 0.1467 Q\ \Delta T_w$$

$$COP = \frac{Cooling}{P_{total}} = \frac{0.1467 Q\ \Delta T_w}{P_{total}}$$

The portion of chiller pumping power required to deliver the chilled water volume in the primary-loop was ignored for this evaluation.

Another performance metric we calculated is the ratio of total power divided by the cooling transported by the modular system. This is similar to chiller efficiency defined as power demand per cooling transferred. Represented in kW per cooling ton, a lower value of this ratio indicates a higher cooling energy efficiency at which the modular system is performing.

$$MSE = \frac{12000 P_{total}}{Cooling} = \frac{12000 P_{total}}{60\rho Q C_p \Delta T_w} = 24 \frac{P_{total}}{Q \Delta T_w}$$

Where:

Modular System Efficiency (MSE): ratio of total cooling power to cooling transported, in kW/ton
Q: Averaged water flow rate measured in gallon per minute
$\Delta T_w$ : Measured water temperatures rise, in °F

An alternative metric, defined as the modular system's power utilization index, is the ratio of power demand for the modular system to computer load under selected operating conditions. A higher value of the power index indicates higher cooling energy demand for the modular system at a given server load under an operation condition.

$$PI = \frac{P_{total}}{P_{server}}$$

## 3.8 Summary of findings and conclusions

The measurement and data collection system deployed in this study was reliable and accurate, and provided continuous monitoring of a wide range of critical parameters. It also provided real-time data display during the course of the experimental study. Data analysis was further enabled by writing custom database queries to parse the raw data collected to provide the ability for effective analysis of the large amount of data collected during the testing.

The software program used in the study to measure and monitor the power to the test environment effectively created various load/power consumption scenarios (based on the reference measures) to make sure the necessary power draw was generated and maintained required for all the tests in this study. Each rack was capable of consuming over 10kW and depending on the server load set points, the program was used to set load levels (e.g., 2.5kW, 5kW, 7.5kW, 10kW or maximum) by turning on/off the necessary amount of servers and by running the server power benchmarking tool at full load.

The overall coverage of operating conditions ranged from 65°F to 80°F for inlet air temperatures, and the server loads ranging from 1.7 kW/rack up to 10.4 kW/rack

The inlet air temperature distribution in this study was largely uniform, from the bottom to the top of the server racks, and from rack to rack. For example, the difference between maximum and minimum average inlet temperature ranged from less than 0.1F up to 2F, with the standard deviation ranging from less than 0.1F to 1.5°F. The temperature non-uniformity among the two racks tested was not noticeable because the temperature control appeared to be fairly effective within its desired set point as shown in Table 1. Using a local controller, the system ensures that all components are operating at preset levels to support the removal of specific heat loads.

Table 7 shows the results from the tests performed at the facility including: server load; average inlet/outlet air temperatures monitored at three different heights for both server racks; cooling delivered by the modular system; power demand of the modular system; and three performance metrics in this study: COP; modular system efficiency; and PI.

**Table 7 Actual Test Conditions and Results**

| Test Point | Server Load per Rack (kW/rack) | Average Inlet Air Temperature (F) | Average Outlet Air Temperature (F) | Chilled Water Temperature (F) | Chilled Water Flowrate (gpm) | Total Cooling (kW) | Total Power for Cooling Module (kW) | Total Power for Server (kW) | COP | ModEff (kW/ton) | Power Index |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9.8 | 68 | 99 | 50 | 12.7 | 24.2 | 2.0 | 19.5 | 12.1 | 0.29 | 0.10 |
| 2 | 9.8 | 72 | 102 | 50 | 14.3 | 20.9 | 2.0 | 19.5 | 10.6 | 0.33 | 0.10 |
| 3 | 9.8 | 77 | 106 | 50 | 12.9 | 17.1 | 2.0 | 19.5 | 8.6 | 0.41 | 0.10 |
| 4 | 9.8 | 78 | 110 | 50 | 8.2 | 21.6 | 2.0 | 19.5 | 10.9 | 0.32 | 0.10 |
| 5 | 9.8 | 72 | 102 | 60 | 14.3 | 20.9 | 2.0 | 19.5 | 10.6 | 0.33 | 0.10 |
| 6 | 9.8 | 75 | 106 | 60 | 16.1 | 26.0 | 2.0 | 19.5 | 13.0 | 0.27 | 0.10 |
| 7 | 9.8 | 75 | 106 | 60 | 16.1 | 21.3 | 2.0 | 19.5 | 10.6 | 0.33 | 0.10 |
| 8 | 9.8 | 79 | 110 | 60 | 10.6 | 20.2 | 2.0 | 19.5 | 10.1 | 0.35 | 0.10 |
| 9 | 9.8 | 83 | 115 | 70 | 16.1 | 26.0 | 2.0 | 19.5 | 13.1 | 0.27 | 0.10 |
| 10 | 9.8 | 83 | 115 | 70 | 16.1 | 21.3 | 2.0 | 19.5 | 10.7 | 0.33 | 0.10 |
| 11 | 9.8 | 83 | 115 | 70 | 16.1 | 21.3 | 2.0 | 19.5 | 10.7 | 0.33 | 0.10 |
| 12 | 4.9 | 67 | 92 | 50 | 6.6 | 12.6 | 1.5 | 9.8 | 8.3 | 0.42 | 0.16 |
| 13 | 4.9 | 72 | 94 | 50 | 5.3 | 11.6 | 1.5 | 9.8 | 7.8 | 0.45 | 0.15 |
| 14 | 4.9 | 76 | 98 | 50 | 4.2 | 11.2 | 1.5 | 9.8 | 7.5 | 0.47 | 0.15 |
| 15 | 4.9 | 80 | 103 | 50 | 3.4 | 12.1 | 1.5 | 9.8 | 8.1 | 0.44 | 0.15 |
| 16 | 4.9 | 67 | 92 | 60 | 16.1 | 14.2 | 1.5 | 9.8 | 9.4 | 0.37 | 0.15 |
| 17 | 4.9 | 70 | 97 | 60 | 7.7 | 10.1 | 1.5 | 9.8 | 6.8 | 0.52 | 0.15 |
| 18 | 4.9 | 74 | 100 | 60 | 5.3 | 10.1 | 1.5 | 9.8 | 6.7 | 0.52 | 0.15 |
| 19 | 4.9 | 79 | 102 | 60 | 5.8 | 11.9 | 1.5 | 9.8 | 8.0 | 0.44 | 0.15 |
| 20 | 4.9 | 77 | 98 | 70 | 16.1 | 9.5 | 2.0 | 9.8 | 4.7 | 0.74 | 0.20 |
| 21 | 4.9 | 76 | 99 | 70 | 16.1 | 14.2 | 1.5 | 9.8 | 9.4 | 0.38 | 0.16 |
| 22 | 4.9 | 76 | 99 | 70 | 16.1 | 9.5 | 1.1 | 9.8 | 8.3 | 0.42 | 0.12 |

The testing determined that different IT equipment and environmental operating conditions affected the cooling delivery efficiency of the modular cooling units. Specifically, variations in server power load and inlet air temperature resulted in different COP, cooling efficiency (kW/ton), and power index for modular Cooling System 3.

Generally, total modular cooling power demand stabilized at each of the server loads, e.g., mostly around 2.0 kW for full server load, and 1.1 - 1.5 kW for half server load. The cooling power demand decreased when lower server loads were in operation.

Under a similar rack power load and the same chilled water supply temperature, the COP of the modular system tended to decrease with an increase in inlet supply air temperature, while modular system cooling kW/ton value exhibited a reversed trend. In addition, the PI values appeared to be virtually unchanged for a similar rack power load with various inlet air temperatures.

Under the different chilled water supply temperatures (50°F, 60°F and 70°F) and with similar operating and environmental conditions (rack power loads and inlet air temperatures), the performance metrics – COP, kW/Ton, and PI, largely remained unchanged. This may be due to the fact that inherent power demand of the modular system and the total cooling supplied by the modular system remained largely the same under the same server load, regardless of variations in inlet supply temperature or chilled water temperature. Or, the modular system was capable of providing the necessary cooling at various supply water temperatures with effective water flow and air temperature control, without incurring additional power demand for cooling.

Overall, the kW/ton values of Cooling System 3 increased slightly with elevated chilled water temperature ranging from 50°F to 70°F with the increase in rack power loads, with the magnitude in the range of less than 0.3 up to 0.6 kW/ton.

With chilled water temperatures ranging from 50°F to 70°F, the COP values of the modular cooling decreased with the decrease in server loads – indicating a higher energy efficiency in transporting cooling when challenged with higher rack power loads in this study. The PI values did not exhibit clear correlation with the change in server loads.

The modular liquid cooling system provided sufficient cooling to the server racks in all test conditions, while controlling inlet air temperature with good uniformity. With control and monitoring of all parameters regulated by a local controller, we were able to establish a specific set point for the desired server air inlet temperature. By constantly monitoring the various temperature and flow parameters, the modular system's controller effectively regulated water flow and fan speed to achieve preset rack inlet supply air temperatures. The liquid rack cooling system also demonstrated superior capability and effectiveness in controlling inlet air temperature compared to the other systems tested in this study.

Overall, the COP ranged from 5 up to 13; MSE (kW/ton) from 0.3 up to 0.5 kW/ton; and PI from 0.1 to 0.2, exhibiting an energy efficiency level at par with traditional CRAHs under the selected operating and environmental conditions (rack power load and inlet air temperature). We believe that the reason that this system did not perform more efficiently than traditional CRAH units, was because the rack power load we had available to us in this test was only 1/3 of total cooling system capacity; thus penalizing its kW/ton performance. If this modular liquid cooling system had been tested with higher rack power loads (20-30 kW/rack), the efficiency levels may have been up to 50% higher than experienced in this study.

Power for the variable speed fans in this system is controlled at four discrete levels corresponding to four speed set points. In order to further save fan energy and improve kW/Ton and COP values of the system, we recommend that the vendor consider using electric commutation fans to provide continuous 0-100% adjustability in future generations of the product.

The use of modular, scalable cooling systems, such as the unit in this evaluation, may increase the overall data center efficiency while maintaining effective control over inlet air temperatures at desired levels especially when optimized with the central cooling plant. The results of our testing support the hypothesis that these types of liquid cooling

systems may be able to perform effectively without chillers using only evaporative cooling in cool, dry climates.

The findings from this study indicate that by implementing liquid cooling in lieu of traditional CRAH units, the overall kW/Ton in the data center could be reduced. This type of modular cooling system also provides increased flexibility in data center configuration and layout.

This evaluation does not include the assessment of the potential energy savings possible if this cooling system technology was used for the entire data center. In addition, we did not test this system's cooling performance and energy efficiency in a redundant and/or failed operating condition.

We also recommend that the reader of these individual reports, consider not only the energy efficiency performance of the modular scalable cooling system but the system's capability and effectiveness to maintain server inlet air temperature within ASHRAE recommended levels and the potential dependence on other cooling or humidification in the data center. In closing, in order to quantify or estimate the impact of modular, scalable cooling systems on overall data center energy efficiency, one must also assess their integration with the rest of the data center eco-system, the temperature range of chilled water available from the plant, the local weather conditions where the datacenter is located, and the power density characteristics of the data center.

## 3.9 Acknowledgements

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# Evaluation for a Modular, Scalable Passive Cooling System In Data Centers

## Final Report

## To

## The California Energy Commission

**Issued:** **December 21, 2008**

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# 4 Evaluation for a Modular, Scalable Passive Cooling System in Data Centers

## 4.1 Problem Statement

Enterprise data centers and IT equipment product development and research data center labs require continuous cooling to maintain inlet air temperatures within recommended operating levels for the IT equipment. The consolidation and higher density aggregation of slim compute, storage and networking hardware has resulted in higher power density/ft² than the commonly used raised floor, CRAC design was originally conceived to handle.

The result is that in many existing data centers and in the majority of newly constructed data centers, the performance of the ventilation and cooling systems is less than optimal. Current IT computing trends indicate that IT equipment manufacturers are designing their equipment to operate in "conventional" data center environments by providing alternative cooling solutions to either their equipment or relying on supplemental cooling in rack or row systems.

This trend to higher power density resulting from current and future generations of servers has created significant opportunities for precision cooling suppliers to engineer and manufacture packaged modular and scalable systems that will significantly improve efficiency while solving the thermal challenges, improving reliability, and allowing for future needs and growth.

Such pre-engineered and manufactured systems may be a significant improvement over current design; however, without an energy efficiency focus, they could also lead to even lower energy efficiencies in the overall data center support infrastructure

The research objective of the project was to evaluate several commercially available, modular localized cooling systems to test the research thesis that these types of close coupled cooling solutions will be more energy efficient than traditional legacy data center cooling systems.

## 4.2 Technical objectives

This report is the result of a test plan that was developed with the participants' input to include specific design characteristics of the selected modular localized cooling solution provided by vendor 4 for a data center located in Sun Microsystems, Inc. The evaluation included monitoring and measurement of selected parameters, and establishing and calculating energy efficiency metrics for the selected product, which is a modular, scalable passive liquid-rack cooling system in this study.

The scope is to quantify energy performance of the modular cooling unit as it corresponds to server load and inlet air temperature.

The information generated from this testing when combined with a concurrent research study to document the energy efficiency of the host data center's central chilled water

cooling plant can be used to estimate potential energy savings from implementing modular cooling compared to conventional cooling in data centers.

The project intends to evaluate a modular localized cooling solution provided by vendor 4 for a data center located at Sun Microsystems, Inc. The evaluation included monitoring and measurement of selected parameters, and establishing and calculating efficiency metrics for the selected product, which is a modular, scalable passive cooling system in this study. The scope is to quantify energy performance of the modular cooling unit corresponding to various server loads and inlet air temperatures, under various chilled-water supply temperatures.

The information generated from this study may be used to estimate potential energy savings from implementing modular cooling compared to conventional cooling in data centers. This modular, scalable cooling system is a heat exchanger utilizing water at a temperature higher than the room dew-point temperature. It is therefore a passive modular passive system for which direct electric power is not required to deliver cooling from the heat exchanger (only the described water flow is required).

## *4.3 Technical information on the characteristics of cooling systems, servers*

The evaluation tests were performed in a data center space located in Santa Clara, California. The datacenter area is approximately 12,800 square feet, with a ceiling height of 13 ft 6 inches and no raised floor. All server racks and support equipment are installed directly on the slab floor. There were various types of servers, rack sizes and shapes from various vendors. The data center was specifically designed to support racks with any type of IT equipment.

Power, chilled water, and communication cables to the server racks were provided through overhead cable trays. 700 tons of cooling is provided to the space from the central chilled water plant for cooling the IT equipment. The chilled water is supplied by a 2,000 ton central chilled water plant.

Power for thirty six 150kW PDUs was provided through a 480v AC bus way system. The 150kW power distribution units (PDUs) were located throughout the space. The PDUs transform the power from 480v AC to 208v AC for distribution to the server racks. The data center currently can support 190 watts/ft$^2$ of floor area. The design load per rack footprint was 5kW/rack with growth to 9kW/rack.

### 4.3.1 Modular passive cooling system

The passive cooling system studied consisted of a single, 77”H x 26”W x 5.5”D modular system (air-to-water heat exchanger) attached to rear door of the server rack. Since the rear-door heat exchanger replaces the standard rear door, the installed module adds 4” to the total rack depth, not 5.5”. The modular system does not utilize electrical power to operate.

The modular system has a water-cooled device that mounts on the rear of the server rack to cool the heated server exhaust air. A supply hose delivers *above room dew point temperature* (ADP) conditioned water to the heat exchanger. Another hose delivers

warmed return water back to the water pump or chiller. In this report, we refer to this as a secondary cooling loop. The primary cooling loop supplies building chilled water to secondary ADP cooling loops and air conditioning units. The passive cooling module is designed to remove up to 102,400 BTU (30kW) of heat. Figure 1 is a side view of the modular system.

**Figure 8 Side View of the Passive Modular system with Rear Door Open**

In order to test the effectiveness of the modular system under various supply water temperatures, an additional coolant distribution unit (CDU) was installed and connected to the modular system. The CDU consists of a water-to-water heat exchanger that provides isolation between the primary chilled water and secondary cooling water loops that are connected to the module. The CDU utilizes an internal secondary loop pump and measures primary and secondary water pressures, temperatures and flow rates.

The passive rear-door modular cooling system was tested in a hot/cold aisle configuration with ambient room air drawn through the servers through the front of the equipment by the internal server fans which is then heated by the servers and exhausted out the rear of the rack.

### 4.3.2 Server

The IT or heat load in each server rack was provided by 40 standard Sun V20 1U servers, each with a size of 28”x17”x1.75”for the one server rack tested. The maximum load per server rack was 10. 9kW for all temperature setpoints tested. Details of the servers provided in this study are publicly available [1].

### 4.3.3 Server power management

Using a commercially available software program as the “control program”, the load within each rack was effectively controlled at desired levels by dynamically turning on and off servers and running the program [2] at various CPU loads to achieve the desired power consumption and resulting heat load to test the energy efficiency of the modular cooling system. Prior to the test, reference measurements on each type of server that was being used in the rack were performed to measure idle and loaded power consumption.

To achieve the desired partial or full power load level (kW/rack) to be tested, the number of servers needed to run at 100% load was calculated and the program turned the rest off. For example to achieve the desired heat load levels in the test plan, the number of servers running at full load per rack were as follows: 10kW - 33 servers; 7.5kW - 25 servers; 5kW - 17 servers; 2.5kW - 9 servers.

Although all of the servers used in the test configuration were the same, the initial reference measurements identified that they had significantly different power consumption due to different memory or computing configurations installed.

Therefore, to achieve and maintain the desired full or partial power load per rack during each test sequence, the monitoring system collected real time measurements of server power from the rack power strips and the program used this information to turn on or off additional servers as necessary to maintain the desired power load levels.

To monitor the inlet air temperature being delivered to the test rack by the modular cooling system, air temperature probes were installed at the top, middle and bottom of the rack. To improve the response time of these sensors, the power to the servers installed at these rack elevations were maintained on during each testing sequence. Prior to starting a specific modular cooling system test sequence, the total power consumption of the rack was verified against the readings of the power strip and adjusted as needed until the power consumption was stable.

## *4.4 Measured parameters*

- Power demand of servers and modular system
  - Actual power demand for servers used in this study.
  - Actual power demand for the CDU.
- Air temperature
  - Cold inlet air temperature to the server rack

    There were three temperature sensors (RTDs) installed at the top, middle, and bottom positions (0.65”, 37.5”, and 69”, respectively)

- o Hot outlet air temperature from the server racks

  There were three temperature sensors (RTDs) installed at the top, middle, and bottom positions (0.65.”, 37.5”, and 69”, respectively)

- Outdoor air temperatures (dry-bulb & relative humidity).
- Cooling module entering and leaving chilled water temperatures

  Chilled water temperatures in the supply and return pipes were measured by installing two temperature sensors on the surface of the water pipes, with insulation material wrapped around.

- Cooling module chilled water flow rates
- Cooling module entering and leaving chilled water pressure differential.
- In addition to the real-time measurements taken of the test environment, the following parameters were recorded manually to quantify the power demand in the data center and the energy use of the central chilled water plant: total IT equipment power; total central chilled water plant power; primary chilled water flow and chilled water temperatures (supply and return); chilled water supply/return differential pressure. This data was used to perform an engineering analysis to determine the central chilled water plant energy efficiency to estimate the potential energy savings versus using a conventional raised, CRAH cooling system and the modular, scalable cooling system in this Power demand of servers and modular system

## *4.5 Data acquisition system*

Data collection for the test environment was performed using a commercially available data acquisition system [3]. Data collection for the central chilled water plant was collected from both the site energy management system and from field measurements taken were continuous monitoring data points were not available. Data points were measured over the duration of the study, gathered from the manufacturer's modular cooling equipment (where available), the Sun servers, the rack power strips, and an array of power meters, flow meters, pressure transducers, and RTD temperature sensors.

Data was gathered by local network appliances via a variety of network and serial communication protocols from the meters, the servers, and various analog sensors through I/O modules. After initial local processing and alarm checking, data was reported to a remote server and stored in a relational database. Similar data points were measured for each rack cooling technology, and stored in a shared relational database at a remote server. The real-time data was available through a web application, allowing users to monitor and manage the study remotely in real time. Access controls ensured that each manufacturer could see only its own data, while the designated host had access to all data.

Two power meters measured the energy use of the cooling unit and rack of servers. Smart power strips reported current for each rack. RTDs were placed at three heights on each rack, front and back, as well as at the inlet and outlet of the fan units. Ambient

temperature and humidity were measured on the cold-aisle. Various internal server temperatures were gathered from selected servers, as reported by the servers themselves. Supply and return chilled water conditions were measured using a flow meter, pressure transducers, and RTDs. The cooling modules themselves also reported water conditions, fan speed, air temperatures, and cooling output power.

## 4.6 Test procedures and operating conditions

The parametric test matrix with varying inlet air temperature (68°F, 72°F, 76°F, 80°F) against elevated supply water temperature (50°F, 60°F, 70°F) and achievable server loads (50%, 100%) is presented in the following table.

**Table 8 Set Points for Test Conditions**

| Supply water temperature (F) | Inlet air temperature set point (F) | Targeted total server load (kW) for one servers rack | Various server loads (kW) per rack | |
|---|---|---|---|---|
| | | | 100% | 50% |
| 50 | 68 | 10.9 | 10.9 | 5.5 |
| 50 | 72 | 10.9 | 10.9 | 5.5 |
| 50 | 76 | 10.9 | 10.9 | 5.5 |
| 50 | 80 | 10.9 | 10.9 | 5.5 |
| 60 | 68 | 10.9 | 10.9 | 5.5 |
| 60 | 72 | 10.9 | 10.9 | 5.5 |
| 60 | 76 | 10.9 | 10.9 | 5.5 |
| 60 | 80 | 10.9 | 10.9 | 5.5 |
| 70 | - | 10.9 | 10.9 | 5.5 |
| 70 | 72 | 10.9 | 10.9 | 5.5 |
| 70 | 76 | 10.9 | 10.9 | 5.5 |
| 70 | 80 | 10.9 | 10.9 | 5.5 |

- Control and adjust the cold aisle air temperature (server inlet air temperature) at discrete set point of from 80°F down to 68°F, with steps of 4°F.
- For each desired inlet air temperature level, identify the level of available and applicable full server load (e.g., 10.9 kW for the rack tested). Allow sufficient operating time, and perform steady-state testing and monitoring.
- Decrease the server power from 100% (~10.9kW) to 50% (~ 5.5 kW/rack). Perform steady-state testing and monitoring at 50% load.
- Control secondary loop water supply temperature to 70°F, 60°F & 50°F.

Note that for the majority of the testing, we used space heaters to raise the temperature of air entering the inlet of servers. We observed that a reasonably small movement or change of the heaters could cause a noticeable change in the sensor temperatures. The temperature for the "entire" air volume was not uniformly adjusted however, which could lead to an inaccuracy of the "true" profile for actual room air temperatures. This setup

could understate the performance of the water system since the system would have to remove more heat if the whole room were "truly" warmer. Since we did not measure the system airflow and the added fan heat for each test condition we could analyze the magnitude of the error or bias. The author acknowledges that had we performed an air balance vs. a water balance, the modular cooling system may have performed closer to test results performed by the vendor in a more controlled lab environment vs. an operating data center where we performed the testing.

Therefore, for the purposes of this evaluation we focused our analysis on waterside and power monitoring readings rather than airside calculations. .

## 4.7 Performance metrics for the passive modular cooling

There is no active electric power demand for operating the passive heat exchanger device to cool servers in the rack. However, we regard the hydraulic power of the water flow within the secondary loop (connecting the rear door heat exchanger with the CDU) as the power demand needed for operating the modular cooling device in this evaluation.

In order to characterize its own thermal performance, we use the ratio of cooling delivered by the modular passive system to the total hydraulic power demand for the water flow in the secondary loop, defined as “coefficient of performance (COP).” Normally COP of a modular system is the ratio of the heat removed by the module to the work supplied to the module. The COP can be calculated under applicable operating conditions (a range determined by inlet air temperature, rack power load, and supply water temperature).

In this evaluation, the work supplied is the hydraulic power required to produce the required water flow rate through the modular passive system, while the heat removed is equivalent to the cooling provided by the rear door.

$$COP = \frac{Cooling}{P_{hydraulic}}$$

Where Cooling is the cooling provided by the modular passive system and $P_{hydraulic}$ is calculated by the multiplication of the water differential pressure flow rate using the following equation:

$P_{hydraulic\ power} = 0.43506\ Q\Delta P/1000$, kW

Where

$\Delta P$: pressure differential between secondary-loop supply and return water flow, in psi.
Q: Averaged water flow rate measured in gallons per minute

Because the CDU was only used to provide variable varied chilled water supply temperature (e.g., 50°F. 60°F, or 70°F), the actual power required for the CDU operation is not considered to be part of power demand for the modular passive system evaluated in this study.

The actual cooling provided by the modular passive system can be calculated from the rise in the secondary-loop chilled water temperature the chilled water flow rate, using the following formula:

Where

$$Cooling = \frac{60 \rho Q C_p \Delta T_w}{3412.1}$$

Cooling is delivered by the modular passive system, in kW.

ρ: Water density in lb/gal, assuming water density ρ of 8.34 lbm/gal (or 62.4 lbm/$ft^3$)

Q: Averaged water flow rate measured in gallon per minute

Cp: Specific thermal conductivity of water, 1 BTU/F-lbm

$\Delta T_w$ : Measured water temperatures rise, in °F

Therefore,

$$Cooling = 0.1467 Q\ \Delta T_w$$

$$COP = \frac{Cooling}{P_{total}} = 337.1 \frac{\Delta T_w}{\Delta P}$$

Because this modular passive cooling system requires no internal fans or additional pumping energy, its COP is proportional to the ratio of the secondary water temperature differential to the secondary water pressure differential. Our testing confirmed our hypothesis for a sensible cooling coil such as the modular passive system provided by vendor 4. The chiller pumping power required to deliver the chilled water volume in the primary-loop was ignored for this evaluation in keeping with the evaluation of the other vendor's systems.

Another performance metric we calculated is the ratio of total power divided by the cooling transported by the modular system. This is similar to chiller efficiency defined as power demand per cooling transferred. Represented in kW per cooling ton, a lower value of this ratio indicates a higher cooling energy efficiency at which the modular system is performing.

$$MSE = \frac{12000(0.43506\ Q\Delta P)/1000}{Cooling}$$

$$MSE = \frac{12(0.43506\ Q\Delta P)}{60\rho Q C_p \Delta T_w} = 1.0431x10^{-4}\frac{\Delta P}{\Delta T_w}$$

where

Module System Efficiency (MSE): Ratio of total hydraulic power for cooling to cooling delivered, in kW/ton
Q: Averaged water flow rate measured in gallon per minute
ΔP: Measured water pressure difference between secondary-loop supply and return, in psi.
Cooling is delivered by the modular passive system, in BTU/hr.

An alternative metric, defined as the module's power index (PI), is the ratio of power demand for the modular passive system to computer load under selected operating conditions. A higher value of the power index indicates higher cooling energy demand for the modular passive system at a given server load under an operation condition.

$$PI = \frac{P_{hydraulic}}{P_{server}}$$

## 4.8 Summary of findings and conclusions

The facility measurement system deployed in this study was reliable and accurate, and provided wide range of critical parameters under monitoring. It has also provided real-time data display during the course of the experimental study, and supported the study's data analysis effectively.

The software program used in the study effectively created various load/power consumption scenarios (based on the reference measures) to make sure the necessary power draw was generated and maintained required for all the tests in this study. Each rack was capable of consuming over 10 kW and depending on the server load set points; the program was used to set load levels by turning on/off the necessary amount of servers and by running the benchmarking tool at full load.

Based on the actual sever load achieved, the level of inlet air temperature set points and the available temperature control within the test space, the actual operating conditions may and may not be fully achieved as planned in the set point matrix shown in Table 1.

The actual operating conditions achieved in this evaluation are shown in

Table 9. The actual inlet temperature was not able to go down to as low as 68°F as originally planned based on the 'whole room' temperature of approximately 70°F. The overall coverage of operating conditions ranged from 70°F to 83°F for inlet air temperature, server loads from 4.8 kW/rack to 11.2 kW/rack and supply water temperature of 50°F, 60°F, and 70°F.

Table 5 shows the results from the tests performed at the facility including: rack power load; average inlet/outlet air temperatures monitored at three different heights for the server rack; cooling delivered by the modular passive cooling system (heat exchanger); hydraulic power demand of the modular system; and three performance metrics: hydraulic based COP; module system efficiency; and power index.

Table 9 Actual Test Conditions and Results

| Server Load per Rack (kW/rack) | Average Inlet Air Temperature (F) | Average Outlet Air Temperature (F) | Chilled Water Temperature (F) | Chilled Water Flowrate (gpm) | Total Cooling (kW) | Hydraulic Power for Cooling Module (kW) | Total Power for Server (kW) | Hydraulic power based COP | Hydraulic power based ModEff (kW/ton) | Hydraulic power based Power Index |
|---|---|---|---|---|---|---|---|---|---|---|
| 10.8 | 70 | 92 | 52 | 9.9 | 8.1 | 0.047 | 10.8 | 171.7 | 0.02 | 0.004 |
| 10.8 | 73 | 120 | 51 | 10.2 | 9.3 | 0.049 | 10.8 | 190.1 | 0.02 | 0.005 |
| 10.9 | 76 | 121 | 53 | 9.7 | 9.1 | 0.046 | 10.9 | 196.2 | 0.02 | 0.004 |
| 11.2 | 82 | 129 | 51 | 11.1 | 12.2 | 0.053 | 11.2 | 229.9 | 0.02 | 0.005 |
| 10.8 | 70 | 117 | 60 | 9.1 | 6.3 | 0.043 | 10.8 | 144.1 | 0.02 | 0.004 |
| 10.8 | 74 | 120 | 60 | 9.1 | 6.9 | 0.043 | 10.8 | 159.4 | 0.02 | 0.004 |
| 10.9 | 76 | 122 | 60 | 9.0 | 7.4 | 0.039 | 10.9 | 188.8 | 0.02 | 0.004 |
| 11.1 | 81 | 129 | 60 | 9.2 | 8.7 | 0.040 | 11.1 | 219.2 | 0.02 | 0.004 |
| 10.9 | 70 | 117 | 70 | 9.7 | 5.1 | 0.042 | 10.9 | 121.4 | 0.03 | 0.004 |
| 10.9 | 73 | 120 | 70 | 9.7 | 5.7 | 0.046 | 10.9 | 122.6 | 0.03 | 0.004 |
| 11.1 | 82 | 128 | 70 | 8.9 | 6.9 | 0.043 | 11.1 | 162.5 | 0.02 | 0.004 |
| 11.2 | 82 | 129 | 60 | 9.2 | 8.9 | 0.044 | 11.2 | 202.3 | 0.02 | 0.004 |
| 5.7 | 73 | 83 | 49 | 10.7 | 6.0 | 0.051 | 5.7 | 116.5 | 0.03 | 0.009 |
| 5.8 | 73 | 118 | 50 | 9.4 | 5.1 | 0.045 | 5.8 | 113.4 | 0.03 | 0.008 |
| 5.8 | 79 | 121 | 50 | 9.8 | 5.6 | 0.047 | 5.8 | 119.6 | 0.03 | 0.008 |
| 5.8 | 83 | 122 | 49 | 11.2 | 7.2 | 0.054 | 5.8 | 134.9 | 0.03 | 0.009 |
| 5.8 | 73 | 116 | 60 | 9.0 | 4.0 | 0.043 | 5.8 | 92.0 | 0.04 | 0.007 |
| 5.8 | 73 | 116 | 60 | 8.9 | 3.9 | 0.043 | 5.8 | 92.0 | 0.04 | 0.007 |
| 5.8 | 78 | 121 | 60 | 8.9 | 4.2 | 0.043 | 5.8 | 98.1 | 0.04 | 0.007 |
| 4.8 | 83 | 121 | 60 | 9.0 | 4.1 | 0.043 | 4.8 | 95.0 | 0.04 | 0.009 |
| 5.8 | 73 | 116 | 70 | 9.4 | 2.9 | 0.045 | 5.8 | 64.4 | 0.05 | 0.008 |
| 5.8 | 73 | 116 | 70 | 9.5 | 3.4 | 0.046 | 5.8 | 73.6 | 0.05 | 0.008 |
| 5.8 | 79 | 121 | 70 | 9.3 | 3.5 | 0.044 | 5.8 | 79.7 | 0.04 | 0.008 |
| 6.6 | 83 | 122 | 70 | 9.4 | 3.4 | 0.045 | 6.6 | 76.6 | 0.05 | 0.007 |

The testing determined that different IT equipment and environmental operating conditions affected the cooling delivery efficiency of the modular cooling unit. Specifically, variations in server power load and inlet air temperature resulted in different hydraulic COP, cooling efficiency (kW/ton), and power index for modular Cooling System 4.

Total cooling hydraulic power remained very low and stable at each of the rack power loads; varying between 0.04-0.05 kW for full rack power load and half load, respectively. Under a similar rack power load and the same chilled water supply temperature, the COP of the modular passive system tended to increase with an increase of inlet air temperature, while the module's cooling kW/ton values remained low and stable. Similarly, the PI values were also very low and remained virtually unchanged for a similar rack power load with various inlet air temperatures.

In this study, we have examined how this modular passive system performed under different chilled water supply temperatures. Specifically, the performance of the modular passive system with 50°F-70°F supply water was tested and evaluated for full and partial rack power loads, by the installation of secondary water loop. Under different chilled water supply temperatures (50°F, 60°F and 70°F) and similar operating conditions (e.g., rack power loads); the COP tended to decrease with an increase in inlet air temperature, while the kW/Ton and PI values largely remained unchanged.

COP decreased as the rack power load decreased. In general, the kW/ton and PI values increased with an increase in rack power loads, with the magnitude of change in kW/ton of 0.02 to 0.05 kW/ton, and PI of 0.004 to 0.009. This indicated that rather insignificant power was required for transporting chilled water flow through the passive rear door heat exchanger system.

We also found that at elevated supply water temperature (50°F-70°F), the modular passive system performed well, delivering reasonable cooling to the server rack under partial as well as full load scenarios. Our testing indicates that this technology is significantly more energy-efficient than traditional CRAH cooling units.

Overall, the hydraulic COP ranged from 64 to 220; module system efficiency (kW/ton) values ranged from 0.02 to 0.05 kW/ton; and PI was constant at less than 0.01, exhibiting highly energy efficient operation under the various operating and environmental conditions (rack power load, inlet air temperature load and supply water temperature) tested in this study. The passive cooling system performed effectively with higher supply water temperature (from 50°F to 70°F), and better than some of the other systems evaluated.

While the design passive cooling inherently ensures superior energy efficiency compared to other modular cooling systems that required electric power, it should be noted that this cooling technology relies on the ability of the server fans to overcome the static pressure drop across the heat exchanger. The passive cooling system tested ability to meet the cooling requirements of the IT equipment housed in the rack, or be room neutral is based upon the ambient air inlet temperature within the data center.

Furthermore, it should be noted that the passive system in the study exhibited no direct capability or effectiveness in the control of inlet air temperatures due to its design.

The use of modular, scalable cooling systems, such as the unit in this evaluation, may increase the overall data center efficiency especially when optimized with the central cooling plant. The results of our testing support the hypothesis that these types of liquid cooling systems may be able to perform effectively without chillers using only evaporative cooling in cool, dry climates.

The findings from this study indicate that by implementing liquid cooling in lieu of traditional CRAH units, the overall kW/Ton in the data center could be reduced. This type of modular cooling system also provides increased flexibility in data center configuration and layout.

This evaluation does not include the assessment of the potential energy savings possible if this cooling system technology was used for the entire data center. We also recommend that the reader of these individual reports, consider not only the energy

efficiency performance of the modular scalable cooling system but the system's capability and effectiveness to maintain server inlet air temperature within ASHRAE recommended levels and the potential dependence on other cooling or humidification in the data center.

In closing, in order to quantify or estimate the impact of modular, scalable cooling systems on overall data center energy efficiency, one must also assess their integration with the rest of the data center eco-system, the temperature range of chilled water available from the plant, the local weather conditions where the datacenter is located, and the power density characteristics of the data center.

## 4.9 Acknowledgements

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# APPENDIX F:
# Contract Task 2.2.3 Encouraging Air Economizers

## Energy Implications of Economizer Use in California Data Centers

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## Abstract

In the US, data center operations currently account for about 61 billion kWh/y of electricity consumption, which is more than 1.5% of total demand. Data center energy consumption is rising rapidly, having doubled in the last five years. A substantial portion of data-center energy use is dedicated to removing the heat generated by the computer equipment. Data-center cooling load might be met with substantially reduced energy consumption with the use of air-side economizers. This energy saving measure, however, has been shown to expose servers to an order-of-magnitude increase in indoor particle concentrations with an unquantified increase in the risk of equipment failure. An alternative energy saving option is the use of water-side economizers, which do not affect the indoor particle concentration but require additional mechanical equipment and tend to be less beneficial in high humidity areas. Published research has only presented qualitative benefits of economizer use, providing industry with inadequate information on which to base their design decisions. Energy savings depend on local climate and the specific building-design characteristics. In this paper, based on building energy models, we report energy savings for air-side and water-side economizer use in data centers in several climate zones in California. Results show that in terms of energy savings, air-side economizers consistently outperform water-side economizers, though the performance difference varies by location. Model results also show that conventional humidity restrictions must by relaxed or removed to gain the energy benefits of air-side economizers.

## Introduction

Data centers are computing facilities that house the electronic equipment used for data processing, networking and storage. Rapid growth in computational demand emerging from various sectors of the economy is causing strong rates of increase in servers and IT-related hardware (IDC 2007). Server performance has doubled every two years since 1999, leading to increasingly higher densities of heat dissipation within data centers (Belady 2007). A substantial proportion of energy consumption in data centers is dedicated to the cooling load associated with

electronic power dissipation (Tschudi et al. 2003). A recent study estimates that US data centers account for 61 billion kWh or 1.5% of the nation's annual electricity consumption (US DOE 2007a). This corresponds to an electricity bill of approximately $4.5 billion in 2006 (EPA 2007). The environmental impact is substantial because 70% of the electricity in US is generated in power plants that burn fossil fuel (EIA 2007). Improved data center cooling technologies have the potential to provide significant energy savings. Cost savings and environmental benefits might also accrue.

A typical data center consists of rows of tall (2 m) cabinets or racks in which the servers, data storage and networking equipment are vertically arrayed. The cooling of data-center equipment is accomplished using computer room air conditioners (CRACs), which supply cold air to a raised-floor plenum beneath the racks. The CRAC system air handler is placed on the data center floor while chilled water in transported from compressor-based chillers to the CRAC cooling coils. More efficient cooling systems employ low outside air temperatures to reduce chiller load. Cooling towers that use ambient air to directly cool or precool the chilled water are known as water-side or fluid-side economizers. This type of system has been claimed to cut cooling-energy costs by as much as 70% (ASHRAE HVAC Fundamentals Handbook 2005) during economizer operation. Based on local weather data in San Jose, water-side economizers can be used for more than one-third of the year (PG&E 2006). An alternate data center arrangement uses air-handling units (AHU) and an air-side economizer. Such systems directly provide outdoor air for cooling whenever the temperature of outside air is lower than the set-point for return-air temperature in the data center. In San Francisco's cool climate, outside air could contribute to some level of air-side cooling for nearly all hours of the year (Syska Hennessy 2007). The use of air-side economizers brings with it an associated concern about contamination including moisture from humidity that may possibly threaten equipment reliability. Deliquescent sulfate, nitrate and chloride salts, in a humid environment (> 40% relative humidity) can cause corrosion, accumulate and become conductive, and may lead to electrical short-circuiting (Rice et al. 1981; Sinclair et al. 1990; Litvak et al. 2000). In this paper, the energy implications of a data center using a CRAC system will be compared with alternative cooling systems using air-side or water-side economizers for five different California climate zones. The modeling results and discussion focus on understanding the energy implications for both type of economizers and their effectiveness in different climate zones. The equipment reliability concerns associated with air-side economizers are acknowledged to be important, but addressing it is beyond the scope of the present paper.

## Methods

### Data center design scenarios

Energy-use simulations were performed for three different data center HVAC design scenarios (Figure 1). The baseline case considers a data center using conventional "computer room air conditioning" (CRAC) units. In this scenario, CRAC units are placed directly on the computer room floor. Air enters the top of a CRAC unit, passes across the cooling coils, and is then discharged to the underfloor plenum. Perforations in the floor tiles in front of the server racks allow the cool air to exit from the plenum into the data-center room. Fans within the computer servers draw the conditioned air upward and through the servers to remove equipment-

generated heat. After exiting the backside of the server housing, the warm air rises and is transported to the intake of a CRAC unit. Most air circulation in the baseline scenario is internal to the data center. A small amount of air is supplied through a rooftop AHU to positively pressurize the room and to supply outside air for occupants. Cooling is provided by a water-cooled chiller plant. Refrigerant in the chillers is used to cool water through heat exchangers at the evaporator. The chilled water is then piped to the CRAC units on the data center floor. Waste heat from the chiller refrigerant is removed by water through heat exchangers in the condenser. Condenser water is piped from the cooling towers, which cools the water through interaction with the outside air. This baseline design is common to most mid- to large-size data centers (Tschudi et al. 2003; Rumsey 2005; Syska Hennessy 2007).

The water-side economizer (WSE) scenario assumes a CRAC unit layout similar to that of the baseline case, except that additional heat exchangers are installed between the condenser water in the cooling towers and the chilled water supplied to the CRAC units. Under appropriate weather conditions, the cooling towers can cool the condenser water enough to cool the chilled water in the CRAC units directly, without operating the chiller plant. The CRAC units and chiller plant are assumed to be the same as in the baseline scenario.

The air-side economizer scenario (ASE) requires a different type of air delivery than typically found in a data center with conventional CRAC units. AHUs are placed outside of the data center room, commonly on the rooftop, and air is then sent to and from the computer racks through ducts. A ducted air delivery system creates greater air resistance than a conventional CRAC unit layout, though this system better prevents cold and warm air from unintentionally mixing within the data center. When the outside air temperature is equal to or below the temperature of the air supplied to cool the server, the AHU can directly draw outside air into the data center and exhaust all of the return air after it has passed across the computer servers. The movement of 100% outside air through the system can require more fan energy than the baseline case, as the economizer design requires more ducting, which increases air resistance through the system. However, during this 100% outside air mode the cooling is provided without operating the chiller, chilled water pumps, condenser water pumps, or the cooling tower fans. Outside air is also provided instead of recirculated air whenever the outside air temperature is greater than the supply air temperature but lower than that of the return air. Under this condition the chiller must operate, but the cooling required of the chiller is less than in a case with complete recirculation.

**Energy modeling protocol**

For each design scenario, the model calculations assume a 30,000 $ft^2$ (2800 $m^2$) data center with an internal heat density of approximately 80 $W/ft^2$ (0.86 $kW/m^2$; 2.4 MW total) This size and power density are characteristic of data centers evaluated in previous studies (Shehabi et al. 2008; Greenberg et al. 2006; Tschudi et al. 2003). The size of data centers varies greatly; 30,000 $ft^2$ is within the largest industry size classification, which is responsible for most servers in the US (IDC 2007). Power density in data centers is rapidly increasing (Uptime Institute 2000) and a power density of 80 $W/ft^2$ is currently considered to be of low- to mid-range (Rumsey 2008).

Basic properties of the modeled data center for all three scenarios are summarized in Table 1. Energy demand is calculated as the sum of the loads generated by servers, chiller use, fan operation, transformer and uninterruptible power supply (UPS) losses, and building lighting. The chiller encompasses coolant compressor, chilled water pumps, condensing water pumps, humidification pumps, and cooling-tower fans. Energy demand for servers, UPS, and lighting are constant, unaffected by the different design scenarios, but are included to determine total building-energy use. The base case and WSE scenarios assume conventional humidity restrictions recommend by ASHRAE (ASHRAE 2005). The ASE scenario assumes no humidity restriction, which is an adjustment required to gain ASE benefits as is typical in ASE implementation (Rumsey 2008). Air-side economizers also require a different air distribution design and the fan parameters associated with each design scenario are listed in Table 2. The properties of other pumps and fans throughout the HVAC system remain constant for all three scenarios. Values are from previous data-center energy analyses (Rumsey 2008; Rumsey 2005).

The energy modeling approach used in this study applies a previously used protocol (Rumsey 2008; Rumsery 2005) and is based on a combination of fundamental HVAC sizing equations that apply equipment size and efficiencies observed through professional experience. Building energy modeling is typically performed using energy models such as DOE-2, which simultaneously models heat sources and losses within the building and through the building envelope. However, models such as DOE-2 are not designed to incorporate some of the HVAC characteristics unique to data centers. Also, data centers have floor-area-weighted power densities that are 15-100 times higher than those of typical commercial buildings (Greenberg et al. 2006). This allows accurate modeling of data-center energy use to focus exclusively on internal heat load and the thermal properties of outdoor air entering the building. This is the approach taken in this study, as heat generated from data center occupants and heat transfer through the building envelope are negligible relative to the heat produced by servers. The building envelope may influence the cooling load in low-density data centers housed in older buildings that have minimal insulation. Evaluating this building type is worthy of exploration, but the required analysis is more complex and outside the scope of the present paper.

Both air-side and water-side economizers are designed to allow the chiller to shut down or reduce chiller energy load under appropriate weather conditions. Less overall energy is required for operation when the chiller load is reduced, but chiller efficiency is compromised. Changes in chiller efficiency used in this analysis are shown in Figure 2, representing a water-cooled centrifugal chiller with a capacity > 300 tons and condenser water temperature of 80 °F. A chilled water temperature of 45 °F, which is standard practice for data center operation, is used in the base case and ASE scenario. The WSE scenario uses a chilled water temperature of 52 °F, which is common when using water-side economizers. This increases needed airflow rates but allows greater use of the water-side economizers. The curves are based on the DOE2.1E software model and apply coefficients specified in the Nonresidential Alternative Calculation Method (ACM) Approval Manual for the 2005 Building Energy Efficiency Standards for Residential and Nonresidential Buildings (CEC 2005).

Annual data center energy use is evaluated for each of the three configuration scenarios assuming that a data center building is located in each of the five cities shown in Figure 3. Weather conditions at each city are based on hourly DOE2.1E weather data for California climate zones (CEC 2005).

## Results and Discussion

Results from each scenario modeled are presented in Table 3 as a "performance ratio" which equals the ratio of total building energy divided by the energy required to operate the computer servers. Lower value of the performance ratio implies better energy utilization of the HVAC system. The performance ratio for the base case is 1.55 and, as expected, is the same for all the cities analyzed, since the operation of this design is practically independent of outdoor weather conditions. The base case performance ratio is better than the current stock of data centers in the US (EPA 2007; Koomey 2007) because the base case represents newer data centers with water-cooled chillers, which are more efficient than the air-cooled chillers and direct expansion (DX) cooling systems found in older data centers.

The performance ratios for the ASE and WSE scenarios show air-side economizers consistently provide savings relative to the base case, though the difference in savings between the two scenarios varies. It is important the note that even small changes in the performance ratio results in significant savings, given the large amount of energy used in data centers. For example, reducing the performance ratio at the model data center in San Jose from 1.55 to 1.44 represents a savings of about 1.9 million kWh/y, which corresponds to a cost savings of more than $130,000/y (assuming $0.07/kWh).

Figure 4 shows the disaggregation of the cooling systems' annual energy use, normalized by floor area, for each modeled data center by location and design scenario. The annual energy use dedicated to the servers, USP, and lighting is 584, 95, and 9 kWh/ft$^2$, respectively. These energy values are independent of the climate and HVAC design in scenario and not included in the graphs in Figure 4. Economizer use is typically controlled by combination of outside air temperature, humidity, and enthalpy; however results shown in Figure 4 are for economizer use controlled by outside air temperature only. Results show that the ASE scenario provides the greatest savings in San Francisco while Fresno provides the least ASE savings. Sacramento benefited the most from the WSE scenario while minimal savings were realized in Los Angeles and San Francisco. The San Francisco WSE scenario, where significant gains would be expected because of the cool climate, is hindered by chiller part-load inefficiencies. The relatively higher moisture content in the San Francisco air increases the latent cooling load in the model and causes the chiller plant to reach the capacity limit of the first chiller more often, activating a second chiller. The second chiller shares the cooling load equally with the first, resulting in a transition from one chiller at a high load factor (efficient operation) to two chillers at slightly above half the load factor (less efficient operation). The results from the WSE scenario in San Francisco emphasize the need for engineers to model the hour-by-hour load, rather than just the peak load, and to size chillers such that all active chillers at any moment will be running near their most efficient operating point.

Figure 5 shows that removing the humidity restrictions commonly applied to data centers is necessary to gain ASE energy savings. As the relative humidity (RH) ranged is narrowed, energy use from the fans begins to sharply increase, surpassing the equivalent baseline energy in most of the cities. Humidity levels are often restricted in data centers to minimize potential server reliability issues. ASHRAE's guidelines released in 2005 for data centers provide a "recommend" RH range between 40-55% and an "allowable" range between 20-80% (ASHRAE

2005). There is minimal cost in applying the more conservative ASHRAE RH restrictions in conventional data center design, such as the baseline in this study shown in Figure 5. The influence of humidity on server performance, however, is poorly documented and the need for humidity restrictions is increasingly being questioned (Fontecchio 2007). The energy saving difference between adhering to ASHRAE's recommend RH range versus the allowable RH range is substantial, and warrants further investigation.

## Conclusion

Employing the energy-saving measures evaluated in this paper would require a shift in conventional data center design and operation. Various operational concerns must be addressed before widespread adoption of these technologies could be expected in data-center buildings. This paper contributes to the informed implementation of air-side and water-side economizers by assessing the energy benefits of adopting these efficiency improvements. Air-side economizers are shown to consistently outperform water-side economizers in California, though the difference in performance varies by the climate conditions of the locations evaluated. Furthermore, the models show that conventional humidity restrictions must by relaxed or removed to substantially realize the energy benefits of air-side economizers. As the data center economy continues to rapidly grow, energy efficiency will continue to emerge as an important financial and environmental concern. The results presented here contribute to our understanding of different design implications and should assist decision makers in the implementation of energy-efficient data centers.

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## Table 1: Data Center Characteristics Common to All Design Scenarios

| **Data Center Parameters** | |
|---|---|
| Floor Area | 30,000 $ft^2$ |
| UPS Waste Heat | 326 kW |
| Data Center Lights | 30 kW |
| Total Rack Load | 2000 kW |
| Total Internal Load | 2,356 kW |
| Average Internal Load Density | 79 $W/ft^2$ |
| Minimum Ventilation | 4,500 $ft^3/min$ |
| Supply Air Temperature | 55 ¡F |
| Return Air Drybulb Setpoint | 72 ¡F |
| Chiller Capacity | 1750 kW |
| Number of Chillers | 3 |

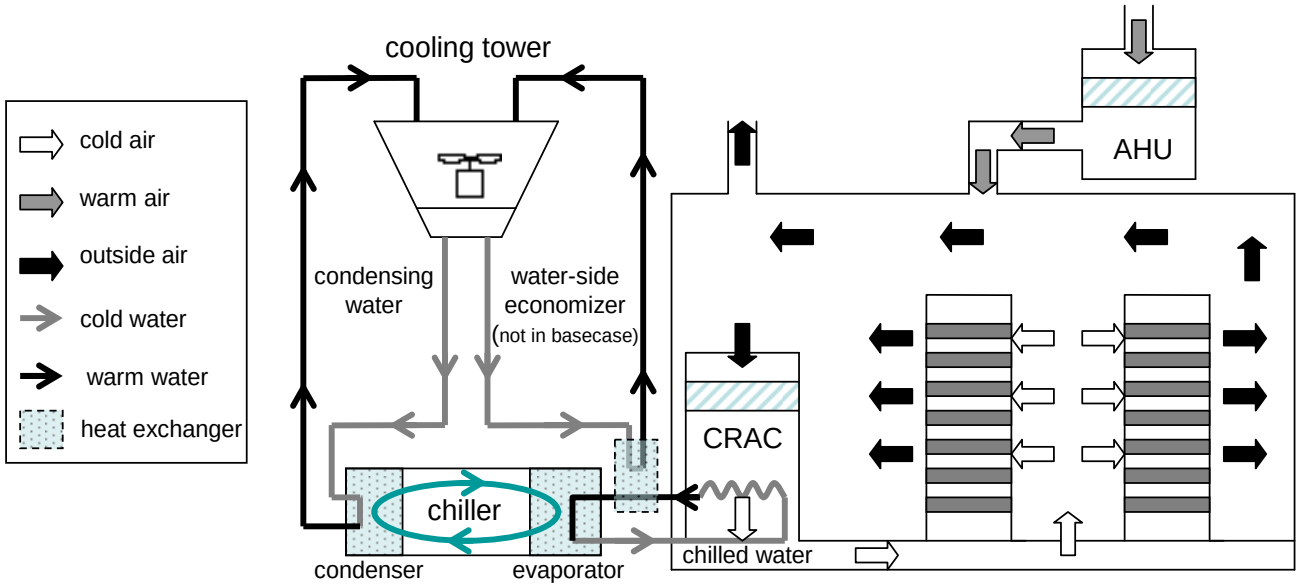
## Table 2: Data Center Fan Properties

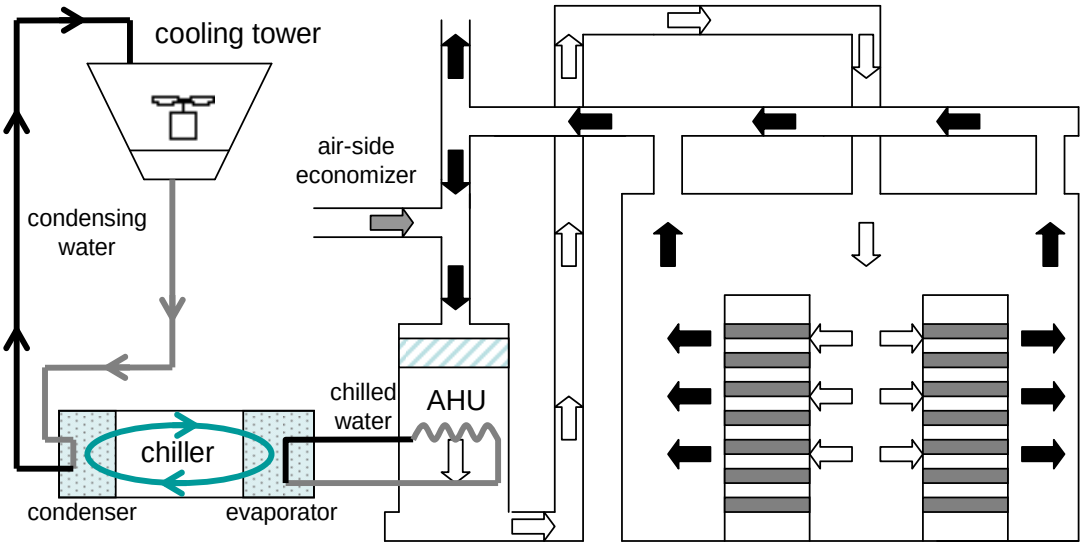
| **Fan System Parameters** | **Baseline and WSE** | | | **ASE** | |
|---|---|---|---|---|---|
| | MUAH | Exhaust | CRACs | Supply | Relief |
| Total Air Flow (cfm) | 4,500 | 4,500 | 495,000 | 437,758 | 437,758 |
| Fan Motor Size, Nominal (hp) | 7.5 | 3 | 10 | 30 | 50 |
| Number of Fans | 1 | 1 | 30 | 10 | 5 |
| Fan Efficiency | 53.3% | 44.0% | 55.6% | 63.8% | 67.5% |
| Fan Drive Efficiency | 95% | 95% | 95% | 95% | 95% |
| Fan Motor Efficiency | 89.6% | 86.2% | 90.1% | 92.5% | 93.2% |
| VFD Efficiency | n/a | n/a | n/a | 98% | 98% |
| Total Static Pressure Drop (in w.g.) | 3.5 | 1 | 1.6 | 2 | 1 |

## Table 3: Ratio of Total Building Energy to Computer Server Energy

| | **San Jose** | **San Francisco** | **Sacramento** | **Fresno** | **Los Angeles** |
|---|---|---|---|---|---|
| **Baseline** | 1.55 | 1.55 | 1.55 | 1.55 | 1.55 |
| **Air-side Economizer** | 1.44 | 1.42 | 1.44 | 1.46 | 1.46 |
| **Water-side Economizer** | 1.53 | 1.54 | 1.53 | 1.53 | 1.54 |

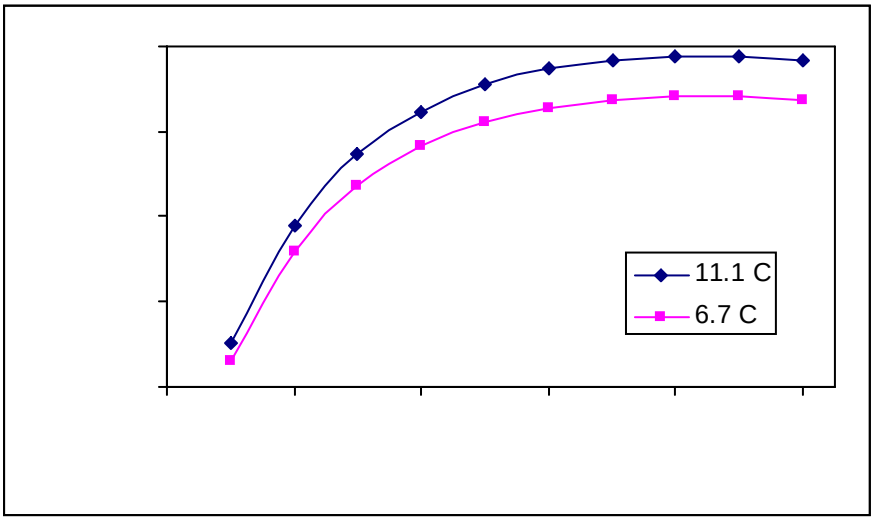
**Figure 1: Schematic of Data Center Cooling Design Scenarios**




Air and water flow schematic for the basecase and water-side economizer scenarios (above).
Air and water flow schematic for the air-side economizer scenario (below).

**Figure 2: Assumed Part Load Performance of Data Center Chillers**




Part load efficiencies for a water-cooled centrifugal chiller with a capacity >300 tons and an condenser water temperature of 26.7 °C (CEC, 2005))

**Figure 3: Evaluated Climate Zone Locations**

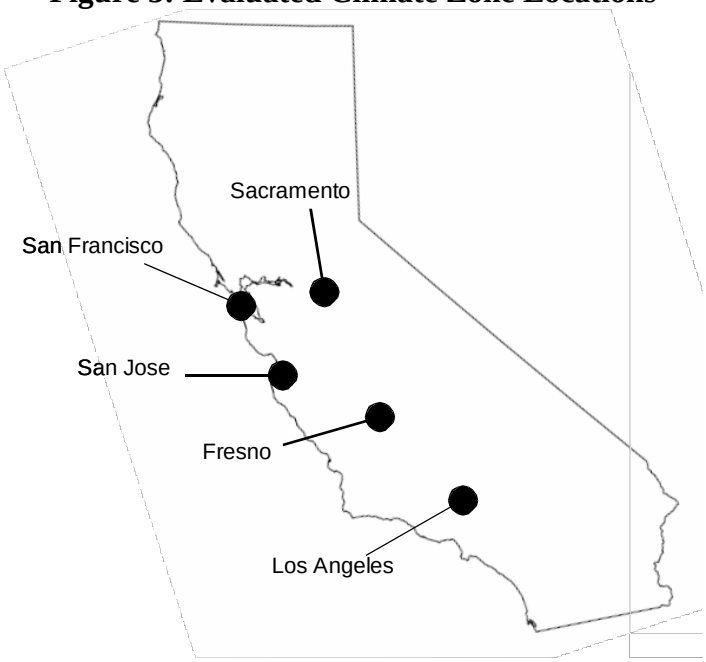
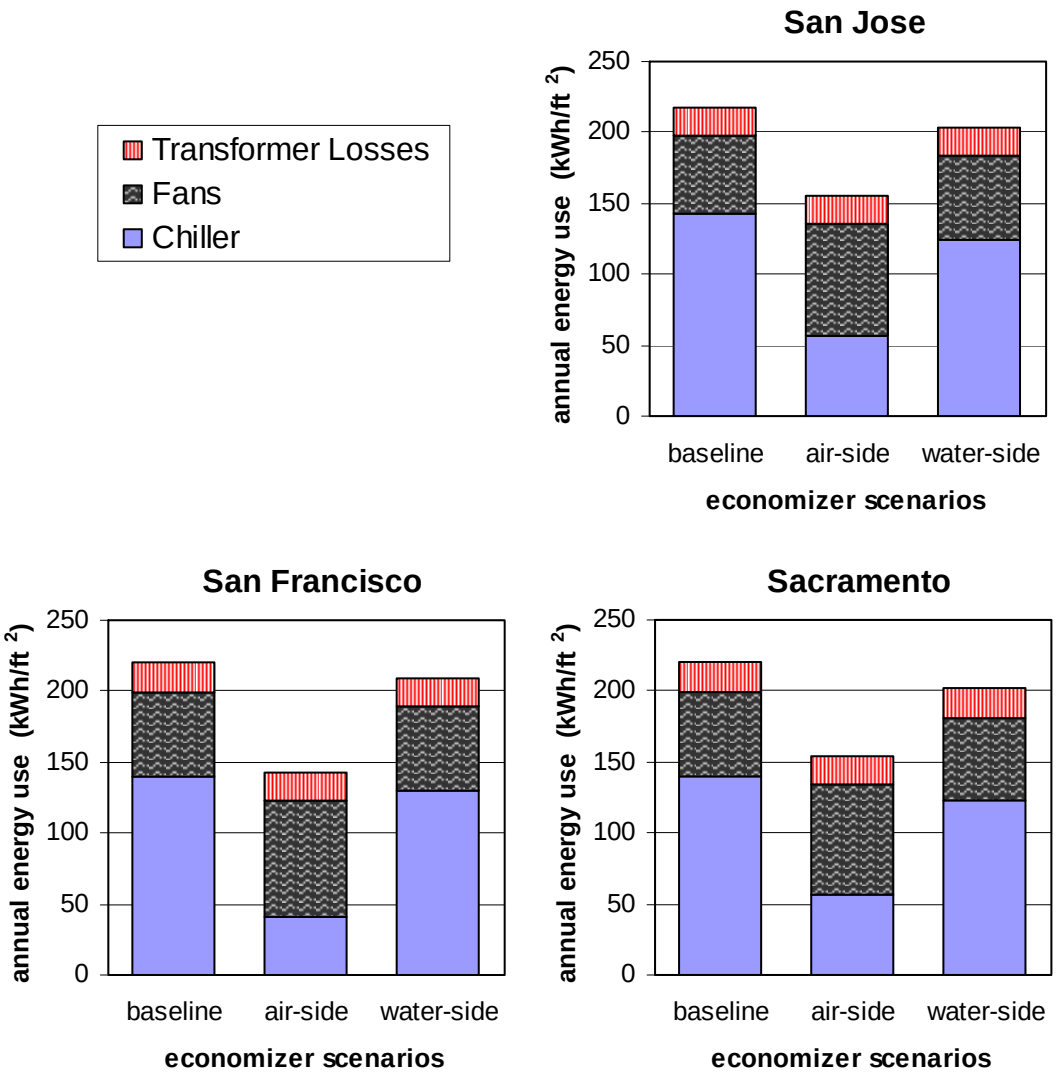


**Figure 4: Disaggregated Energy Use (Climate Dependent Values Only)**



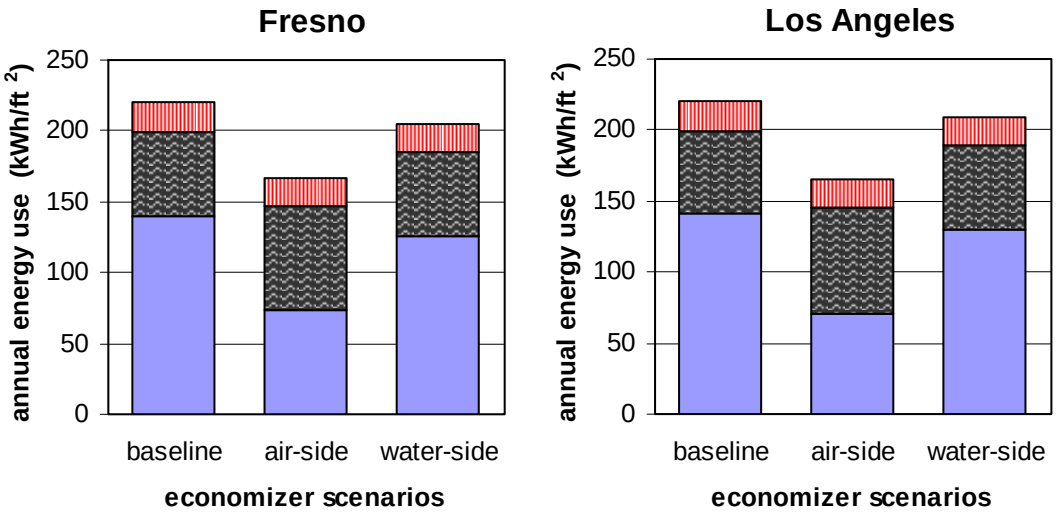
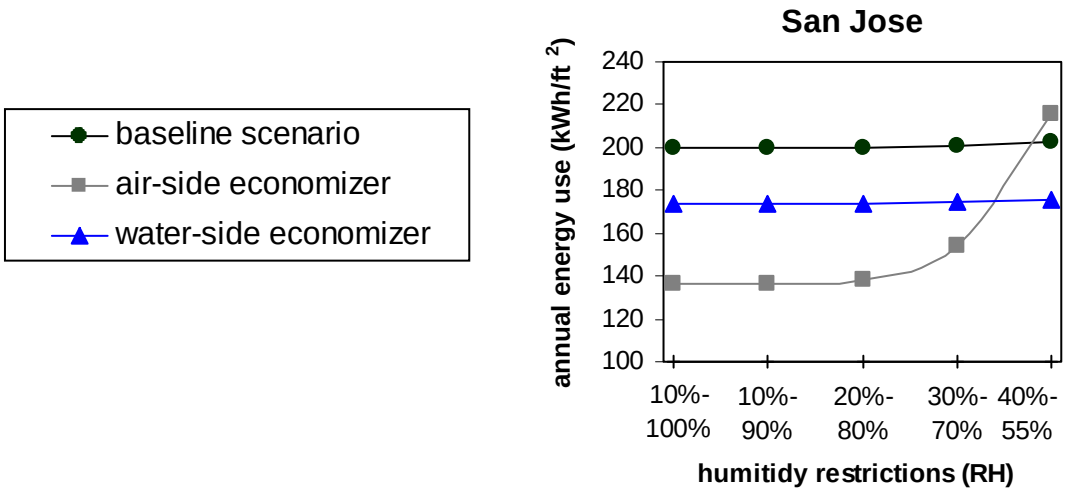
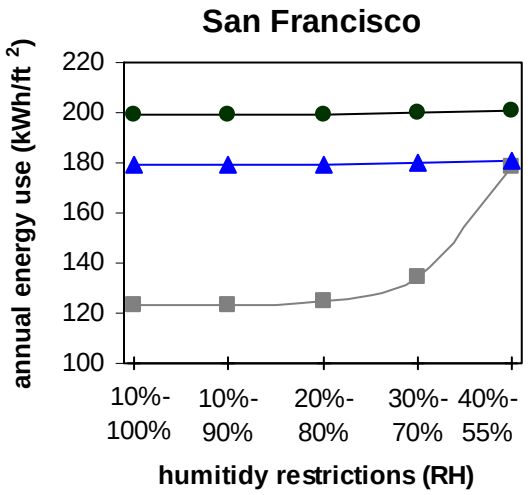
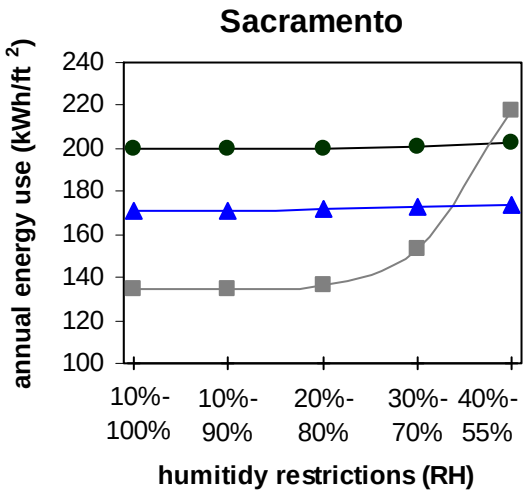
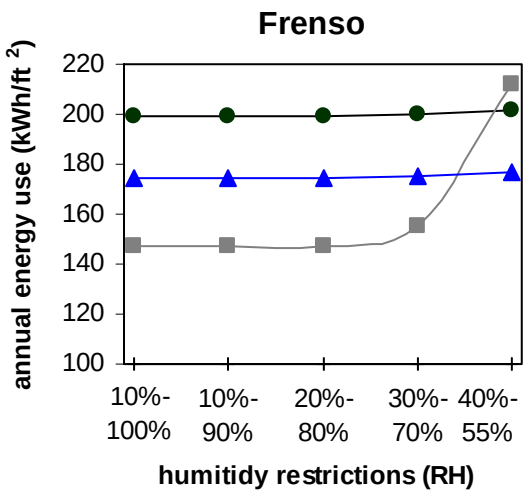

Fresno
Los Angeles
annual energy use (kWh/ft 2)
250
200
150
100
50
0
baseline
air-side
water-side
economizer scenarios

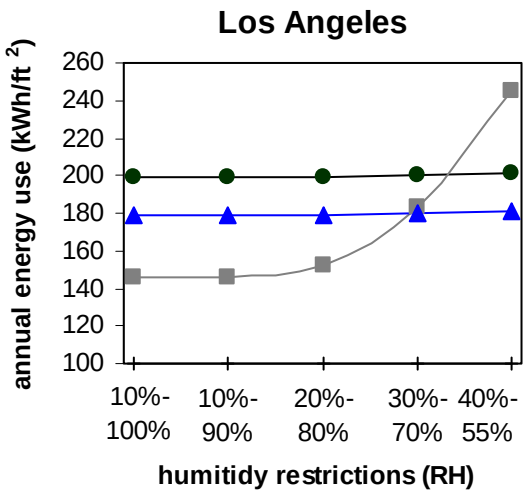
**Figure 5: Chiller and Fan Energy Resulting from Humidity Restrictions**




San Francisco
annual energy use (kWh/ft 2)
220
200
180
160
140
120
100
10%-100%
10%-90%
20%-80%
30%-70%
40%-55%
humitidy restrictions (RH)


Sacramento
annual energy use (kWh/ft 2)
240
220
200
180
160
140
120
100
10%-100%
10%-90%
20%-80%
30%-70%
40%-55%
humitidy restrictions (RH)


Frenso
annual energy use (kWh/ft 2)
220
200
180
160
140
120
100
10%-100%
10%-90%
20%-80%
30%-70%
40%-55%
humitidy restrictions (RH)


Los Angeles
annual energy use (kWh/ft 2)
260
240
220
200
180
160
140
120
100
10%-100%
10%-90%
20%-80%
30%-70%
40%-55%
humitidy restrictions (RH)

**Draft Report – Air Economizer study**

**Objective**

The goal of this task is to reduce cooling energy use in data centers by understanding the potential benefits and risks of air-side economizers. Specifically, this task aims to provide a real world understanding of the energy savings from using an air-side economizer, and also address the savings and contamination implications from the use of improved filtration schemes. In addition, it works to overcome barriers to economizer use by addressing server failure concerns associated with air contaminants and by exploring potential mitigation strategies.

**Approach**

Particle concentrations are measured in a data center enabled with economizer operation while using filtration of varying levels of efficiency. Three different types of HVAC filters were installed during the monitoring period. Immediately before the monitoring period, new HVAC filters with a Minimum Efficiency Reporting Value (MERV) of seven were installed. These are the filters commonly used at this data center. Previous studies have observed that MERV 7 filters are common to most data centers. During the monitoring period the MERV 7 filters were removed and replaced with MERV 11 filter, and then again replaced with MERV 14 filters. The increased MERV rating indicates greater efficiency of particle removal by the filter. Particle concentrations are measured and documented under each filtration type for both active and inactive economizer use.

Information regarding data center power demand was gathered from the energy management control system (EMCS) during the same period as particle monitoring. Life-cycle costing of each filtration scenario is performed to also address initial cost, maintenance, and filter life.

**Results**

***Particle Concentration Measurements***

Particle counts measured at the Sunnyvale data center under different HVAC filter scenarios are represented as mass concentrations in Table 1. For each measurement period, both the indoor and outdoor mass concentrations are averaged separately for the hours under high air conditions (economizer on) and low air conditions (economizer off).

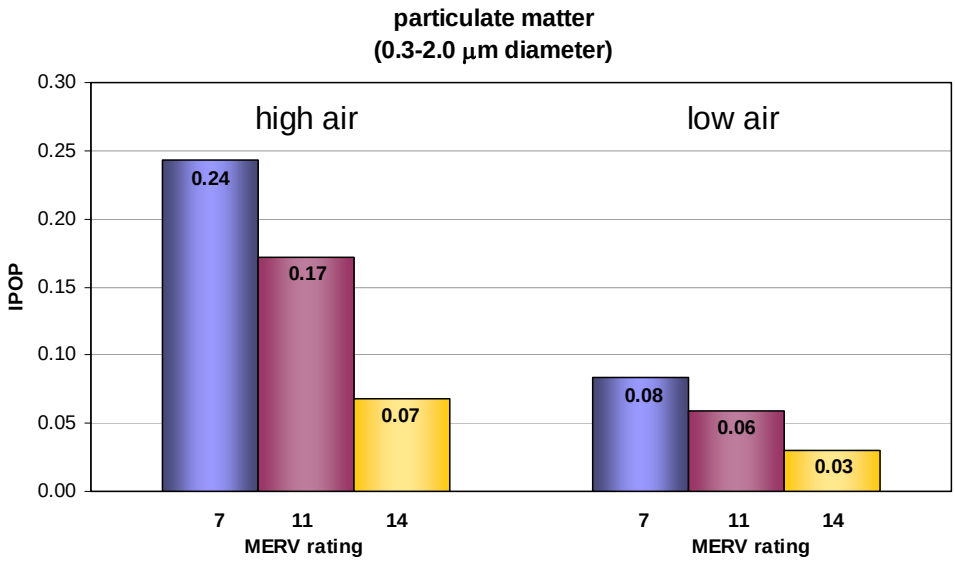
*Table 1: Particle mass concentrations under each HVAC filtration scenario*

| | | 0.3-2.0 μm Particle Concentration (μg/m$^3$) | | | | |
|---|---|---|---|---|---|---|
| Mesurement Period | | | High Air | | Low Air | |
| Start Time | End Time | Filter Type | Out | In | Out | In |
| 8/8/08 13:00 | 8/11/08 12:30 | MERV 7 | 10.17 | 2.47 | 5.16 | 0.43 |
| 8/25/08 15:00 | 8/29/08 13:00 | MERV 11 | 13.18 | 2.27 | 6.53 | 0.38 |
| 8/18/08 19:45 | 8/20/08 11:30 | MERV 14 | 3.25 | 0.22 | 0.85 | 0.03 |

The Indoor Proportion of Outdoor Particles (IPOP) is an indicator that can be used to compare the ability of the HVAC system to remove outdoor particles from entering the data

center. IPOP values for high air (economizer on) and low air (economizer off) under the three HVAC filter scenarios measured are presented in Figure 1. As expected, the IPOP is relatively greater during high air periods and increased filter MERV ratings (increased removal efficiency) results in reduced IPOP values. A key finding shown in Figure 1 is that the IPOP value for the MERV 14 filters is lower when the economizer is active than the IPOP value of the conventionally used MERV 7 filters when the economizer is off. This finding indicates that a data center with an economizer that use MERV 14 filters can expect lower indoor particle concentrations than a conventional data center without an economizer and using MERV 7 filters.

*Figure 1: Indoor Proportion of Outdoor Particles under each HVAC filtration scenario*




***Filter Life Cycle Costing***

The lifecycle costing comparison between a baseline data center using chilled water air handling units (AHU) and an economizer based system (using MERV 7 filters), is determined from a model that simulates the energy consumption of the Net App data center at Sunnyvale. The data center has an area of 6780 $ft^2$ with an internal load density of approximately 131 $W/sf^2$.

Results of the annual HVAC energy savings are presented in Table 2. The annual HVAC energy savings in the economizer scenario in comparison to the baseline is 37%. The cost of implementing an air-handling system in both the scenarios is as per typical estimates for a data center in San Jose. At the end of the first year of operation, labor and material costs are added to the implementation cost to generate the total expense. This expense figure is deducted from the energy cost savings to provide the net savings.

| | Baseline system | Economizer system |
|---|---|---|
| Annual HVAC energy use | 2,467,552 kWh/y | 1,560,502 kWh/y |
| Annual HVAC energy savings | - | 935,649 kWh/y |
| Annual HVAC energy cost savings | - | $80,726 |
| Annual HVAC savings % | - | 37% |

Table 2: Annual HVAC energy usage, and savings for baseline and economizer scenarios

The lifecycle cost assumes an 8% discount rate in the analysis. The inflation rate for electricity, material and energy costs is assumed to be 3%. Utility incentive is limited to 50% of the total incremental cost of implementation. The relative net present value is the difference between the net present values of the economizer and baseline data centers. A summary of the lifecycle costing of the economizer based system in comparison to the baseline for a 10-year period is presented in Table 3. Implementing an economizer based system has a simple payback period of less than 4 months. The relative net present value increases from $0.56 M to $0.94 M for a 20-year period. Refer to the appendix section for details on the energy model and lifecycle costing.

| | |
|---|---|
| Simple payback | 0.3 years |
| Relative net present value | $557,535 |
| Internal rate of return | 162% |

Table 3: Lifecycle costing results of the economizer scenario with reference to the baseline

***HVAC Energy Data Measurements***

This experimental study was carried out at a Net App data center in Sunnyvale, California. The data center has an area of 6780 $ft^2$ with rows of racks arranged in cold-aisle hot-aisle configuration. The facility is cooled by air-side economizer (ASE) based air handling units (AHUs). The AHUs are located in a room adjacent to the data center. The ASE allowed outside air to remove the heat generated by the servers when the outdoor conditions were within the operating set-points. For outdoor temperatures above $70^0$ F the economizer system would shut off. The economizer system uses no active humidity control but locks out outside the 20-80% relative humidity range (present ASHRAE allowable range 40-55% relative humidity, proposed is 30-55%).

The impact of “free” economizer cooling, and the load considering the improved filtration system on the HVAC system power consumption, was determined for three different HVAC MERV filter types. The first scenario was the baseline case which consisted of a chilled-water cooled AHU system with no economizer use. The second was the typical operation scenario using an AHU based economizer system with MERV 7 filters. The third scenario consisted of two stages of improved filtration with the use of 65% efficient MERV 11 filters, followed by 95% efficient MERV 14 filters. The pressure drop across the filters and inside the

supply duct was measured for each filter type. The outdoor air temperature and relative humidity, and the pressure difference across the filter and duct system was normalized to a unit scale for the analysis. However, for temperature alone, the rise rather than the absolute value is normalized. The rise in a particular day is the difference between the day's temperature and that of the coldest day during the observation period.

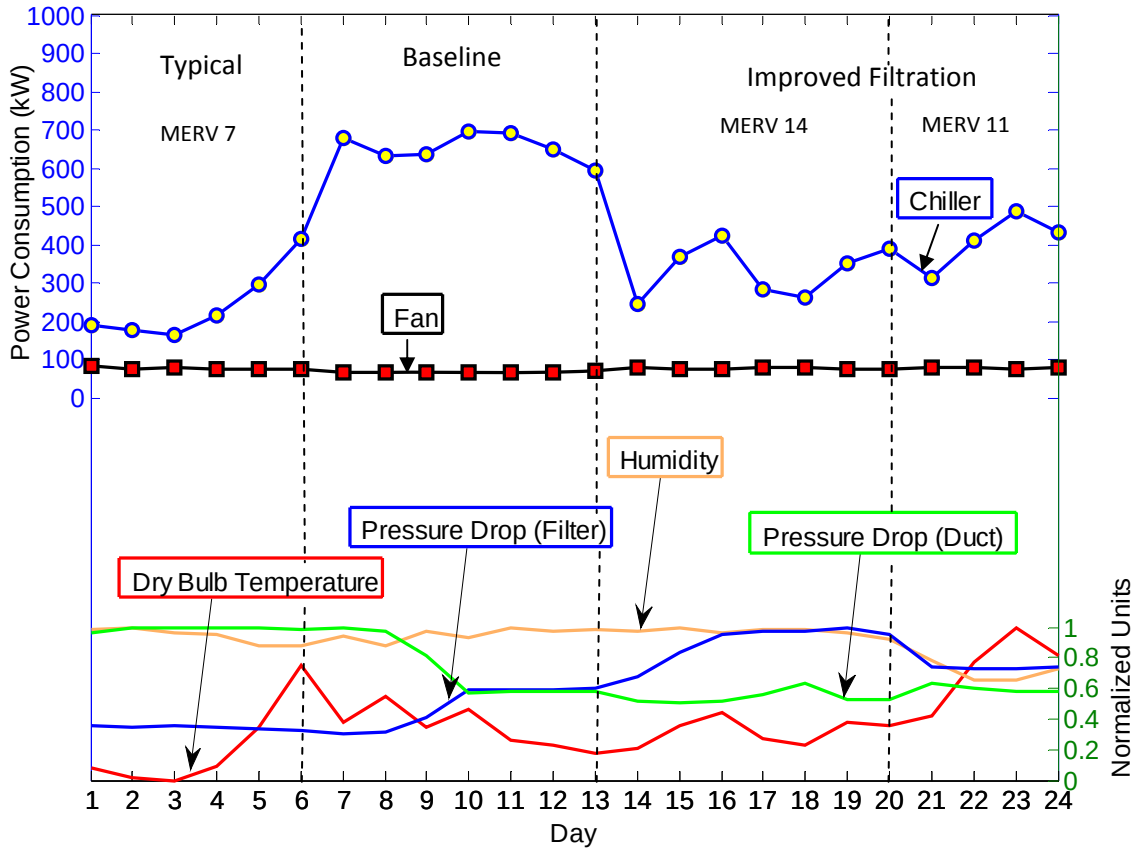



Figure 2: Variation in chiller and fan power with normalized units of outdoor temperature and pressure drop

The upper part of Figure 2 shows the variation in chiller and fan power consumption in the baseline, typical and improved filtration scenarios, while the lower part highlights normalized changes in duct and filter pressure drops. The total HVAC consumption was substantially greater in the baseline case in comparison to all the three filtration based economizer systems due to a decrease in chiller energy consumption. With reference to the chiller power consumption of the baseline scenario, the typical economizer used 64% less while the improved filtration scenario decreased it by 44%. However, the daily fan power consumption in the typical and improved filtration scenarios increased only nominally with reference to the baseline. Further, the chiller consumption in the improved filtration scenario increased in comparison to the typical economizer operation. An analysis of the filter and duct pressure drops explains this anomaly. It was observed that with improved filter efficiency the pressure drop across the filters increased,

while the supply fans were unable to provide the additional air flow because they operated close to maximum speed. This lead to a decrease in pressure drop in the supply duct, which in turn reduced the air flow rate. The decrease in air flow was compensated by increasing the chiller operation to lower the supply air temperature in the data center. Further, the outdoor air temperature rose during the improved filtration period thereby increasing the cooling load on the chiller.

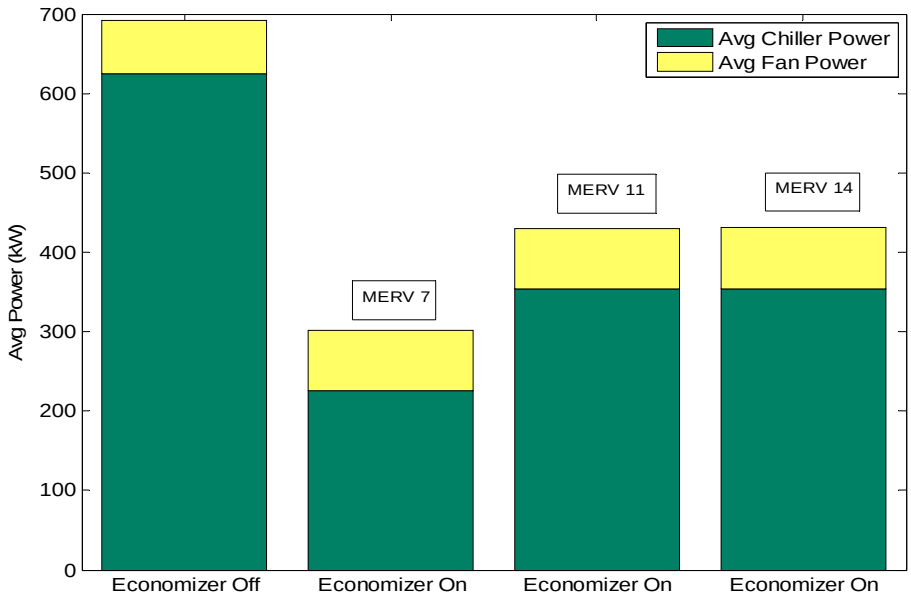



Figure 3: Average HVAC power consumption in the four scenarios

| Scenario | Average chiller power (kW) | Average fan power (kW) | Total HVAC (kW) | Estimate of HVAC energy (GWh/y) | Savings with reference to baseline |
|---|---|---|---|---|---|
| Baseline (economizer off) | 625 | 67 | 692 | 6.1 | - |
| Typical (economizer on - MERV 7) | 225 | 76 | 301 | 2.6 | 56% |
| Improved filtration (economizer on – MERV 11) | 353 | 77 | 430 | 3.7 | 38% |
| Improved filtration (economizer on – MERV 14) | 353 | 78 | 431 | 3.7 | 38% |

Table 4: Average chiller, fan and total HVAC consumption during each of the four scenarios

Figure 3 shows the breakdown of average HVAC power consumption into chiller and fan consumption for all the four scenarios. The savings numbers and percentages are presented in

Table 4. The economizer based MERV 7 scenario provided the maximum HVAC energy savings of 56% over the baseline. The improved filtration economizer scenarios provide HVAC savings of 38%, in comparison to the baseline.

***Documented Equipment Failures***

In this study it was demonstrated that the filter-based economizer system provided substantial HVAC savings of up to 56% over the chilled water air handling system. The results are summarized in Table 4. However, particulate and gaseous contaminants as well as humidity from outside air are perceived to degrade server reliability. This prevents the wide-spread adoption of energy efficient air-side economizers by the industry. The two primary mechanisms of electronic circuit degradation are the decrease in electrical isolation of electronic components, and corrosion. Ionic and/or corrosive contaminants, like sulfates, nitrates, sulfides, and chlorides are the species of primary concern.

Research to address air-side economizer based contamination provided information on a single server failure occurrence in a Northern California data center. In this facility, the dynamic content adapter (DCA) in a set of blade servers had failed. A material analysis of the servers conveyed that accumulation of ionic contaminants containing sulfur and chlorine had decreased the surface insulation resistance thereby causing leakage of current. Salts containing sulfur and chlorine are primarily generated by humidifiers in data centers, and in some industrial operations however, for this center there was no humidification. As shown in Figure 4, accumulated contamination was observed on the outside and corrosion in the inside of the server. However, this is a rare case with no cause identified. Although LBNL offered to collect failure data anonymously through the ASHRAE Technical Committee 9.9, no documented server failures due to contamination were identified.

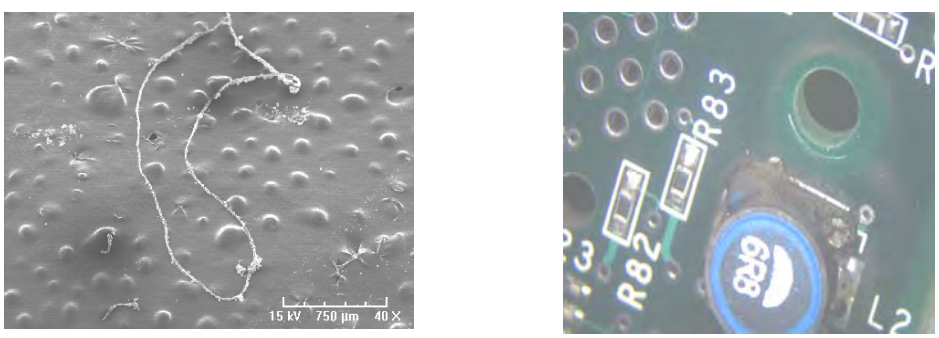



Figure 4: Contamination on the surface (left image), and corrosion inside the server (right image)

***Potential Mitigation Strategies for Equipment Failures***

A two-pronged approach can be adopted to reduce the concern over contaminants affecting server reliability. The first strategy is to reduce the entry of contaminants into the data center. This could be achieved by the use of water-side economizers or air-side economizers in conjunction with improved filtration systems. The second approach would be to install systems like environmental reactivity monitors that passively or actively detect and measure the concentration of corrosive or ionic contaminants in the data center environment. Passive

monitoring using copper and silver corrosion coupons, and real-time monitoring using quartz crystal microbalances could reflect changes of less than 1ppb in the ambient environment. Corrosion coupons are shown in Figure 5.

An alternate approach to detect fine particulate contaminants has been tested in a laboratory environment (Litvak 2000). The experiment used inter-digitated coupons in an environment with high particulate concentration. The accelerated rate of particulate deposition resulted in a decrease in electrical insulation between adjacent components of the coupon. This can be used as method to determine circuit degradation due to contamination.

Figure 5: Copper and silver coupons for environmentally reactive monitoring of contaminants

Reference

Litvak, A., Gadgil, A.J., Fisk, W.J. 2000. “Hygroscopic fine mode particle deposition on electronic circuits and resulting degradation of circuit performance: an experimental study.” Indoor Air 10: 47-56.

*Draft Report 12-31-08*

# Pacific Gas and Electric Company

## Emerging Technologies Program

# Impact of Air Filtration on the Energy and Indoor Air Quality of Economizer-based Data Centers in the PG&E Territory

Lawrence Berkeley National Laboratory

**Issued:** **December 31, 2008**

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**Lawrence Berkeley National Laboratory**

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*Draft Report 12-31-08*

# Impact of Air Filtration on the Energy and Indoor Air Quality of Economizer-based Data Centers in PG&E Territory

## Executive Summary

A significant portion of the high electricity demand in data centers is currently dedicated to building cooling. Data centers must provide continuous air conditioning to address high internal heat loads (heat release from computer servers) and maintain indoor temperatures within recommended operating levels for computers. Air-side economizers, which bring in large amounts of outside air to cool internal loads when weather conditions are favorable, could save cooling energy. However, this technology is not widely adopted because the climate dependant energy savings from air-side economizers are expressed only qualitatively. Further, the lifecycle costing of this system is not well understood. A major barrier to economizer implementation is the fear of increasing pollutants levels in the data center during economizer cycle, and the fear that these pollutants could affect computer server reliability

Strategies to reduce this economizer implementation barrier are explored in this study. Pollutants of concern are measured in a data center enabled with economizer operation while using air filtration of varying levels of efficiency.

Study results are summarized below:

1. The empirical energy data from the economizer based MERV 7 scenario provided the maximum HVAC energy savings of 56% over a conventional data center without economizers. The improved filtration economizer scenarios also provide substantial HVAC savings in comparison to the conventional case.

2. The energy model of the San Jose data center for 5 different PG&E locations indicated that the annual savings varied from 30% to 46% based on local climate. This corresponds to an average DCiE of 0.72 which is substantially higher than the typical 0.55 value, which is as per the LBNL benchmarking studies.

3. The lifecycle costing of the economizer (MERV 7) and conventional air handling unit based system provided a relative net present value of $0.3 M, with a simple payback period of 0.6 years.

4. The percentage of outdoor particles entering the data center when more efficient (MERV 14) filters are used is lower when the economizer is active compared that of conventionally used (MERV 7) filters when the economizer is off. This finding indicates

that a data center with an economizer that uses MERV 14 filters can expect lower indoor particle concentrations than typically found in conventional data centers without economizers.

5. Measured outdoor particle concentrations are often highest during the times of day when economizers would be used, such as evening and night periods. This may be heavily influenced by the specific location of the data center.

6. A higher percentage of outdoor particles composed of black carbon or sulfate, both pollutants of concern, were measured in the data center compared to the general particle concentrations measured. A lower percentage of outdoor particles composed of nitrate, also a particle of concern, were measured in the data center compared to the general particle concentrations measured

The average particle concentrations measured at the data center under each filter scenario are shown in Table 1. The Results section contains a discussion of the individual findings from each scenario.

*Table ES1: Particle mass concentrations under each HVAC filtration scenario*

| | | 0.3-2.0 μm Particle Concentration (μg/m$^3$) | | | | |
|---|---|---|---|---|---|---|
| Mesurement Period | | | High Air | | Low Air | |
| Start Time | End Time | Filter Type | Out | In | Out | In |
| 8/8/08 13:00 | 8/11/08 12:30 | MERV 7 | 10.17 | 2.47 | 5.16 | 0.43 |
| 8/25/08 15:00 | 8/29/08 13:00 | MERV 11 | 13.18 | 2.27 | 6.53 | 0.38 |
| 8/18/08 19:45 | 8/20/08 11:30 | MERV 14 | 3.25 | 0.22 | 0.85 | 0.03 |

## Objective

The goal of the project is to encourage the use of air economizers in data centers by developing a framework for making energy and lifecycle cost comparisons for various filtration options and to better understand the impact of climate on data centers. Specifically, this task aims to provide a real world understanding of the energy savings from using an air-side economizer. Further, this study works to overcome barriers to economizer use by addressing server failure concerns associated with air contaminants and by exploring improved filtration as a potential mitigation strategy. An energy model will be used that considers weather (temperature and humidity) and ambient particle concentrations for five different climate zones within the PG&E territory in California.

Data centers require continuous air conditioning to remove high internal heat loads (heat generated from IT and facility equipment) and maintain environmental conditions within IT equipment recommended operating levels. Air economizer cycles, which bring in large amounts of outside air to cool internal loads during mild outside weather conditions, could save cooling energy by reducing chiller operation. However, there is reluctance from many data center operators to use this common cooling technique due to fear of equipment damage from introducing outside air pollutants which over time could cause equipment failures. While improved filtration could be used to reduce indoor particle concentration this mitigation strategy appears to be rarely used. The performance of improved filtration has not been verified in data centers and high efficiency filters can increase flow resistance, which could potentially increase fan power.

In this study particle concentrations are measured in a data center enabled with economizer operation while using filtration of varying levels of efficiency. Particle concentrations are measured in terms of physical and chemical properties and documented under each filtration type for both active and inactive economizer use, while also monitoring any changes to operational energy use.

The results presented in this report have the potential to reduce the energy associated with data center operation by removing a common barrier to economizer implementation. This analysis of mechanical filtration in data centers identifies strategies that maintain contamination levels at or near non-economizer levels while maximizing energy savings and minimizing additional cost.

## Methods and Procedures

### *Data Center Layout*

The sampling site is the Net App data center in Sunnyvale, California. It located within an office building. Energy and air quality information were gathered through the month of August, 2008. This Sunnyvale data center is designed with an economizer mechanical cooling system. In this system, conditioned air is ducted from air handling units (AHU) into the data center room to remove heat generated from the multiple rows of computer servers on the data center floor. The data center is served by eight separate AHUs. Each AHU has an air-side economizer, chilled water cooling coils, two supply and two exhaust fans. The cool conditioned air from the AHU is sent via a ducted supply to the ceiling vents in the data center. Cool air is drawn in by the fans in the server equipment. The warmed air leaving the servers is then removed from the room through another set of ceiling vents and returned to the AHUs, which are located in a mechanical room adjacent to the data center. At the AHU, some of the return air is exhausted while the rest is mixed with outside air, and passed through a row of filters, then conditioned and supplied to the data center again. Figure 1 shows the air-flow schematic of the data center and AHU rooms.

The system is fitted with an economizer, allowing the amount of outside air to adjust depending on outside temperature conditions. When the outside air temperature drops below a temperature setpoint, the amount of outside air entering the data center through the economizer increases to 100% (high outside air mode). When the outside air temperature rises above another temperature setpoint, the amount of outside air entering the data center is reduced to approximately 1%, with return air from the data center accounting for the rest (low outside air mode). This distribution of high and low outside air modes is consistent with common practice in data centers with economizers. The data center has no humidity control, but the economizer system locks out when the outdoor relative humidity is not in the 20%-80% range.

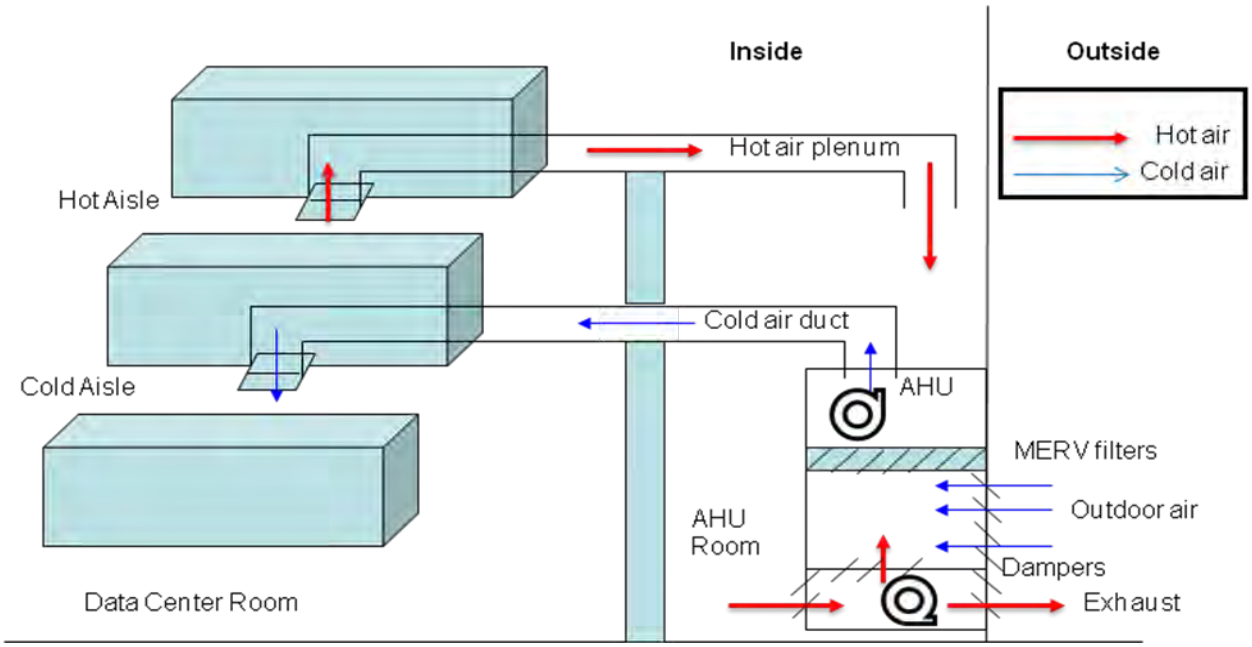



Figure 1: Airflow schematic of economizer system (chiller plant not shown here)

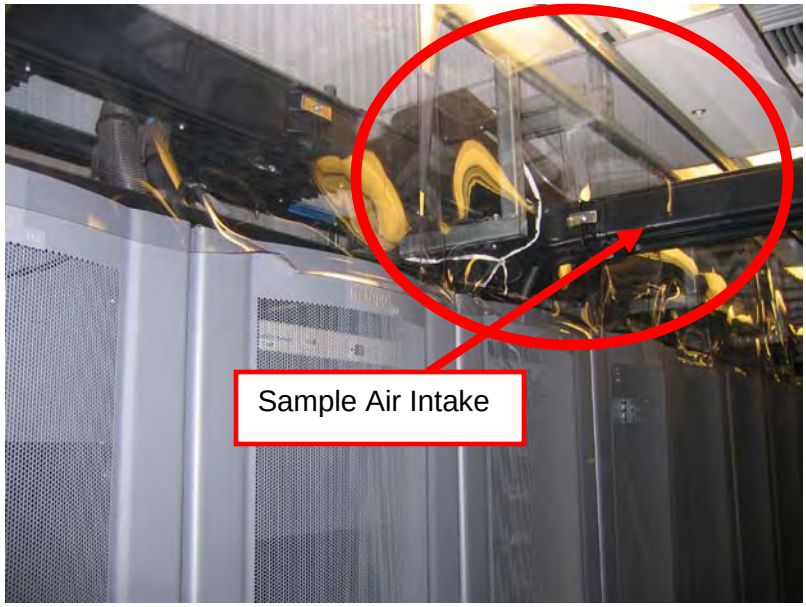
***Experimental Design***

Three different types of HVAC filters were installed during the monitoring period. Immediately before the monitoring period, new HVAC filters with a Minimum Efficiency Reporting Value (MERV) of seven were installed. These are the filters commonly used at this data centers, consistent with most data centers. During the monitoring period the MERV 7 filters were removed and replaced with MERV 11 filters, and then again replaced with MERV 14 filters. The increased MERV rating indicates a greater efficiency of particle removal by the filter.

Two particle counters were placed within the data center to measure absolute concentrations of both indoor and outdoor particle concentrations under three different Heating Ventilation Air Conditioning (HVAC) filtration scenarios. These real-time measurements allow the Indoor Proportion of Outdoor Particles (IPOP) to be calculated, which can be used to estimate filter performance and predict indoor particle levels on different outdoor concentrations. The indoor particle counter was located to measure the particle concentration entering the servers. The particle counter was placed on top of the server rack, with the intake tube extended in front of a server rack at a height of approximately 7 ft. As shown in Figure 2, the outdoor particle counter was placed within the air handling unit at the outside air intake, prior to any filtration, to monitor the outdoor particle concentration entering the air handling units (AHUs) that serve the data center.

*Figure 2: MetOne237B Optical Particle Counter located in AHU at the data center*

*Figure 3: Second MetOne237B Optical Particle Counter above server rack*




Particles composed of black carbon were measured using a Magee Scientific AE22 Aethalometer placed within the data center. Black carbon particles, commonly referred to as "soot," can be emitted during combustion processes and is commonly associated with tailpipe emissions from diesel trucks. An Aethalometer uses the light absorbing properties of black carbon to calculate particle mass by measuring differences in light transmission through a collected sample. The

Aethalometer used was programmed to calculate black carbon concentrations in one minute intervals. Two sets of 0.5 inch diameter copper tubing, each approximately 25 meters in length, were used to collect air from both inside and outside of the data center to the Aethalometer. A pump connected downstream of the tubing draws sample air through the tubing at 25 liters/minute. The air sample then enters a cyclone separator to remove particles larger than 2.5 µm in diameter. After passing through the cyclone, 4 liters/minute of the sample is then sent to Aethalometer while discarding the remaining 19 liters/minute of sample air. Note that the 25 liters/minute flow rate is necessary for proper operation of the cyclone separator. A timed solenoid valve system was used to draw air through the outside air tubing for 20 minutes and then switch to drawing air through the inside air tubing for 20 minutes. The valves toggled in 20 minutes intervals throughout the experiment period.

*Figure 4: Aethalometer system on the data center floor*

Determining the composition of the particles entering the data center requires collecting particle mass samples and performing an Ion Chromatography (IC) analysis. Mass samples of airborne particle were collected by designing a particle capturing system. A description of this system is presented in the Appendix.

*Figure 5: Particle Capturing System used for outdoor (left) and indoor (right) measurements*

***Measurement Protocols***

Particle concentrations were measured using Met-One 237B optical particle counters (OPC). The particle counters were tested prior to the monitoring period to insure that each particle counter produced similar results under the same conditions. OPCs detect particles by correlating particle size to light scattering, so this measurement system is able to distinguish between particle size. However OPC measurement to do distinguish between particle composition, so the particles could be comprised of various materials, including carbonaceous (black carbon and organic carbon), ionic salts (sulfate and nitrate), or any other airborne material. The particle counters provide size-resolved counts for different size bins depending on particle diameter. Four size bins; 0.3-.5 µm, 0.5-.7 µm, 0.7-1.0 µm, and 1.0-2.0 µm, were used to represent fine particle mass concentration. The fine particle mass concentration was estimated by assuming a log-normal mass distribution of the particles across each measured size range. Assuming this type of mass distribution allows the mass median diameter within each bin to be calculated as the geometric mean of that bin. The particle density is assumed to be 1.5 g/cm3. Equation 1 shows the mass concentration was calculated by adding the mass from each size bin, i. The mass

for each size bin is calculated as the product of the particle count (PC), particle density (ρ), and mass median volume, where the particle diameter, Di, is the geometric mean for the size bin.

Measurements were taken in 10 minute increments, where air is pulled through the particle counter at a rate of 0.1 ft3/sec for three minutes. The counter then pauses for 7 minutes before beginning the next particle counting cycle.

Equation 1: Particle count to mass concentration conversion

$$MassConc = \sum PC_i \left( \rho \frac{\Pi}{6} D_i^{\,3} \right)$$

Aethalometer measurements of black carbon were taken in one-minute intervals, with the Aethalometer switching between analyzing outdoor and indoor air every 20 minutes. For each 20 minutes period, the average of measurements between minute nine and 19 were used to represent the black carbon concentration during that period. The first nine minutes of data were discarded because previous reports have shown that sudden changes in temperature and humidity, which can occur when the switching sample air locations, can corrupt the first few minutes of measurements before the Aethalometer equilibrates to the new conditions. The final minute was discarded as a precautionary measure to ensure measurements within each 20 minutes period were distinctly separated.

The air sample filters in the particle sampling system (Figure 5) were analyzed for particle content by a series of different procedures. Quartz filters were measured for concentrations of black carbon and organic carbon through Thermal Optical Analysis (TOA). This process involves exposing the quartz filters to increasingly higher temperatures and measuring the amount of carbon dioxide released. The molecular concentration of carbon dioxide released, and the temperature of that release is then used to back-calculate the amount of black and organic carbon particles that resided on the filter. The Teflon filters were equilibrated and then weighed with off-site a microbalance both before and after experimentation to determine the absolute particle mass collected on each filter. The Teflon filters were placed in a humidity equilibration chamber for a minimum of 24 hours before each microbalance measurement to ensure that water molecules on the filter did not affect the measurements. The Teflon filters were then extracted to autosampler vials and analyzed for common ions, such as sulfate and nitrate, using a Dionex 2020 Ion Chromatograph. The nylon filters were analysis for nitrate concentrations using the same ion chromatography procedure. The cellulose filters, which had been impregnated with citric acid to capture ammonia, used an ammonium electrode to correlate collected ammonia with electrical conductivity**.**

### *HVAC Energy Data Measurements*

This experimental study was carried out at a Net App data center in Sunnyvale, California. The data center has an area of 6780 $ft^2$ with rows of racks arranged in cold-aisle hot-aisle configuration. The facility is cooled by air-side economizer (ASE) based air handling units (AHUs). The AHUs are located in a room adjacent to the data center. The ASE allowed outside air to remove the heat generated by the servers when the outdoor conditions were within the operating set-points. For outdoor temperatures above $70^0$ F the economizer system would switch from complete outside air mode to partial mode. In the partial mode the supply air is a mix of outside air and return air. The economizer system uses no active humidity control but locks out outside the 20-80% relative humidity range (present ASHRAE allowable range 40-55% relative humidity, proposed is 30-55%). It was observed that during the period of the study, the outside temperatures were above $70^0$F between 1 PM to 6 PM, and during this interval the economizer was shut off. In the remaining 18 hours of a day the economizer operation was manually kept to full outside air mode.

The impact of "free" cooling from the air-side economizer, on the HVAC system power consumption was determined for three different HVAC scenarios. The first scenario was the baseline case which consisted of a chilled-water cooled AHU system with no economizer use. The second was the typical operation scenario for the Net App data center using an AHU based economizer system with MERV 7 filters. The third scenario consisted of two stages of improved filtration with the use of 65% efficient MERV 11 filters, followed by 95% efficient MERV 14 filters. The pressure drop across the filters and inside the supply duct was measured for each filter type. The outdoor air temperature and relative humidity, and the pressure difference across the filter and duct system was normalized to a unit scale for the analysis. However, for temperature alone, the rise rather than the absolute value is normalized. The rise in a particular day is the difference between the day's temperature and that of the coldest day during the observation period. Details of the measurement are present in the Appendix section. The authors would like to thank Dave Shroyer, Rick Turner, Rudy Tajalle and Cameron Smith for their assistance at the Net App data center.

## Energy Modeling Protocol

Energy modeling was performed for baseline and proposed HVAC design scenarios. The baseline considered a data center using conventional air-handling units (AHU). The AHUs are placed in a room adjacent to the data center room. Cool air from the AHUs passes through the ducted supply system and is discharged from the ceiling vents into the cold aisle. The server fans draw the cool air through the servers to remove the heat generated by the server equipment. The warm air rises in the hot aisle and travels back via the plenum to be discharged in the AHU

room. The return air is re-circulated across the cooling coils, and discharged into the supply duct. Cooling is provided by a water cooled chiller plant. The proposed design scenario incorporated air-side economizers in an AHU-based system. The air-flow configuration of this scenario is shown in Figure 6. The AHU in the proposed economizer scenario used relief or exhaust fans in the return air-stream to remove the excess air through the exhaust dampers. The exhaust fans were operated only when the economizer system was running. This allowed the discharge of excess air, thereby maintaining a slightly positive pressure in the data center room. The simulation for the proposed scenario considered temperature and relative humidity variations for five different climate zones in the PG&E territory. The five zones covered the climate-dependant modeling were San Jose, San Francisco, Redding, Sacramento, and Fresno.

For each HVAC design scenario, the model parameters were similar to the space and HVAC parameters of the Net App data center facility in San Jose. The area of the facility was 6780 $ft^2$ with an internal load density of approximately 131 $W/sf^2$. For the proposed case, the upper dry bulb temperature for the economizer was set at $70^0$ F, and the allowable relative humidity range was between 20%-80%. Details of the HVAC parameters and operating setpoints for both the baseline and proposed scenarios are present in the appendix section.

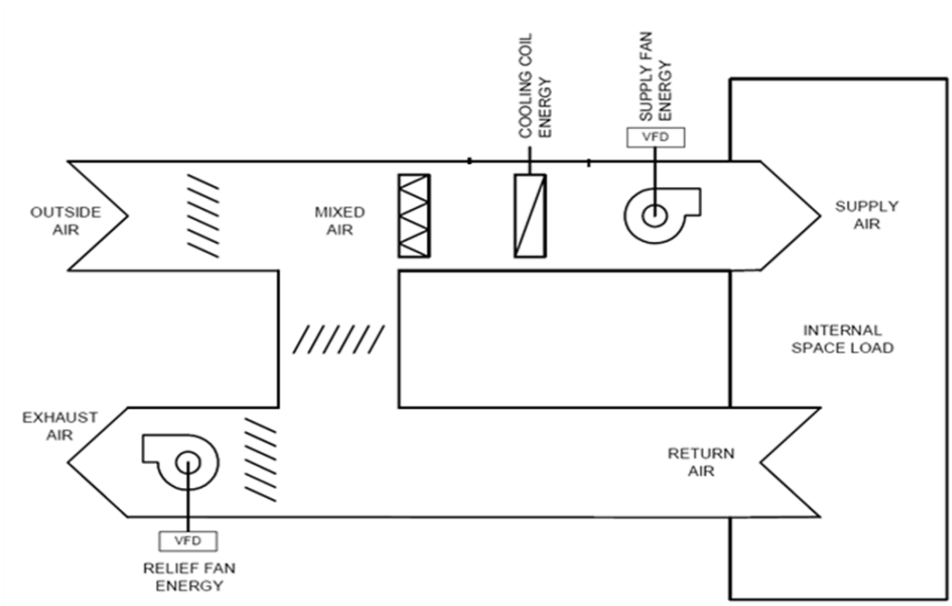



Figure 6: Air flow schematic for an air-side economizer system (courtesy Rumsey Engineers)

### *Life-cycle Costing of Air-side Economizer System*

The lifecycle costing comparison between a baseline data center using AHUs, and an economizer based system (using MERV 7 filters) is determined from a model that simulates the energy

consumption of the Net App data center at Sunnyvale. As mentioned in the previous section, the data center has an area of 6780 $ft^2$ with an internal load density of approximately 131 $W/sf^2$. The life-cycle costing assumes an 8% discount rate in the analysis. The inflation rate for electricity, material and energy costs is assumed to be 3%. Utility incentive is limited to 50% of the total incremental cost of implementation. Refer to the appendix section for details on the energy model and lifecycle costing.

## Results and Discussion

### *HVAC Energy Data Measurements*

Figure 7 shows the variation in HVAC measurements for the typical, baseline and improved filtration scenarios. The upper part of Figure 7 shows the variation in chiller and fan power consumption in all the scenarios, while the lower part highlights normalized changes in duct and filter pressure drops. The total HVAC consumption was substantially greater in the baseline case in comparison to all the three filtration based economizer systems due to a decrease in chiller energy consumption. With reference to the chiller power consumption of the baseline scenario, the typical economizer used 64% less while the improved filtration scenario decreased it by 44%. However, the daily fan power consumption in the typical and improved filtration scenarios increased only nominally with reference to the baseline. Further, the chiller consumption in the improved filtration scenario increased in comparison to the typical economizer operation. An analysis of the filter and duct pressure drops explains this anomaly. It was observed that with improved filter efficiency the pressure drop across the filters increased, while the supply fans were unable to provide the additional air flow because they operated close to maximum speed. This lead to a decrease in pressure drop in the supply duct, which in turn reduced the air flow rate. The decrease in air flow was compensated by increasing the chiller operation to lower the supply air temperature in the data center. Further, the outdoor air temperature rose during the improved filtration period thereby increasing the cooling load on the chiller.

Figure 8 shows the breakdown of average HVAC power consumption into chiller and fan consumption for all the four scenarios. The savings numbers and percentages are presented in Table 1. The economizer based MERV 7 scenario provided the maximum HVAC energy savings of 56% over the baseline. The improved filtration economizer scenarios provide HVAC savings of 38%, in comparison to the baseline.

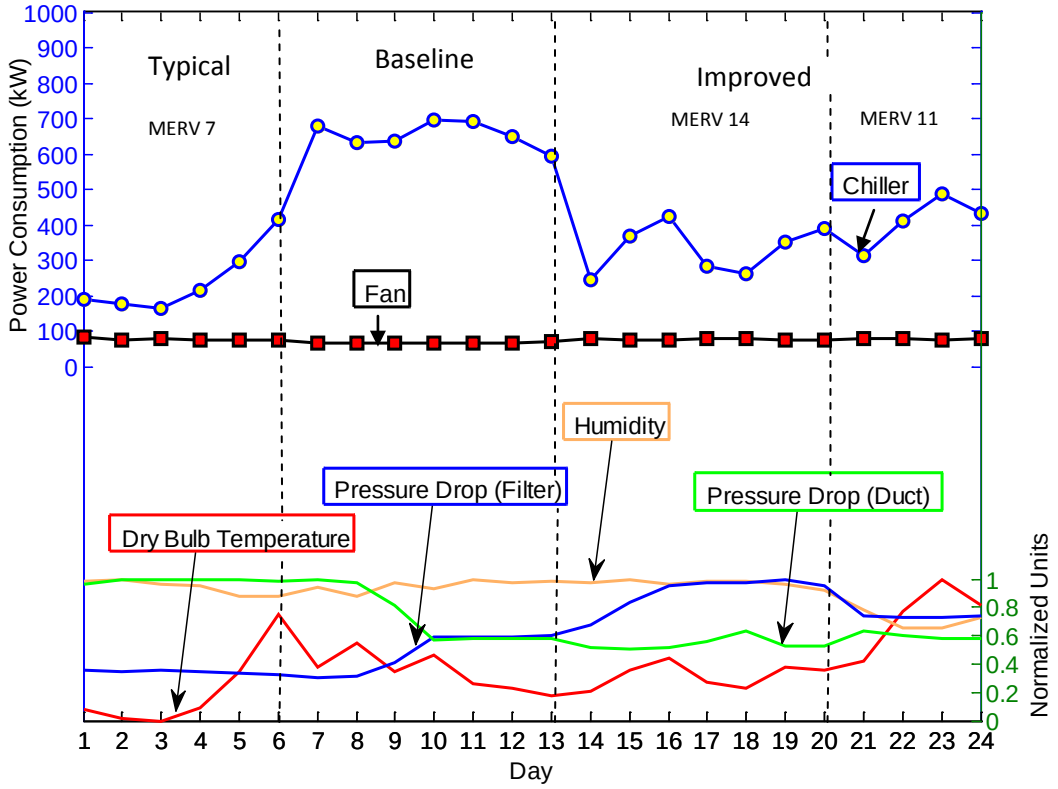



Figure 7: HVAC power with normalized units of outdoor temperature and pressure drop

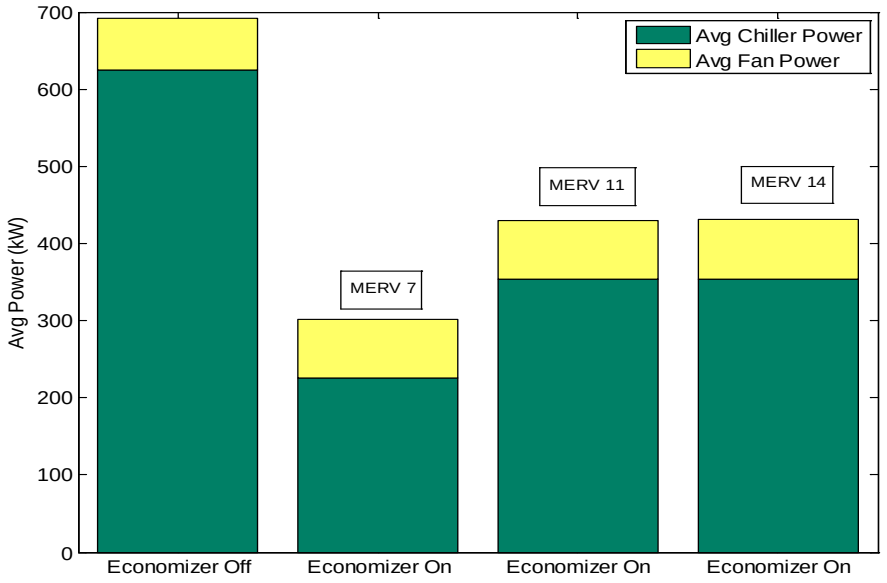



Figure 8: Average HVAC power consumption in the four scenarios

| Scenario | Average chiller power (kW) | Average fan power (kW) | Total HVAC (kW) | Estimate of HVAC energy (GWh/y) | Savings with reference to baseline |
|---|---|---|---|---|---|
| Baseline (economizer off) | 625 | 67 | 692 | 6.1 | - |
| Typical (economizer on - MERV 7) | 225 | 76 | 301 | 2.6 | 56% |
| Improved filtration (economizer on – MERV 11) | 353 | 77 | 430 | 3.7 | 38% |
| Improved filtration (economizer on – MERV 14) | 353 | 78 | 431 | 3.7 | 38% |

Table 1: Average chiller, fan and total HVAC consumption during each of the four scenarios

***Energy Modeling of Economizer-based Data Centers***

The data center infrastructure efficiency (DCiE) metric is the ratio of the energy consumed by the server equipment by the total data center energy use. The higher the value of this metric, the better is the energy performance of the data center. According to LBNL benchmarking studies, the DCiE value for a typical data center is 0.55. A comparison of the DCiE ratios of the five climate dependant economizer based systems with the base case is shown in Figure 9. The performance of the baseline is better than typical data centers because it utilizes an efficient water-cooled chiller plant, and low resistance supply duct system. Further, the transformers and uninterrupted power supplies (UPS) are in a separate room adjacent to the data center, and hence do not add to the cooling load from the server equipment. The air-side economizer system for all five climate zones in the P&E territory performed significantly better than the baseline. Redding having the coolest climate had a DCiE of 0.73, while San Jose was 0.72.

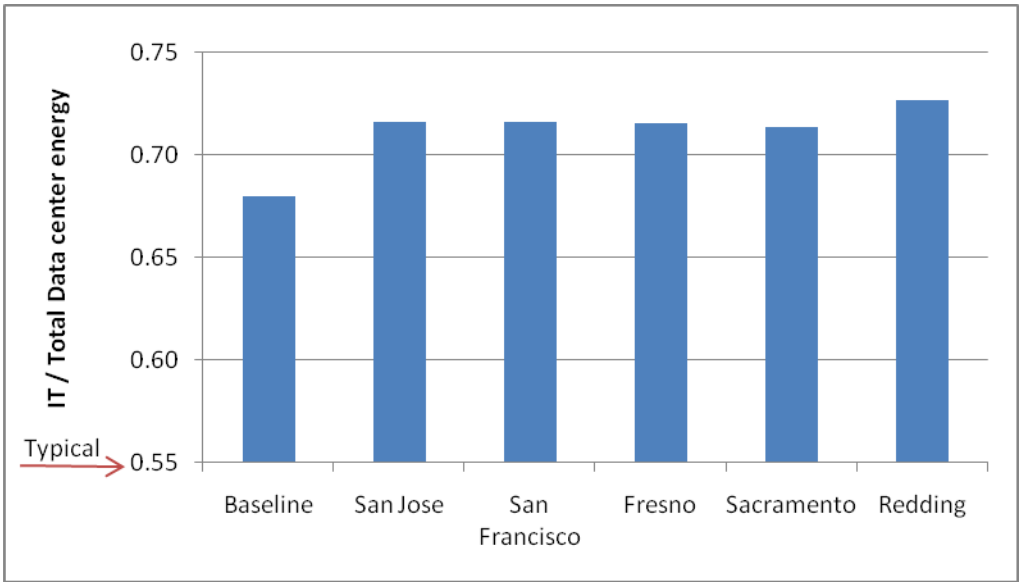



Figure 9: DCiE comparison of baseline and economizer based data centers

Figure 10 shows the disaggregation of the cooling systems' energy use for the baseline and air-side economizer scenarios for different climate zones. The energy loss due to waste heat from the transformers is also included since it is dependent on the overall energy consumption. The energy consumption of the data center server equipment, lighting, UPS and transformer systems is assumed to be constant for all the scenarios. In comparison to the baseline, the economizer system in San Jose would annually save 570 MWh which is equivalent to HVAC energy savings of 33%. Table 2 shows the HVAC energy savings of the economizer based system in comparison to the baseline scenario. The HVAC energy savings for the economizer system translates into substantial energy cost savings. Among the five zones, Sacramento was the warmest with HVAC savings of 30%, while Redding being comparatively cooler garnered 46%.

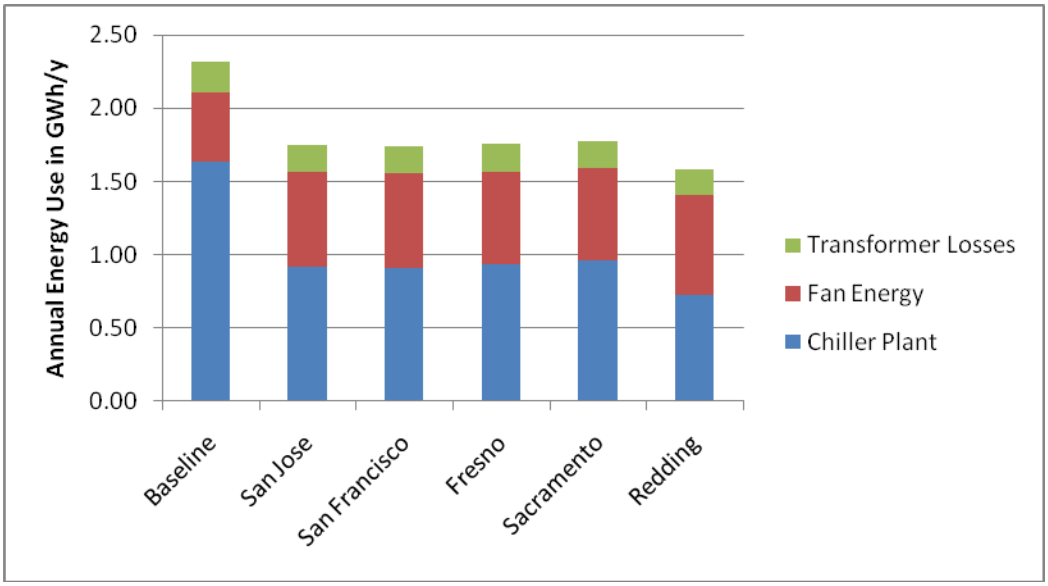



Figure 10: Annual energy use from climate dependent HVAC systems and transformer waste heat

| System | Baseline | San Jose | San Francisco | Fresno | Sacramento | Redding |
|---|---|---|---|---|---|---|
| HVAC energy in MWh/y | 2,316 | 1,746 | 1,739 | 1,754 | 1,777 | 1,583 |
| HVAC savings in MWh/y | - | 570 | 576 | 562 | 538 | 732 |
| HVAC savings % | - | 32.6 | 33.2 | 32.1 | 30.3 | 46.3% |
| Annual energy cost savings in $ | - | 43,800 | 46,500 | 43,900 | 42,900 | 57,600 |

Table 2: HVAC energy and cost savings of baseline and air-side economizer scenarios

### *Life-cycle Costing of Air-side Economizer System*

Results of the annual HVAC energy savings are presented in Table 3. The annual HVAC energy savings in the economizer scenario in comparison to the baseline is 32%. The cost of implementing an air-handling system in both the scenarios is as per typical estimates for a data center in San Jose. The utility incentive is deducted from the difference in implementation cost to

obtain the first cost. At the end of the first year of operation, labor and material costs are added to the first cost to generate the total expense. This expense figure is deducted from the energy cost savings to provide the net savings.

| | Baseline | Air-side economizer | Difference |
|---|---|---|---|
| First year energy cost | $1.15 M | $1.10 M | $43.8 K |
| Implementation cost | $0.25 M | $ 0.30 M | -$50.8 K |

Table 3: Annual HVAC energy savings and implementation cost for baseline and air-side economizer scenarios in San Jose

The relative net present value is the difference between the net present values of the economizer and baseline data centers. A summary of the lifecycle costing of the economizer based system in comparison to the baseline for a 10-year period is presented in Table 4. Implementing an economizer based system has a simple payback period of around 7 months. The relative net present value increases from $0.3 M to $0.5 M for a 20-year period.

| | |
|---|---|
| Simple payback | 0.6 years |
| Relative net present value | $0.3 M |
| Internal rate of return | 170% |

Table 4: Lifecycle costing results of the economizer scenario with reference to the baseline

***Particle Measurements***

Particle counts measured at the Sunnyvale data center under different HVAC filter scenarios are represented as mass concentrations in Table 5. For each measurement period, both the indoor and outdoor mass concentrations are averaged separately for the hours under high air conditions (economizer on) and low air conditions (economizer off). The particle concentrations measured during the MERV 7 period match well with particle measurements conducted at this data center under a previous report (Data Center Economizer Contamination and Humidity Study, 2007). MERV 7 filters were also being used during those previous measurements.

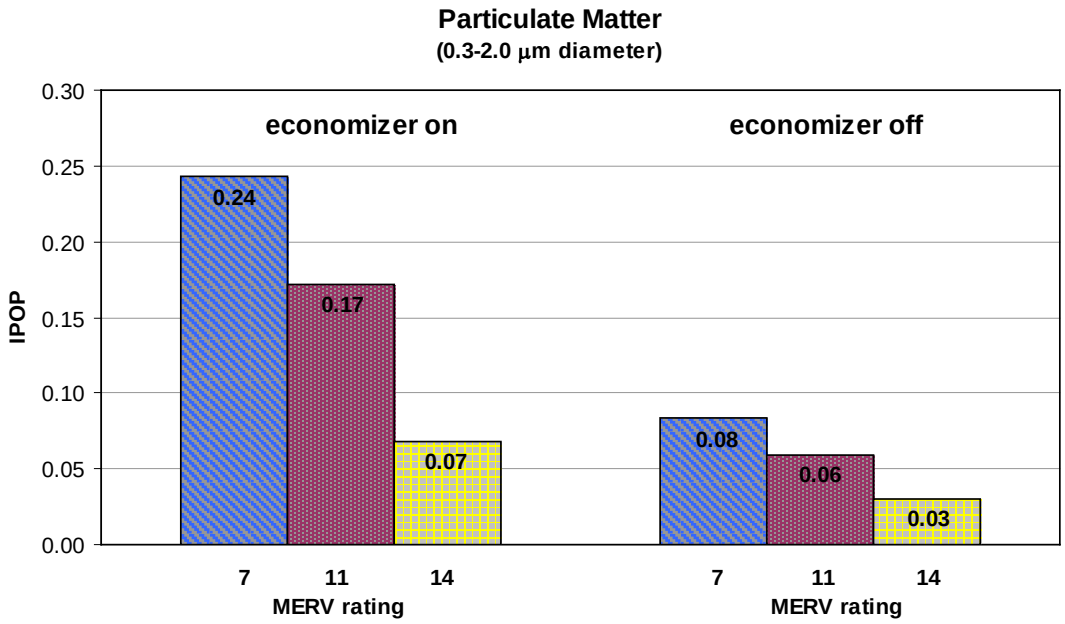
*Table 5: Particle mass concentrations (OPC Measurements)*

| | | 0.3-2.0 μm Particle Concentration (μg/m$^3$) | | | | |
|---|---|---|---|---|---|---|
| Mesurement Period | | | High Air | | Low Air | |
| Start Time | End Time | Filter Type | Out | In | Out | In |
| 8/8/08 13:00 | 8/11/08 12:30 | MERV 7 | 10.17 | 2.47 | 5.16 | 0.43 |
| 8/25/08 15:00 | 8/29/08 13:00 | MERV 11 | 13.18 | 2.27 | 6.53 | 0.38 |
| 8/18/08 19:45 | 8/20/08 11:30 | MERV 14 | 3.25 | 0.22 | 0.85 | 0.03 |

The Indoor Proportion of Outdoor Particles (IPOP) is an indicator that can be used to compare the ability of the HVAC system to remove outdoor particles from entering the data center. IPOP values for high air (economizer on) and low air (economizer off) under the three HVAC filter scenarios measured are presented in Figure 11. As expected, the IPOP is relatively greater during high air periods and increased filter MERV ratings (increased removal efficiency) results in reduced IPOP values. A key finding shown in Figure 5 is that the IPOP value for the MERV 14 filters is lower when the economizer is active than the IPOP value of the conventionally used MERV 7 filters when the economizer is off. This finding indicates that a data center with an economizer that use MERV 14 filters can expect lower indoor particle concentrations than a conventional data center without an economizer and using MERV 7 filters.

As shown in Table 5, the IPOP value measured during the MERV 14 period is based on outdoor concentrations that are lower than the other two monitoring periods. The physical processes responsible for particle removal on filters are typically considered linear (i.e. the removal scales proportionally to the outdoor concentration). However, removal efficiency varies by particle size. Within the size range of the OPC measurements (0.3-2.0 μm diameter) the larger particles are more easily removed than the smaller ones. The lower outdoor particle concentration during the MERV 14 period is partly due to fewer large particles, which heavily contribute to overall mass, being airborne at that time. Evaluation of the OPC measurements show that smaller particles comprise a higher percentage of the total outdoor mass concentration during the MERV 14 period compared to the MERV 7 and 11 periods. This indicates that IPOP from the MERV 14 filters in this study represents a conservative measurement, and that lower IPOP values could be expected under higher outdoor concentrations. Furthermore, increased particle deposition on filters actually increases removal efficiency. This indicates that the IPOP measured here with new MERV 14 filters and exposed to low outdoor concentrations is, again, a conservative estimate since minimal particle deposition had occurred on the filters.

*Figure 11: Indoor Proportion of Outdoor Particles (OPC Measurements)*




Noticeable in Table 5 is that, within the same measurement period, the outdoor particle concentrations were higher when the economizer was operating compared to the hours when the economizer was shut off. This may be due to a combination of different factors. The economizers are active during nighttime hours; when the mixing height of the atmosphere can be lower, resulting in an increase in ambient particle concentrations. Also, the economizers are active during commute hours, increasing outdoor particle emissions from vehicular traffic. This data center can be particularly sensitive to vehicular emission since the air intake at the Sunnyvale data center is located less than 200 meters from a major freeway. The changes in outdoor and indoor particle concentrations with time are presented for each measurement period in Figures 15-17. The economizers were shut off approximately from the hours of noon to 6:00PM and a distinct decrease and then increase in indoor particle concentration can be observed corresponding with these times of the day. Fluctuations in outdoor concentrations are also clearly observed in Figures 15 and 16, though to a much less extent in Figure 17. The reduced outdoor fluctuations during the MERV 14 measurements (Figure 17) are probably due to the lower absolute concentrations during this period.

*Figure 15: Indoor and outdoor mass concentrations with MERV 7 filters (OPC Measurements)*

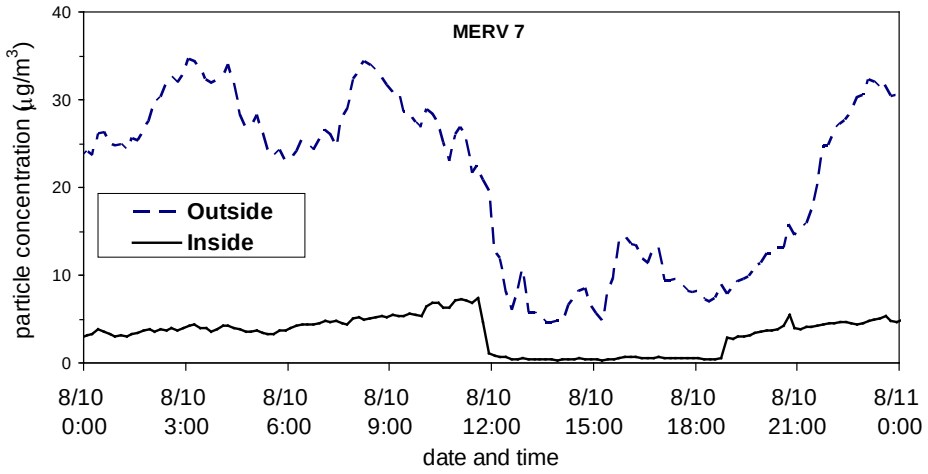



*Figure 16: Indoor and outdoor mass concentrations with MERV 11 filters (OPC Measurements)*

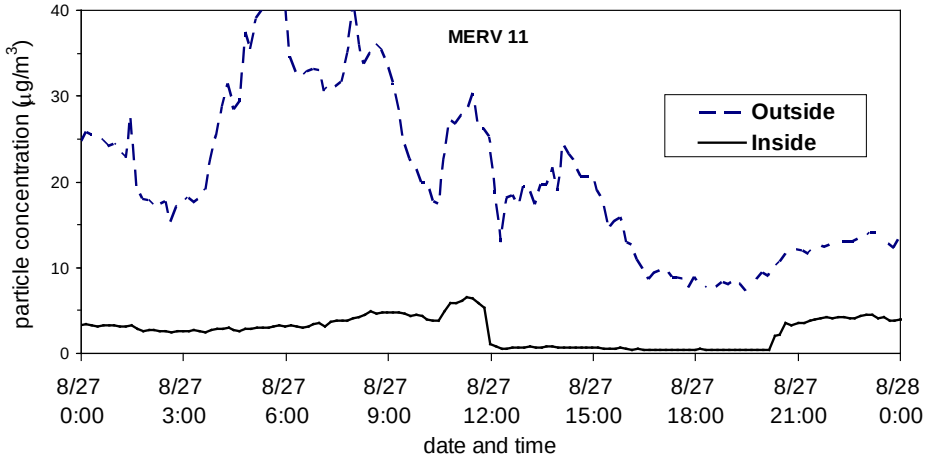



*Figure 17: Indoor and outdoor mass concentrations with MERV 14 filters (OPC Measurements)*

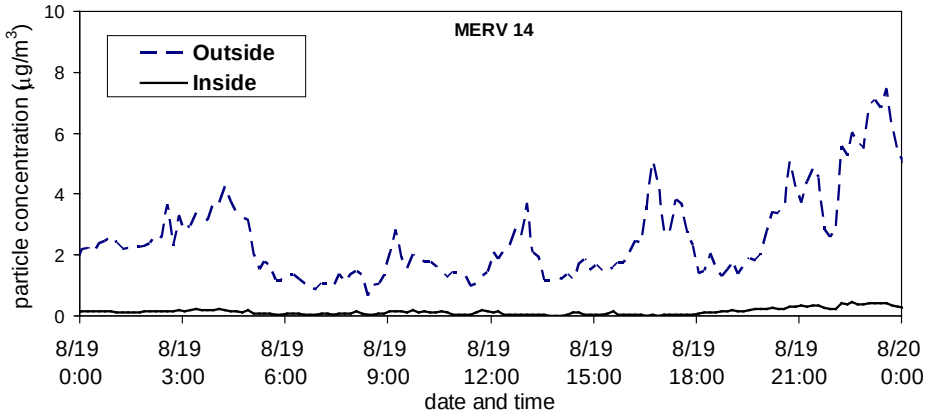
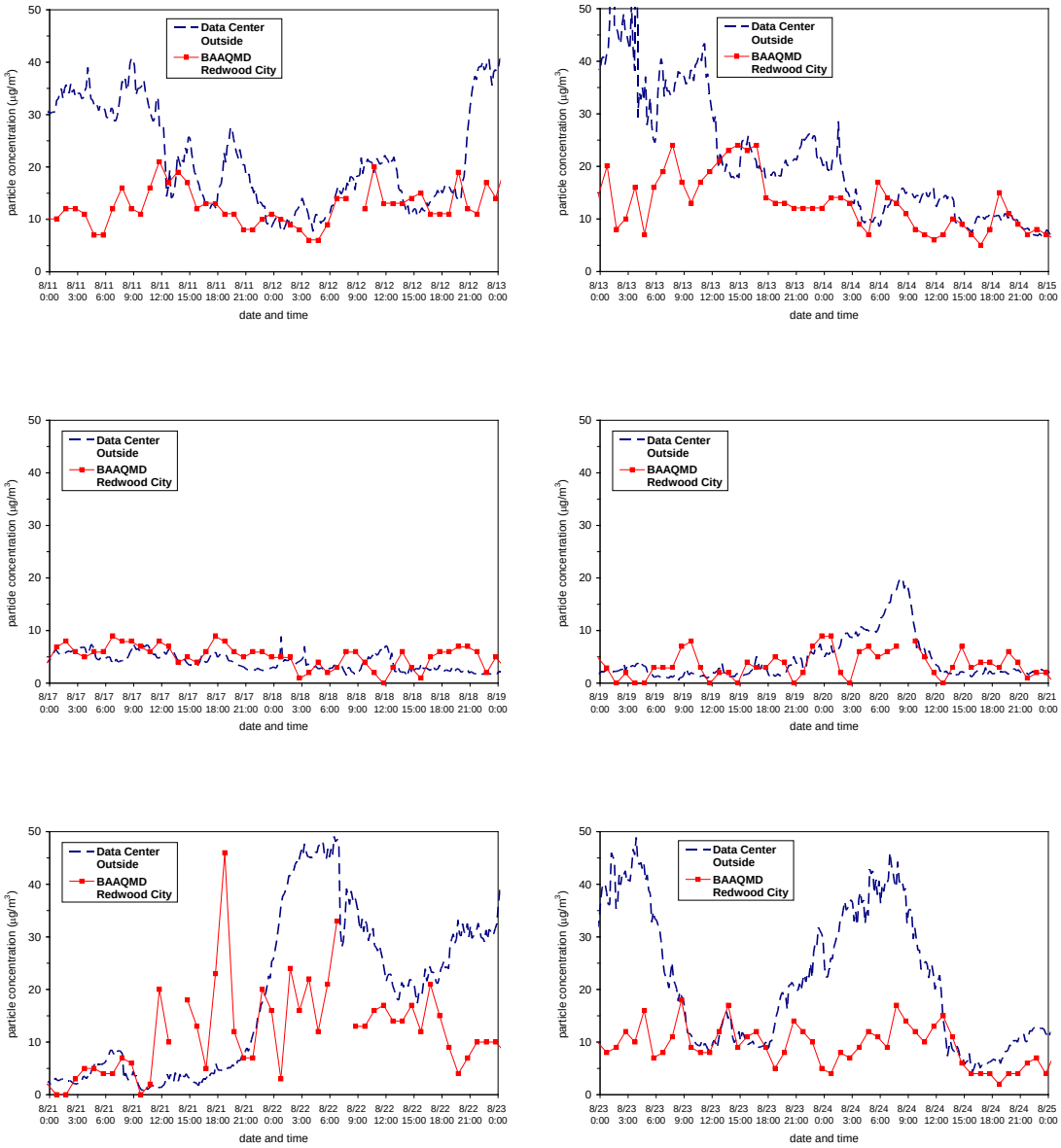
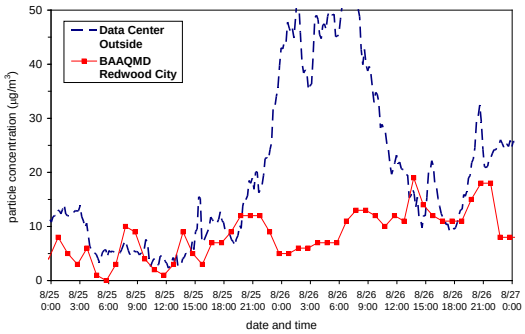


*Figure 18: BAAQMD comparison of outdoor mass particle concentrations (OPC Measurements)*




Data Center Outside
BAAQMD Redwood City
particle concentration (µg/m³)
date and time

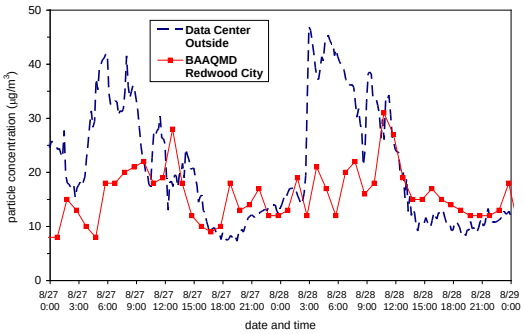

Data Center Outside
BAAQMD Redwood City
particle concentration (µg/m³)
date and time

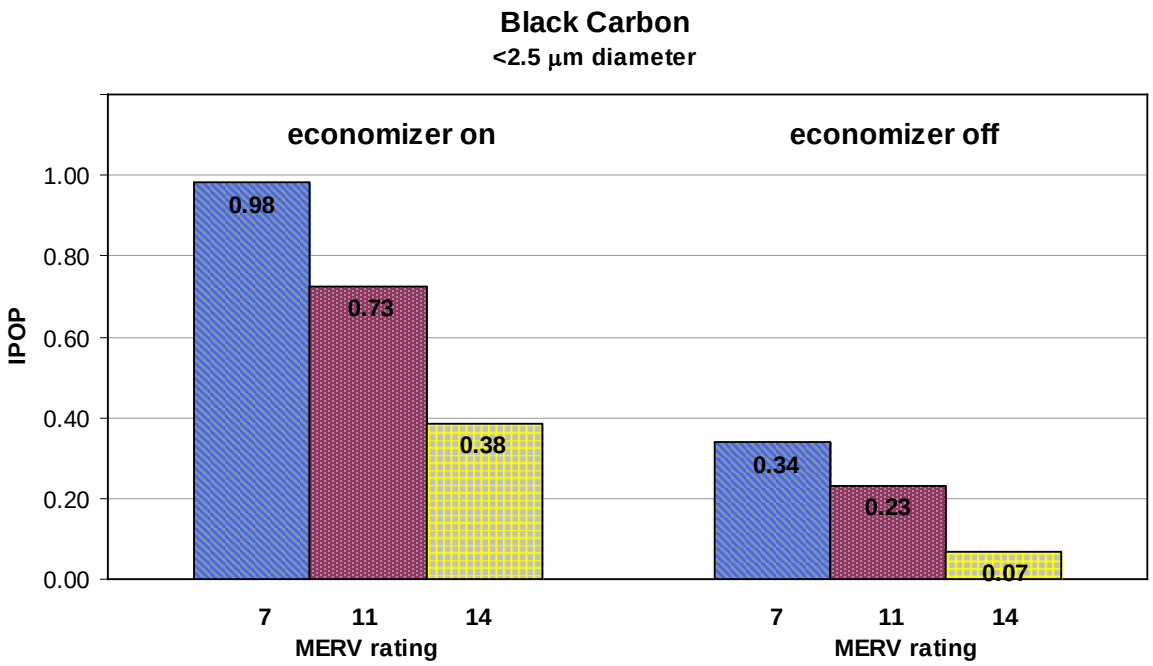
Table 5, as well as tables 6-8 presented below, all show drastically reduced outdoor concentrations of their respective particle types measured during MERV 14 filter monitoring period. To ensure that this outdoor concentration drop was not an indication of experimental error, the outdoor particle concentrations measured in this study were compared to regionally available outdoor particle concentration data from the Bay Area Air Quality Management District (BAAQMD) during these measurement periods. The BAAQMD data represents measurement from their sampling site in Redwood City, which is approximately 15 miles away from the Sunnyvale data center. Figure 18 shows a comparison of the outdoor concentrations measured in this study and the BAAQMD data. The relative drop in outdoor concentration during the MERV 14 measurements matches well for both data sets, indicating that the particle concentration drop is a result of meteorological changes rather than any changes in the study. Also observable in the BAAQMD comparison is that the somewhat rapid increases in outdoor particle concentration at the data center during many of the economizer on periods did not occur in the BAAQMD data. This highlights that particle emission sources in close proximity to the data center, such as the adjacent highway, may be significantly contributing to these increases in outdoor particle concentrations.

Table 6 shows the average black carbon measurements under each filtration scenario, again separated between economizer on periods and economizer off periods. The IPOP trends for black carbon is similar to that observed for particle, in that improved filtration reduces the black carbon IPOP and the MERV 14 IPOP during economizer on periods is comparable to the MERV 7 IPOP during economizer off periods. However, it is interesting to note that across all filter scenarios the proportion of black carbon that penetrates into the data center is greater than that of particle. For example, Table 6 and Figure 12 show that the MERV 7 filters essentially provide no protection from black carbon entering the data center during economizer on periods.

*Table 6: Black carbon mass concentrations (Aethalometer Measurements)*

| | | <2.5 μm Black Carbon Concentration (ng/m$^3$) | | | | |
|---|---|---|---|---|---|---|
| Mesurement Period | | | High Air | | Low | |
| Start Time | End Time | Filter Type | Out | In | Out | In |
| 8/8/08 13:00 | 8/9/08 12:30 | MERV 7 | 149.82 | 147.50 | 155.81 | 52.73 |
| 8/25/08 15:00 | 8/29/08 13:00 | MERV 11 | 928.27 | 673.78 | 650.86 | 150.13 |
| 8/18/08 19:45 | 8/20/08 11:30 | MERV 14 | 202.25 | 77.49 | 172.04 | 11.87 |

*Figure 12: Black Carbon Indoor Proportion of Outdoor Particles (Aethalometer Measurements)*

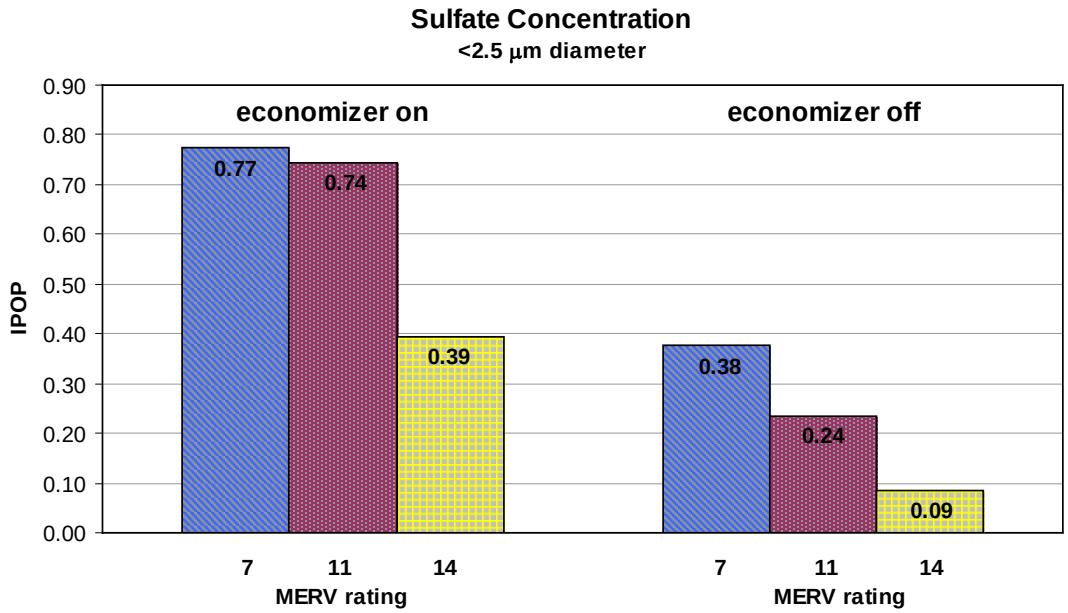



Indoor and outdoor concentrations of particles containing sulfate and nitrate particles are presented in Tables 7 and 8. As mentioned previously, particles containing these ions are of special concern in data centers due to their ability to absorbed water (deliquesce) can create conductive bridging between isolated conductors within computer servers. Figure 13 shows that sulfate particles tend to penetrate into the data center at a high proportion than the IPOPs measured from optical particle counting (the results shown in Figure 11). This indicates that, if sulfate is the primary particle type of concern, optical particle counting may not be an ideal proxy for estimating the proportion of dangerous pollutants entering a data center.

*Table 7: Sulfate mass concentrations (Mass Based Measurements)*

| | | <2.5 μm Sulfate Concentration (μg/m$^3$) | | | | |
|---|---|---|---|---|---|---|
| Mesurement Period | | | High Air | | Low | |
| Start Time | End Time | Filter Type | Out | In | Out | In |
| 8/8/08 13:00 | 8/11/08 12:30 | MERV 7 | 1.84 | 1.42 | 1.48 | 0.56 |
| 8/25/08 15:00 | 8/29/08 13:00 | MERV 11 | 1.24 | 0.92 | 1.58 | 0.37 |
| 8/18/08 19:45 | 8/20/08 11:30 | MERV 14 | 0.94 | 0.37 | 0.35 | 0.03 |

*Figure 13: Sulfate Indoor Proportion of Outdoor Particles (Mass Based Measurements)*

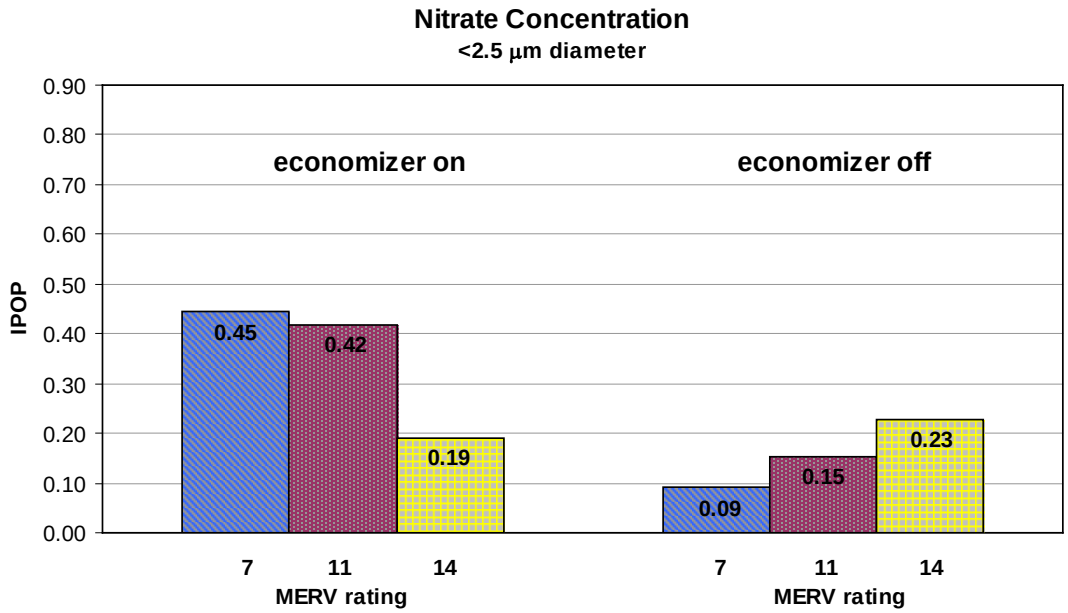



The IPOP measurements for nitrate particles, shown in Figure 14, are much lower than the IPOP counterpart for sulfate under nearly every scenario. The typically lower nitrate IPOP many to due to nitrate particles volatilizing once inside the data center. As mentioned previously, sulfate particles are thermodynamically stable while nitrate particles can easily convert to their gaseous constituents. The volatilization may also be responsible for the paradoxical nitrate IPOP values under the economizer off scenario, which could also be exacerbated by the very low nitrate concentrations measured during those periods.

*Table 8: Nitrate mass concentrations (Mass Based Measurements)*

| | | <2.5 µm Nitrate Concentration (µg/m$^3$) | | | | |
|---|---|---|---|---|---|---|
| Mesurement Period | | | High Air | | Low | |
| Start Time | End Time | Filter Type | Out | In | Out | In |
| 8/8/08 13:00 | 8/11/08 12:30 | MERV 7 | 1.08 | 0.48 | 1.18 | 0.11 |
| 8/25/08 15:00 | 8/29/08 13:00 | MERV 11 | 1.44 | 0.60 | 2.48 | 0.38 |
| 8/18/08 19:45 | 8/20/08 11:30 | MERV 14 | 0.20 | 0.04 | 0.16 | 0.04 |

*Figure 14: Nitrate Indoor Proportion of Outdoor Particles (Mass Based Measurements)*




While results from this study show that MERV 14 filters allow economizer use while maintaining pollutant concentration at non-economizer levels, it is important to note that there is no indication that such low pollutant levels are necessary. Industry concentration limits vary considerably. ASHRAE's "Design Considerations for Data and Communications Equipment Centers" sets a limit that is acknowledged by ASHRAE as a conservative guideline. The ASHRAE particle concentration limits are shown in Table 9. The ASHRAE guidelines suggest a fine particle concentration limit is set at 15 µg/m$^3$. The OPC measurements from this study primarily consisted of particles in the fine particle range and comparing our results to a 15 µg/m$^3$ annual limit shows the MERV 7 filters provide concentrations significantly below the limit. Measured sulfate and nitrate concentrations are also significantly below the ASHRAE limit. However, for data center operators that are not willing to tolerate any increase in pollutants levels, the use of MERV 14 filters appears to be a good alternative.

*Table 9: ASHRAE annual average particle concentration limits for data centers*

| Contaminants | Concentration |
|---|---|
| Airborne Particles (TSP) | 20 µg /m$^3$ |
| Coarse Particles | < 10 µg /m$^3$ |
| Fine Particles | 15 µg /m$^3$ |
| Water Soluble Salts | 10 µg /m$^3$ max - total |
| Sulfate | 10 µg /m$^3$ |
| Nitrites | 5 µg /m$^3$ |

## Conclusion

Previous studies have shown that data centers typically operate under very low contamination levels and allow for large energy savings. Empirical results from a data center in San Jose indicate that the energy savings in an economizer based system is around 56% in comparison to a conventional air-handling based system. The improved filtration economizer scenarios also provide substantial HVAC savings in comparison to the conventional case. The energy model of the San Jose data center for 5 different PG&E locations indicated that the annual savings varied from 30% to 46% based on local climate. This corresponds to an average DCiE of 0.72 which is substantially higher than the typical 0.55 value, which is as per the LBNL benchmarking studies.
The lifecycle costing of the economizer (MERV 7) and conventional air handling unit based system provided a relative net present value of $0.3 M, with a simple payback period of 0.6 years.
The potential for economizers to increase the particle concentration in data centers serves as a deterrent to economizer implementation, even if the increase is still be below the most conservative particle standards. The results of this study show that when MERV 14 filters are used during economizer use, the percentage of outdoor particles entering the data center is at or below the levels measured when using conventional MERV 7 filters without economizer operation. This finding indicates that a data center with an economizer that uses MERV 14 filters can expect lower indoor particle concentrations than typically found in conventional data centers without economizers. Measurement of chemical specific particles indicates that IPOP values for black carbon and sulfate are high than general particle concentrations measured, while the nitrate IPOP is lower. Results also indicate that measured outdoor particle concentrations are often highest during the times of day when economizers would typically be used, such as evening and night periods. Comparison with BAAQMD data indicates that this may be heavily influenced by the specific location of the data center.

## Recommendations

Results from this project show that economizer operation can be achieved without increasing pollutant concentrations in the data center environment by implementing improved filtration. However, the results from this project also indicate, anecdotally, that improved filtration may reduce the energy savings associated with economizer use. Given these results, the need for enhanced filtration and a more thorough investigation of the energy penalty associated with these filters should be explored. Below is a description of future research tasks that would complement the research from this project.

1. Identify methods of failure and estimate failure probability:
   Work in collaboration with server manufacturers and the ASHRAE data center committee to document the types of failures that have occurred, such as current leakage or heat trapping. Identify the causes of the failure, beyond hygroscopic particles, and explain the believed mechanism by which these failures occur. Outdoor pollutant characteristics may vary by location within California. Review how the size and chemical composition influences equipment problems. Address the contribution of deposited fibers, which may enhance circuit failure rates by contributing to current bridging between isolated conductors. Identify and possibly developing potential methods to estimate the probability of failure under given pollutant conditions. For example, the applicability of percolation theory could be explored to correlate the probability of particle bridging with the volume of particles deposited in a given space.

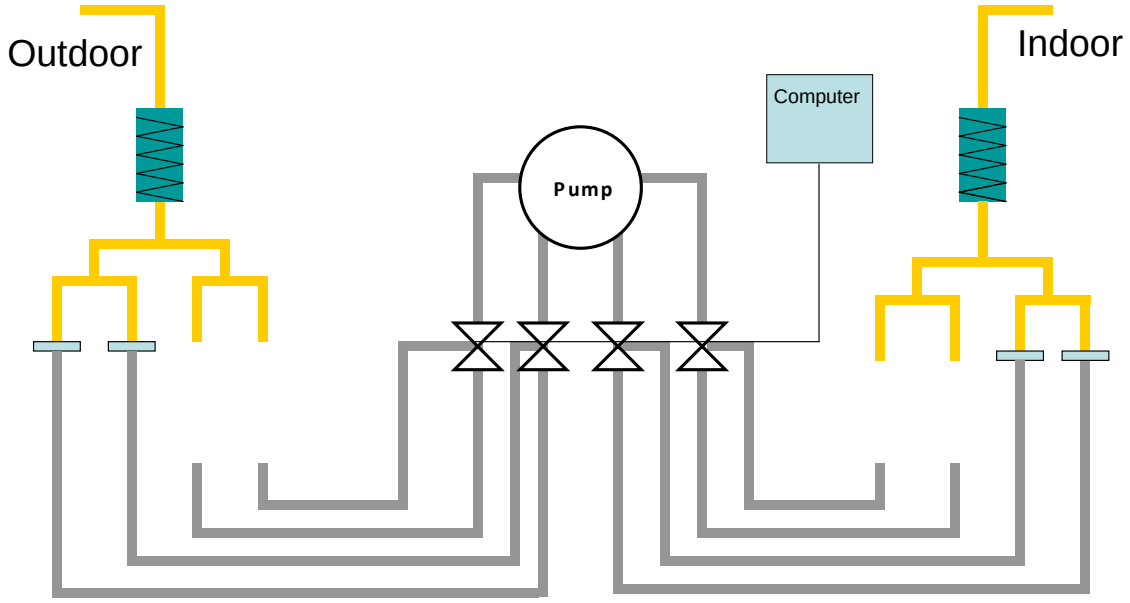
2. Determine energy penalty for enhance filtration in data center within the PG&E territory:
   The energy penalty of enhanced filtration observed at the Sunnyvale data center is specific to that HVAC design and the meteorological conditions during experimentation. Methods to prevent AHU fans from reaching maximum flow rates should be researched. Energy penalties should be estimated that allow results to be extrapolated to a broad range of data center designs. A combination of empirical practices and energy modeling could be performed to estimate the energy penalty of improved filtrations. Economic life cycle costing and environmental life cycle analysis of improved filtration could then be performed to determine when such filtration is warranted.

## Appendix A

### Particle Sampling System

Two identical particle sample systems were developed; one to measure indoor air and the other for outdoor air. Each of these sample systems were connected through plastic tubing to a set of valves and then joined at a single pump used to draw air through the tubing. For each sampling system, sample air enters 0.5 inch copper tubing, approximately five feet in length, at a flow rate of 25 liters/minute. The air sample then enters a cyclone separator to remove particles larger than 2.5 µm in diameter. After passing through the cyclone, the copper tubing branches to allow sample air to pass through four sample filters; two quartz filters to collect elemental and organic carbon, and two "denuder" filters to determine ammonium sulfate and ammonium nitrate concentrations in the sample particle through IC analysis. The value system is designed to have sample air passes through one of the quartz filters and one of the denuder filters when the HVAC economizers are on, and the switch and have sample air pass through the other quartz and denuder filters when the economizer is off. As mentioned previously, the economizers were set to be off during the hours of noon to 6:00PM and on during the remaining hours. The valves in the sample systems diverted air to the appropriate sample filters according to this economizer schedule.

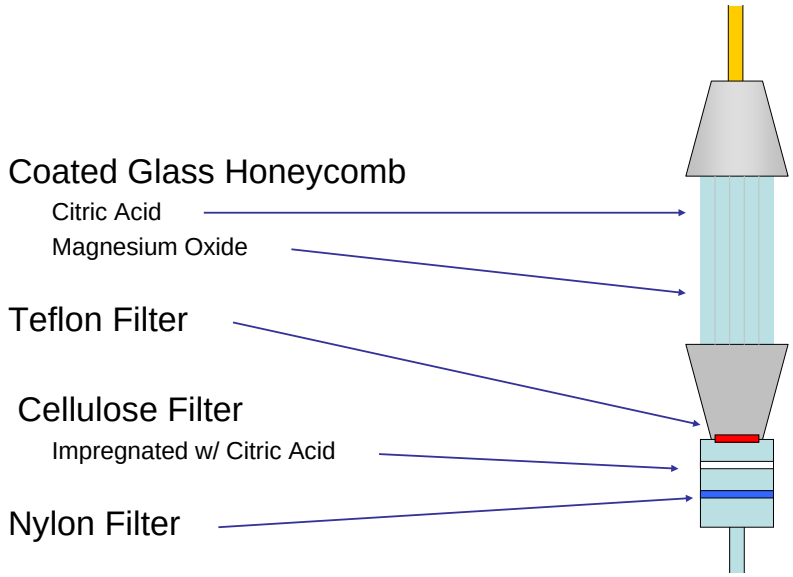
*Figure 15: Schematic of particle sampling system*




The denuder filter system was required so that the collected samples could be accurately measured for their chemical composition by IC analysis. Since IC determines the amount of specific ions, such as sulfate or nitrate, gases containing these ions must be removed from the air

sample, so the ions measured can be accurately ascribed to particulate matter. The denuder system is shown in Figure 15. Sample air moves through the copper tubing from the top into a glass honeycomb structure, which separates the airflow into many narrow passageways. Gas molecules diffuse, or divert away from the airstream, much faster than particles. This causes the gas molecules to collide with the sides of the narrow passageways before exiting the honeycomb denuder. The particles, however, exit the honeycomb denuder before straying far enough to collide with the passageway walls. The honeycomb denuder was coated on one end with citric acid (an acid) and the other end with magnesium oxide (a base). The citric acid is use to react with and thereby remove any ammonia gas from the air sample. The magnesium oxide removes any nitrate and sulfate gases. After exiting the honeycomb denuder, the air sample is collected on a Teflon filter (marked in red in Figure 16). Ammonium nitrate particles are volatile and any ammonium nitrate particles collected on the Teflon filters can potentially volatilize into its constituent gases (ammonia and nitric acid). To account for the ammonium nitrate particles that may volatilize off the Teflon filters, two extra filters are added to the denuder filter system, downstream of the Teflon filter, to capture the gas phase constituents. A cellulose filter impregnated with citric acid (shown in white in Figure 16) is used to collect the volatilized ammonia gas. A nylon filter (shown in blue in Figure 16) is used to collect the volatilized nitric acid gas. Note that particle volatilization is not an issue with sulfate particles due to their thermodynamic stability.

*Figure 16: Particle chemical speciation system ('denuder filter")*



**Appendix B**

**ACEEE 2008 Conference Publication**

# Energy Implications of Economizer Use in California Data Centers

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## Abstract

In the US, data center operations currently account for about 61 billion kWh/y of electricity consumption, which is more than 1.5% of total demand. Data center energy consumption is rising rapidly, having doubled in the last five years. A substantial portion of data-center energy use is dedicated to removing the heat generated by the computer equipment. Data-center cooling load might be met with substantially reduced energy consumption with the use of air-side economizers. This energy saving measure, however, has been shown to expose servers to an order-of-magnitude increase in indoor particle concentrations with an unquantified increase in the risk of equipment failure. An alternative energy saving option is the use of water-side economizers, which do not affect the indoor particle concentration but require additional mechanical equipment and tend to be less beneficial in high humidity areas. Published research has only presented qualitative benefits of economizer use, providing industry with inadequate information on which to base their design decisions. Energy savings depend on local climate and the specific building-design characteristics. In this paper, based on building energy models, we report energy savings for air-side and water-side economizer use in data centers in several climate zones in California. Results show that in terms of energy savings, air-side economizers consistently outperform water-side economizers, though the performance difference varies by location. Model results also show that conventional humidity restrictions must by relaxed or removed to gain the energy benefits of air-side economizers.

## Introduction

Data centers are computing facilities that house the electronic equipment used for data processing, networking and storage. Rapid growth in computational demand emerging from various sectors of the economy is causing strong rates of increase in servers and IT-related hardware (IDC 2007). Server performance has doubled every two years since 1999, leading to increasingly higher densities of heat dissipation within data centers (Belady 2007). A substantial proportion of energy consumption in data centers is dedicated to the cooling load associated with electronic power dissipation (Tschudi et al. 2003). A recent study estimates that US data centers account for 61 billion kWh or 1.5% of the nation's annual electricity consumption (US DOE

2007a). This corresponds to an electricity bill of approximately $4.5 billion in 2006 (EPA 2007). The environmental impact is substantial because 70% of the electricity in US is generated in power plants that burn fossil fuel (EIA 2007). Improved data center cooling technologies have the potential to provide significant energy savings. Cost savings and environmental benefits might also accrue.

A typical data center consists of rows of tall (2 m) cabinets or racks in which the servers, data storage and networking equipment are vertically arrayed. The cooling of data-center equipment is accomplished using computer room air conditioners (CRACs), which supply cold air to a raised-floor plenum beneath the racks. The CRAC system air handler is placed on the data center floor while chilled water in transported from compressor-based chillers to the CRAC cooling coils. More efficient cooling systems employ low outside air temperatures to reduce chiller load. Cooling towers that use ambient air to directly cool or precool the chilled water are known as water-side or fluid-side economizers. This type of system has been claimed to cut cooling-energy costs by as much as 70% (ASHRAE HVAC Fundamentals Handbook 2005) during economizer operation. Based on local weather data in San Jose, water-side economizers can be used for more than one-third of the year (PG&E 2006). An alternate data center arrangement uses air-handling units (AHU) and an air-side economizer. Such systems directly provide outdoor air for cooling whenever the temperature of outside air is lower than the set-point for return-air temperature in the data center. In San Francisco's cool climate, outside air could contribute to some level of air-side cooling for nearly all hours of the year (Syska Hennessy 2007). The use of air-side economizers brings with it an associated concern about contamination including moisture from humidity that may possibly threaten equipment reliability. Deliquescent sulfate, nitrate and chloride salts, in a humid environment (> 40% relative humidity) can cause corrosion, accumulate and become conductive, and may lead to electrical short-circuiting (Rice et al. 1981; Sinclair et al. 1990; Litvak et al. 2000). In this paper, the energy implications of a data center using a CRAC system will be compared with alternative cooling systems using air-side or water-side economizers for five different California climate zones. The modeling results and discussion focus on understanding the energy implications for both type of economizers and their effectiveness in different climate zones. The equipment reliability concerns associated with air-side economizers are acknowledged to be important, but addressing it is beyond the scope of the present paper.

## Methods

### Data center design scenarios

Energy-use simulations were performed for three different data center HVAC design scenarios (Figure 1). The baseline case considers a data center using conventional "computer room air conditioning" (CRAC) units. In this scenario, CRAC units are placed directly on the computer room floor. Air enters the top of a CRAC unit, passes across the cooling coils, and is then discharged to the underfloor plenum. Perforations in the floor tiles in front of the server racks allow the cool air to exit from the plenum into the data-center room. Fans within the computer servers draw the conditioned air upward and through the servers to remove equipment-generated heat. After exiting the backside of the server housing, the warm air rises and is transported to the intake of a CRAC unit. Most air circulation in the baseline scenario is internal to the data center. A small amount of air is supplied through a rooftop AHU to positively

pressurize the room and to supply outside air for occupants. Cooling is provided by a water-cooled chiller plant. Refrigerant in the chillers is used to cool water through heat exchangers at the evaporator. The chilled water is then piped to the CRAC units on the data center floor. Waste heat from the chiller refrigerant is removed by water through heat exchangers in the condenser. Condenser water is piped from the cooling towers, which cools the water through interaction with the outside air. This baseline design is common to most mid- to large-size data centers (Tschudi et al. 2003; Rumsey 2005; Syska Hennessy 2007).

The water-side economizer (WSE) scenario assumes a CRAC unit layout similar to that of the baseline case, except that additional heat exchangers are installed between the condenser water in the cooling towers and the chilled water supplied to the CRAC units. Under appropriate weather conditions, the cooling towers can cool the condenser water enough to cool the chilled water in the CRAC units directly, without operating the chiller plant. The CRAC units and chiller plant are assumed to be the same as in the baseline scenario.

The air-side economizer scenario (ASE) requires a different type of air delivery than typically found in a data center with conventional CRAC units. AHUs are placed outside of the data center room, commonly on the rooftop, and air is then sent to and from the computer racks through ducts. A ducted air delivery system creates greater air resistance than a conventional CRAC unit layout, though this system better prevents cold and warm air from unintentionally mixing within the data center. When the outside air temperature is equal to or below the temperature of the air supplied to cool the server, the AHU can directly draw outside air into the data center and exhaust all of the return air after it has passed across the computer servers. The movement of 100% outside air through the system can require more fan energy than the baseline case, as the economizer design requires more ducting, which increases air resistance through the system. However, during this 100% outside air mode the cooling is provided without operating the chiller, chilled water pumps, condenser water pumps, or the cooling tower fans. Outside air is also provided instead of recirculated air whenever the outside air temperature is greater than the supply air temperature but lower than that of the return air. Under this condition the chiller must operate, but the cooling required of the chiller is less than in a case with complete recirculation.

**Energy modeling protocol**

For each design scenario, the model calculations assume a 30,000 $ft^2$ (2800 $m^2$) data center with an internal heat density of approximately 80 $W/ft^2$ (0.86 $kW/m^2$; 2.4 MW total) This size and power density are characteristic of data centers evaluated in previous studies (Shehabi et al. 2008; Greenberg et al. 2006; Tschudi et al. 2003). The size of data centers varies greatly; 30,000 $ft^2$ is within the largest industry size classification, which is responsible for most servers in the US (IDC 2007). Power density in data centers is rapidly increasing (Uptime Institute 2000) and a power density of 80 $W/ft^2$ is currently considered to be of low- to mid-range (Rumsey 2008).

Basic properties of the modeled data center for all three scenarios are summarized in Table 1. Energy demand is calculated as the sum of the loads generated by servers, chiller use, fan operation, transformer and uninterruptible power supply (UPS) losses, and building lighting. The chiller encompasses coolant compressor, chilled water pumps, condensing water pumps, humidification pumps, and cooling-tower fans. Energy demand for servers, UPS, and lighting

are constant, unaffected by the different design scenarios, but are included to determine total building-energy use. The base case and WSE scenarios assume conventional humidity restrictions recommend by ASHRAE (ASHRAE 2005). The ASE scenario assumes no humidity restriction, which is an adjustment required to gain ASE benefits as is typical in ASE implementation (Rumsey 2008). Air-side economizers also require a different air distribution design and the fan parameters associated with each design scenario are listed in Table 2. The properties of other pumps and fans throughout the HVAC system remain constant for all three scenarios. Values are from previous data-center energy analyses (Rumsey 2008; Rumsey 2005).

The energy modeling approach used in this study applies a previously used protocol (Rumsey 2008; Rumsery 2005) and is based on a combination of fundamental HVAC sizing equations that apply equipment size and efficiencies observed through professional experience. Building energy modeling is typically performed using energy models such as DOE-2, which simultaneously models heat sources and losses within the building and through the building envelope. However, models such as DOE-2 are not designed to incorporate some of the HVAC characteristics unique to data centers. Also, data centers have floor-area-weighted power densities that are 15-100 times higher than those of typical commercial buildings (Greenberg et al. 2006). This allows accurate modeling of data-center energy use to focus exclusively on internal heat load and the thermal properties of outdoor air entering the building. This is the approach taken in this study, as heat generated from data center occupants and heat transfer through the building envelope are negligible relative to the heat produced by servers. The building envelope may influence the cooling load in low-density data centers housed in older buildings that have minimal insulation. Evaluating this building type is worthy of exploration, but the required analysis is more complex and outside the scope of the present paper.

Both air-side and water-side economizers are designed to allow the chiller to shut down or reduce chiller energy load under appropriate weather conditions. Less overall energy is required for operation when the chiller load is reduced, but chiller efficiency is compromised. Changes in chiller efficiency used in this analysis are shown in Figure 2, representing a water-cooled centrifugal chiller with a capacity > 300 tons and condenser water temperature of 80 °F. A chilled water temperature of 45 °F, which is standard practice for data center operation, is used in the base case and ASE scenario. The WSE scenario uses a chilled water temperature of 52 °F, which is common when using water-side economizers. This increases needed airflow rates but allows greater use of the water-side economizers. The curves are based on the DOE2.1E software model and apply coefficients specified in the Nonresidential Alternative Calculation Method (ACM) Approval Manual for the 2005 Building Energy Efficiency Standards for Residential and Nonresidential Buildings (CEC 2005).

Annual data center energy use is evaluated for each of the three configuration scenarios assuming that a data center building is located in each of the five cities shown in Figure 3. Weather conditions at each city are based on hourly DOE2.1E weather data for California climate zones (CEC 2005).

## Results and Discussion

Results from each scenario modeled are presented in Table 3 as a “performance ratio” which equals the ratio of total building energy divided by the energy required to operate the computer servers. Lower value of the performance ratio implies better energy utilization of the

HVAC system. The performance ratio for the base case is 1.55 and, as expected, is the same for all the cities analyzed, since the operation of this design is practically independent of outdoor weather conditions. The base case performance ratio is better than the current stock of data centers in the US (EPA 2007; Koomey 2007) because the base case represents newer data centers with water-cooled chillers, which are more efficient than the air-cooled chillers and direct expansion (DX) cooling systems found in older data centers.

The performance ratios for the ASE and WSE scenarios show air-side economizers consistently provide savings relative to the base case, though the difference in savings between the two scenarios varies. It is important the note that even small changes in the performance ratio results in significant savings, given the large amount of energy used in data centers. For example, reducing the performance ratio at the model data center in San Jose from 1.55 to 1.44 represents a savings of about 1.9 million kWh/y, which corresponds to a cost savings of more than $130,000/y (assuming $0.07/kWh).

Figure 4 shows the disaggregation of the cooling systems' annual energy use, normalized by floor area, for each modeled data center by location and design scenario. The annual energy use dedicated to the servers, USP, and lighting is 584, 95, and 9 kWh/ft$^2$, respectively. These energy values are independent of the climate and HVAC design in scenario and not included in the graphs in Figure 4. Economizer use is typically controlled by combination of outside air temperature, humidity, and enthalpy; however results shown in Figure 4 are for economizer use controlled by outside air temperature only. Results show that the ASE scenario provides the greatest savings in San Francisco while Fresno provides the least ASE savings. Sacramento benefited the most from the WSE scenario while minimal savings were realized in Los Angeles and San Francisco. The San Francisco WSE scenario, where significant gains would be expected because of the cool climate, is hindered by chiller part-load inefficiencies. The relatively higher moisture content in the San Francisco air increases the latent cooling load in the model and causes the chiller plant to reach the capacity limit of the first chiller more often, activating a second chiller. The second chiller shares the cooling load equally with the first, resulting in a transition from one chiller at a high load factor (efficient operation) to two chillers at slightly above half the load factor (less efficient operation). The results from the WSE scenario in San Francisco emphasize the need for engineers to model the hour-by-hour load, rather than just the peak load, and to size chillers such that all active chillers at any moment will be running near their most efficient operating point.

Figure 5 shows that removing the humidity restrictions commonly applied to data centers is necessary to gain ASE energy savings. As the relative humidity (RH) ranged is narrowed, energy use from the fans begins to sharply increase, surpassing the equivalent baseline energy in most of the cities. Humidity levels are often restricted in data centers to minimize potential server reliability issues. ASHRAE's guidelines released in 2005 for data centers provide a "recommend" RH range between 40-55% and an "allowable" range between 20-80% (ASHRAE 2005). There is minimal cost in applying the more conservative ASHRAE RH restrictions in conventional data center design, such as the baseline in this study shown in Figure 5. The influence of humidity on server performance, however, is poorly documented and the need for humidity restrictions is increasingly being questioned (Fontecchio 2007). The energy saving difference between adhering to ASHRAE's recommend RH range versus the allowable RH range is substantial, and warrants further investigation.

## Conclusion

Employing the energy-saving measures evaluated in this paper would require a shift in conventional data center design and operation. Various operational concerns must be addressed before widespread adoption of these technologies could be expected in data-center buildings. This paper contributes to the informed implementation of air-side and water-side economizers by assessing the energy benefits of adopting these efficiency improvements. Air-side economizers are shown to consistently outperform water-side economizers in California, though the difference in performance varies by the climate conditions of the locations evaluated. Furthermore, the models show that conventional humidity restrictions must by relaxed or removed to substantially realize the energy benefits of air-side economizers. As the data center economy continues to rapidly grow, energy efficiency will continue to emerge as an important financial and environmental concern. The results presented here contribute to our understanding of different design implications and should assist decision makers in the implementation of energy-efficient data centers.

## Acknowledgments

We thank Rumsey Engineers for their assistance in running energy models and data center operators that helped determine conventional HVAC parameters. This project was funded by Pacific Gas & Electric and by the University of California Energy Institute, California Studies Grant Program. Some of this work was performed at LBNL under the U.S. Department of Energy Contract No. DE-AC02-05CH11231.

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## Table 1: Data Center Characteristics Common to All Design Scenarios

| Data Center Parameters | |
|---|---|
| Floor Area | 30,000 $ft^2$ |
| UPS Waste Heat | 326 kW |
| Data Center Lights | 30 kW |
| Total Rack Load | 2000 kW |
| Total Internal Load | 2,356 kW |
| Average Internal Load Density | 79 $W/ft^2$ |
| Minimum Ventilation | 4,500 $ft^3/min$ |
| Supply Air Temperature | 55 ¡F |
| Return Air Drybulb Setpoint | 72 ¡F |
| Chiller Capacity | 1750 kW |
| Number of Chillers | 3 |

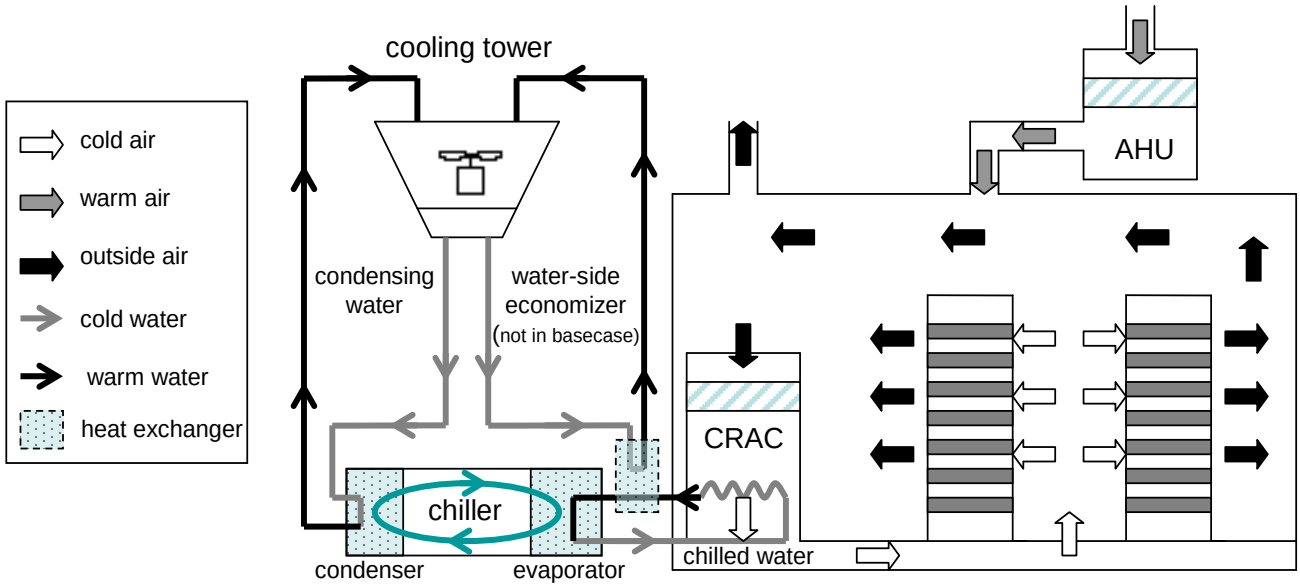
## Table 2: Data Center Fan Properties

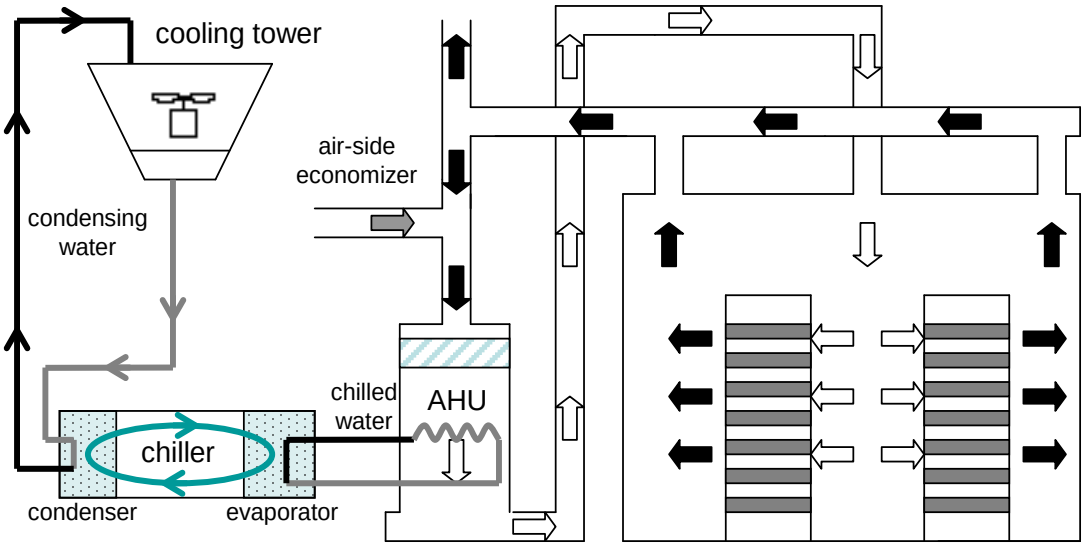
| Fan System Parameters | Baseline and WSE | | | ASE | |
|---|---|---|---|---|---|
| | MUAH | Exhaust | CRACs | Supply | Relief |
| Total Air Flow (cfm) | 4,500 | 4,500 | 495,000 | 437,758 | 437,758 |
| Fan Motor Size, Nominal (hp) | 7.5 | 3 | 10 | 30 | 50 |
| Number of Fans | 1 | 1 | 30 | 10 | 5 |
| Fan Efficiency | 53.3% | 44.0% | 55.6% | 63.8% | 67.5% |
| Fan Drive Efficiency | 95% | 95% | 95% | 95% | 95% |
| Fan Motor Efficiency | 89.6% | 86.2% | 90.1% | 92.5% | 93.2% |
| VFD Efficiency | n/a | n/a | n/a | 98% | 98% |
| Total Static Pressure Drop (in w.g.) | 3.5 | 1 | 1.6 | 2 | 1 |

## Table 3: Ratio of Total Building Energy to Computer Server Energy

| | San Jose | San Francisco | Sacramento | Fresno | Los Angeles |
|---|---|---|---|---|---|
| **Baseline** | 1.55 | 1.55 | 1.55 | 1.55 | 1.55 |
| **Air-side Economizer** | 1.44 | 1.42 | 1.44 | 1.46 | 1.46 |
| **Water-side Economizer** | 1.53 | 1.54 | 1.53 | 1.53 | 1.54 |

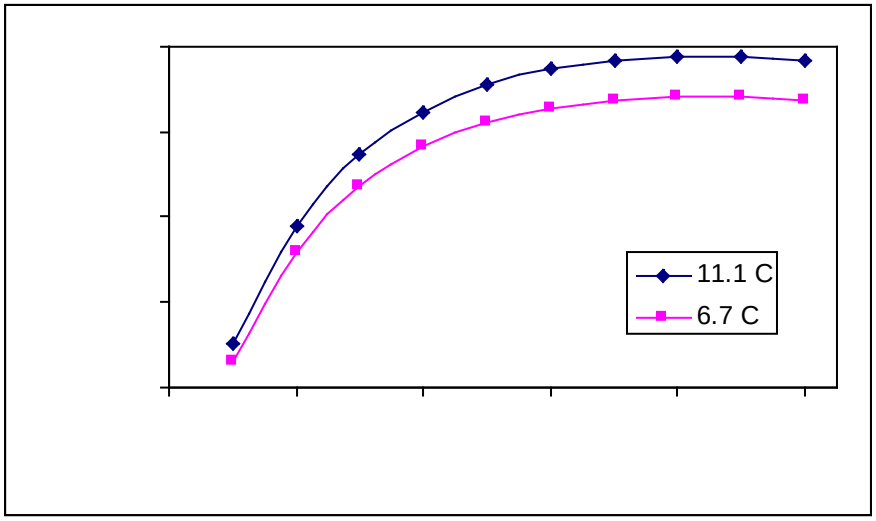
**Figure 1: Schematic of Data Center Cooling Design Scenarios**




Air and water flow schematic for the basecase and water-side economizer scenarios (above).
Air and water flow schematic for the air-side economizer scenario (below).

**Figure 2: Assumed Part Load Performance of Data Center Chillers**




Part load efficiencies for a water-cooled centrifugal chiller with a capacity >300 tons and an condenser water temperature of 26.7 °C (CEC, 2005))

**Figure 3: Evaluated Climate Zone Locations**

**Figure 4: Disaggregated Energy Use (Climate Dependent Values Only)**

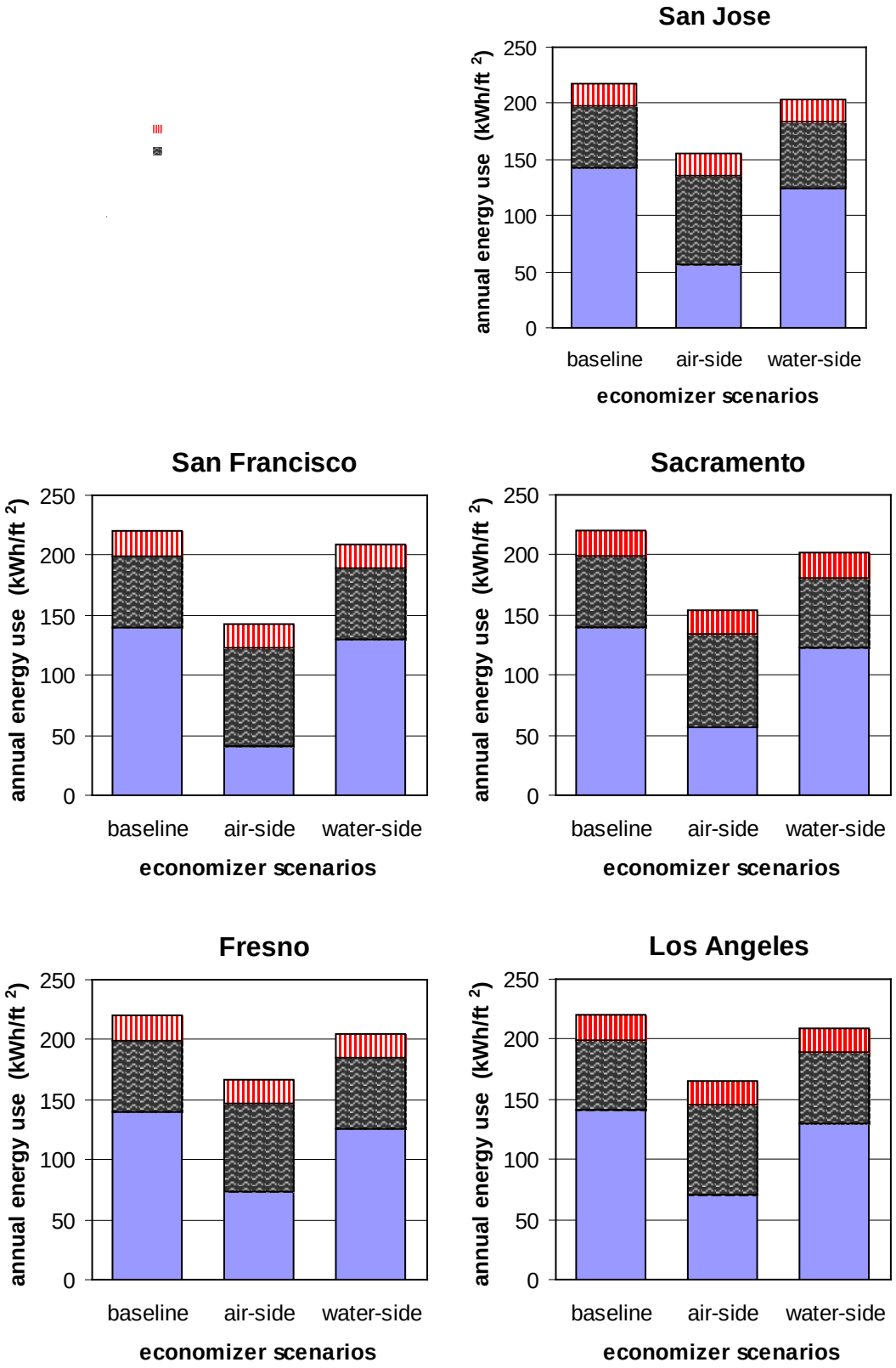
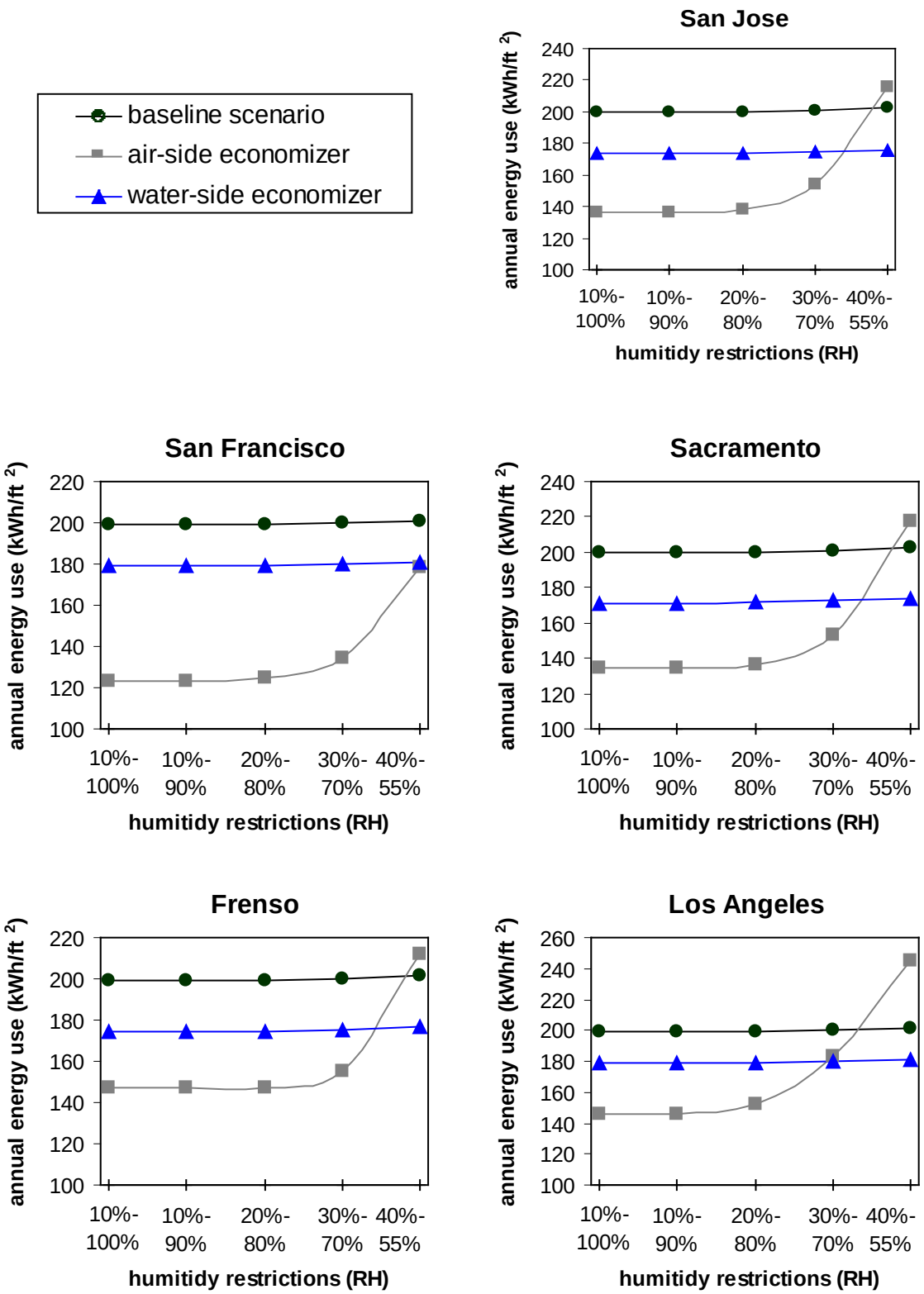


**Figure 5: Chiller and Fan Energy Resulting from Humidity Restrictions**



## Appendix C

## Climate-Dependent Data Center Modeling

# CHW AHUs

# CEC Zone 4 (San Jose)

# Annual Total Electric Energy Use, Baseline

**Assumptions**

This scenario assumes seven 500 kVa modules. The efficiencies for the modules are drawn from Powersmith data sheets. Where data points were not provided we have estimated values according to a standard transformer curve profile. We assume that the number, size, and efficiency of the modules are the same for the baseline and proposed case.

We assume that all active transformer modules are loaded to an equal percentage.

All transformers are assumed to be of the linear type.

The power factor is assumed to be 1.00 (kW = kVA).

Transformers are not located in an air-conditioned space, so they do not impose a cooling load.

The transformers serve the rack, UPS, lighting, and chilled water plant loads.

**Input Parameters**

| | | | |
|---|---|---|---|
| Transformer Module Size: | 500 | kVA | See Transformers sheet |

**Annual Energy Use**

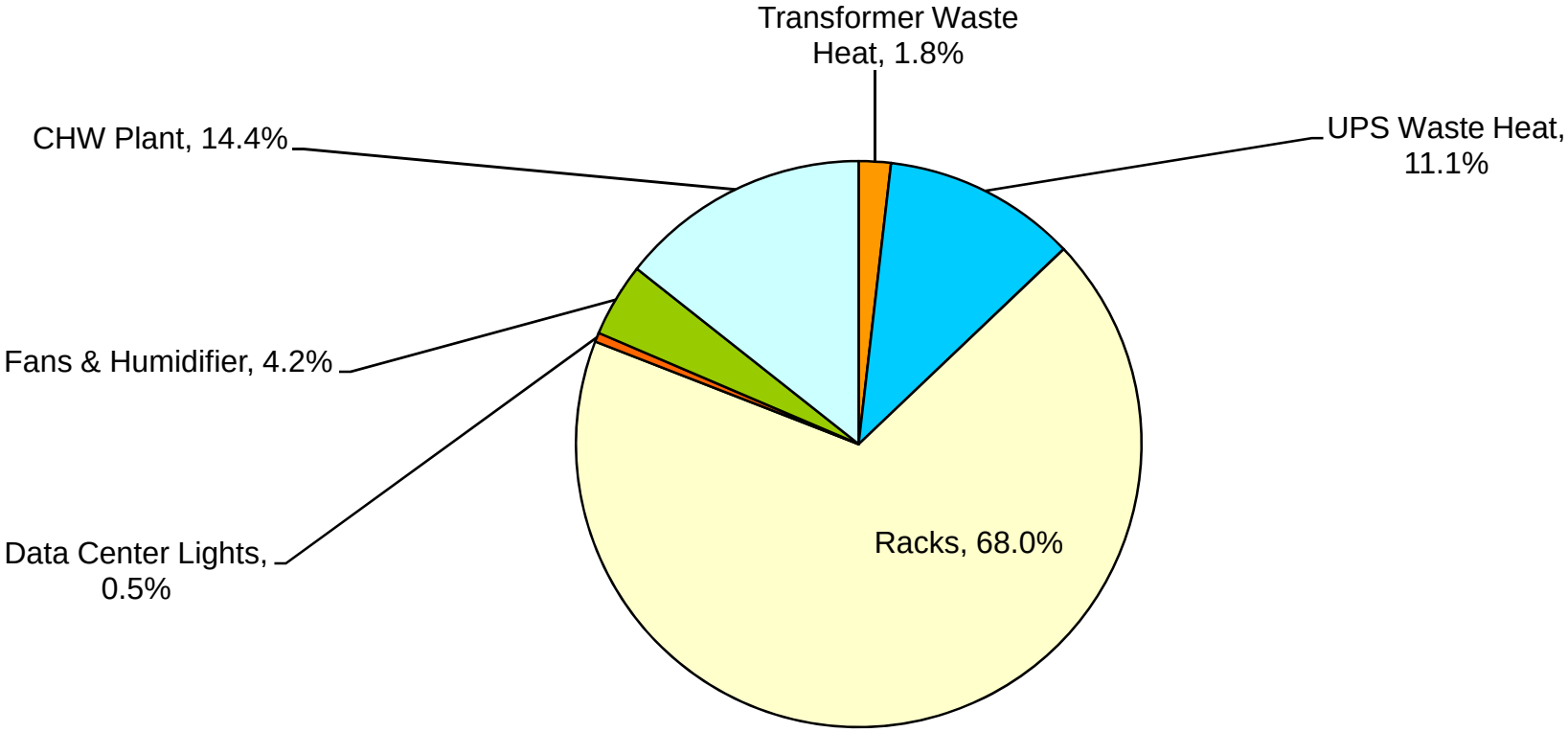
| System | Baseline | |
|---|---|---|
| | kWh/yr | Percent of Total |
| Transformer Waste Heat | 207,778 | 1.8% |
| UPS Waste Heat | 1,256,917 | 11.1% |
| Racks | 7,721,064 | 68.0% |
| Data Center Lights | 59,393 | 0.5% |
| Fans & Humidifier | 478,182 | 4.2% |
| CHW Plant | 1,630,665 | 14.4% |
| Total | 11,353,999 | 100.0% |

**Hourly Calculations**

| Date | Hour | Required Transformer Output Power | | | | | Transformer Modules | | | Transformer Total Input Power Demand | Trans-former Waste Heat | Peak Summer Power Demand |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | UPS Input Power | Data Center Lights | Fans and Humidifier | CHW Plant | Total | Quant. | Load Factor | Module Effic. | | | |
| | | kW | kW | kW | kW | kW | | % | % | kW | kW | kW |
| 1-Jan | 1 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 2 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 3 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 4 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 5 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 6 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 7 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 8 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 9 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 10 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 11 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 12 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 30-Jun | 13 | 1,025 | 7 | 55 | 195 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | 1,305 |
| 30-Jun | 14 | 1,025 | 7 | 55 | 195 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | 1,305 |
| 30-Jun | 15 | 1,025 | 7 | 55 | 195 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | 1,305 |
| 30-Jun | 16 | 1,025 | 7 | 55 | 194 | 1,280 | 3 | 85% | 98.2% | 1,304 | 24 | 1,304 |
| 30-Jun | 17 | 1,025 | 7 | 55 | 195 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | 1,305 |
| 30-Jun | 18 | 1,025 | 7 | 55 | 193 | 1,280 | 3 | 85% | 98.2% | 1,303 | 24 | 1,303 |
| 30-Jun | 19 | 1,025 | 7 | 55 | 195 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | n/a |
| 30-Jun | 20 | 1,025 | 7 | 55 | 192 | 1,278 | 3 | 85% | 98.2% | 1,302 | 24 | n/a |
| 30-Jun | 21 | 1,025 | 7 | 55 | 190 | 1,277 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 30-Jun | 22 | 1,025 | 7 | 55 | 189 | 1,276 | 3 | 85% | 98.2% | 1,299 | 24 | n/a |
| 30-Jun | 23 | 1,025 | 7 | 55 | 189 | 1,275 | 3 | 85% | 98.2% | 1,299 | 24 | n/a |
| 30-Jun | 24 | 1,025 | 7 | 55 | 180 | 1,266 | 3 | 84% | 98.2% | 1,290 | 24 | n/a |
| 1-Jul | 1 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 1-Jul | 2 | 1,025 | 7 | 55 | 189 | 1,276 | 3 | 85% | 98.2% | 1,299 | 24 | n/a |
| 1-Jul | 3 | 1,025 | 7 | 55 | 193 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | n/a |
| 1-Jul | 4 | 1,025 | 7 | 55 | 184 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 1-Jul | 5 | 1,025 | 7 | 55 | 184 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 1-Jul | 6 | 1,025 | 7 | 55 | 184 | 1,270 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 1-Jul | 7 | 1,025 | 7 | 55 | 193 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | n/a |
| 1-Jul | 8 | 1,025 | 7 | 55 | 189 | 1,275 | 3 | 85% | 98.2% | 1,299 | 24 | n/a |
| 1-Jul | 9 | 1,025 | 7 | 55 | 190 | 1,277 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 1-Jul | 10 | 1,025 | 7 | 55 | 191 | 1,277 | 3 | 85% | 98.2% | 1,301 | 24 | n/a |
| 1-Jul | 11 | 1,025 | 7 | 55 | 197 | 1,283 | 3 | 86% | 98.2% | 1,307 | 24 | n/a |
| 1-Jul | 12 | 1,025 | 7 | 55 | 198 | 1,284 | 3 | 86% | 98.2% | 1,308 | 24 | n/a |
| 31-Dec | 13 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 14 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 15 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 16 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 17 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 18 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 19 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 20 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 21 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 22 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 23 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 24 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| Sum | | 8,977,981 | 59,393 | 478,182 | 1,630,665 | 11,146,221 | | | | 11,353,999 | 207,778 | 1,063,955 |
| Ave | | 1,025 | 7 | 55 | 186 | 1,272 | 3.00 | 85% | 98.2% | 1,296 | 24 | 1,304 |
| Max | | 1,025 | 7 | 55 | 202 | 1,288 | 3 | 86% | 98.2% | 1,312 | 24 | 1,312 |
| Min | | 1,025 | 7 | 55 | 179 | 1,265 | 3 | 84% | 98.2% | 1,289 | 24 | 1,289 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# Data Center Infrastructure Efficiency (DCIE)
# Baseline




DCIE = Rack Energy / Total Energy = 0.680

# Space Parameters

**Assumptions**
Chilled water CRAC values are based on the Liebert Deluxe System 3, Model 740C.

| | Baseline | Units | Sources |
|---|---|---|---|
| **Input Parameters** | | | |
| ***Space Dimensions*** | | | |
| Floor Area | 6,780 | sf | Email from Dave Shroyer, 10/13/08. |
| ***Occupancy Schedule*** | | | |
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | Datacenter assumed to operate 8,760 hours per year |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | Datacenter assumed to operate 8,760 hours per year |
| ***HVAC System Type & Setpoints*** | | | |
| Air Delivery System | VAV | | The proposed system uses VAV air handlers. |
| Return Air Drybulb Setpoint | 89.5 | °F | Selected to get a 22 deg-F delta-T, email from Rupa Ganguly on 9/30/08. |
| Supply Air Drybulb Setpoint (VAV Systems Only) | 67.5 | °F | Estimate from email from Rupa Ganguly on 9/30/08. |
| Supply Air Design Flow Rate (CAV Systems Only) | | cfm | Total air flow provided by selected number & size of CRAC units and expected total static pressure drop of open HACA arrangement. |
| Active Humidity Control? | yes | | Humidity control is baseline practice. |
| Drybulb Temp at RH Sensor Location | 89.5 | °F | Humidity sensor is assumed to be mounted on the data center ceiling. |
| Allowed Relative Humidity, Maximum | 55% | RH | ASHRAE recommended value. |
| Allowed Relative Humidity, Minimum | 30% | RH | ASHRAE recommended value. |
| CHWST Setpoint, Primary | 44 | °F | Baseline CHWST setpoint value. |
| CHWST Setpoint, Secondary | 44 | °F | We are not considering CHWST reset. |
| Adiabatic Humdifier Power Draw | 0.000 | kW/ (lb of H20/hr) | No adiabatic humidifier. |

| | Baseline | Units | Sources |
|---|---|---|---|
| ***Cooling Load*** | | | |
| Total Rack Load, Occupied | 881 | kW | Calculated from rack load of 130 W/sf, email from Dave Shroyer, 10/13/08. |
| Total Rack Load, Unoccupied | n/a | kW | Rack load does not vary with occupancy. |
| Average Lighting Density | 1.0 | W/sf | Typical value. |
| ***Ventilation Requirement*** | | | |
| Minimum Ventilation Requirement | 0.15 | cfm/sf | CA Title 24 requirement for office space. |
| ***Boiler Data*** | | | |
| HHW Boiler Efficiency | 82% | % | Baseline value. |
| Gas-fired Humidifier Efficiency | 76% | % | Baseline value. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| ***HVAC System Type & Setpoints*** | | | |
| Occupied Supply Air Drybulb | | °F | = RAT - Occupied Load / (1.08 * cfm) |
| Unoccupied Supply Air Drybulb | | °F | A datacenter is assumed always occupied. |
| Occupied Supply Air Flow Rate | 127,545 | cfm | = Load / (1.08 * Delta-T) |
| Unoccupied Suppllly Air Flow Rate | n/a | | A datacenter is assumed always occupied. |
| Air Side Delta-T | 22 | °F | Subtract |
| ***Cooling Load*** | | | |
| UPS Waste Heat | 0 | kW | Not included in cooling load. |
| Data Center Lights | 7 | kW | Average lighting density times space floor area. |
| Total Internal Load, Occupied | 888 | kW | Rack load, UPS waste heat, lights. |
| Total Internal Load, Occupied | 253 | tons | Convert to tons |
| Total Internal Load, Occupied | 3,030 | kBTU/hr | Convert to kBTU/hr |
| Average Internal Load Density, Occupied | 131 | W/sf | Divide by floor area |
| Total Internal Load, Unoccupied | n/a | kW | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | tons | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | kBTU/hr | A datacenter is assumed always occupied. |
| Average Internal Load Density, Unoccupied | n/a | W/sf | A datacenter is assumed always occupied. |
| ***Ventilation Requirement*** | | | |
| Min Allowed Ventilation Volumetric Air Flow Rate | 1,017 | cfm | Floor area times minimum ventilation requirement. |

# Weather Data

Source: California Energy Commission
Data Set: California Climate Zone 4 (CZ04RV2)

| Date | Hour | Outside Air | | | | | |
|---|---|---|---|---|---|---|---|
| | | Drybulb Temp. | Dewpoint Temp. | Relative Humidity | Atmospheric Pressure | Wetbulb Temp. | Enthalpy |
| | | °F | °F | % | psia | °F | BTU/lb |
| 1-Jan | 1 | 44.1 | 39.6 | 84% | 14.6 | 41.9 | 16.1 |
| 1-Jan | 2 | 42.6 | 40.6 | 93% | 14.6 | 41.7 | 16.0 |
| 1-Jan | 3 | 41.2 | 38.1 | 89% | 14.6 | 39.8 | 15.1 |
| 1-Jan | 4 | 40.3 | 37.4 | 89% | 14.6 | 38.9 | 14.7 |
| 1-Jan | 5 | 38.8 | 36.7 | 92% | 14.6 | 37.9 | 14.3 |
| 1-Jan | 6 | 37.9 | 36.0 | 92% | 14.6 | 37.0 | 13.9 |
| 1-Jan | 7 | 37.4 | 35.4 | 92% | 14.6 | 36.5 | 13.6 |
| 1-Jan | 8 | 33.3 | 32.2 | 96% | 14.6 | 32.8 | 12.1 |
| 1-Jan | 9 | 36 | | | | 36.0 | 13.4 |
| 1-Jan | 10 | 37 | | | | 37.4 | 14.0 |
| 1-Jan | 11 | 41 | | | | 41.7 | 16.0 |
| 1-Jan | 12 | 46 | | | | 43.2 | 16.8 |
| 30-Jun | 13 | 87 | | | | 66.7 | 31.3 |
| 30-Jun | 14 | 82 | | | | 68.1 | 32.5 |
| 30-Jun | 15 | 79 | | | | 68.2 | 32.6 |
| 30-Jun | 16 | 79.7 | 60.8 | 52% | 14.5 | 67.0 | 31.6 |
| 30-Jun | 17 | 78.3 | 62.2 | 58% | 14.5 | 67.5 | 32.1 |
| 30-Jun | 18 | 76.6 | 60.6 | 58% | 14.5 | 66.1 | 31.0 |
| 30-Jun | 19 | 77.0 | 63.0 | 62% | 14.5 | 67.6 | 32.1 |
| 30-Jun | 20 | 74.5 | 58.5 | 57% | 14.5 | 64.0 | 29.4 |
| 30-Jun | 21 | 72.1 | 55.0 | 55% | 14.5 | 61.5 | 27.5 |
| 30-Jun | 22 | 69.6 | 52.7 | 55% | 14.5 | 59.4 | 26.1 |
| 30-Jun | 23 | 68.0 | 50.4 | 53% | 14.5 | 57.5 | 24.8 |
| 30-Jun | 24 | 66.9 | 47.8 | 50% | 14.5 | 55.9 | 23.8 |
| 1-Jul | 1 | 65.8 | 57.2 | 74% | 14.5 | 60.5 | 26.9 |
| 1-Jul | 2 | 63.7 | 57.6 | 80% | 14.5 | 59.7 | 26.4 |
| 1-Jul | 3 | 60.6 | 54.7 | 81% | 14.5 | 57.1 | 24.6 |
| 1-Jul | 4 | 58.6 | 48.6 | 69% | 14.5 | 52.9 | 22.0 |
| 1-Jul | 5 | 57.0 | 48.9 | 74% | 14.5 | 52.4 | 21.7 |
| 1-Jul | 6 | 55.9 | 50.0 | 80% | 14.5 | 52.5 | 21.8 |
| 1-Jul | 7 | 60.6 | 55.6 | 83% | 14.5 | 57.5 | 24.8 |
| 1-Jul | 8 | 62.6 | 56.7 | 81% | 14.5 | 58.9 | 25.8 |
| 1-Jul | 9 | 66.9 | 59.9 | 78% | 14.5 | 62.4 | 28.2 |
| 1-Jul | 10 | 69.3 | 60.3 | 73% | 14.5 | 63.4 | 28.9 |
| 1-Jul | 11 | 80.1 | 66.0 | 62% | 14.5 | 70.2 | 34.3 |
| 1-Jul | 12 | 77.7 | 67.6 | 71% | 14.5 | 70.6 | 34.7 |
| 31-Dec | 13 | 49.3 | 43.3 | 80% | 14.6 | 46.2 | 18.3 |
| 31-Dec | 14 | 55.0 | 45.1 | 69% | 14.6 | 49.7 | 20.1 |
| 31-Dec | 15 | 55.0 | 45.1 | 69% | 14.6 | 49.7 | 20.1 |
| 31-Dec | 16 | 55.0 | 45.1 | 69% | 14.6 | 49.7 | 20.1 |
| 31-Dec | 17 | 53.8 | 44.8 | 71% | 14.6 | 48.9 | 19.7 |
| 31-Dec | 18 | 52.2 | 44.2 | 74% | 14.6 | 47.9 | 19.2 |
| 31-Dec | 19 | 51.4 | 43.5 | 74% | 14.6 | 47.3 | 18.8 |
| 31-Dec | 20 | 50.4 | 43.5 | 77% | 14.6 | 46.8 | 18.5 |
| 31-Dec | 21 | 49.1 | 42.1 | 77% | 14.6 | 45.6 | 17.9 |
| 31-Dec | 22 | 47.8 | 41.7 | 79% | 14.6 | 44.7 | 17.5 |
| 31-Dec | 23 | 46.6 | 40.5 | 79% | 14.6 | 43.6 | 16.9 |
| 31-Dec | 24 | 45.3 | 39.4 | 80% | 14.6 | 42.5 | 16.4 |
| | Ave | 58.9 | 48.9 | 71% | 14.5 | 53.2 | 22.7 |
| | Max | 97.3 | 76.8 | 100% | 14.8 | 81.0 | 44.9 |
| | Min | 28.4 | 11.8 | 10% | 14.3 | 26.9 | 9.7 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

# Transformer Data

## Baseline

**Parameters**

| | | |
|---|---|---|
| Size | 500 | kVA |

Values in blue are from NEMA Standard TP-1 Transformer Efficiency, Three Phase (Table 4.2). All other values are extrapolated.

| **Linear Efficiency vs. Load Factor** | |
|---|---|
| Load | Efficiency |
| 100% | 97.9% |
| 90% | 98.2% |
| 80% | 98.4% |
| 75% | 98.5% |
| 70% | 98.6% |
| 60% | 98.8% |
| 50% | 98.8% |
| 40% | 98.8% |
| 35% | 98.7% |
| 30% | 98.6% |
| 25% | 98.5% |
| 20% | 98.3% |
| 17% | 98.2% |
| 10% | 97.7% |

# Chiller Data

**Assumptions**
The same chillers are used in the baseline and proposed cases.
We set the chillers to the same size.

**Parameters**

| | Baseline | Units | Sources |
|---|---|---|---|
| Chiller Capacity | 500 | tons | Capacity selected to result in a total of three chillers, with appropriate safety and redundancy factors. |
| Condenser Water Temperature | 80 | °F | Typical value. |
| CHW Supply Temperature | 44 | °F | Typical value. |
| CW Flow Rate | 1,200 | gpm | Assumes a 10F CW delta-T when chiller is a maximum load. |

Values from Baseline Water-Cooled Chilled Water Plant Above 300 tons

| **Chiller Efficiency (kW/ton) at CHWS Temp = 44 F** | |
|---|---|
| Load | Condenser Water Temp (°F) |
| | 80 |
| 100% | 0.529 |
| 90% | 0.526 |
| 80% | 0.526 |
| 70% | 0.530 |
| 60% | 0.539 |
| 50% | 0.557 |
| 40% | 0.590 |
| 30% | 0.653 |
| 20% | 0.792 |
| 10% | 1.234 |

# Cooling Tower Fan Speed Lookup Tables, Baseline

| | |
|---|---|
| Cooling Tower Make & Model Used in Analysis | BAC 3482A |

The following lookup tables were created by drawing information from BAC's Cooling Tower Selection Software, Release 6.02 NA. The fan speeds are expressed in percent.

Fan speed depends on the load on the tower, the condenser water flow rate, the ambient wetbulb temperature, and the temperature of the condenser water leaving the tower (aka the cold condenser water temperature). The lowest fan speed the BAC software wil

**Tower Specifications at Nominal Conditions**

| | | |
|---|---|---|
| Ambient Wetbulb Temperature | 78 | deg F |
| Hot Condenser Water Temperature | 95 | deg F |
| Cold Condenser Water Temperature | 88.7 | deg F |
| Condenser Water Flow Rate, Maximum | 2,600 | gpm |
| Condenser Water Flow Rate, Minimum | 609 | gpm |
| Nominal Cooling Tower Capacity | 679 | tons |
| Cooling Tower Fan Motor Size | 30 | hp |

## 50% Maximum Flow = 1300 gpm

**0 tons, 1300 gpm**

All temperatures in deg F

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**50 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**100 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**150 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**200 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**250 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

## 300 tons, 1300 gpm

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

# UPS Energy Calculation

| UPS System Parameters | Baseline | Units | Comments |
|---|---|---|---|
| **UPS Module Data** | | | |
| Total Rack Load | 881 | kW | From Space sheet. |
| Percentage of Load Served by UPS | 100% | % | We assume all racks are backed up. |
| UPS Load | 881 | kW | Rack load times percentage of load served by UPS. |
| Number of Modules | 5 | | Assumed. |
| Unit Capacity | 500 | kVA | Assumed. |
| Total UPS Capacity | 2,500 | kVA | Unit capacity * number of units |
| Load Factor | 35% | % | UPS load / UPS capacity |
| UPS Efficiency | 86% | % | From LBNL Datacenter UPS benchmarking study. |
| **Energy Use** | | | |
| Annual Energy Use | 8,977,981 | kWh/yr | UPS load / UPS efficiency * 8760 hours |
| Peak Demand | 1,025 | kW | UPS load / UPS efficiency |

# Baseline Heating & Cooling Load, Fan Energy

**Template:** **Air Handler Energy Model_Recirculation with Economizer_v10.3**

**Input Parameters**

| | | | |
|---|---|---|---|
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | From the Space Parameters sheet. |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | From the Space Parameters sheet. |
| Air Delivery System: CAV or VAV? | VAV | | From the Space Parameters sheet. |
| Return Air Drybulb Setpoint | 89.5 | F | From the Space Parameters sheet. |
| Active Humidity Control? | yes | | From the Space Parameters sheet. |
| Drybulb Temp at RH Sensor Location | 89.5 | F | From the Space Parameters sheet. |
| Allowed Relative Humidity, Maximum | 55% | RH | From the Space Parameters sheet. |
| Allowed Relative Humidity, Minimum | 30% | RH | From the Space Parameters sheet. |
| Min Allowed Ventilation Air Flow Rate | 1,017 | cfm | From the Space Parameters sheet. |
| CHWST Setpoint, Primary | 44 | F | From the Space Parameters sheet. |
| CHWST Setpoint during Reset | 44 | F | From the Space Parameters sheet. |
| Adiabatic Humidifier Power Draw | 0.000 | kW/(lb of H20/hr) | From the Space Parameters sheet. |

| | | | |
|---|---|---|---|
| Humidifier: 0=None, 1=Electric, 2=Steam, 3=Adiabatic | 2 | | Assumed. |
| Cooling Plant Type: 1=CHW, 2=DX | 1 | | There is a chilled water plant in the proposed case. |
| CHWST Reset: 0=No, 1=Yes | 0 | | No CHWST in the proposed case. |
| Economizer? | no | | Proposed design includes integrated economizing. |
| Economizer Drybulb Control? | no | | Email from Rupa Ganguly on 9/30/08. |
| Drybulb Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Drybulb Upper Lockout | 78 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Dewpoint Control? | no | | Email from Rupa Ganguly on 9/30/08. |
| Dewpoint Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Dewpoint Upper Lockout | 55 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Enthalpy Control? | no | | Email from Rupa Ganguly on 9/30/08. |
| Enthalpy Lower Lockout | 0 | BTU/lb | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Enthalpy Upper Lockout | 29.75 | BTU/lb | Email from Rupa Ganguly on 9/30/08. |
| Economizer Relative Humidity Control? | no | | Email from Rupa Ganguly on 9/30/08. |
| RH Lower Lockout | 20% | % | Email from Rupa Ganguly on 9/30/08. |
| RH Upper Lockout | 80% | % | Email from Rupa Ganguly on 9/30/08. |

| Fan System Parameters | | Supply | Units | Sources |
|---|---|---|---|---|
| Fan Motor Size, Nominal | | 30 | hp | Sized in accordance with calculated brake horsepower, below. |
| Number of Fans | | 10 | | Arbitrary numbers selected for model. Assuming one supply fan per RAHU. |
| Fan Efficiency | | 63.8% | % | Baseline fan efficiencies for motor sizes indicated. |
| Fan Drive Efficiency | | 95% | % | Typical value for belt drive. |
| Fan Motor Efficiency | | 92.5% | % | Baseline efficiencies. |
| VFD Efficiency | | 98% | % | Supply and relief fans assumed to be equipped with VFDs. |
| Fan Motor and Drive in Airstream? | | 1 | 1=yes, 0=no | Assumption. |
| Econ. In Min. Pos. | Total Static Pressure Drop | 2.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | F | Estimate. |
| Economizer Open | Total Static Pressure Drop | 2.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | F | Estimate. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| Return Air Minimum Dewpoint | 54.1 | F | Dewpoint of return air when RH sensor is at minimum allowed RH. |
| Space Dewpoint at Maximum Allowed Space Humidity | 71.2 | | Corresponds to Space DB and Max Allowed RH. |
| Chilled Water Minimum Temperature Requirement | 64.5 | F | If the cooling system is CHW, the cooling coil is assumed to have a constant approach temperature of 3 deg F. |

| Fan System Parameters | Supply | Units | Comments |
|---|---|---|---|
| Fan Motor Output Power, Maximum | 4.9 | kW | Per fan motor. This is the maximum output brake power each fan motor is called upon to deliver. |
| Fan Motor Output Power, Maximum | 6.6 | hp | Per fan motor. Converted from kW to hp. |

**Error Messages**

OK - Humidifier type identified
OK - Chilled Water Supply Temperature Setpoint is low enough to perform required sensible and latent cooling.
OK - Supply Fan Motor Size Exceeds Maximum Required Supply Fan Motor Output

**Results (Annual Totals)**

| | Baseline | Units |
|---|---|---|
| Cooling Energy Extracted from Airstream | 26,255,791 | kBTU/yr |
| Heating Energy Added to Airstream | 0 | kBTU/yr |
| Humidifier Energy Added to Airstream | 95,779 | kBTU/yr |

| | Baseline | Units |
|---|---|---|
| Humidifier Energy Required | n/a | kWh/yr |
| | 958 | therms/yr |
| Fan Motor Energy Required | 478,182 | kWh/yr |

**Hourly Calculations**

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Amount of Water Needed for Humid-ifying | Energy Required to Sensibly Cool Mixed Air | Energy Req'd to Dehum-idify Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | | | Supply | | | Electric | Steam | Adia-batic | |
| | | | | | | | | | | | | | | | | | | | | | Total Power Input | Air Deliv. Effic. | | | | | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | lbs/hr | kBTU | kBTU | kBTU | kBTU | kW | cfm/kW | tons | kW | therms | kW | therms |
| 1-Jan | 1 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.1 | 53.9 | 44.0 | 21 | 2,981 | 0 | 0 | 22 | 54.6 | 2,337 | 248 | 0.0 | 0.2 | 0.00 | 0.3 |
| 1-Jan | 2 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.1 | 54.0 | 44.0 | 19 | 2,980 | 0 | 0 | 21 | 54.6 | 2,337 | 248 | 0.0 | 0.2 | 0.00 | 0.3 |
| 1-Jan | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.1 | 53.9 | 44.0 | 23 | 2,978 | 0 | 0 | 24 | 54.6 | 2,337 | 248 | 0.0 | 0.2 | 0.00 | 0.3 |
| 1-Jan | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.1 | 53.9 | 44.0 | 24 | 2,977 | 0 | 0 | 26 | 54.6 | 2,337 | 248 | 0.0 | 0.3 | 0.00 | 0.3 |
| 1-Jan | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.1 | 53.9 | 44.0 | 25 | 2,976 | 0 | 0 | 27 | 54.6 | 2,337 | 248 | 0.0 | 0.3 | 0.00 | 0.4 |
| 1-Jan | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.1 | 53.9 | 44.0 | 26 | 2,975 | 0 | 0 | 28 | 54.6 | 2,337 | 248 | 0.0 | 0.3 | 0.00 | 0.4 |
| 1-Jan | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n | | | | | 1,017 | 89.1 | 53.9 | 44.0 | 27 | 2,974 | 0 | 0 | 29 | 54.6 | 2,337 | 248 | 0.0 | 0.3 | 0.00 | 0.4 |
| 1-Jan | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n | | | | | 1,017 | 89.1 | 53.9 | 44.0 | 32 | 2,970 | 0 | 0 | 34 | 54.6 | 2,337 | 247 | 0.0 | 0.3 | 0.00 | 0.4 |
| 1-Jan | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n | | | | | 1,017 | 89.1 | 53.9 | 44.0 | 26 | 2,972 | 0 | 0 | 28 | 54.6 | 2,337 | 248 | 0.0 | 0.3 | 0.00 | 0.4 |
| 1-Jan | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n | | | | | 1,017 | 89.1 | 53.9 | 44.0 | 24 | 2,974 | 0 | 0 | 26 | 54.6 | 2,337 | 248 | 0.0 | 0.3 | 0.00 | 0.3 |
| 1-Jan | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n | | | | | 1,017 | 89.1 | 54.0 | 44.0 | 18 | 2,979 | 0 | 0 | 19 | 54.6 | 2,337 | 248 | 0.0 | 0.2 | 0.00 | 0.2 |
| 1-Jan | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n | | | | | 1,017 | 89.2 | 53.9 | 44.0 | 20 | 2,984 | 0 | 0 | 21 | 54.6 | 2,337 | 249 | 0.0 | 0.2 | 0.00 | 0.3 |
| 30-Jun | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 55.2 | n | | | | | 1,017 | 89.5 | 55.2 | 44.0 | 0 | 3,028 | 0 | 0 | 0 | 54.6 | 2,337 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 60.8 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.4 | 60.8 | 44.0 | 0 | 3,023 | 0 | 0 | 0 | 54.6 | 2,337 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 62.8 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.4 | 62.8 | 44.0 | 0 | 3,020 | 0 | 0 | 0 | 54.6 | 2,337 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 60.8 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.4 | 60.8 | 44.0 | 0 | 3,020 | 0 | 0 | 0 | 54.6 | 2,337 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 17 | 127,545 | 67.5 | 67.5 | 67.5 | 62.2 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.4 | 62.2 | 44.0 | 0 | 3,018 | 0 | 0 | 0 | 54.6 | 2,337 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 18 | 127,545 | 67.5 | 67.5 | 67.5 | 60.6 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.4 | 60.6 | 44.0 | 0 | 3,016 | 0 | 0 | 0 | 54.6 | 2,337 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 19 | 127,545 | 67.5 | 67.5 | 67.5 | 63.0 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.4 | 63.0 | 44.0 | 0 | 3,017 | 0 | 0 | 0 | 54.6 | 2,337 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 20 | 127,545 | 67.5 | 67.5 | 67.5 | 58.5 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.4 | 58.5 | 44.0 | 0 | 3,014 | 0 | 0 | 0 | 54.6 | 2,337 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 21 | 127,545 | 67.5 | 67.5 | 67.5 | 55.0 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.4 | 55.0 | 44.0 | 0 | 3,011 | 0 | 0 | 0 | 54.6 | 2,337 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 22 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 54.0 | 44.0 | 2 | 3,009 | 0 | 0 | 2 | 54.6 | 2,337 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 23 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 54.0 | 44.0 | 5 | 3,007 | 0 | 0 | 6 | 54.6 | 2,337 | 251 | 0.0 | 0.1 | 0.00 | 0.1 |
| 30-Jun | 24 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 54.0 | 44.0 | 9 | 3,006 | 0 | 0 | 10 | 54.6 | 2,337 | 250 | 0.0 | 0.1 | 0.00 | 0.1 |
| 1-Jul | 1 | 127,545 | 67.5 | 67.5 | 67.5 | 57.2 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 57.2 | 44.0 | 0 | 3,004 | 0 | 0 | 0 | 54.6 | 2,337 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 2 | 127,545 | 67.5 | 67.5 | 67.5 | 57.6 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 57.6 | 44.0 | 0 | 3,002 | 0 | 0 | 0 | 54.6 | 2,337 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 54.7 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 54.7 | 44.0 | 0 | 2,999 | 0 | 0 | 0 | 54.6 | 2,337 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 54.0 | 44.0 | 8 | 2,997 | 0 | 0 | 8 | 54.6 | 2,337 | 250 | 0.0 | 0.1 | 0.00 | 0.1 |
| 1-Jul | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 7 | 2,995 | 0 | 0 | 8 | 54.6 | 2,337 | 250 | 0.0 | 0.1 | 0.00 | 0.1 |
| 1-Jul | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 6 | 2,994 | 0 | 0 | 6 | 54.6 | 2,337 | 249 | 0.0 | 0.1 | 0.00 | 0.1 |
| 1-Jul | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 55.6 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 55.6 | 44.0 | 0 | 2,999 | 0 | 0 | 0 | 54.6 | 2,337 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 56.7 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 56.7 | 44.0 | 0 | 3,001 | 0 | 0 | 0 | 54.6 | 2,337 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 59.9 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 59.9 | 44.0 | 0 | 3,006 | 0 | 0 | 0 | 54.6 | 2,337 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 60.3 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.3 | 60.3 | 44.0 | 0 | 3,008 | 0 | 0 | 0 | 54.6 | 2,337 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 66.0 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.4 | 66.0 | 44.0 | 0 | 3,020 | 0 | 0 | 0 | 54.6 | 2,337 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 67.5 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.4 | 67.5 | 44.0 | 0 | 3,017 | 0 | 0 | 0 | 54.6 | 2,337 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 16 | 2,987 | 0 | 0 | 16 | 54.6 | 2,337 | 249 | 0.0 | 0.2 | 0.00 | 0.2 |
| 31-Dec | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 13 | 2,993 | 0 | 0 | 14 | 54.6 | 2,337 | 249 | 0.0 | 0.1 | 0.00 | 0.2 |
| 31-Dec | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 13 | 2,993 | 0 | 0 | 14 | 54.6 | 2,337 | 249 | 0.0 | 0.1 | 0.00 | 0.2 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Amount of Water Needed for Humid-ifying | Energy Required to Sensibly Cool Mixed Air | Energy Req'd to Dehum-idify Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | | | Supply | | | Electric | Steam | Adia-batic | |
| | | | | | | | | | | | | | | | | | | | | | Total Power Input | Air Deliv. Effic. | | | | | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | lbs/hr | kBTU | kBTU | kBTU | kBTU | kW | cfm/kW | tons | kW | therms | kW | therms |
| 31-Dec | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 13 | 2,993 | 0 | 0 | 14 | 54.6 | 2,337 | 249 | 0.0 | 0.1 | 0.00 | 0.2 |
| 31-Dec | 17 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 13 | 2,992 | 0 | 0 | 14 | 54.6 | 2,337 | 249 | 0.0 | 0.1 | 0.00 | 0.2 |
| 31-Dec | 18 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 14 | 2,990 | 0 | 0 | 15 | 54.6 | 2,337 | 249 | 0.0 | 0.2 | 0.00 | 0.2 |
| 31-Dec | 19 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 15 | 2,989 | 0 | 0 | 16 | 54.6 | 2,337 | 249 | 0.0 | 0.2 | 0.00 | 0.2 |
| 31-Dec | 20 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 15 | 2,988 | 0 | 0 | 16 | 54.6 | 2,337 | 249 | 0.0 | 0.2 | 0.00 | 0.2 |
| 31-Dec | 21 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 17 | 2,987 | 0 | 0 | 18 | 54.6 | 2,337 | 249 | 0.0 | 0.2 | 0.00 | 0.2 |
| 31-Dec | 22 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 18 | 2,985 | 0 | 0 | 19 | 54.6 | 2,337 | 249 | 0.0 | 0.2 | 0.00 | 0.2 |
| 31-Dec | 23 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.2 | 54.0 | 44.0 | 20 | 2,984 | 0 | 0 | 21 | 54.6 | 2,337 | 249 | 0.0 | 0.2 | 0.00 | 0.3 |
| 31-Dec | 24 | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | n/a | n/a | n/a | n/a | n/a | 1,017 | 89.1 | 53.9 | 44.0 | 21 | 2,983 | 0 | 0 | 23 | 54.6 | 2,337 | 249 | 0.0 | 0.2 | 0.00 | 0.3 |
| Sum | | | | | | | 0 | 0 | 0 | 0 | 0 | | | | | 90,365 | 26,254,809 | 982 | 0 | 95,779 | 478,182 | | | 0 | 958 | 0 | 1,260 |
| Ave | | 127,545 | 67.5 | 67.5 | 67.5 | 55.9 | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! | 1,017 | 89.3 | 55.9 | 44.0 | 10.3 | 2,997 | 0 | 0 | 11 | 54.6 | 2,337 | 250 | 0.0 | 0.1 | 0.00 | 0.1 |
| Max | | 127,545 | 67.5 | 67.5 | 67.5 | 67.5 | | | | | | 1,017 | 89.6 | 67.6 | 44.0 | 60.9 | 3,039 | 30 | 0 | 65 | 54.6 | 2,337 | 255 | 0.0 | 0.6 | 0.00 | 0.8 |
| Min | | 127,545 | 67.5 | 67.5 | 67.5 | 54.1 | | | | | | 1,017 | 89.0 | 53.7 | 44.0 | 0.0 | 2,965 | 0 | 0 | 0 | 54.6 | 2,337 | 247 | 0.0 | 0.0 | 0.00 | 0.0 |

# Cooling Tower Energy Use, Baseline

**Assumptions**

The proposed cooling towers are staged in tandem with the baseline chillers (number of active towers = number of active chillers).
The proposed cooling tower fan motors are two-speed (100% and 50%).

**Parameters**

| | | | |
|---|---|---|---|
| Chiller Condenser Water Temperature Setpoint | 80 | °F | Baseline |
| Cooling Tower Fan Motor Size | 30 | hp | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Cooling Tower Condenser Water Flow, Maximum | 2,600 | gpm | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Motor Load Factor at Full Speed | 90% | | Estimate |
| Fan Motor Efficiency | 92.5% | | Baseline |
| Fan Drive Efficiency | 95% | | Belt drive |
| Fan Power, Baseline Cooling Tower, 100% | 22.9 | kW | = 0.746 * motor size * load factor / (drive effic * motor effic) |
| Fan Power, Baseline Cooling Tower, 50% | 2.9 | kW | Fan Law Calculation |

**Hourly Calculations**

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 1-Jan | 1 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 2 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 3 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 4 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 5 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 6 | 37 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 7 | 36 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 8 | 33 | 247 | 1 | 46% | 247 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 9 | 36 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 10 | 37 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 11 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 12 | 43 | 249 | 1 | 46% | 249 | 60 | 80.0 | 41% | 2.3 | 2.9 | 2.3 | 2.9 |
| 30-Jun | 13 | 67 | 252 | 1 | 46% | 252 | 80 | 80.0 | 71% | 16.3 | 22.9 | 16.3 | 22.9 |
| 30-Jun | 14 | 68 | 252 | 1 | 46% | 252 | 80 | 80.0 | 75% | 17.1 | 22.9 | 17.1 | 22.9 |
| 30-Jun | 15 | 68 | 252 | 1 | 46% | 252 | 80 | 80.0 | 75% | 17.1 | 22.9 | 17.1 | 22.9 |
| 30-Jun | 16 | 67 | 252 | 1 | 46% | 252 | 80 | 80.0 | 71% | 16.3 | 22.9 | 16.3 | 22.9 |
| 30-Jun | 17 | 68 | 252 | 1 | 46% | 252 | 80 | 80.0 | 75% | 17.1 | 22.9 | 17.1 | 22.9 |
| 30-Jun | 18 | 66 | 251 | | | | | | 68% | 15.6 | 22.9 | 15.6 | 22.9 |
| 30-Jun | 19 | 68 | 251 | | | | | | 75% | 17.1 | 22.9 | 17.1 | 22.9 |
| 30-Jun | 20 | 64 | 251 | | | | | | 63% | 14.4 | 22.9 | 14.4 | 22.9 |
| 30-Jun | 21 | 61 | 251 | | | | | | 56% | 12.9 | 22.9 | 12.9 | 22.9 |
| 30-Jun | 22 | 59 | 251 | | | | | | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 30-Jun | 23 | 58 | 251 | | | | | | 52% | 11.8 | 22.9 | 11.8 | 22.9 |
| 30-Jun | 24 | 56 | 250 | 1 | 46% | 250 | 70 | 80.0 | 49% | 2.8 | 2.9 | 2.8 | 2.9 |
| 1-Jul | 1 | 60 | 250 | 1 | 46% | 250 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 1-Jul | 2 | 60 | 250 | 1 | 46% | 250 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 1-Jul | 3 | 57 | 250 | 1 | 46% | 250 | 70 | 80.0 | 50% | 11.5 | 22.9 | 11.5 | 22.9 |
| 1-Jul | 4 | 53 | 250 | 1 | 46% | 250 | 65 | 80.0 | 46% | 2.6 | 2.9 | 2.6 | 2.9 |
| 1-Jul | 5 | 52 | 250 | 1 | 46% | 250 | 65 | 80.0 | 45% | 2.6 | 2.9 | 2.6 | 2.9 |
| 1-Jul | 6 | 52 | 249 | 1 | 46% | 249 | 65 | 80.0 | 45% | 2.6 | 2.9 | 2.6 | 2.9 |
| 1-Jul | 7 | 57 | 250 | 1 | 46% | 250 | 70 | 80.0 | 50% | 11.5 | 22.9 | 11.5 | 22.9 |
| 1-Jul | 8 | 59 | 250 | 1 | 46% | 250 | 70 | 80.0 | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 1-Jul | 9 | 62 | 250 | 1 | 46% | 250 | 75 | 80.0 | 58% | 13.4 | 22.9 | 13.4 | 22.9 |
| 1-Jul | 10 | 63 | 251 | 1 | 46% | 251 | 75 | 80.0 | 60% | 13.8 | 22.9 | 13.8 | 22.9 |
| 1-Jul | 11 | 70 | 252 | 1 | 46% | 252 | 80 | 80.0 | 83% | 19.0 | 22.9 | 19.0 | 22.9 |
| 1-Jul | 12 | 71 | 251 | 1 | 46% | 251 | 80 | 80.0 | 87% | 20.0 | 22.9 | 20.0 | 22.9 |
| 31-Dec | 13 | 46 | 249 | 1 | 46% | 249 | 60 | 80.0 | 42% | 2.4 | 2.9 | 2.4 | 2.9 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 31-Dec | 14 | 50 | 249 | 1 | 46% | 249 | 65 | 80.0 | 44% | 2.5 | 2.9 | 2.5 | 2.9 |
| 31-Dec | 15 | 50 | 249 | 1 | 46% | 249 | 65 | 80.0 | 44% | 2.5 | 2.9 | 2.5 | 2.9 |
| 31-Dec | 16 | 50 | 249 | 1 | 46% | 249 | 65 | 80.0 | 44% | 2.5 | 2.9 | 2.5 | 2.9 |
| 31-Dec | 17 | 49 | 249 | 1 | 46% | 249 | 65 | 80.0 | 43% | 2.5 | 2.9 | 2.5 | 2.9 |
| 31-Dec | 18 | 48 | 249 | 1 | 46% | 249 | 65 | 80.0 | 43% | 2.4 | 2.9 | 2.4 | 2.9 |
| 31-Dec | 19 | 47 | 249 | 1 | 46% | 249 | 65 | 80.0 | 42% | 2.4 | 2.9 | 2.4 | 2.9 |
| 31-Dec | 20 | 47 | 249 | 1 | 46% | 249 | 65 | 80.0 | 42% | 2.4 | 2.9 | 2.4 | 2.9 |
| 31-Dec | 21 | 46 | 249 | 1 | 46% | 249 | 60 | 80.0 | 42% | 2.4 | 2.9 | 2.4 | 2.9 |
| 31-Dec | 22 | 45 | 249 | 1 | 46% | 249 | 60 | 80.0 | 41% | 2.4 | 2.9 | 2.4 | 2.9 |
| 31-Dec | 23 | 44 | 249 | 1 | 46% | 249 | 60 | 80.0 | 41% | 2.4 | 2.9 | 2.4 | 2.9 |
| 31-Dec | 24 | 43 | 249 | 1 | 46% | 249 | 60 | 80.0 | 41% | 2.3 | 2.9 | 2.3 | 2.9 |
| Sum | | | | | | | | | | | | 58,496 | 86,410 |
| Ave | | 53 | 250 | 1.000 | 46% | 250 | 68 | 80.0 | 50% | 6.7 | 9.9 | 6.7 | 9.9 |
| Max | | 81 | 255 | 1 | 46% | 255 | 90 | 90.0 | 98% | 22.5 | 22.9 | 22.5 | 22.9 |
| Min | | 27 | 247 | 1 | 46% | 247 | 50 | 80.0 | 38% | 2.2 | 2.9 | 2.2 | 2.9 |

No. of hours in year that actual CW temp > 80: 56

# CHW Pump Energy Use, Baseline

**Template Name:** **CHW Pump Energy Model_v1.01**

**Assumptions**

There is one operating constant-speed primary CHW pump per active chiller.
All of the primary CHW pumps are identical.
There is one operating variable-speed secondary CHW pump.

**Results**

| | Baseline | Units |
|---|---|---|
| CHW Pump Energy Required | 259,515 | kWh/yr |
| Ave CHW Pump System Effic. | 60.7 | gpm/kW |

***Primary Pumps***

**Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T across evaporator. |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

***Secondary Pump***

**Input Parameters**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 650 | 612 | gpm | Nominal: 650.<br>Design: 255-ton peak load, 10F CHW delta-T. |
| Head | 100 | 100 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 70% | 70% | | Nominal: Baseline for 75 hp motor.<br>Design: Baseline for 75 hp motor. |
| Pump Motor Size | 125 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 94.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 98% | | | Secondary pumps are variable speed. |
| Secondary CHW Loop Delta-T | | 10 | F | Estimate. |

**Calculations**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 22.1 | hp | (flow * head) / (3960 * pump effic) |
| Pump VFD Input Power | | 17.8 | kW | 0.746 * hp / motor effic / VFD effic |

**Error Messages**

OK -- Primary Pump Motor is not undersized.
OK -- Secondary Pump Motor is not undersized.

**Hourly Analysis**

| Date | Hour | Total Cooling Load | No. of Chillers On | Total Primary CHW Flow | Total Primary Pump Power | Secondary Loop CHW Flow | Secondary Pump Power | Total CHW Pump Power | CHW Pump System Efficiency |
|---|---|---|---|---|---|---|---|---|---|
| | | tons | | gpm | kW | gpm | kW | kW | gpm/kW |
| 1-Jan | 1 | 248 | 1 | 1,200 | 12 | 596 | 17 | 29 | 60.9 |
| 1-Jan | 2 | 248 | 1 | 1,200 | 12 | 596 | 17 | 29 | 60.9 |
| 1-Jan | 3 | 248 | 1 | 1,200 | 12 | 596 | 17 | 29 | 61.0 |
| 1-Jan | 4 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 61.0 |
| 1-Jan | 5 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 61.0 |
| 1-Jan | 6 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 61.0 |
| 1-Jan | 7 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 61.0 |
| 1-Jan | 8 | 247 | 1 | 1,200 | 12 | 594 | 17 | 29 | 61.0 |
| 1-Jan | 9 | 248 | | | | | 17 | 29 | 61.0 |
| 1-Jan | 10 | 248 | | | | | 17 | 29 | 61.0 |
| 1-Jan | 11 | 248 | | | | | 17 | 29 | 60.9 |
| 1-Jan | 12 | 249 | | | | | 17 | 30 | 60.9 |
| 30-Jun | 13 | 252 | | | | | 18 | 30 | 60.4 |
| 30-Jun | 14 | 252 | 1 | 1,200 | 12 | 605 | 17 | 30 | 60.5 |
| 30-Jun | 15 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 30-Jun | 16 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 30-Jun | 17 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 30-Jun | 18 | 251 | 1 | 1,200 | 12 | 603 | 17 | 30 | 60.5 |
| 30-Jun | 19 | 251 | 1 | 1,200 | 12 | 603 | 17 | 30 | 60.5 |
| 30-Jun | 20 | 251 | 1 | 1,200 | 12 | 603 | 17 | 30 | 60.6 |
| 30-Jun | 21 | 251 | 1 | 1,200 | 12 | 602 | 17 | 30 | 60.6 |
| 30-Jun | 22 | 251 | 1 | 1,200 | 12 | 602 | 17 | 30 | 60.6 |
| 30-Jun | 23 | 251 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.6 |
| 30-Jun | 24 | 250 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.6 |
| 1-Jul | 1 | 250 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.7 |
| 1-Jul | 2 | 250 | 1 | 1,200 | 12 | 600 | 17 | 30 | 60.7 |
| 1-Jul | 3 | 250 | 1 | 1,200 | 12 | 600 | 17 | 30 | 60.7 |
| 1-Jul | 4 | 250 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.7 |
| 1-Jul | 5 | 250 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.8 |
| 1-Jul | 6 | 249 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.8 |
| 1-Jul | 7 | 250 | 1 | 1,200 | 12 | 600 | 17 | 30 | 60.7 |
| 1-Jul | 8 | 250 | 1 | 1,200 | 12 | 600 | 17 | 30 | 60.7 |
| 1-Jul | 9 | 250 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.6 |
| 1-Jul | 10 | 251 | 1 | 1,200 | 12 | 602 | 17 | 30 | 60.6 |
| 1-Jul | 11 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 1-Jul | 12 | 251 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 31-Dec | 13 | 249 | 1 | 1,200 | 12 | 597 | 17 | 30 | 60.9 |
| 31-Dec | 14 | 249 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.8 |
| 31-Dec | 15 | 249 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.8 |
| 31-Dec | 16 | 249 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.8 |
| 31-Dec | 17 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.8 |
| 31-Dec | 18 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.8 |
| 31-Dec | 19 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.8 |
| 31-Dec | 20 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.8 |
| 31-Dec | 21 | 249 | 1 | 1,200 | 12 | 597 | 17 | 30 | 60.9 |
| 31-Dec | 22 | 249 | 1 | 1,200 | 12 | 597 | 17 | 30 | 60.9 |
| 31-Dec | 23 | 249 | 1 | 1,200 | 12 | 597 | 17 | 30 | 60.9 |
| 31-Dec | 24 | 249 | 1 | 1,200 | 12 | 597 | 17 | 29 | 60.9 |
| Sum | | | | | 108,331 | | 151,184 | 259,515 | |
| Ave | | 250 | 1.000 | 1,200 | 12 | 599 | 17 | 30 | 60.7 |
| Max | | 255 | 1 | 1,200 | 12 | 611 | 18 | 30 | 61.1 |
| Min | | 247 | 1 | 1,200 | 12 | 593 | 17 | 29 | 60.1 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# CHW Plant Energy Use, Baseline

**Assumptions**
All chillers are identical and rotated equally.
There is one operating constant-speed CW pump per active chiller.

| | | | |
|---|---|---|---|
| Electric Chiller Capacity | 500 | tons | Assumed. |
| Number of Electric Chillers | 3 | | Assumed. |
| Total Electric Chiller Capacity | 1,500 | tons | Chiller capacity times number of chillers. |
| Chilled Water Supply Temperature | 44 | F | Baseline. |

**Condenser Water Pump Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

**Results (Annual Totals)**

| | Baseline | Units |
|---|---|---|
| Total Annual Electric Use | 1,630,665 | kWh/yr |
| Summer Peak Electric Demand | 204 | kW |
| Annual Average Cooling Efficiency | 0.745 | kW/ton |

**Hourly Calculations**

| Date | Hour | Total Cooling Load | Chillers | | | | Cooling Tower Power Demand | CHW & CW Pump Power Demand | Total Cooling Plant Power Demand | Summer Peak Demand |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Chillers Operating | Chiller Load Factor | Chiller Effic. | Chiller Power Demand | | | | |
| | | tons | 0-3 | % | kW/ton | kW | kW | kW | kW | kW |
| 1-Jan | 1 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 183 | n/a |
| 1-Jan | 2 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 3 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 4 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 5 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 6 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 7 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 8 | 247 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 9 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 10 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 11 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 12 | 249 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 183 | n/a |
| 30-Jun | 13 | 252 | 1 | 50% | 0.54 | 136 | 16.3 | 42 | 195 | 201 |
| 30-Jun | 14 | 252 | 1 | 50% | 0.54 | 136 | 17.1 | 42 | 195 | 201 |
| 30-Jun | 15 | 252 | 1 | 50% | 0.54 | 136 | 17.1 | 42 | 195 | 201 |
| 30-Jun | 16 | 252 | 1 | 50% | 0.54 | 136 | 16.3 | 42 | 194 | 201 |
| 30-Jun | 17 | 252 | 1 | 50% | 0.54 | 136 | 17.1 | 42 | 195 | 201 |
| 30-Jun | 18 | 251 | 1 | 50% | 0.54 | 135 | 15.6 | 42 | 193 | 201 |
| 30-Jun | 19 | 251 | 1 | 50% | 0.54 | 136 | 17.1 | 42 | 195 | n/a |
| 30-Jun | 20 | 251 | 1 | 50% | 0.54 | 135 | 14.4 | 42 | 192 | n/a |
| 30-Jun | 21 | 251 | 1 | 50% | 0.54 | 135 | 12.9 | 42 | 190 | n/a |
| 30-Jun | 22 | 251 | 1 | 50% | 0.54 | 135 | 12.1 | 42 | 189 | n/a |
| 30-Jun | 23 | 251 | 1 | 50% | 0.54 | 135 | 11.8 | 42 | 189 | n/a |
| 30-Jun | 24 | 250 | 1 | 50% | 0.54 | 135 | 2.8 | 42 | 180 | n/a |
| 1-Jul | 1 | 250 | 1 | 50% | 0.54 | 135 | 12.5 | 42 | 190 | n/a |
| 1-Jul | 2 | 250 | 1 | 50% | 0.54 | 135 | 12.5 | 42 | 189 | n/a |
| 1-Jul | 3 | 250 | 1 | 50% | 0.56 | 139 | 11.5 | 42 | 193 | n/a |
| 1-Jul | 4 | 250 | 1 | 50% | 0.56 | 139 | 2.6 | 42 | 184 | n/a |
| 1-Jul | 5 | 250 | 1 | 50% | 0.56 | 139 | 2.6 | 42 | 184 | n/a |
| 1-Jul | 6 | 249 | 1 | 50% | 0.56 | 139 | 2.6 | 42 | 184 | n/a |
| 1-Jul | 7 | 250 | 1 | 50% | 0.56 | 139 | 11.5 | 42 | 193 | n/a |
| 1-Jul | 8 | 250 | 1 | 50% | 0.54 | 135 | 12.1 | 42 | 189 | n/a |
| 1-Jul | 9 | 250 | 1 | 50% | 0.54 | 135 | 13.4 | 42 | 190 | n/a |
| 1-Jul | 10 | 251 | 1 | 50% | 0.54 | 135 | 13.8 | 42 | 191 | n/a |
| 1-Jul | 11 | 252 | 1 | 50% | 0.54 | 136 | 19.0 | 42 | 197 | n/a |
| 1-Jul | 12 | 251 | 1 | 50% | 0.54 | 136 | 20.0 | 42 | 198 | n/a |
| 31-Dec | 13 | 249 | 1 | 50% | 0.56 | 139 | 2.4 | 42 | 183 | n/a |
| 31-Dec | 14 | 249 | 1 | 50% | 0.56 | 139 | 2.5 | 42 | 183 | n/a |
| 31-Dec | 15 | 249 | 1 | 50% | 0.56 | 139 | 2.5 | 42 | 183 | n/a |
| 31-Dec | 16 | 249 | 1 | 50% | 0.56 | 139 | 2.5 | 42 | 183 | n/a |
| 31-Dec | 17 | 249 | 1 | 50% | 0.56 | 139 | 2.5 | 42 | 183 | n/a |
| 31-Dec | 18 | 249 | 1 | 50% | 0.56 | 139 | 2.4 | 42 | 183 | n/a |
| 31-Dec | 19 | 249 | 1 | 50% | 0.56 | 139 | 2.4 | 42 | 183 | n/a |
| 31-Dec | 20 | 249 | 1 | 50% | 0.56 | 139 | 2.4 | 42 | 183 | n/a |
| 31-Dec | 21 | 249 | 1 | 50% | 0.56 | 139 | 2.4 | 42 | 183 | n/a |
| 31-Dec | 22 | 249 | 1 | 50% | 0.56 | 139 | 2.4 | 42 | 183 | n/a |
| 31-Dec | 23 | 249 | 1 | 50% | 0.56 | 139 | 2.4 | 42 | 183 | n/a |
| 31-Dec | 24 | 249 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 183 | n/a |
| Sum | | 2,187,983 | | | | 1,204,324 | 58,496 | 367,846 | 1,630,665 | 163,302 |
| Ave | | 250 | 1.000 | 50% | 0.55 | 137 | 6.7 | 42 | 186 | 200 |
| Max | | 255 | 1 | 51% | 0.56 | 139 | 22.5 | 42 | 202 | 204 |
| Min | | 247 | 1 | 49% | 0.54 | 135 | 2.2 | 42 | 179 | 180 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# First Year Electric Cost

**Results**

| | Baseline |
|---|---|
| Annual Electric Use Charges | $927,189 |
| Annual Electric Demand Charges | $223,109 |
| Annual Electric Expense | $1,150,298 |

**Rate Schedule**

| | |
|---|---|
| Select current rate schedule | E-19A |
| Select voltage type | Secondary |

| | | Secondary | Primary | Transmission | **Secondary** |
|---|---|---|---|---|---|
| Identifier | Total Demand Rates | $/kW | $/kW | $/kW | $/kW |
| 1 | Peak Summer | 11.54 | 10.43 | 8.13 | 11.54 |
| 2 | Part-Peak Summer | 2.64 | 2.39 | 1.84 | 2.64 |
| 3 | Maximum Summer | 6.62 | 5.63 | 3.72 | 6.62 |
| 4 | Part-Peak Winter | 0.99 | 0.74 | - | 0.99 |
| 5 | Maximum Winter | 6.62 | 5.63 | 3.72 | 6.62 |
| Identifier | Total Energy Rates | $/kWh | $/kWh | $/kWh | $/kWh |
| 1 | Peak Summer | 0.13286 | 0.13251 | 0.09801 | 0.13286 |
| 2 | Part-Peak Summer | 0.09095 | 0.08912 | 0.07843 | 0.09095 |
| 3 | Off-Peak Summer | 0.07383 | 0.07040 | 0.06674 | 0.07383 |
| 4 | Part-Peak Winter | 0.08095 | 0.07653 | 0.07134 | 0.08095 |
| 5 | Off-Peak Winter | 0.07127 | 0.06700 | 0.06326 | 0.07127 |

These rates are applicable for the time period:
**Jan 1, 2008 to Present**

**Hourly Energy Rate Calculations**

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge |
|---|---|---|---|
| | | | Baseline |
| | | | $ |
| 1-Jan | 1 | 5 | $92.11 |
| 1-Jan | 2 | 5 | $92.11 |
| 1-Jan | 3 | 5 | $92.10 |
| 1-Jan | 4 | 5 | $92.09 |
| 1-Jan | 5 | 5 | $92.09 |
| 1-Jan | 6 | 5 | $92.08 |
| 1-Jan | 7 | 5 | $92.08 |
| 1-Jan | 8 | 5 | $92.06 |
| 1-Jan | 9 | 4 | $104.58 |
| 1-Jan | 10 | 4 | $104.59 |
| 1-Jan | 11 | 4 | $104.61 |
| 1-Jan | 12 | 4 | $104.64 |
| 30-Jun | 13 | 1 | $173.35 |
| 30-Jun | 14 | 1 | $173.42 |
| 30-Jun | 15 | 1 | $173.39 |
| 30-Jun | 16 | 1 | $173.29 |
| 30-Jun | 17 | 1 | $173.38 |
| 30-Jun | 18 | 1 | $173.17 |
| 30-Jun | 19 | 2 | $118.68 |
| 30-Jun | 20 | 2 | $118.41 |
| 30-Jun | 21 | 2 | $118.27 |
| 30-Jun | 22 | 3 | $95.94 |
| 30-Jun | 23 | 3 | $95.90 |
| 30-Jun | 24 | 3 | $95.22 |
| 1-Jul | 1 | 3 | $95.95 |
| 1-Jul | 2 | 3 | $95.94 |
| 1-Jul | 3 | 3 | $96.19 |
| 1-Jul | 4 | 3 | $95.51 |
| 1-Jul | 5 | 3 | $95.50 |
| 1-Jul | 6 | 3 | $95.49 |

**Hourly Demand Charge Calculations**

| Hourly Demand | Demand Charge by Rate Period | | | | |
|---|---|---|---|---|---|
| | Proposed | | | | |
| Baseline | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| kW | $ | $ | $ | $ | $ |
| 1,292 | | | $8,556 | | $8,556 |
| 1,292 | | | $8,555 | | $8,555 |
| 1,292 | | | $8,555 | | $8,555 |
| 1,292 | | | $8,554 | | $8,554 |
| 1,292 | | | $8,554 | | $8,554 |
| 1,292 | | | $8,553 | | $8,553 |
| 1,292 | | | $8,553 | | $8,553 |
| 1,292 | | | | | $8,551 |
| 1,292 | | | | $1,279 | $8,552 |
| 1,292 | | | | $1,279 | $8,553 |
| 1,292 | | | | $1,279 | $8,555 |
| 1,293 | | | | $1,280 | $8,557 |
| 1,305 | | | | | $8,637 |
| 1,305 | | | | | $8,641 |
| 1,305 | $15,061 | | $8,640 | | $8,640 |
| 1,304 | $15,051 | | $8,634 | | $8,634 |
| 1,305 | $15,060 | | $8,639 | | $8,639 |
| 1,303 | $15,041 | | $8,628 | | $8,628 |
| 1,305 | | $3,445 | $8,639 | | $8,639 |
| 1,302 | | $3,437 | $8,619 | | $8,619 |
| 1,300 | | $3,433 | $8,608 | | $8,608 |
| 1,299 | | | $8,602 | | $8,602 |
| 1,299 | | | $8,599 | | $8,599 |
| 1,290 | | | $8,538 | | $8,538 |
| 1,300 | | | $8,603 | | $8,603 |
| 1,299 | | | $8,602 | | $8,602 |
| 1,303 | | | $8,625 | | $8,625 |
| 1,294 | | | $8,564 | | $8,564 |
| 1,294 | | | $8,563 | | $8,563 |
| 1,293 | | | $8,563 | | $8,563 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge | Hourly Demand | Demand Charge by Rate Period | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Proposed | | | | |
| | | | Baseline | Baseline | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| | | | $ | kW | $ | $ | $ | $ | $ |
| 1-Jul | 7 | 3 | $96.19 | 1,303 | | | $8,625 | | $8,625 |
| 1-Jul | 8 | 3 | $95.90 | 1,299 | | | $8,599 | | $8,599 |
| 1-Jul | 9 | 2 | $118.28 | 1,300 | | $3,433 | $8,609 | | $8,609 |
| 1-Jul | 10 | 2 | $118.34 | 1,301 | | $3,435 | $8,613 | | $8,613 |
| 1-Jul | 11 | 2 | $118.87 | 1,307 | | $3,450 | $8,652 | | $8,652 |
| 1-Jul | 12 | 2 | $118.96 | 1,308 | | $3,453 | $8,658 | | $8,658 |
| 31-Dec | 13 | 4 | $104.66 | 1,293 | | | $8,559 | $1,280 | $8,559 |
| 31-Dec | 14 | 4 | $104.69 | 1,293 | | | $8,562 | $1,280 | $8,562 |
| 31-Dec | 15 | 4 | $104.69 | 1,293 | | | $8,562 | $1,280 | $8,562 |
| 31-Dec | 16 | 4 | $104.69 | 1,293 | | | $8,562 | $1,280 | $8,562 |
| 31-Dec | 17 | 4 | $104.68 | 1,293 | | | $8,561 | $1,280 | $8,561 |
| 31-Dec | 18 | 4 | $104.67 | 1,293 | | | $8,560 | $1,280 | $8,560 |
| 31-Dec | 19 | 4 | $104.67 | 1,293 | | | $8,560 | $1,280 | $8,560 |
| 31-Dec | 20 | 4 | $104.66 | 1,293 | | | $8,559 | $1,280 | $8,559 |
| 31-Dec | 21 | 4 | $104.65 | 1,293 | | | $8,559 | $1,280 | $8,559 |
| 31-Dec | 22 | 5 | $92.13 | 1,293 | | | $8,558 | | $8,558 |
| 31-Dec | 23 | 5 | $92.13 | 1,293 | | | $8,557 | | $8,557 |
| 31-Dec | 24 | 5 | $92.12 | 1,293 | | | $8,557 | | $8,557 |
| | | Sum | $927,189 | 11,353,999 | | | | | |
| | | Ave | $105.84 | 1296.1 | $15,046 | $3,433 | $8,580 | $1,281 | $8,580 |
| | | Max | $174.30 | 1311.9 | $15,139 | $3,461 | $8,685 | $1,291 | $8,685 |
| | | Min | $91.87 | 1289.0 | $14,878 | $3,404 | $8,533 | $1,276 | $8,533 |

**Monthly Demand Charge Calculations**

| Month | Actual Demand Charge per Rate Period | | | | |
|---|---|---|---|---|---|
| | Proposed | | | | |
| | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| | $ | $ | $ | $ | $ |
| Jan | N/A | N/A | N/A | 1,290 | 8,625 |
| Feb | N/A | N/A | N/A | 1,290 | 8,631 |
| Mar | N/A | N/A | N/A | 1,290 | 8,624 |
| Apr | N/A | N/A | N/A | 1,291 | 8,635 |
| May | 15,133 | 3,454 | 8,681 | N/A | N/A |
| Jun | 15,128 | 3,461 | 8,679 | N/A | N/A |
| Jul | 15,139 | 3,461 | 8,685 | N/A | N/A |
| Aug | 15,128 | 3,457 | 8,678 | N/A | N/A |
| Sep | 15,101 | 3,452 | 8,678 | N/A | N/A |
| Oct | 15,139 | 3,461 | 8,685 | N/A | N/A |
| Nov | N/A | N/A | N/A | 1,290 | 8,627 |
| Dec | N/A | N/A | N/A | 1,290 | 8,629 |
| Sum | 90,767 | 20,746 | 52,085 | 7,740 | 51,772 |
| Ave | 15,128 | 3,458 | 8,681 | 1,290 | 8,629 |
| Max | 15,139 | 3,461 | 8,685 | 1,291 | 8,635 |
| Min | 15,101 | 3,452 | 8,678 | 1,290 | 8,624 |

# Annual Total Gas Energy Use

**Assumptions**
All gas use comes from the heating plant.

**Hourly Calculations**

| Date | Hour | Heating Plant Energy Use |
|---|---|---|
| | | Baseline |
| | | therms |
| 1-Jan | 1 | 0.29 |
| 1-Jan | 2 | 0.27 |
| 1-Jan | 3 | 0.32 |
| 1-Jan | 4 | 0.34 |
| 30-Jun | 13 | 0.00 |
| 30-Jun | 14 | 0.00 |
| 30-Jun | 15 | 0.00 |
| 30-Jun | 16 | 0.00 |
| 30-Jun | 17 | 0.00 |
| 30-Jun | 18 | 0.00 |
| 30-Jun | 19 | 0.00 |
| 30-Jun | 20 | 0.00 |
| 30-Jun | 21 | 0.00 |
| 30-Jun | 22 | 0.03 |
| 30-Jun | 23 | 0.07 |
| 30-Jun | 24 | 0.13 |
| 1-Jul | 1 | 0.00 |
| 1-Jul | 2 | 0.00 |
| 1-Jul | 3 | 0.00 |
| 1-Jul | 4 | 0.11 |
| 1-Jul | 5 | 0.10 |
| 1-Jul | 6 | 0.08 |
| 1-Jul | 7 | 0.00 |
| 1-Jul | 8 | 0.00 |
| 1-Jul | 9 | 0.00 |
| 1-Jul | 10 | 0.00 |
| 1-Jul | 11 | 0.00 |
| 1-Jul | 12 | 0.00 |
| 31-Dec | 13 | 0.22 |
| 31-Dec | 14 | 0.18 |
| 31-Dec | 15 | 0.18 |
| 31-Dec | 16 | 0.18 |
| 31-Dec | 17 | 0.19 |
| 31-Dec | 18 | 0.20 |
| 31-Dec | 19 | 0.21 |
| 31-Dec | 20 | 0.21 |
| 31-Dec | 21 | 0.24 |
| 31-Dec | 22 | 0.25 |
| 31-Dec | 23 | 0.27 |
| 31-Dec | 24 | 0.30 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| | |
|---|---|
| Sum | 1260.25 |
| Ave | 0.14 |
| Max | 0.85 |
| Min | 0.00 |

# First Year Gas Cost

**Gas Use (therms)**

| | Baseline | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | 210 | | 210 |
| Feb | 159 | | 159 |
| Mar | 169 | | 169 |
| Apr | 124 | 124 | |
| May | 52 | 52 | |
| Jun | 29 | 29 | |
| Jul | 15 | 15 | |
| Aug | 13 | 13 | |
| Sep | 17 | 17 | |
| Oct | 53 | 53 | |
| Nov | 179 | | 179 |
| Dec | 240 | | 240 |
| Sum | 1,260 | 303 | 957 |
| Ave | 105 | 43 | 191 |
| Max | 240 | 124 | 240 |
| Min | 13 | 13 | 159 |

**Gas Cost**

| | Baseline | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | | | $252 |
| Feb | | | $191 |
| Mar | | | $203 |
| Apr | | $144 | |
| May | | $61 | |
| Jun | | $33 | |
| Jul | | $17 | |
| Aug | | $15 | |
| Sep | | $20 | |
| Oct | | $61 | |
| Nov | | | $215 |
| Dec | | | $288 |

Annual Totals: $1,500

# CHW AHUs with Air Side Economizing

## CEC Zone 4 (San Jose)

# Summary: CHW AHUs w/ Economizers vs CHW CRACs

**Project** Data Center Energy Model
**Client** LBNL
**Location** CA Climate Zone 4
**Type of Facility** Data Center

**Summary**

| Case 1 | Summer Peak Power Reduction | First-Year Energy Savings | | Estimated Incremental Cost of Implementation | Incentive Based on Rates Alone | Limited to Half the Incremental Implementation Cost [1] | First-Year Energy Cost Savings | | | Simple Payback After Incentive | Relative Net Present Value | Internal Rate of Return | CO2 Reduction |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Electricity | Gas | | | | Electricity | Gas | Total | | | | |
| | kW | kWh/yr | therms | $ | $ | $ | $/year | $/year | $/year | years | $ | % | lbs/yr |
| Baseline vs Air Side Economizing | 42 | 935,649 | - | $ 50,800 | $ 130,991 | $ 25,400 | $ 45,261 | $ - | $ 45,261 | 0.3 | $ 936,220 | 162% | 570,746 |

[1] The  imposes the following limitations on the incentives:
* The incentive is limited to 50% of the total incremental cost of implementation.
* The implementation costs shown here are estimates; the customer may submit their own cost figures if desired.

# Incentive Rates

**PG&E 2008 Non-Residential Incentive Program Rates**

| | Electric | Gas |
|---|---|---|
| | $/kWh | $/therm |
| Daylighting Systems | 0.04 | |
| Lighting Systems (Interior and Outdoor) | 0.05 | |
| HVAC Systems | 0.14 | 0.80 |
| Service Hot Water | | 0.80 |
| Process Systems | 0.08 | 0.80 |
| Refrigeration (Non-Supermarket) | 0.08 | |

**CO2 Emissions Factors**

| | | | |
|---|---|---|---|
| Average Electricity Emissions Factor for California | 0.61 | lb $CO_2$/kWh | Source: www.eia.doe.gov/oiaf/1605/e-factor.html Accessed 10/4/06 |
| $CO_2$ Emission Coefficients Natural Gas (Pipeline) | 11.7 | lbs $CO_2$ / therm | Source: www.eia.doe.gov/oiaf/1605/factors.html Accessed 10/5/06 |

# Annual Total Electric Energy Use, Proposed

**Assumptions**

This scenario assumes seven 500 kVa modules. The efficiencies for the modules are drawn from Powersmith data sheets. Where data points were not provided we have estimated values according to a standard transformer curve profile. We assume that the number, size, and efficiency of the modules are the same for the baseline and proposed case.

We assume that all active transformer modules are loaded to an equal percentage.

All transformers are assumed to be of the linear type.

The power factor is assumed to be 1.00 (kW = kVA).

Transformers are not located in an air-conditioned space, so they do not impose a cooling load.

The transformers serve the rack, UPS, lighting, and chilled water plant loads.

**Input Parameters**

| | | | |
|---|---|---|---|
| Transformer Module Size: | 500 | kVA | See Transformers sheet |

**Annual Energy Use**

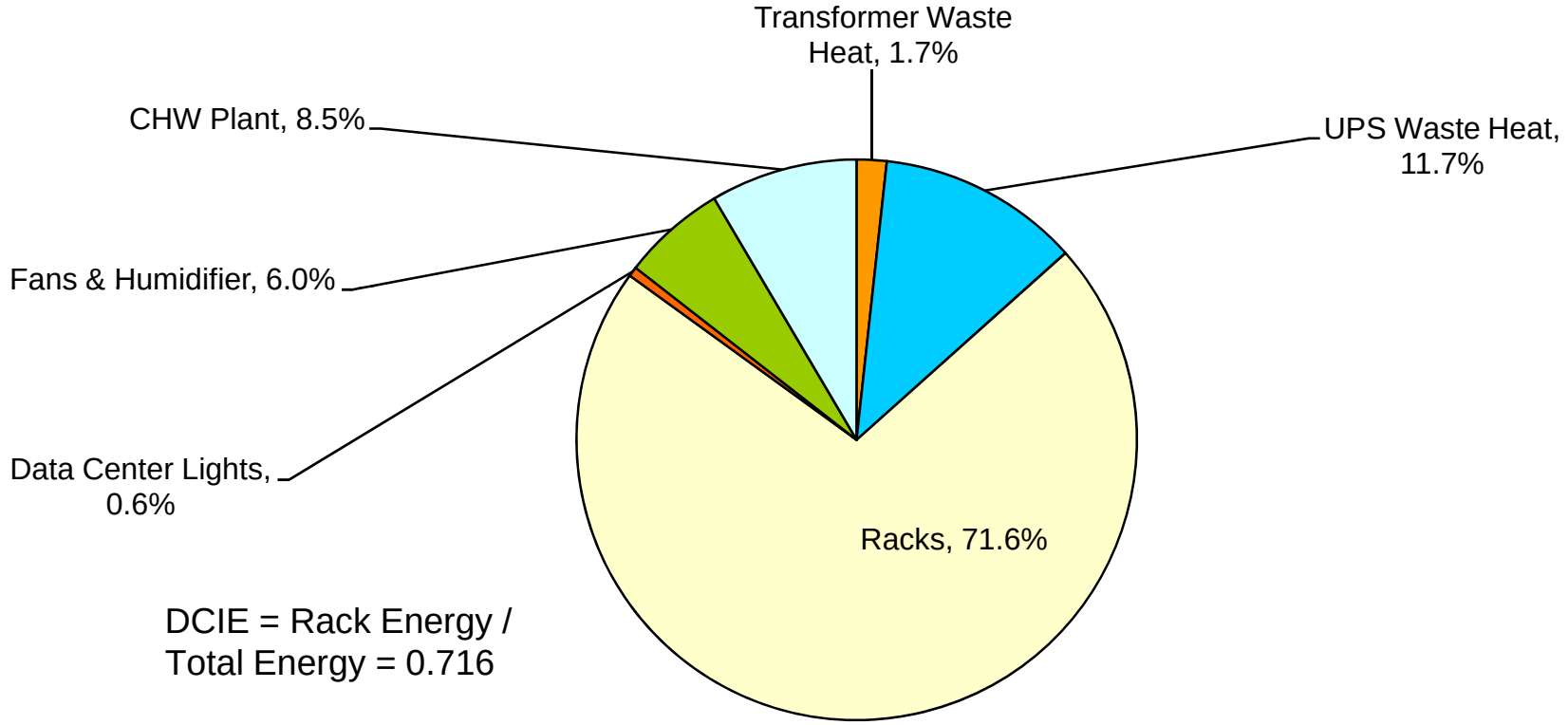
| System | Proposed | |
|---|---|---|
| | kWh/yr | Percent of Total |
| Transformer Waste Heat | 185,865 | 1.7% |
| UPS Waste Heat | 1,256,917 | 11.7% |
| Racks | 7,721,064 | 71.6% |
| Data Center Lights | 59,393 | 0.6% |
| Fans & Humidifier | 644,977 | 6.0% |
| CHW Plant | 915,525 | 8.5% |
| Total | 10,783,741 | 100.0% |

**Hourly Calculations**

| Date | Hour | Required Transformer Output Power | | | | | Transformer Modules | | | Transformer Total Input Power Demand | Trans-former Waste Heat | Peak Summer Power Demand |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | UPS Input Power | Data Center Lights | Fans and Humidifier | CHW Plant | Total | Quant. | Load Factor | Module Effic. | | | |
| | | kW | kW | kW | kW | kW | | % | % | kW | kW | kW |
| 1-Jan | 1 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 1-Jan | 2 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 3 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 4 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 5 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 6 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 7 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 8 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 9 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 10 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 11 | 1,025 | 7 | 55 | 182 | 1,289 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 12 | 1,025 | 7 | 98 | 0 | 1,130 | 3 | 75% | 98.4% | 1,148 | 18 | n/a |
| 30-Jun | 13 | 1,025 | 7 | 55 | 195 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | 1,305 |
| 30-Jun | 14 | 1,025 | 7 | 55 | 195 | 1,282 | 3 | 85% | 98.2% | 1,305 | 24 | 1,305 |
| 30-Jun | 15 | 1,025 | 7 | 55 | 195 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | 1,305 |
| 30-Jun | 16 | 1,025 | 7 | 55 | 194 | 1,281 | 3 | 85% | 98.2% | 1,304 | 24 | 1,304 |
| 30-Jun | 17 | 1,025 | 7 | 55 | 195 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | 1,305 |
| 30-Jun | 18 | 1,025 | 7 | 55 | 193 | 1,280 | 3 | 85% | 98.2% | 1,304 | 24 | 1,304 |
| 30-Jun | 19 | 1,025 | 7 | 55 | 195 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | n/a |
| 30-Jun | 20 | 1,025 | 7 | 55 | 192 | 1,278 | 3 | 85% | 98.2% | 1,302 | 24 | n/a |
| 30-Jun | 21 | 1,025 | 7 | 55 | 190 | 1,277 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 30-Jun | 22 | 1,025 | 7 | 80 | 67 | 1,179 | 3 | 79% | 98.4% | 1,198 | 19 | n/a |
| 30-Jun | 23 | 1,025 | 7 | 80 | 44 | 1,156 | 3 | 77% | 98.4% | 1,174 | 19 | n/a |
| 30-Jun | 24 | 1,025 | 7 | 80 | 0 | 1,112 | 3 | 74% | 98.5% | 1,129 | 17 | n/a |
| 1-Jul | 1 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 1-Jul | 2 | 1,025 | 7 | 55 | 189 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 1-Jul | 3 | 1,025 | 7 | 55 | 193 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | n/a |
| 1-Jul | 4 | 1,025 | 7 | 99 | 0 | 1,131 | 3 | 75% | 98.4% | 1,149 | 18 | n/a |
| 1-Jul | 5 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 1-Jul | 6 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 1-Jul | 7 | 1,025 | 7 | 55 | 193 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | n/a |
| 1-Jul | 8 | 1,025 | 7 | 55 | 189 | 1,275 | 3 | 85% | 98.2% | 1,299 | 24 | n/a |
| 1-Jul | 9 | 1,025 | 7 | 55 | 190 | 1,277 | 3 | 85% | 98.2% | 1,301 | 24 | n/a |
| 1-Jul | 10 | 1,025 | 7 | 55 | 191 | 1,277 | 3 | 85% | 98.2% | 1,301 | 24 | n/a |
| 1-Jul | 11 | 1,025 | 7 | 55 | 197 | 1,283 | 3 | 86% | 98.2% | 1,307 | 24 | n/a |
| 1-Jul | 12 | 1,025 | 7 | 55 | 198 | 1,284 | 3 | 86% | 98.2% | 1,308 | 24 | n/a |
| 31-Dec | 13 | 1,025 | 7 | 100 | 0 | 1,131 | 3 | 75% | 98.4% | 1,150 | 18 | n/a |
| 31-Dec | 14 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 15 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 16 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 17 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 18 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 19 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 20 | 1,025 | 7 | 100 | 0 | 1,132 | 3 | 75% | 98.4% | 1,150 | 18 | n/a |
| 31-Dec | 21 | 1,025 | 7 | 100 | 0 | 1,131 | 3 | 75% | 98.4% | 1,150 | 18 | n/a |
| 31-Dec | 22 | 1,025 | 7 | 99 | 0 | 1,131 | 3 | 75% | 98.4% | 1,149 | 18 | n/a |
| 31-Dec | 23 | 1,025 | 7 | 98 | 0 | 1,130 | 3 | 75% | 98.4% | 1,148 | 18 | n/a |
| 31-Dec | 24 | 1,025 | 7 | 98 | 0 | 1,129 | 3 | 75% | 98.4% | 1,148 | 18 | n/a |
| Sum | | 8,977,981 | 59,393 | 644,977 | 915,525 | 10,597,876 | | | | 10,783,741 | 185,865 | 1,055,635 |
| Ave | | 1,025 | 7 | 74 | 105 | 1,210 | 3.00 | 81% | 98.3% | 1,231 | 21 | 1,294 |
| Max | | 1,025 | 7 | 101 | 202 | 1,288 | 3 | 86% | 98.5% | 1,312 | 24 | 1,312 |
| Min | | 1,025 | 7 | 55 | 0 | 1,112 | 3 | 74% | 98.2% | 1,129 | 17 | 1,129 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# Data Center Infrastructure Efficiency (DCIE)
# Proposed




DCIE = Rack Energy / Total Energy = 0.716

# Space Parameters

**Assumptions**
Chilled water CRAC values are based on the Liebert Deluxe System 3, Model 740C.

| | Proposed | Units | Sources |
|---|---|---|---|
| **Input Parameters** | | | |
| ***Space Dimensions*** | | | |
| Floor Area | 6,780 | sf | Email from Dave Shroyer, 10/13/08. |
| ***Occupancy Schedule*** | | | |
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | Datacenter assumed to operate 8,760 hours per year |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | Datacenter assumed to operate 8,760 hours per year |
| ***HVAC System Type & Setpoints*** | | | |
| Air Delivery System | VAV | | The proposed system uses VAV air handlers. |
| Return Air Drybulb Setpoint | 89.5 | °F | Selected to get a 22 deg-F delta-T, email from Rupa Ganguly on 9/30/08. |
| Supply Air Drybulb Setpoint (VAV Systems Only) | 67.5 | °F | Estimate from email from Rupa Ganguly on 9/30/08. |
| Supply Air Design Flow Rate (CAV Systems Only) | | cfm | Total air flow provided by selected number & size of CRAC units and expected total static pressure drop of open HACA arrangement. |
| Active Humidity Control? | no | | Humidity control is baseline practice. The proposed facility will have no active humidity control. |
| Drybulb Temp at RH Sensor Location | 89.5 | °F | Humidity sensor is assumed to be mounted on the data center ceiling. |
| Allowed Relative Humidity, Maximum | 100% | RH | Assumed based on no humidity control. |
| Allowed Relative Humidity, Minimum | 1% | RH | Assumed based on no humidity control. |
| CHWST Setpoint, Primary | 44 | °F | Baseline CHWST setpoint value. |
| CHWST Setpoint, Secondary | 44 | °F | We are not considering CHWST reset. |
| Adiabatic Humdifier Power Draw | 0.000 | kW/ (lb of H20/hr) | No adiabatic humidifier. |

| | Proposed | Units | Sources |
|---|---|---|---|
| ***Cooling Load*** | | | |
| Total Rack Load, Occupied | 881 | kW | Calculated from rack load of 130 W/sf, email from Dave Shroyer, 10/13/08. |
| Total Rack Load, Unoccupied | n/a | kW | Rack load does not vary with occupancy. |
| Average Lighting Density | 1.0 | W/sf | Typical value. |
| ***Ventilation Requirement*** | | | |
| Minimum Ventilation Requirement | 0.15 | cfm/sf | CA Title 24 requirement for office space. |
| ***Boiler Data*** | | | |
| HHW Boiler Efficiency | 82% | % | Baseline value. |
| Gas-fired Humidifier Efficiency | 76% | % | Baseline value. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| ***HVAC System Type & Setpoints*** | | | |
| Occupied Supply Air Drybulb | | °F | = RAT - Occupied Load / (1.08 * cfm) |
| Unoccupied Supply Air Drybulb | | °F | A datacenter is assumed always occupied. |
| Occupied Supply Air Flow Rate | 127,545 | cfm | = Load / (1.08 * Delta-T) |
| Unoccupied Suppllly Air Flow Rate | n/a | | A datacenter is assumed always occupied. |
| Air Side Delta-T | 22 | °F | Subtract |
| ***Cooling Load*** | | | |
| UPS Waste Heat | 0 | kW | Not included in cooling load. |
| Data Center Lights | 7 | kW | Average lighting density times space floor area. |
| Total Internal Load, Occupied | 888 | kW | Rack load, UPS waste heat, lights. |
| Total Internal Load, Occupied | 253 | tons | Convert to tons |
| Total Internal Load, Occupied | 3,030 | kBTU/hr | Convert to kBTU/hr |
| Average Internal Load Density, Occupied | 131 | W/sf | Divide by floor area |
| Total Internal Load, Unoccupied | n/a | kW | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | tons | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | kBTU/hr | A datacenter is assumed always occupied. |
| Average Internal Load Density, Unoccupied | n/a | W/sf | A datacenter is assumed always occupied. |
| ***Ventilation Requirement*** | | | |
| Min Allowed Ventilation Volumetric Air Flow Rate | 1,017 | cfm | Floor area times minimum ventilation requirement. |

# Weather Data

Source: California Energy Commission
Data Set: California Climate Zone 4 (CZ04RV2)

| Date | Hour | Outside Air | | | | | |
|---|---|---|---|---|---|---|---|
| | | Drybulb Temp. | Dewpoint Temp. | Relative Humidity | Atmospheric Pressure | Wetbulb Temp. | Enthalpy |
| | | °F | °F | % | psia | °F | BTU/lb |
| 1-Jan | 1 | 44.1 | 39.6 | 84% | 14.6 | 41.9 | 16.1 |
| 1-Jan | 2 | 42.6 | 40.6 | 93% | 14.6 | 41.7 | 16.0 |
| 1-Jan | 3 | 41.2 | 38.1 | 89% | 14.6 | 39.8 | 15.1 |
| 1-Jan | 4 | 40.3 | 37.4 | 89% | 14.6 | 38.9 | 14.7 |
| 1-Jan | 5 | 38.8 | 36.7 | 92% | 14.6 | 37.9 | 14.3 |
| 1-Jan | 6 | 37.9 | 36.0 | 92% | 14.6 | 37.0 | 13.9 |
| 1-Jan | 7 | 37.4 | 35.4 | 92% | 14.6 | 36.5 | 13.6 |
| 1-Jan | 8 | 33.3 | 32.2 | 96% | 14.6 | 32.8 | 12.1 |
| 1-Jan | 9 | 36 | | | | 36.0 | 13.4 |
| 1-Jan | 10 | 37 | | | | 37.4 | 14.0 |
| 1-Jan | 11 | 41 | | | | 41.7 | 16.0 |
| 1-Jan | 12 | 46 | | | | 43.2 | 16.8 |
| 30-Jun | 13 | 87 | | | | 66.7 | 31.3 |
| 30-Jun | 14 | 82 | | | | 68.1 | 32.5 |
| 30-Jun | 15 | 79 | | | | 68.2 | 32.6 |
| 30-Jun | 16 | 79.7 | 60.8 | 52% | 14.5 | 67.0 | 31.6 |
| 30-Jun | 17 | 78.3 | 62.2 | 58% | 14.5 | 67.5 | 32.1 |
| 30-Jun | 18 | 76.6 | 60.6 | 58% | 14.5 | 66.1 | 31.0 |
| 30-Jun | 19 | 77.0 | 63.0 | 62% | 14.5 | 67.6 | 32.1 |
| 30-Jun | 20 | 74.5 | 58.5 | 57% | 14.5 | 64.0 | 29.4 |
| 30-Jun | 21 | 72.1 | 55.0 | 55% | 14.5 | 61.5 | 27.5 |
| 30-Jun | 22 | 69.6 | 52.7 | 55% | 14.5 | 59.4 | 26.1 |
| 30-Jun | 23 | 68.0 | 50.4 | 53% | 14.5 | 57.5 | 24.8 |
| 30-Jun | 24 | 66.9 | 47.8 | 50% | 14.5 | 55.9 | 23.8 |
| 1-Jul | 1 | 65.8 | 57.2 | 74% | 14.5 | 60.5 | 26.9 |
| 1-Jul | 2 | 63.7 | 57.6 | 80% | 14.5 | 59.7 | 26.4 |
| 1-Jul | 3 | 60.6 | 54.7 | 81% | 14.5 | 57.1 | 24.6 |
| 1-Jul | 4 | 58.6 | 48.6 | 69% | 14.5 | 52.9 | 22.0 |
| 1-Jul | 5 | 57.0 | 48.9 | 74% | 14.5 | 52.4 | 21.7 |
| 1-Jul | 6 | 55.9 | 50.0 | 80% | 14.5 | 52.5 | 21.8 |
| 1-Jul | 7 | 60.6 | 55.6 | 83% | 14.5 | 57.5 | 24.8 |
| 1-Jul | 8 | 62.6 | 56.7 | 81% | 14.5 | 58.9 | 25.8 |
| 1-Jul | 9 | 66.9 | 59.9 | 78% | 14.5 | 62.4 | 28.2 |
| 1-Jul | 10 | 69.3 | 60.3 | 73% | 14.5 | 63.4 | 28.9 |
| 1-Jul | 11 | 80.1 | 66.0 | 62% | 14.5 | 70.2 | 34.3 |
| 1-Jul | 12 | 77.7 | 67.6 | 71% | 14.5 | 70.6 | 34.7 |
| 31-Dec | 13 | 49.3 | 43.3 | 80% | 14.6 | 46.2 | 18.3 |
| 31-Dec | 14 | 55.0 | 45.1 | 69% | 14.6 | 49.7 | 20.1 |
| 31-Dec | 15 | 55.0 | 45.1 | 69% | 14.6 | 49.7 | 20.1 |
| 31-Dec | 16 | 55.0 | 45.1 | 69% | 14.6 | 49.7 | 20.1 |
| 31-Dec | 17 | 53.8 | 44.8 | 71% | 14.6 | 48.9 | 19.7 |
| 31-Dec | 18 | 52.2 | 44.2 | 74% | 14.6 | 47.9 | 19.2 |
| 31-Dec | 19 | 51.4 | 43.5 | 74% | 14.6 | 47.3 | 18.8 |
| 31-Dec | 20 | 50.4 | 43.5 | 77% | 14.6 | 46.8 | 18.5 |
| 31-Dec | 21 | 49.1 | 42.1 | 77% | 14.6 | 45.6 | 17.9 |
| 31-Dec | 22 | 47.8 | 41.7 | 79% | 14.6 | 44.7 | 17.5 |
| 31-Dec | 23 | 46.6 | 40.5 | 79% | 14.6 | 43.6 | 16.9 |
| 31-Dec | 24 | 45.3 | 39.4 | 80% | 14.6 | 42.5 | 16.4 |
| | Ave | 58.9 | 48.9 | 71% | 14.5 | 53.2 | 22.7 |
| | Max | 97.3 | 76.8 | 100% | 14.8 | 81.0 | 44.9 |
| | Min | 28.4 | 11.8 | 10% | 14.3 | 26.9 | 9.7 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

# Transformer Data

## Proposed

**Parameters**

| | | |
|---|---|---|
| Size | 500 | kVA |

Values in blue are from NEMA Standard TP-1 Transformer Efficiency, Three Phase (Table 4.2). All other values are extrapolated.

| **Linear Efficiency vs. Load Factor** | |
|---|---|
| Load | Efficiency |
| 100% | 97.9% |
| 90% | 98.2% |
| 80% | 98.4% |
| 75% | 98.5% |
| 70% | 98.6% |
| 60% | 98.8% |
| 50% | 98.8% |
| 40% | 98.8% |
| 35% | 98.7% |
| 30% | 98.6% |
| 25% | 98.5% |
| 20% | 98.3% |
| 17% | 98.2% |
| 10% | 97.7% |

# Chiller Data

**Assumptions**
The same chillers are used in the baseline and proposed cases.
We set the chillers to the same size.

**Parameters**

| | Baseline | Proposed | Units | Sources |
|---|---|---|---|---|
| Chiller Capacity | 500 | 500 | tons | Capacity selected to result in a total of three chillers, with appropriate safety and redundancy factors. |
| Condenser Water Temperature | 80 | 80 | °F | Typical value. |
| CHW Supply Temperature | 44 | 44 | °F | Typical value. |
| CW Flow Rate | 1,200 | 1,200 | gpm | Assumes a 10F CW delta-T when chiller is a maximum load. |

Values from Baseline Water-Cooled Chilled Water Plant Above 300 tons

| **Chiller Efficiency (kW/ton) at CHWS Temp = 44 F** | |
|---|---|
| Load | Condenser Water Temp (°F) |
| | 80 |
| 100% | 0.529 |
| 90% | 0.526 |
| 80% | 0.526 |
| 70% | 0.530 |
| 60% | 0.539 |
| 50% | 0.557 |
| 40% | 0.590 |
| 30% | 0.653 |
| 20% | 0.792 |
| 10% | 1.234 |

# Cooling Tower Fan Speed Lookup Tables, Proposed

| | |
|---|---|
| Cooling Tower Make & Model Used in Analysis | BAC 3482A |

The following lookup tables were created by drawing information from BAC's Cooling Tower Selection Software, Release 6.02 NA. The fan speeds are expressed in percent.

Fan speed depends on the load on the tower, the condenser water flow rate, the ambient wetbulb temperature, and the temperature of the condenser water leaving the tower (aka the cold condenser water temperature). The lowest fan speed the BAC software wil

**Tower Specifications at Nominal Conditions**

| | | |
|---|---|---|
| Ambient Wetbulb Temperature | 78 | deg F |
| Hot Condenser Water Temperature | 95 | deg F |
| Cold Condenser Water Temperature | 88.7 | deg F |
| Condenser Water Flow Rate, Maximum | 2,600 | gpm |
| Condenser Water Flow Rate, Minimum | 609 | gpm |
| Nominal Cooling Tower Capacity | 679 | tons |
| Cooling Tower Fan Motor Size | 30 | hp |

## 50% Maximum Flow = 1300 gpm

**0 tons, 1300 gpm**

All temperatures in deg F

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**50 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**100 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**150 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**200 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**250 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**300 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

# UPS Energy Calculation

| UPS System Parameters | Proposed | Units | Comments |
|---|---|---|---|
| **UPS Module Data** | | | |
| Total Rack Load | 881 | kW | From Space sheet. |
| Percentage of Load Served by UPS | 100% | % | We assume all racks are backed up. |
| UPS Load | 881 | kW | Rack load times percentage of load served by UPS. |
| Number of Modules | 5 | | Assumed. |
| Unit Capacity | 500 | kVA | Assumed. |
| Total UPS Capacity | 2,500 | kVA | Unit capacity * number of units |
| Load Factor | 35% | % | UPS load / UPS capacity |
| UPS Efficiency | 86% | % | From LBNL Datacenter UPS benchmarking study. |
| **Energy Use** | | | |
| Annual Energy Use | 8,977,981 | kWh/yr | UPS load / UPS efficiency * 8760 hours |
| Peak Demand | 1,025 | kW | UPS load / UPS efficiency |

# Proposed Heating & Cooling Load, Fan Energy

**Template:** **Air Handler Energy Model_Recirculation with Economizer_v10.3**

**Input Parameters**

| | | | |
|---|---|---|---|
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | From the Space Parameters sheet. |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | From the Space Parameters sheet. |
| Air Delivery System: CAV or VAV? | VAV | | From the Space Parameters sheet. |
| Return Air Drybulb Setpoint | 89.5 | F | From the Space Parameters sheet. |
| Active Humidity Control? | no | | From the Space Parameters sheet. |
| Drybulb Temp at RH Sensor Location | 89.5 | F | From the Space Parameters sheet. |
| Allowed Relative Humidity, Maximum | 100% | RH | From the Space Parameters sheet. |
| Allowed Relative Humidity, Minimum | 1% | RH | From the Space Parameters sheet. |
| Min Allowed Ventilation Air Flow Rate | 1,017 | cfm | From the Space Parameters sheet. |
| CHWST Setpoint, Primary | 44 | F | From the Space Parameters sheet. |
| CHWST Setpoint during Reset | 44 | F | From the Space Parameters sheet. |
| Adiabatic Humidifier Power Draw | 0.000 | kW/(lb of H20/hr) | From the Space Parameters sheet. |

| | | | |
|---|---|---|---|
| Humidifier: 0=None, 1=Electric, 2=Steam, 3=Adiabatic | 0 | | No active humidification in the proposed case. |
| Cooling Plant Type: 1=CHW, 2=DX | 1 | | There is a chilled water plant in the proposed case. |
| CHWST Reset: 0=No, 1=Yes | 0 | | No CHWST in the proposed case. |
| Economizer? | yes | | Proposed design includes integrated economizing. |
| Economizer Drybulb Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Drybulb Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Drybulb Upper Lockout | 78 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Dewpoint Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Dewpoint Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Dewpoint Upper Lockout | 55 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Enthalpy Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Enthalpy Lower Lockout | 0 | BTU/lb | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Enthalpy Upper Lockout | 29.75 | BTU/lb | Email from Rupa Ganguly on 9/30/08. |
| Economizer Relative Humidity Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| RH Lower Lockout | 20% | % | Email from Rupa Ganguly on 9/30/08. |
| RH Upper Lockout | 80% | % | Email from Rupa Ganguly on 9/30/08. |

| Fan System Parameters | | Supply | Relief | Units | Sources |
|---|---|---|---|---|---|
| Fan Motor Size, Nominal | | 30 | 50 | hp | Sized in accordance with calculated brake horsepower, below. |
| Number of Fans | | 10 | 5 | | Arbitrary numbers selected for model. Assuming one supply fan per RAHU. |
| Fan Efficiency | | 63.8% | 67.5% | % | Baseline fan efficiencies for motor sizes indicated. |
| Fan Drive Efficiency | | 95% | 95% | % | Typical value for belt drive. |
| Fan Motor Efficiency | | 92.5% | 93.2% | % | Baseline efficiencies. |
| VFD Efficiency | | 98% | 98% | % | Supply and relief fans assumed to be equipped with VFDs. |
| Fan Motor and Drive in Airstream? | | 1 | n/a | 1=yes, 0=no | Assumption. |
| Econ. In Min. Pos. | Total Static Pressure Drop | 2.00 | 8.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | n/a | F | Calculated based on maximum fan motor output power. |
| Economizer Open | Total Static Pressure Drop | 2.00 | 1.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | n/a | F | Calculated based on maximum fan motor output power. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| Return Air Minimum Dewpoint | 0.0 | F | Dewpoint of return air when RH sensor is at minimum allowed RH. |
| Space Dewpoint at Maximum Allowed Space Humidity | 89.5 | | Corresponds to Space DB and Max Allowed RH. |
| Chilled Water Minimum Temperature Requirement | 64.5 | F | If the cooling system is CHW, the cooling coil is assumed to have a constant approach temperature of 3 deg F. |

| Fan System Parameters | Supply | Relief | Units | Comments |
|---|---|---|---|---|
| Fan Motor Output Power, Maximum | 4.9 | 8.5 | kW | Per fan motor. This is the maximum output brake power each fan motor is called upon to deliver. |
| Fan Motor Output Power, Maximum | 6.6 | 11.4 | hp | Per fan motor. Converted from kW to hp. |

**Error Messages**

OK - RH minimum does not require humidifier. No humidifier identified.
OK - Chilled Water Supply Temperature Setpoint is low enough to perform required sensible and latent cooling.
OK - Supply Fan Motor Size Exceeds Maximum Required Supply Fan Motor Output
OK - Relief Fan Motor Size Exceeds Maximum Required Relief Fan Motor Output

**Results (Annual Totals)**

| | Proposed | Units |
|---|---|---|
| Cooling Energy Extracted from Airstream | 14,407,118 | kBTU/yr |
| Heating Energy Added to Airstream | 0 | kBTU/yr |
| Humidifier Energy Added to Airstream | 0 | kBTU/yr |

| | Proposed | Units |
|---|---|---|
| Humidifier Energy Required | n/a | kWh/yr |
| | n/a | therms/yr |
| Fan Motor Energy Required | 644,977 | kWh/yr |

**Hourly Calculations**

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Energy Required to Sensibly Cool Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | | | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | Supply | | Relief | | Total Power Input | | Electric | Steam | Adia-batic | |
| | | | | | | | | | | | | | | | | | | | Total Power Input | Air Deliv. Effic. | Total Power Input | Air Deliv. Effic. | | | | | | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | kBTU | kBTU | kBTU | kW | cfm/kW | kW | cfm/kW | kW | tons | kW | therms | kW | therms |
| 1-Jan | 1 | 127,545 | 67.5 | 67.5 | 67.5 | 39.6 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.6 | 44.0 | 2,981 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 2 | 127,545 | 67.5 | 67.5 | 67.5 | 40.6 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 40.6 | 44.0 | 2,979 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 38.1 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 38.1 | 44.0 | 2,977 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 37.4 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.4 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 36.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 36.7 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 36.0 | | | | | 1 | 1,017 | 89.1 | 36.0 | 44.0 | 2,974 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 35.4 | | | | | 1 | 1,017 | 89.1 | 35.4 | 44.0 | 2,973 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 32.2 | | | | | 1 | 1,017 | 89.1 | 32.2 | 44.0 | 2,969 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 247 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 36.0 | | | | | 1 | 1,017 | 89.1 | 36.0 | 44.0 | 2,972 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 37.4 | | | | | 1 | 1,017 | 89.1 | 37.4 | 44.0 | 2,973 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 41.7 | | | | | 1 | 1,017 | 89.1 | 41.7 | 44.0 | 2,978 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 40.1 | | | | | 0 | 70,727 | 65.5 | 40.1 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 43.5 | 1,624 | 98.1 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 55.2 | 1 | 1 | 1 | 0 | 1 | 1,017 | 89.5 | 55.2 | 44.0 | 3,028 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 60.8 | 1 | 1 | 1 | 0 | 1 | 1,017 | 89.4 | 60.8 | 44.0 | 3,023 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 62.8 | 1 | 1 | 1 | 0 | 1 | 1,017 | 89.4 | 62.8 | 44.0 | 3,020 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 60.8 | 1 | 1 | 1 | 0 | 1 | 1,017 | 89.4 | 60.8 | 44.0 | 3,020 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 17 | 127,545 | 67.5 | 67.5 | 67.5 | 62.2 | 1 | 1 | 1 | 0 | 1 | 1,017 | 89.4 | 62.2 | 44.0 | 3,018 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 18 | 127,545 | 67.5 | 67.5 | 67.5 | 60.6 | 0 | 1 | 1 | 0 | 1 | 1,017 | 89.4 | 60.6 | 44.0 | 3,016 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 19 | 127,545 | 67.5 | 67.5 | 67.5 | 63.0 | 0 | 1 | 1 | 0 | 1 | 1,017 | 89.4 | 63.0 | 44.0 | 3,017 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 20 | 127,545 | 67.5 | 67.5 | 67.5 | 58.5 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.4 | 58.5 | 44.0 | 3,014 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 21 | 127,545 | 67.5 | 67.5 | 67.5 | 55.0 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.4 | 55.0 | 44.0 | 3,011 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 22 | 127,545 | 67.5 | 67.5 | 67.5 | 52.7 | 0 | 0 | 0 | 0 | 0 | 127,545 | 69.6 | 52.7 | 44.0 | 292 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 24 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 23 | 127,545 | 67.5 | 67.5 | 67.5 | 50.4 | 0 | 0 | 0 | 0 | 0 | 127,545 | 68.0 | 50.4 | 44.0 | 69 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 6 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 24 | 127,545 | 67.5 | 67.5 | 67.5 | 47.8 | 0 | 0 | 0 | 0 | 0 | 127,545 | 66.9 | 47.8 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 1 | 127,545 | 67.5 | 67.5 | 67.5 | 57.2 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 57.2 | 44.0 | 3,004 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 2 | 127,545 | 67.5 | 67.5 | 67.5 | 57.6 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 57.6 | 44.0 | 3,002 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 54.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.3 | 54.7 | 44.0 | 2,999 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 48.6 | 0 | 0 | 0 | 0 | 0 | 99,193 | 65.5 | 48.6 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 44.9 | 2,210 | 99.5 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 48.9 | 0 | 0 | 0 | 0 | 0 | 94,245 | 65.5 | 48.9 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.0 | 2,050 | 100.6 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 50.0 | 0 | 0 | 0 | 0 | 0 | 91,212 | 65.5 | 50.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.4 | 1,967 | 100.9 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 55.6 | 0 | 1 | 0 | 1 | 1 | 1,017 | 89.3 | 55.6 | 44.0 | 2,999 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 56.7 | 0 | 1 | 0 | 1 | 1 | 1,017 | 89.3 | 56.7 | 44.0 | 3,001 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 59.9 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 59.9 | 44.0 | 3,006 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 60.3 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 60.3 | 44.0 | 3,008 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 66.0 | 1 | 1 | 1 | 0 | 1 | 1,017 | 89.4 | 66.0 | 44.0 | 3,020 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 67.5 | 0 | 1 | 1 | 0 | 1 | 1,017 | 89.4 | 67.5 | 44.0 | 3,017 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 43.3 | 0 | 0 | 0 | 0 | 0 | 76,108 | 65.5 | 43.3 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 45.1 | 1,687 | 99.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 45.1 | 0 | 0 | 0 | 0 | 0 | 88,830 | 65.5 | 45.1 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.5 | 1,910 | 101.1 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 45.1 | 0 | 0 | 0 | 0 | 0 | 88,830 | 65.5 | 45.1 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.5 | 1,910 | 101.1 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Energy Required to Sensibly Cool Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | | | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | Supply | | Relief | | Total Power Input | | Electric | Steam | Adia-batic | |
| | | | | | | | | | | | | | | | | | | | Total Power Input | Air Deliv. Effic. | Total Power Input | Air Deliv. Effic. | | | | | | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | kBTU | kBTU | kBTU | kW | cfm/kW | kW | cfm/kW | kW | tons | kW | therms | kW | therms |
| 31-Dec | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 45.1 | 0 | 0 | 0 | 0 | 0 | 88,830 | 65.5 | 45.1 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.5 | 1,910 | 101.1 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 17 | 127,545 | 67.5 | 67.5 | 67.5 | 44.8 | 0 | 0 | 0 | 0 | 0 | 85,697 | 65.5 | 44.8 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.5 | 1,843 | 101.1 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 18 | 127,545 | 67.5 | 67.5 | 67.5 | 44.2 | 0 | 0 | 0 | 0 | 0 | 81,979 | 65.5 | 44.2 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.2 | 1,775 | 100.8 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 19 | 127,545 | 67.5 | 67.5 | 67.5 | 43.5 | 0 | 0 | 0 | 0 | 0 | 80,428 | 65.5 | 43.5 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.0 | 1,749 | 100.6 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 20 | 127,545 | 67.5 | 67.5 | 67.5 | 43.5 | 0 | 0 | 0 | 0 | 0 | 78,209 | 65.5 | 43.5 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 45.6 | 1,716 | 100.2 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 21 | 127,545 | 67.5 | 67.5 | 67.5 | 42.1 | 0 | 0 | 0 | 0 | 0 | 75,769 | 65.5 | 42.1 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 45.0 | 1,682 | 99.6 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 22 | 127,545 | 67.5 | 67.5 | 67.5 | 41.7 | 0 | 0 | 0 | 0 | 0 | 73,478 | 65.5 | 41.7 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 44.4 | 1,654 | 99.0 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 23 | 127,545 | 67.5 | 67.5 | 67.5 | 40.5 | 0 | 0 | 0 | 0 | 0 | 71,321 | 65.5 | 40.5 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 43.7 | 1,630 | 98.3 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 24 | 127,545 | 67.5 | 67.5 | 67.5 | 39.4 | 0 | 0 | 0 | 0 | 0 | 69,287 | 65.5 | 39.4 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 43.0 | 1,610 | 97.6 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| Sum | | | | | | | 576 | 2,561 | 1,160 | 2,704 | 4,760 | | | | | ######## | 0 | 0 | 478,182 | | 166,795 | | ###### | | 0 | 0 | 0 | 0 |
| Ave | | 127,545 | 67.5 | 67.5 | 67.5 | 48.8 | 0.066 | 0.292 | 0.132 | 0.309 | 0.543 | 42,688 | 78.6 | 48.8 | 44.0 | 1,645 | 0 | 0 | 54.6 | 2,337 | 19.0 | 4,895 | 73.6 | 137 | 0.0 | 0.0 | 0.00 | 0.0 |
| Max | | 127,545 | 67.5 | 67.5 | 67.5 | 67.5 | | | | | | 127,545 | 89.6 | 67.6 | 44.0 | 3,039 | 0 | 0 | 54.6 | 2,337 | 46.5 | 7,022 | 101.1 | 255 | 0.0 | 0.0 | 0.00 | 0.0 |
| Min | | 127,545 | 67.5 | 67.5 | 67.5 | 11.8 | | | | | | 1,017 | 65.5 | 11.8 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 0.1 | 1,514 | 54.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |

# Cooling Tower Energy Use, Proposed

**Assumptions**

The proposed cooling towers are staged in tandem with the baseline chillers (number of active towers = number of active chillers).
The proposed cooling tower fan motors are two-speed (100% and 50%).

**Parameters**

| | | | |
|---|---|---|---|
| Chiller Condenser Water Temperature Setpoint | 80 | °F | Baseline |
| Cooling Tower Fan Motor Size | 30 | hp | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Cooling Tower Condenser Water Flow, Maximum | 2,600 | gpm | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Motor Load Factor at Full Speed | 90% | | Estimate |
| Fan Motor Efficiency | 92.5% | | Baseline |
| Fan Drive Efficiency | 95% | | Belt drive |
| Fan Power, Baseline Cooling Tower, 100% | 22.9 | kW | = 0.746 * motor size * load factor / (drive effic * motor effic) |
| Fan Power, Baseline Cooling Tower, 50% | 2.9 | kW | Fan Law Calculation |

**Hourly Calculations**

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 1-Jan | 1 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 2 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 3 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 4 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 5 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 6 | 37 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 7 | 36 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 8 | 33 | 247 | 1 | 46% | 247 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 9 | 36 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 10 | 37 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 11 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 12 | 43 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 30-Jun | 13 | 67 | 252 | 1 | 46% | 252 | 80 | 80.0 | 71% | 16.3 | 22.9 | 16.3 | 22.9 |
| 30-Jun | 14 | 68 | 252 | 1 | 46% | 252 | 80 | 80.0 | 75% | 17.1 | 22.9 | 17.1 | 22.9 |
| 30-Jun | 15 | 68 | 252 | 1 | 46% | 252 | 80 | 80.0 | 75% | 17.1 | 22.9 | 17.1 | 22.9 |
| 30-Jun | 16 | 67 | 252 | 1 | 46% | 252 | 80 | 80.0 | 71% | 16.3 | 22.9 | 16.3 | 22.9 |
| 30-Jun | 17 | 68 | 252 | 1 | 46% | 252 | 80 | 80.0 | 75% | 17.1 | 22.9 | 17.1 | 22.9 |
| 30-Jun | 18 | 66 | 251 | | | | | | 68% | 15.6 | 22.9 | 15.6 | 22.9 |
| 30-Jun | 19 | 68 | 251 | | | | | | 75% | 17.1 | 22.9 | 17.1 | 22.9 |
| 30-Jun | 20 | 64 | 251 | | | | | | 63% | 14.4 | 22.9 | 14.4 | 22.9 |
| 30-Jun | 21 | 61 | 251 | | | | | | 56% | 12.9 | 22.9 | 12.9 | 22.9 |
| 30-Jun | 22 | 59 | 24 | | | | | | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 30-Jun | 23 | 58 | 6 | | | | | | 52% | 11.8 | 22.9 | 11.8 | 22.9 |
| 30-Jun | 24 | 56 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 1 | 60 | 250 | 1 | 46% | 250 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 1-Jul | 2 | 60 | 250 | 1 | 46% | 250 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 1-Jul | 3 | 57 | 250 | 1 | 46% | 250 | 70 | 80.0 | 50% | 11.5 | 22.9 | 11.5 | 22.9 |
| 1-Jul | 4 | 53 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 5 | 52 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 6 | 52 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 7 | 57 | 250 | 1 | 46% | 250 | 70 | 80.0 | 50% | 11.5 | 22.9 | 11.5 | 22.9 |
| 1-Jul | 8 | 59 | 250 | 1 | 46% | 250 | 70 | 80.0 | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 1-Jul | 9 | 62 | 250 | 1 | 46% | 250 | 75 | 80.0 | 58% | 13.4 | 22.9 | 13.4 | 22.9 |
| 1-Jul | 10 | 63 | 251 | 1 | 46% | 251 | 75 | 80.0 | 60% | 13.8 | 22.9 | 13.8 | 22.9 |
| 1-Jul | 11 | 70 | 252 | 1 | 46% | 252 | 80 | 80.0 | 83% | 19.0 | 22.9 | 19.0 | 22.9 |
| 1-Jul | 12 | 71 | 251 | 1 | 46% | 251 | 80 | 80.0 | 87% | 20.0 | 22.9 | 20.0 | 22.9 |
| 31-Dec | 13 | 46 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 31-Dec | 14 | 50 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 15 | 50 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 16 | 50 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 17 | 49 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 18 | 48 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 19 | 47 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 20 | 47 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 21 | 46 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 22 | 45 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 23 | 44 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 24 | 43 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| Sum | | | | | | | | | | | | 46,878 | 70,594 |
| Ave | | 53 | 137 | 0.572 | 46% | 137 | 71 | 80.0 | 55% | 5.4 | 8.1 | 5.4 | 8.1 |
| Max | | 81 | 255 | 1 | 46% | 255 | 90 | 90.0 | 98% | 22.5 | 22.9 | 22.5 | 22.9 |
| Min | | 27 | 0 | 0 | 46% | 0 | 50 | 80.0 | 38% | 0.0 | 0.0 | 0.0 | 0.0 |

No. of hours in year that actual CW temp > 80: 56

# CHW Pump Energy Use, Proposed

**Template Name:** **CHW Pump Energy Model_v1.01**

**Assumptions**

There is one operating constant-speed primary CHW pump per active chiller.
All of the primary CHW pumps are identical.
There is one operating variable-speed secondary CHW pump.

**Results**

| | Proposed | Units |
|---|---|---|
| CHW Pump Energy Required | 144,604 | kWh/yr |
| Ave CHW Pump System Effic. | 62.4 | gpm/kW |

***Primary Pumps***

**Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T across evaporator. |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

***Secondary Pump***

**Input Parameters**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 650 | 612 | gpm | Nominal: 650.<br>Design: 255-ton peak load, 10F CHW delta-T. |
| Head | 100 | 100 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 70% | 70% | | Nominal: Baseline for 75 hp motor.<br>Design: Baseline for 75 hp motor. |
| Pump Motor Size | 125 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 94.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 98% | | | Secondary pumps are variable speed. |
| Secondary CHW Loop Delta-T | | 10 | F | Estimate. |

**Calculations**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 22.1 | hp | (flow * head) / (3960 * pump effic) |
| Pump VFD Input Power | | 17.8 | kW | 0.746 * hp / motor effic / VFD effic |

**Error Messages**

OK -- Primary Pump Motor is not undersized.
OK -- Secondary Pump Motor is not undersized.

**Hourly Analysis**

| Date | Hour | Total Cooling Load | No. of Chillers On | Total Primary CHW Flow | Total Primary Pump Power | Secondary Loop CHW Flow | Secondary Pump Power | Total CHW Pump Power | CHW Pump System Efficiency |
|---|---|---|---|---|---|---|---|---|---|
| | | tons | | gpm | kW | gpm | kW | kW | gpm/kW |
| 1-Jan | 1 | 248 | 1 | 1,200 | 12 | 596 | 17 | 29 | 60.9 |
| 1-Jan | 2 | 248 | 1 | 1,200 | 12 | 596 | 17 | 29 | 60.9 |
| 1-Jan | 3 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 61.0 |
| 1-Jan | 4 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 61.0 |
| 1-Jan | 5 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 61.0 |
| 1-Jan | 6 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 61.0 |
| 1-Jan | 7 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 61.0 |
| 1-Jan | 8 | 247 | 1 | 1,200 | 12 | 594 | 17 | 29 | 61.1 |
| 1-Jan | 9 | 248 | | | | | 17 | 29 | 61.0 |
| 1-Jan | 10 | 248 | | | | | 17 | 29 | 61.0 |
| 1-Jan | 11 | 248 | | | | | 17 | 29 | 61.0 |
| 1-Jan | 12 | 0 | | | | | 0 | 0 | n/a |
| 30-Jun | 13 | 252 | | | | | 18 | 30 | 60.4 |
| 30-Jun | 14 | 252 | 1 | 1,200 | 12 | 605 | 17 | 30 | 60.5 |
| 30-Jun | 15 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 30-Jun | 16 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 30-Jun | 17 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 30-Jun | 18 | 251 | 1 | 1,200 | 12 | 603 | 17 | 30 | 60.5 |
| 30-Jun | 19 | 251 | 1 | 1,200 | 12 | 603 | 17 | 30 | 60.5 |
| 30-Jun | 20 | 251 | 1 | 1,200 | 12 | 603 | 17 | 30 | 60.6 |
| 30-Jun | 21 | 251 | 1 | 1,200 | 12 | 602 | 17 | 30 | 60.6 |
| 30-Jun | 22 | 24 | 1 | 1,200 | 12 | 58 | 1 | 13 | 97.6 |
| 30-Jun | 23 | 6 | 1 | 1,200 | 12 | 14 | 0 | 12 | 97.7 |
| 30-Jun | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 1 | 250 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.7 |
| 1-Jul | 2 | 250 | 1 | 1,200 | 12 | 600 | 17 | 30 | 60.7 |
| 1-Jul | 3 | 250 | 1 | 1,200 | 12 | 600 | 17 | 30 | 60.7 |
| 1-Jul | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 7 | 250 | 1 | 1,200 | 12 | 600 | 17 | 30 | 60.7 |
| 1-Jul | 8 | 250 | 1 | 1,200 | 12 | 600 | 17 | 30 | 60.7 |
| 1-Jul | 9 | 250 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.6 |
| 1-Jul | 10 | 251 | 1 | 1,200 | 12 | 602 | 17 | 30 | 60.6 |
| 1-Jul | 11 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 1-Jul | 12 | 251 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 31-Dec | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| Sum | | | | | 61,969 | | 82,635 | 144,604 | |
| Ave | | 137 | 0.572 | 686 | 7 | 329 | 9 | 17 | 62.4 |
| Max | | 255 | 1 | 1,200 | 12 | 611 | 18 | 30 | 97.9 |
| Min | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60.1 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# CHW Plant Energy Use, Proposed

**Assumptions**
All chillers are identical and rotated equally.
There is one operating constant-speed CW pump per active chiller.

| | | | |
|---|---|---|---|
| Electric Chiller Capacity | 500 | tons | Assumed. |
| Number of Electric Chillers | 3 | | Assumed. |
| Total Electric Chiller Capacity | 1,500 | tons | Chiller capacity times number of chillers. |
| Chilled Water Supply Temperature | 44 | F | Baseline. |

**Condenser Water Pump Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

**Results (Annual Totals)**

| | Proposed | Units |
|---|---|---|
| Total Annual Electric Use | 915,525 | kWh/yr |
| Summer Peak Electric Demand | 204 | kW |
| Annual Average Cooling Efficiency | 0.763 | kW/ton |

**Hourly Calculations**

| Date | Hour | Total Cooling Load | Chillers | | | | Cooling Tower Power Demand | CHW & CW Pump Power Demand | Total Cooling Plant Power Demand | Summer Peak Demand |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Chillers Operating | Chiller Load Factor | Chiller Effic. | Chiller Power Demand | | | | |
| | | tons | 0-3 | % | kW/ton | kW | kW | kW | kW | kW |
| 1-Jan | 1 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 183 | n/a |
| 1-Jan | 2 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 3 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 4 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 5 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 6 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 7 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 8 | 247 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 9 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 10 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 11 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 12 | 0 | 0 | [illegible] | [illegible] | 0 | [illegible] | 0 | 0 | n/a |
| 30-Jun | 13 | 252 | 1 | 50% | 0.54 | 136 | 16.3 | 42 | 195 | 201 |
| 30-Jun | 14 | 252 | 1 | 50% | 0.54 | 136 | 17.1 | 42 | 195 | 201 |
| 30-Jun | 15 | 252 | 1 | 50% | 0.54 | 136 | 17.1 | 42 | 195 | 201 |
| 30-Jun | 16 | 252 | 1 | 50% | 0.54 | 136 | 16.3 | 42 | 194 | 201 |
| 30-Jun | 17 | 252 | 1 | 50% | 0.54 | 136 | 17.1 | 42 | 195 | 201 |
| 30-Jun | 18 | 251 | 1 | 50% | 0.54 | 135 | 15.6 | 42 | 193 | 201 |
| 30-Jun | 19 | 251 | 1 | 50% | 0.54 | 136 | 17.1 | 42 | 195 | n/a |
| 30-Jun | 20 | 251 | 1 | 50% | 0.54 | 135 | 14.4 | 42 | 192 | n/a |
| 30-Jun | 21 | 251 | 1 | 50% | 0.54 | 135 | 12.9 | 42 | 190 | n/a |
| 30-Jun | 22 | 24 | 1 | 5% | 1.23 | 30 | 12.1 | 25 | 67 | n/a |
| 30-Jun | 23 | 6 | 1 | 1% | 1.23 | 7 | 11.8 | 25 | 44 | n/a |
| 30-Jun | 24 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 1 | 250 | 1 | 50% | 0.54 | 135 | 12.5 | 42 | 190 | n/a |
| 1-Jul | 2 | 250 | 1 | 50% | 0.54 | 135 | 12.5 | 42 | 189 | n/a |
| 1-Jul | 3 | 250 | 1 | 50% | 0.56 | 139 | 11.5 | 42 | 193 | n/a |
| 1-Jul | 4 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 5 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 6 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 7 | 250 | 1 | 50% | 0.56 | 139 | 11.5 | 42 | 193 | n/a |
| 1-Jul | 8 | 250 | 1 | 50% | 0.54 | 135 | 12.1 | 42 | 189 | n/a |
| 1-Jul | 9 | 250 | 1 | 50% | 0.54 | 135 | 13.4 | 42 | 190 | n/a |
| 1-Jul | 10 | 251 | 1 | 50% | 0.54 | 135 | 13.8 | 42 | 191 | n/a |
| 1-Jul | 11 | 252 | 1 | 50% | 0.54 | 136 | 19.0 | 42 | 197 | n/a |
| 1-Jul | 12 | 251 | 1 | 50% | 0.54 | 136 | 20.0 | 42 | 198 | n/a |
| 31-Dec | 13 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 14 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 15 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 16 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 17 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 18 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 19 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 20 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 21 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 22 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 23 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 24 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| Sum | | 1,200,593 | | | | 662,074 | 46,878 | 206,573 | 915,525 | 152,982 |
| Ave | | 137 | 0.572 | 48% | 0.33 | 76 | 5.4 | 24 | 105 | 187 |
| Max | | 255 | 1 | 51% | 1.23 | 139 | 22.5 | 42 | 202 | 204 |
| Min | | 0 | 0 | 0% | 0.00 | 0 | 0.0 | 0 | 0 | 0 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# First Year Electric Cost

**Results**

| | Proposed |
|---|---|
| Annual Electric Use Charges | $883,373 |
| Annual Electric Demand Charges | $223,134 |
| Annual Electric Expense | $1,106,507 |

**Rate Schedule**

| | |
|---|---|
| Select current rate schedule | E-19A |
| Select voltage type | Secondary |

| | | Secondary | Primary | Transmission | **Secondary** |
|---|---|---|---|---|---|
| Identifier | Total Demand Rates | $/kW | $/kW | $/kW | $/kW |
| 1 | Peak Summer | 11.54 | 10.43 | 8.13 | 11.54 |
| 2 | Part-Peak Summer | 2.64 | 2.39 | 1.84 | 2.64 |
| 3 | Maximum Summer | 6.62 | 5.63 | 3.72 | 6.62 |
| 4 | Part-Peak Winter | 0.99 | 0.74 | - | 0.99 |
| 5 | Maximum Winter | 6.62 | 5.63 | 3.72 | 6.62 |
| Identifier | Total Energy Rates | $/kWh | $/kWh | $/kWh | $/kWh |
| 1 | Peak Summer | 0.13286 | 0.13251 | 0.09801 | 0.13286 |
| 2 | Part-Peak Summer | 0.09095 | 0.08912 | 0.07843 | 0.09095 |
| 3 | Off-Peak Summer | 0.07383 | 0.07040 | 0.06674 | 0.07383 |
| 4 | Part-Peak Winter | 0.08095 | 0.07653 | 0.07134 | 0.08095 |
| 5 | Off-Peak Winter | 0.07127 | 0.06700 | 0.06326 | 0.07127 |

These rates are applicable for the time period:
**Jan 1, 2008 to Present**

**Hourly Energy Rate Calculations**

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge Proposed |
|---|---|---|---|
| | | | $ |
| 1-Jan | 1 | 5 | $92.12 |
| 1-Jan | 2 | 5 | $92.11 |
| 1-Jan | 3 | 5 | $92.11 |
| 1-Jan | 4 | 5 | $92.10 |
| 1-Jan | 5 | 5 | $92.09 |
| 1-Jan | 6 | 5 | $92.09 |
| 1-Jan | 7 | 5 | $92.09 |
| 1-Jan | 8 | 5 | $92.07 |
| 1-Jan | 9 | 4 | $104.59 |
| 1-Jan | 10 | 4 | $104.59 |
| 1-Jan | 11 | 4 | $104.62 |
| 1-Jan | 12 | 4 | $92.93 |
| 30-Jun | 13 | 1 | $173.37 |
| 30-Jun | 14 | 1 | $173.44 |
| 30-Jun | 15 | 1 | $173.41 |
| 30-Jun | 16 | 1 | $173.31 |
| 30-Jun | 17 | 1 | $173.40 |
| 30-Jun | 18 | 1 | $173.18 |
| 30-Jun | 19 | 2 | $118.70 |
| 30-Jun | 20 | 2 | $118.43 |
| 30-Jun | 21 | 2 | $118.28 |
| 30-Jun | 22 | 3 | $88.47 |
| 30-Jun | 23 | 3 | $86.69 |
| 30-Jun | 24 | 3 | $83.33 |
| 1-Jul | 1 | 3 | $95.96 |
| 1-Jul | 2 | 3 | $95.95 |
| 1-Jul | 3 | 3 | $96.20 |
| 1-Jul | 4 | 3 | $84.86 |
| 1-Jul | 5 | 3 | $84.94 |
| 1-Jul | 6 | 3 | $84.97 |

**Hourly Demand Charge Calculations**

| Hourly Demand | Demand Charge by Rate Period | | | | |
|---|---|---|---|---|---|
| | Proposed | | | | |
| Proposed | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| kW | $ | $ | $ | $ | $ |
| 1,293 | | | $8,557 | | $8,557 |
| 1,292 | | | $8,556 | | $8,556 |
| 1,292 | | | $8,555 | | $8,555 |
| 1,292 | | | $8,555 | | $8,555 |
| 1,292 | | | $8,554 | | $8,554 |
| 1,292 | | | $8,554 | | $8,554 |
| 1,292 | | | $8,554 | | $8,554 |
| 1,292 | | | | | $8,552 |
| 1,292 | | | | $1,279 | $8,553 |
| 1,292 | | | | $1,279 | $8,554 |
| 1,292 | | | | $1,279 | $8,556 |
| 1,148 | | | | $1,137 | $7,600 |
| 1,305 | | | | | $8,638 |
| 1,305 | | | | | $8,642 |
| 1,305 | $15,062 | | $8,641 | | $8,641 |
| 1,304 | $15,053 | | $8,635 | | $8,635 |
| 1,305 | $15,061 | | $8,640 | | $8,640 |
| 1,304 | $15,043 | | $8,629 | | $8,629 |
| 1,305 | | $3,445 | $8,640 | | $8,640 |
| 1,302 | | $3,438 | $8,620 | | $8,620 |
| 1,300 | | $3,433 | $8,609 | | $8,609 |
| 1,198 | | | $7,933 | | $7,933 |
| 1,174 | | | $7,773 | | $7,773 |
| 1,129 | | | $7,472 | | $7,472 |
| 1,300 | | | $8,604 | | $8,604 |
| 1,300 | | | $8,603 | | $8,603 |
| 1,303 | | | $8,626 | | $8,626 |
| 1,149 | | | $7,609 | | $7,609 |
| 1,151 | | | $7,616 | | $7,616 |
| 1,151 | | | $7,619 | | $7,619 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge Proposed | Hourly Demand Proposed | Demand Charge by Rate Period Proposed: Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
|---|---|---|---|---|---|---|---|---|---|
| | | | $ | kW | $ | $ | $ | $ | $ |
| 1-Jul | 7 | 3 | $96.20 | 1,303 | | | $8,626 | | $8,626 |
| 1-Jul | 8 | 3 | $95.91 | 1,299 | | | $8,600 | | $8,600 |
| 1-Jul | 9 | 2 | $118.29 | 1,301 | | $3,434 | $8,610 | | $8,610 |
| 1-Jul | 10 | 2 | $118.35 | 1,301 | | $3,435 | $8,614 | | $8,614 |
| 1-Jul | 11 | 2 | $118.88 | 1,307 | | $3,451 | $8,653 | | $8,653 |
| 1-Jul | 12 | 2 | $118.97 | 1,308 | | $3,453 | $8,659 | | $8,659 |
| 31-Dec | 13 | 4 | $93.06 | 1,150 | | | $7,611 | $1,138 | $7,611 |
| 31-Dec | 14 | 4 | $93.18 | 1,151 | | | $7,620 | $1,140 | $7,620 |
| 31-Dec | 15 | 4 | $93.18 | 1,151 | | | $7,620 | $1,140 | $7,620 |
| 31-Dec | 16 | 4 | $93.18 | 1,151 | | | $7,620 | $1,140 | $7,620 |
| 31-Dec | 17 | 4 | $93.18 | 1,151 | | | $7,620 | $1,140 | $7,620 |
| 31-Dec | 18 | 4 | $93.15 | 1,151 | | | $7,618 | $1,139 | $7,618 |
| 31-Dec | 19 | 4 | $93.13 | 1,151 | | | $7,616 | $1,139 | $7,616 |
| 31-Dec | 20 | 4 | $93.10 | 1,150 | | | $7,614 | $1,139 | $7,614 |
| 31-Dec | 21 | 4 | $93.06 | 1,150 | | | $7,610 | $1,138 | $7,610 |
| 31-Dec | 22 | 5 | $81.88 | 1,149 | | | $7,606 | | $7,606 |
| 31-Dec | 23 | 5 | $81.84 | 1,148 | | | $7,601 | | $7,601 |
| 31-Dec | 24 | 5 | $81.78 | 1,148 | | | $7,597 | | $7,597 |
| | | Sum | $883,373 | 10,783,741 | | | | | |
| | | Ave | $100.84 | 1231.0 | $14,941 | $3,350 | $8,149 | $1,166 | $8,149 |
| | | Max | $174.32 | 1312.0 | $15,141 | $3,462 | $8,686 | $1,291 | $8,686 |
| | | Min | $80.44 | 1128.7 | $13,025 | $2,980 | $7,472 | $1,117 | $7,472 |

**Monthly Demand Charge Calculations**

| Month | Actual Demand Charge per Rate Period Proposed: Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
|---|---|---|---|---|---|
| | $ | $ | $ | $ | $ |
| Jan | N/A | N/A | N/A | 1,290 | 8,625 |
| Feb | N/A | N/A | N/A | 1,290 | 8,632 |
| Mar | N/A | N/A | N/A | 1,290 | 8,625 |
| Apr | N/A | N/A | N/A | 1,291 | 8,636 |
| May | 15,134 | 3,455 | 8,682 | N/A | N/A |
| Jun | 15,129 | 3,461 | 8,680 | N/A | N/A |
| Jul | 15,141 | 3,461 | 8,686 | N/A | N/A |
| Aug | 15,129 | 3,457 | 8,679 | N/A | N/A |
| Sep | 15,103 | 3,452 | 8,679 | N/A | N/A |
| Oct | 15,141 | 3,462 | 8,686 | N/A | N/A |
| Nov | N/A | N/A | N/A | 1,290 | 8,628 |
| Dec | N/A | N/A | N/A | 1,290 | 8,630 |
| Sum | 90,777 | 20,748 | 52,090 | 7,741 | 51,777 |
| Ave | 15,130 | 3,458 | 8,682 | 1,290 | 8,629 |
| Max | 15,141 | 3,462 | 8,686 | 1,291 | 8,636 |
| Min | 15,103 | 3,452 | 8,679 | 1,290 | 8,625 |

# Annual Total Gas Energy Use

**Assumptions**
All gas use comes from the heating plant.

**Hourly Calculations**

| Date | Hour | Heating Plant Energy Use |
|---|---|---|
| | | Proposed |
| | | therms |
| 1-Jan | 1 | 0.00 |
| 1-Jan | 2 | 0.00 |
| 1-Jan | 3 | 0.00 |
| 1-Jan | 4 | 0.00 |
| 30-Jun | 13 | 0.00 |
| 30-Jun | 14 | 0.00 |
| 30-Jun | 15 | 0.00 |
| 30-Jun | 16 | 0.00 |
| 30-Jun | 17 | 0.00 |
| 30-Jun | 18 | 0.00 |
| 30-Jun | 19 | 0.00 |
| 30-Jun | 20 | 0.00 |
| 30-Jun | 21 | 0.00 |
| 30-Jun | 22 | 0.00 |
| 30-Jun | 23 | 0.00 |
| 30-Jun | 24 | 0.00 |
| 1-Jul | 1 | 0.00 |
| 1-Jul | 2 | 0.00 |
| 1-Jul | 3 | 0.00 |
| 1-Jul | 4 | 0.00 |
| 1-Jul | 5 | 0.00 |
| 1-Jul | 6 | 0.00 |
| 1-Jul | 7 | 0.00 |
| 1-Jul | 8 | 0.00 |
| 1-Jul | 9 | 0.00 |
| 1-Jul | 10 | 0.00 |
| 1-Jul | 11 | 0.00 |
| 1-Jul | 12 | 0.00 |
| 31-Dec | 13 | 0.00 |
| 31-Dec | 14 | 0.00 |
| 31-Dec | 15 | 0.00 |
| 31-Dec | 16 | 0.00 |
| 31-Dec | 17 | 0.00 |
| 31-Dec | 18 | 0.00 |
| 31-Dec | 19 | 0.00 |
| 31-Dec | 20 | 0.00 |
| 31-Dec | 21 | 0.00 |
| 31-Dec | 22 | 0.00 |
| 31-Dec | 23 | 0.00 |
| 31-Dec | 24 | 0.00 |
| | Sum | 0.00 |
| | Ave | 0.00 |
| | Max | 0.00 |
| | Min | 0.00 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# First Year Gas Cost

**Gas Use (therms)**

| | Proposed | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | 0 | | 0 |
| Feb | 0 | | 0 |
| Mar | 0 | | 0 |
| Apr | 0 | 0 | |
| May | 0 | 0 | |
| Jun | 0 | 0 | |
| Jul | 0 | 0 | |
| Aug | 0 | 0 | |
| Sep | 0 | 0 | |
| Oct | 0 | 0 | |
| Nov | 0 | | 0 |
| Dec | 0 | | 0 |
| Sum | 0 | 0 | 0 |
| Ave | 0 | 0 | 0 |
| Max | 0 | 0 | 0 |
| Min | 0 | 0 | 0 |

**Gas Cost**

| | Proposed | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | | | $0 |
| Feb | | | $0 |
| Mar | | | $0 |
| Apr | | $0 | |
| May | | $0 | |
| Jun | | $0 | |
| Jul | | $0 | |
| Aug | | $0 | |
| Sep | | $0 | |
| Oct | | $0 | |
| Nov | | | $0 |
| Dec | | | $0 |

Annual Totals: $0

# Incremental Cost of Implementation

| *Description* | *Cost* | *Source* |
|---|---|---|
| **Baseline** | | |
| Ten CHW air hanlders, installed. | $254,000 | $25,400 per VAV AHU (15,000 cfm unit), as per RS Means 2008, 23-73-13-2360, for San Jose. |
| **Proposed** | | |
| Ten VAV CHW air handlers with economizers, installed. | $304,800 | $25,400 per VAV AHU (15,000 cfm unit), as per RS Means 2008, 23-73-13-2360, for San Jose. Includes an assumed 20% cost increase for economizer. |
| **Incremental Cost** | | |
| Difference between baseline & proposed | $50,800 | Difference between proposed and baseline. |

# Life Cycle Cost

**Template:** **Life Cycle Cost_v2.0**

**General Notes**
Negative values are expenses, positive values are income or savings.

**Costs, in Year Zero dollars.**

| | Baseline | Proposed | Difference | Source |
|---|---|---|---|---|
| First Cost | | | -$50,800 | See Implementation Cost sheet. |
| Annual Electric Cost | -$1,187,233 | -$1,106,507 | $80,726 | See Electric Cost sheet. |
| Annual Gas Cost | $0 | $0 | $0 | See Gas Cost sheet. |
| Annual Energy Cost | -$1,187,233 | -$1,106,507 | $80,726 | Sum previous two lines. |
| Annual Material Cost | | | -$500 | Estimated incremental cost of AHU air filters. |
| Annual Labor Cost | | | -$2,000 | Estimate of incremental air handler maintenance cost. |

**Incentive**

| | | |
|---|---|---|
| Estimated total incentive for this project | $25,400 | See the Summary sheet. |

**Financial Parameters**

| | | |
|---|---|---|
| Cost of Borrowed Capital | 7.0% | Typical assumption. |
| Highest-Yielding Current Investment Opportunity | 8.0% | Typical assumption. |
| Discount Rate | 8.0% | Greater of previous two lines. |
| Inflation in Prices of Energy | | |
| Natural Gas Rate | 6.0% | Assumed. |
| Average Inflation of Electric Use and Electric Demand Rates | 3.0% | Assumed. |
| Escalation in Material Costs | 3.0% | Assumed. |
| Inflation in Price of Labor | 3.0% | Assumed. |

**Life Cycle Costs, Adjusted for Inflation**

| Year | Annual Energy Costs | | Differences | | | | |
|---|---|---|---|---|---|---|---|
| | Baseline | Proposed | Energy | Material | Labor | Total | |
| 0 | | | | | | -$50,800 | First Cost |
| 1 | -$1,222,850 | -$1,139,702 | $83,148 | -$515 | -$2,060 | $80,573 | |
| 2 | -$1,259,536 | -$1,173,893 | $85,642 | -$530 | -$2,122 | $82,990 | |
| 3 | -$1,297,322 | -$1,209,110 | $88,211 | -$546 | -$2,185 | $85,480 | |
| 4 | -$1,336,241 | -$1,245,383 | $90,858 | -$563 | -$2,251 | $88,044 | |
| 5 | -$1,376,329 | -$1,282,745 | $93,584 | -$580 | -$2,319 | $90,685 | |
| 6 | -$1,417,618 | -$1,321,227 | $96,391 | -$597 | -$2,388 | $93,406 | |
| 7 | -$1,460,147 | -$1,360,864 | $99,283 | -$615 | -$2,460 | $96,208 | |
| 8 | -$1,503,951 | -$1,401,690 | $102,261 | -$633 | -$2,534 | $99,094 | |
| 9 | -$1,549,070 | -$1,443,741 | $105,329 | -$652 | -$2,610 | $102,067 | |
| 10 | -$1,595,542 | -$1,487,053 | $108,489 | -$672 | -$2,688 | $105,129 | |
| 11 | -$1,643,408 | -$1,531,665 | $111,744 | -$692 | -$2,768 | $108,283 | |
| 12 | -$1,692,710 | -$1,577,614 | $115,096 | -$713 | -$2,852 | $111,532 | |
| 13 | -$1,743,492 | -$1,624,943 | $118,549 | -$734 | -$2,937 | $114,878 | |
| 14 | -$1,795,797 | -$1,673,691 | $122,105 | -$756 | -$3,025 | $118,324 | |
| 15 | -$1,849,670 | -$1,723,902 | $125,768 | -$779 | -$3,116 | $121,874 | |
| 16 | -$1,905,161 | -$1,775,619 | $129,542 | -$802 | -$3,209 | $125,530 | |
| 17 | -$1,962,315 | -$1,828,888 | $133,428 | -$826 | -$3,306 | $129,296 | |
| 18 | -$2,021,185 | -$1,883,754 | $137,431 | -$851 | -$3,405 | $133,175 | |
| 19 | -$2,081,820 | -$1,940,267 | $141,554 | -$877 | -$3,507 | $137,170 | |
| 20 | -$2,144,275 | -$1,998,475 | $145,800 | -$903 | -$3,612 | $141,285 | |

**Proposed Measure(s) vs Baseline**

| | | |
|---|---|---|
| Simple Payback | 0.3 | years |
| Relative Net Present Value | $936,220 | |
| Internal Rate of Return | 162% | |

# CHW AHUs with Air Side Economizing

## CEC Zone 11 (Redding)

# Annual Total Electric Energy Use, Proposed

**Assumptions**

This scenario assumes seven 500 kVa modules. The efficiencies for the modules are drawn from Powersmith data sheets. Where data points were not provided we have estimated values according to a standard transformer curve profile. We assume that the number, size, and efficiency of the modules are the same for the baseline and proposed case.

We assume that all active transformer modules are loaded to an equal percentage.

All transformers are assumed to be of the linear type.

The power factor is assumed to be 1.00 (kW = kVA).

Transformers are not located in an air-conditioned space, so they do not impose a cooling load.

The transformers serve the rack, UPS, lighting, and chilled water plant loads.

**Input Parameters**

| | | | |
|---|---|---|---|
| Transformer Module Size: | 500 | kVA | See Transformers sheet |

**Annual Energy Use**

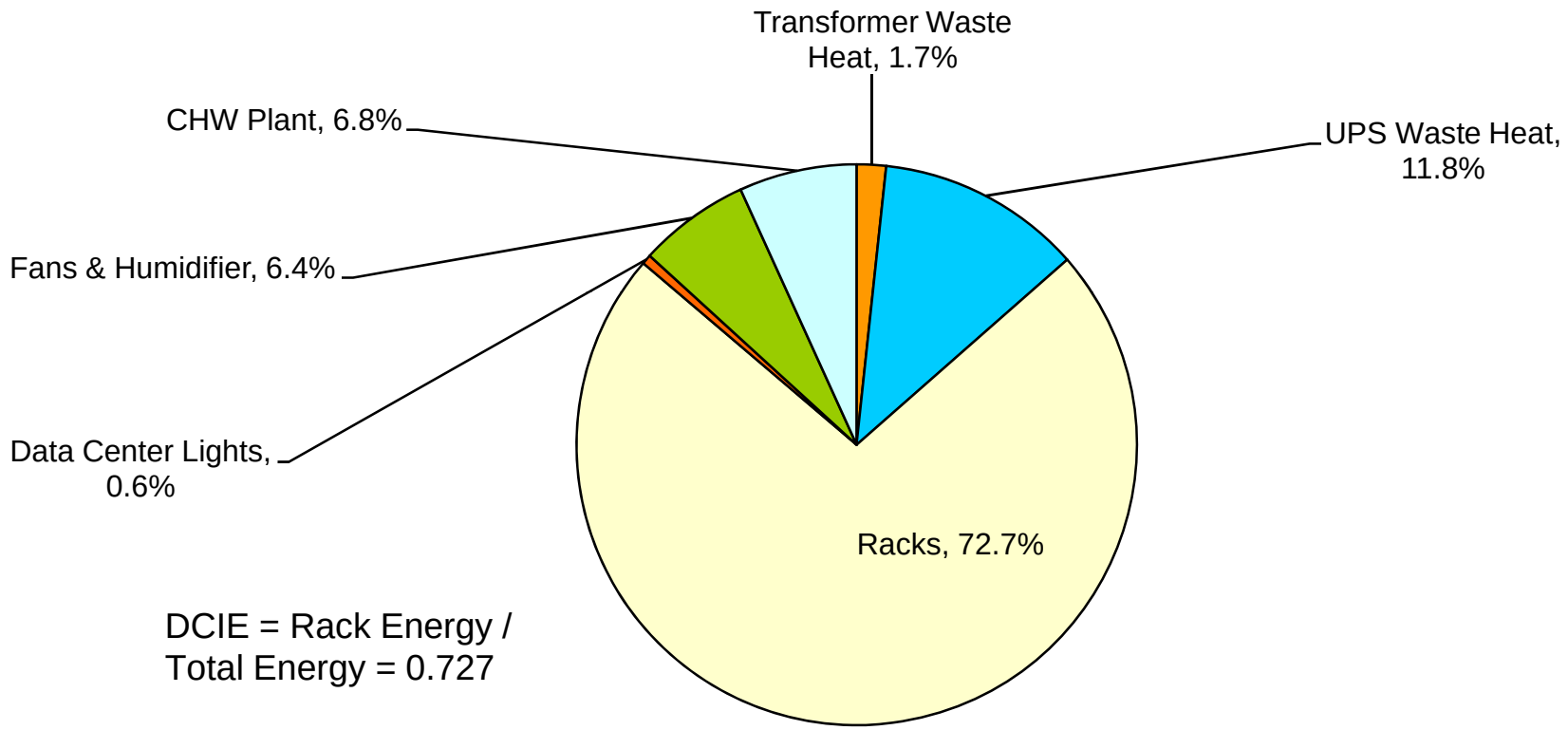
| System | Proposed | |
|---|---|---|
| | kWh/yr | Percent of Total |
| Transformer Waste Heat | 179,649 | 1.7% |
| UPS Waste Heat | 1,256,917 | 11.8% |
| Racks | 7,721,064 | 72.7% |
| Data Center Lights | 59,393 | 0.6% |
| Fans & Humidifier | 682,610 | 6.4% |
| CHW Plant | 721,540 | 6.8% |
| Total | 10,621,172 | 100.0% |

**Hourly Calculations**

| Date | Hour | Required Transformer Output Power | | | | | Transformer Modules | | | Transformer Total Input Power Demand | Trans-former Waste Heat | Peak Summer Power Demand |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | UPS Input Power | Data Center Lights | Fans and Humidifier | CHW Plant | Total | Quant. | Load Factor | Module Effic. | | | |
| | | kW | kW | kW | kW | kW | | % | % | kW | kW | kW |
| 1-Jan | 1 | 1,025 | 7 | 55 | 182 | 1,268 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 2 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 3 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 4 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 5 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 6 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 7 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 8 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 9 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 10 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 11 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 12 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 30-Jun | 13 | 1,025 | 7 | 55 | 192 | 1,278 | 3 | 85% | 98.2% | 1,302 | 24 | 1,302 |
| 30-Jun | 14 | 1,025 | 7 | 55 | 192 | 1,278 | 3 | 85% | 98.2% | 1,302 | 24 | 1,302 |
| 30-Jun | 15 | 1,025 | 7 | 55 | 192 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | 1,303 |
| 30-Jun | 16 | 1,025 | 7 | 55 | 192 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | 1,303 |
| 30-Jun | 17 | 1,025 | 7 | 55 | 192 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | 1,303 |
| 30-Jun | 18 | 1,025 | 7 | 55 | 192 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | 1,303 |
| 30-Jun | 19 | 1,025 | 7 | 55 | 192 | 1,279 | 3 | 85% | 98.2% | 1,302 | 24 | n/a |
| 30-Jun | 20 | 1,025 | 7 | 55 | 191 | 1,277 | 3 | 85% | 98.2% | 1,301 | 24 | n/a |
| 30-Jun | 21 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 30-Jun | 22 | 1,025 | 7 | 80 | 110 | 1,222 | 3 | 81% | 98.2% | 1,245 | 23 | n/a |
| 30-Jun | 23 | 1,025 | 7 | 80 | 110 | 1,222 | 3 | 81% | 98.2% | 1,245 | 23 | n/a |
| 30-Jun | 24 | 1,025 | 7 | 80 | 96 | 1,208 | 3 | 81% | 98.2% | 1,230 | 23 | n/a |
| 1-Jul | 1 | 1,025 | 7 | 80 | 73 | 1,185 | 3 | 79% | 98.4% | 1,204 | 19 | n/a |
| 1-Jul | 2 | 1,025 | 7 | 80 | 79 | 1,191 | 3 | 79% | 98.4% | 1,210 | 19 | n/a |
| 1-Jul | 3 | 1,025 | 7 | 80 | 68 | 1,180 | 3 | 79% | 98.4% | 1,199 | 19 | n/a |
| 1-Jul | 4 | 1,025 | 7 | 80 | 69 | 1,180 | 3 | 79% | 98.4% | 1,199 | 19 | n/a |
| 1-Jul | 5 | 1,025 | 7 | 80 | 87 | 1,199 | 3 | 80% | 98.4% | 1,218 | 19 | n/a |
| 1-Jul | 6 | 1,025 | 7 | 80 | 110 | 1,222 | 3 | 81% | 98.2% | 1,245 | 23 | n/a |
| 1-Jul | 7 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 1-Jul | 8 | 1,025 | 7 | 55 | 190 | 1,277 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 1-Jul | 9 | 1,025 | 7 | 55 | 190 | 1,277 | 3 | 85% | 98.2% | 1,301 | 24 | n/a |
| 1-Jul | 10 | 1,025 | 7 | 55 | 191 | 1,278 | 3 | 85% | 98.2% | 1,301 | 24 | n/a |
| 1-Jul | 11 | 1,025 | 7 | 55 | 192 | 1,278 | 3 | 85% | 98.2% | 1,302 | 24 | n/a |
| 1-Jul | 12 | 1,025 | 7 | 55 | 193 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | n/a |
| 31-Dec | 13 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 14 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 15 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 16 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 17 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 18 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 19 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 20 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 21 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 22 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 23 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 24 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| Sum | | 8,977,981 | 59,393 | 682,610 | 721,540 | 10,441,523 | | | | 10,621,172 | 179,649 | 1,044,923 |
| Ave | | 1,025 | 7 | 78 | 82 | 1,192 | 3.00 | 79% | 98.3% | 1,212 | 21 | 1,281 |
| Max | | 1,025 | 7 | 101 | 199 | 1,286 | 3 | 86% | 98.5% | 1,310 | 24 | 1,310 |
| Min | | 1,025 | 7 | 55 | 0 | 1,112 | 3 | 74% | 98.2% | 1,129 | 17 | 1,129 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# Data Center Infrastructure Efficiency (DCIE)
# Proposed




DCIE = Rack Energy / Total Energy = 0.727

# Space Parameters

**Assumptions**
Chilled water CRAC values are based on the Liebert Deluxe System 3, Model 740C.

| | Proposed | Units | Sources |
|---|---|---|---|
| **Input Parameters** | | | |
| ***Space Dimensions*** | | | |
| Floor Area | 6,780 | sf | Email from Dave Shroyer, 10/13/08. |
| ***Occupancy Schedule*** | | | |
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | Datacenter assumed to operate 8,760 hours per year |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | Datacenter assumed to operate 8,760 hours per year |
| ***HVAC System Type & Setpoints*** | | | |
| Air Delivery System | VAV | | The proposed system uses VAV air handlers. |
| Return Air Drybulb Setpoint | 89.5 | °F | Selected to get a 22 deg-F delta-T, email from Rupa Ganguly on 9/30/08. |
| Supply Air Drybulb Setpoint (VAV Systems Only) | 67.5 | °F | Estimate from email from Rupa Ganguly on 9/30/08. |
| Supply Air Design Flow Rate (CAV Systems Only) | | cfm | Total air flow provided by selected number & size of CRAC units and expected total static pressure drop of open HACA arrangement. |
| Active Humidity Control? | no | | Humidity control is baseline practice. The proposed facility will have no active humidity control. |
| Drybulb Temp at RH Sensor Location | 89.5 | °F | Humidity sensor is assumed to be mounted on the data center ceiling. |
| Allowed Relative Humidity, Maximum | 100% | RH | Assumed based on no humidity control. |
| Allowed Relative Humidity, Minimum | 1% | RH | Assumed based on no humidity control. |
| CHWST Setpoint, Primary | 44 | °F | Baseline CHWST setpoint value. |
| CHWST Setpoint, Secondary | 44 | °F | We are not considering CHWST reset. |
| Adiabatic Humdifier Power Draw | 0.000 | kW/ (lb of H20/hr) | No adiabatic humidifier. |

| | Proposed | Units | Sources |
|---|---|---|---|
| ***Cooling Load*** | | | |
| Total Rack Load, Occupied | 881 | kW | Calculated from rack load of 130 W/sf, email from Dave Shroyer, 10/13/08. |
| Total Rack Load, Unoccupied | n/a | kW | Rack load does not vary with occupancy. |
| Average Lighting Density | 1.0 | W/sf | Typical value. |
| ***Ventilation Requirement*** | | | |
| Minimum Ventilation Requirement | 0.15 | cfm/sf | CA Title 24 requirement for office space. |
| ***Boiler Data*** | | | |
| HHW Boiler Efficiency | 82% | % | Baseline value. |
| Gas-fired Humidifier Efficiency | 76% | % | Baseline value. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| ***HVAC System Type & Setpoints*** | | | |
| Occupied Supply Air Drybulb | | °F | = RAT - Occupied Load / (1.08 * cfm) |
| Unoccupied Supply Air Drybulb | | °F | A datacenter is assumed always occupied. |
| Occupied Supply Air Flow Rate | 127,545 | cfm | = Load / (1.08 * Delta-T) |
| Unoccupied Suppllly Air Flow Rate | n/a | | A datacenter is assumed always occupied. |
| Air Side Delta-T | 22 | °F | Subtract |
| ***Cooling Load*** | | | |
| UPS Waste Heat | 0 | kW | From UPS calculation sheet. The UPS units are in conditioned space, so the UPS waste heat is a load on the cooling system. |
| Data Center Lights | 7 | kW | Average lighting density times space floor area. |
| Total Internal Load, Occupied | 888 | kW | Rack load, UPS waste heat, lights. |
| Total Internal Load, Occupied | 253 | tons | Convert to tons |
| Total Internal Load, Occupied | 3,030 | kBTU/hr | Convert to kBTU/hr |
| Average Internal Load Density, Occupied | 131 | W/sf | Divide by floor area |
| Total Internal Load, Unoccupied | n/a | kW | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | tons | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | kBTU/hr | A datacenter is assumed always occupied. |
| Average Internal Load Density, Unoccupied | n/a | W/sf | A datacenter is assumed always occupied. |
| ***Ventilation Requirement*** | | | |
| Min Allowed Ventilation Volumetric Air Flow Rate | 1,017 | cfm | Floor area times minimum ventilation requirement. |

# Weather Data

Source: California Energy Commission
Data Set: California Climate Zone 11 (CZ11RV2) - Redding

| Date | Hour | Outside Air | | | | | |
|---|---|---|---|---|---|---|---|
| | | Drybulb Temp. | Dewpoint Temp. | Relative Humidity | Atmospheric Pressure | Wetbulb Temp. | Enthalpy |
| | | °F | °F | % | psia | °F | BTU/lb |
| 1-Jan | 1 | 33.8 | 36.3 | 89% | 14.4 | 32.6 | 12.1 |
| 1-Jan | 2 | 39.6 | 36.7 | 89% | 14.4 | 38.2 | 14.5 |
| 1-Jan | 3 | 40.1 | 37.2 | 89% | 14.4 | 38.7 | 14.7 |
| 1-Jan | 4 | 40.3 | 37.4 | 89% | 14.4 | 38.9 | 14.8 |
| 1-Jan | 5 | 39.6 | 37.2 | 91% | 14.4 | 38.5 | 14.6 |
| 1-Jan | 6 | 37.6 | 36.1 | 94% | 14.4 | 36.9 | 13.9 |
| 1-Jan | 7 | 36.0 | 34.9 | 96% | 14.4 | 35.5 | 13.3 |
| 1-Jan | 8 | 36.5 | 36.0 | 98% | 14.4 | 36.3 | 13.6 |
| 1-Jan | 9 | 37 | | | | 36.9 | 13.9 |
| 1-Jan | 10 | 37 | | | | 37.4 | 14.1 |
| 1-Jan | 11 | 39 | | | | 38.9 | 14.8 |
| 1-Jan | 12 | 41 | | | | 40.6 | 15.6 |
| 30-Jun | 13 | 89 | | | | 62.3 | 28.1 |
| 30-Jun | 14 | 90 | | | | 62.4 | 28.2 |
| 30-Jun | 15 | 91 | | | | 62.9 | 28.5 |
| 30-Jun | 16 | 92.1 | 43.2 | 18% | 14.3 | 62.9 | 28.6 |
| 30-Jun | 17 | 90.7 | 43.7 | 20% | 14.3 | 63.0 | 28.7 |
| 30-Jun | 18 | 89.6 | 44.6 | 21% | 14.3 | 62.8 | 28.5 |
| 30-Jun | 19 | 89.2 | 46.2 | 23% | 14.3 | 63.4 | 29.0 |
| 30-Jun | 20 | 82.4 | 43.3 | 25% | 14.3 | 59.7 | 26.4 |
| 30-Jun | 21 | 78.4 | 43.3 | 29% | 14.3 | 58.5 | 25.5 |
| 30-Jun | 22 | 76.6 | 45.5 | 33% | 14.3 | 58.5 | 25.6 |
| 30-Jun | 23 | 75.2 | 45.0 | 34% | 14.3 | 57.8 | 25.1 |
| 30-Jun | 24 | 73.8 | 45.5 | 36% | 14.3 | 57.3 | 24.8 |
| 1-Jul | 1 | 72.3 | 40.1 | 31% | 14.3 | 54.7 | 23.2 |
| 1-Jul | 2 | 71.1 | 40.3 | 33% | 14.2 | 54.4 | 23.0 |
| 1-Jul | 3 | 70.3 | 41.2 | 35% | 14.2 | 54.4 | 23.1 |
| 1-Jul | 4 | 70.3 | 42.4 | 36% | 14.2 | 54.7 | 23.3 |
| 1-Jul | 5 | 71.6 | 41.4 | 33% | 14.2 | 54.8 | 23.3 |
| 1-Jul | 6 | 75.2 | 42.6 | 31% | 14.2 | 56.8 | 24.5 |
| 1-Jul | 7 | 78.8 | 43.9 | 29% | 14.2 | 58.6 | 25.8 |
| 1-Jul | 8 | 83.5 | 40.1 | 22% | 14.2 | 59.2 | 26.1 |
| 1-Jul | 9 | 88.2 | 36.5 | 16% | 14.2 | 59.5 | 26.3 |
| 1-Jul | 10 | 92.8 | 32.7 | 12% | 14.2 | 60.2 | 26.7 |
| 1-Jul | 11 | 95.2 | 34.7 | 12% | 14.2 | 61.5 | 27.6 |
| 1-Jul | 12 | 97.5 | 36.9 | 12% | 14.2 | 62.8 | 28.6 |
| 31-Dec | 13 | 41.2 | 37.2 | 86% | 14.5 | 39.4 | 15.0 |
| 31-Dec | 14 | 42.6 | 38.7 | 86% | 14.5 | 40.8 | 15.6 |
| 31-Dec | 15 | 45.3 | 41.4 | 86% | 14.5 | 43.4 | 16.9 |
| 31-Dec | 16 | 43.9 | 39.9 | 86% | 14.5 | 42.0 | 16.2 |
| 31-Dec | 17 | 43.9 | 39.9 | 86% | 14.5 | 42.0 | 16.2 |
| 31-Dec | 18 | 42.6 | 40.6 | 93% | 14.5 | 41.7 | 16.1 |
| 31-Dec | 19 | 42.3 | 40.3 | 93% | 14.5 | 41.4 | 15.9 |
| 31-Dec | 20 | 41.4 | 39.4 | 93% | 14.5 | 40.5 | 15.5 |
| 31-Dec | 21 | 40.6 | 39.7 | 97% | 14.5 | 40.3 | 15.4 |
| 31-Dec | 22 | 39.9 | 39.9 | 100% | 14.5 | 39.9 | 15.2 |
| 31-Dec | 23 | 39.4 | 38.8 | 98% | 14.5 | 39.1 | 14.9 |
| 31-Dec | 24 | 39.2 | 37.6 | 94% | 14.5 | 38.5 | 14.6 |
| | Ave | 60.8 | 39.9 | 53% | 14.4 | 49.7 | 20.7 |
| | Max | 104.7 | 61.0 | 100% | 14.6 | 71.3 | 35.4 |
| | Min | 27.0 | 3.4 | 5% | 14.1 | 23.2 | 8.3 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

# Transformer Data

## Proposed

**Parameters**

| | | |
|---|---|---|
| Size | 500 | kVA |

Values in blue are from NEMA Standard TP-1 Transformer Efficiency, Three Phase (Table 4.2). All other values are extrapolated.

| **Linear Efficiency vs. Load Factor** | |
|---|---|
| Load | Efficiency |
| 100% | 97.9% |
| 90% | 98.2% |
| 80% | 98.4% |
| 75% | 98.5% |
| 70% | 98.6% |
| 60% | 98.8% |
| 50% | 98.8% |
| 40% | 98.8% |
| 35% | 98.7% |
| 30% | 98.6% |
| 25% | 98.5% |
| 20% | 98.3% |
| 17% | 98.2% |
| 10% | 97.7% |

# Chiller Data

**Assumptions**
The same chillers are used in the baseline and proposed cases.
We set the chillers to the same size.

**Parameters**

| | Proposed | Units | Sources |
|---|---|---|---|
| Chiller Capacity | 500 | tons | Capacity selected to result in a total of three chillers, with appropriate safety and redundancy factors. |
| Condenser Water Temperature | 80 | °F | Typical value. |
| CHW Supply Temperature | 44 | °F | Typical value. |
| CW Flow Rate | 1,200 | gpm | Assumes a 10F CW delta-T when chiller is a maximum load. |

Values from Baseline Water-Cooled Chilled Water Plant Above 300 tons

| **Chiller Efficiency (kW/ton) at CHWS Temp = 44 F** | |
|---|---|
| Load | Condenser Water Temp (°F) |
| | 80 |
| 100% | 0.529 |
| 90% | 0.526 |
| 80% | 0.526 |
| 70% | 0.530 |
| 60% | 0.539 |
| 50% | 0.557 |
| 40% | 0.590 |
| 30% | 0.653 |
| 20% | 0.792 |
| 10% | 1.234 |

# Cooling Tower Fan Speed Lookup Tables, Proposed

| | |
|---|---|
| Cooling Tower Make & Model Used in Analysis | BAC 3482A |

The following lookup tables were created by drawing information from BAC's Cooling Tower Selection Software, Release 6.02 NA. The fan speeds are expressed in percent.

Fan speed depends on the load on the tower, the condenser water flow rate, the ambient wetbulb temperature, and the temperature of the condenser water leaving the tower (aka the cold condenser water temperature). The lowest fan speed the BAC software wil

**Tower Specifications at Nominal Conditions**

| | | |
|---|---|---|
| Ambient Wetbulb Temperature | 78 | deg F |
| Hot Condenser Water Temperature | 95 | deg F |
| Cold Condenser Water Temperature | 88.7 | deg F |
| Condenser Water Flow Rate, Maximum | 2,600 | gpm |
| Condenser Water Flow Rate, Minimum | 609 | gpm |
| Nominal Cooling Tower Capacity | 679 | tons |
| Cooling Tower Fan Motor Size | 30 | hp |

## 50% Maximum Flow = 1300 gpm

**0 tons, 1300 gpm**

All temperatures in deg F

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**50 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**100 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**150 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**200 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**250 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**300 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

# UPS Energy Calculation

| UPS System Parameters | Proposed | Units | Comments |
|---|---|---|---|
| **UPS Module Data** | | | |
| Total Rack Load | 881 | kW | From Space sheet. |
| Percentage of Load Served by UPS | 100% | % | We assume all racks are backed up. |
| UPS Load | 881 | kW | Rack load times percentage of load served by UPS. |
| Number of Modules | 5 | | Assumed. |
| Unit Capacity | 500 | kVA | Assumed. |
| Total UPS Capacity | 2,500 | kVA | Unit capacity * number of units |
| Load Factor | 35% | % | UPS load / UPS capacity |
| UPS Efficiency | 86% | % | From LBNL Datacenter UPS benchmarking study. |
| **Energy Use** | | | |
| Annual Energy Use | 8,977,981 | kWh/yr | UPS load / UPS efficiency * 8760 hours |
| Peak Demand | 1,025 | kW | UPS load / UPS efficiency |

# Proposed Heating & Cooling Load, Fan Energy, Energy Savings

**Template:** **Air Handler Energy Model_Recirculation with Economizer_v10.3**

**Input Parameters**

| | | | |
|---|---|---|---|
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | From the Space Parameters sheet. |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | From the Space Parameters sheet. |
| Air Delivery System: CAV or VAV? | VAV | | From the Space Parameters sheet. |
| Return Air Drybulb Setpoint | 89.5 | F | From the Space Parameters sheet. |
| Active Humidity Control? | no | | From the Space Parameters sheet. |
| Drybulb Temp at RH Sensor Location | 89.5 | F | From the Space Parameters sheet. |
| Allowed Relative Humidity, Maximum | 100% | RH | From the Space Parameters sheet. |
| Allowed Relative Humidity, Minimum | 1% | RH | From the Space Parameters sheet. |
| Min Allowed Ventilation Air Flow Rate | 1,017 | cfm | From the Space Parameters sheet. |
| CHWST Setpoint, Primary | 44 | F | From the Space Parameters sheet. |
| CHWST Setpoint during Reset | 44 | F | From the Space Parameters sheet. |
| Adiabatic Humidifier Power Draw | 0.000 | kW/(lb of H20/hr) | From the Space Parameters sheet. |

| | | | |
|---|---|---|---|
| Humidifier: 0=None, 1=Electric, 2=Steam, 3=Adiabatic | 0 | | No active humidification in the proposed case. |
| Cooling Plant Type: 1=CHW, 2=DX | 1 | | There is a chilled water plant in the proposed case. |
| CHWST Reset: 0=No, 1=Yes | 0 | | No CHWST in the proposed case. |
| Economizer? | yes | | Proposed design includes integrated economizing. |
| Economizer Drybulb Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Drybulb Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Drybulb Upper Lockout | 78 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Dewpoint Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Dewpoint Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Dewpoint Upper Lockout | 55 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Enthalpy Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Enthalpy Lower Lockout | 0 | BTU/lb | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Enthalpy Upper Lockout | 29.75 | BTU/lb | Email from Rupa Ganguly on 9/30/08. |
| Economizer Relative Humidity Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| RH Lower Lockout | 20% | % | Email from Rupa Ganguly on 9/30/08. |
| RH Upper Lockout | 80% | % | Email from Rupa Ganguly on 9/30/08. |

| Fan System Parameters | | Supply | Relief | Units | Sources |
|---|---|---|---|---|---|
| Fan Motor Size, Nominal | | 30 | 50 | hp | Sized in accordance with calculated brake horsepower, below. |
| Number of Fans | | 10 | 5 | | Arbitrary numbers selected for model. Assuming one supply fan per RAHU. |
| Fan Efficiency | | 63.8% | 67.5% | % | Baseline fan efficiencies for motor sizes indicated. |
| Fan Drive Efficiency | | 95% | 95% | % | Typical value for belt drive. |
| Fan Motor Efficiency | | 92.5% | 93.2% | % | Baseline efficiencies. |
| VFD Efficiency | | 98% | 98% | % | Supply and relief fans assumed to be equipped with VFDs. |
| Fan Motor and Drive in Airstream? | | 1 | n/a | 1=yes, 0=no | Assumption. |
| Econ. In Min. Pos. | Total Static Pressure Drop | 2.00 | 8.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | n/a | F | Calculated based on maximum fan motor output power. |
| Economizer Open | Total Static Pressure Drop | 2.00 | 1.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | n/a | F | Calculated based on maximum fan motor output power. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| Return Air Minimum Dewpoint | 0.0 | F | Dewpoint of return air when RH sensor is at minimum allowed RH. |
| Space Dewpoint at Maximum Allowed Space Humidity | 89.5 | | Corresponds to Space DB and Max Allowed RH. |
| Chilled Water Minimum Temperature Requirement | 64.5 | F | If the cooling system is CHW, the cooling coil is assumed to have a constant approach temperature of 3 deg F. |

| Fan System Parameters | Supply | Relief | Units | Comments |
|---|---|---|---|---|
| Fan Motor Output Power, Maximum | 4.9 | 8.5 | kW | Per fan motor. This is the maximum output brake power each fan motor is called upon to deliver. |
| Fan Motor Output Power, Maximum | 6.6 | 11.4 | hp | Per fan motor. Converted from kW to hp. |

**Error Messages**

OK - RH minimum does not require humidifier. No humidifier identified.
OK - Chilled Water Supply Temperature Setpoint is low enough to perform required sensible and latent cooling.
OK - Supply Fan Motor Size Exceeds Maximum Required Supply Fan Motor Output
OK - Relief Fan Motor Size Exceeds Maximum Required Relief Fan Motor Output

**Results (Annual Totals)**

| | Proposed | Units |
|---|---|---|
| Cooling Energy Extracted from Airstream | 10,907,858 | kBTU/yr |
| Heating Energy Added to Airstream | 0 | kBTU/yr |
| Humidifier Energy Added to Airstream | 0 | kBTU/yr |

| | Proposed | Units |
|---|---|---|
| Humidifier Energy Required | n/a | kWh/yr |
| | n/a | therms/yr |
| Fan Motor Energy Required | 682,610 | kWh/yr |

**Hourly Calculations**

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Energy Required to Sensibly Cool Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | | | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | Supply | | Relief | | Total Power Input | | Electric | Steam | Adia-batic | |
| | | | | | | | | | | | | | | | | | | | Total Power Input | Air Deliv. Effic. | Total Power Input | Air Deliv. Effic. | | | | | | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | kBTU | kBTU | kBTU | kW | cfm/kW | kW | cfm/kW | kW | tons | kW | therms | kW | therms |
| 1-Jan | 1 | 127,545 | 67.5 | 67.5 | 67.5 | 36.3 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 36.3 | 44.0 | 2,969 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 247 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 2 | 127,545 | 67.5 | 67.5 | 67.5 | 36.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 36.7 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 37.2 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.2 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 37.4 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.4 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 37.2 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.2 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 36.1 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 36.1 | 44.0 | 2,973 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 34.9 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 34.9 | 44.0 | 2,972 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 36.0 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 36.0 | 44.0 | 2,972 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 36.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 36.7 | 44.0 | 2,973 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 37.4 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.4 | 44.0 | 2,973 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 38.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 38.7 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 40.3 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 40.3 | 44.0 | 2,977 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 42.6 | 1 | 0 | 0 | 0 | 1 | 1,017 | 89.5 | 42.6 | 44.0 | 3,031 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 42.8 | 1 | 0 | 0 | 1 | 1 | 1,017 | 89.5 | 42.8 | 44.0 | 3,032 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 43.0 | 1 | 0 | 0 | 1 | 1 | 1,017 | 89.5 | 43.0 | 44.0 | 3,032 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 43.2 | 1 | 0 | 0 | 1 | 1 | 1,017 | 89.5 | 43.2 | 44.0 | 3,033 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 17 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | 1 | 0 | 0 | 0 | 1 | 1,017 | 89.5 | 43.7 | 44.0 | 3,032 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 18 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.5 | 44.6 | 44.0 | 3,031 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 19 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.5 | 46.2 | 44.0 | 3,030 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 20 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.4 | 43.3 | 44.0 | 3,023 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 21 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.4 | 43.3 | 44.0 | 3,018 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 22 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 76.6 | 45.5 | 44.0 | 1,259 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 105 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 23 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 75.2 | 45.0 | 44.0 | 1,061 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 88 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 24 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 73.8 | 45.5 | 44.0 | 862 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 72 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 1 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 72.3 | 40.1 | 44.0 | 664 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 55 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 2 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 71.1 | 40.3 | 44.0 | 490 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 41 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 41.2 | 0 | 0 | 0 | 0 | 0 | 127,545 | 70.3 | 41.2 | 44.0 | 391 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 33 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 42.4 | 0 | 0 | 0 | 0 | 0 | 127,545 | 70.3 | 42.4 | 44.0 | 391 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 33 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 41.4 | 0 | 0 | 0 | 0 | 0 | 127,545 | 71.6 | 41.4 | 44.0 | 565 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 47 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 42.6 | 0 | 0 | 0 | 0 | 0 | 127,545 | 75.2 | 42.6 | 44.0 | 1,061 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 88 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 43.9 | 1 | 0 | 0 | 0 | 1 | 1,017 | 89.4 | 43.9 | 44.0 | 3,019 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 40.1 | 1 | 0 | 0 | 0 | 1 | 1,017 | 89.5 | 40.1 | 44.0 | 3,024 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 36.5 | 1 | 0 | 0 | 1 | 1 | 1,017 | 89.5 | 36.5 | 44.0 | 3,029 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 32.7 | 1 | 0 | 0 | 1 | 1 | 1,017 | 89.5 | 32.7 | 44.0 | 3,034 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 34.7 | 1 | 0 | 0 | 1 | 1 | 1,017 | 89.5 | 34.7 | 44.0 | 3,037 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 36.9 | 1 | 0 | 0 | 1 | 1 | 1,017 | 89.6 | 36.9 | 44.0 | 3,039 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 37.2 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.2 | 44.0 | 2,977 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 38.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 38.7 | 44.0 | 2,979 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 41.4 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 41.4 | 44.0 | 2,982 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Energy Required to Sensibly Cool Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | | | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | Supply | | Relief | | | | | | | |
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | Total Power Input | Air Deliv. Effic. | Total Power Input | Air Deliv. Effic. | Total Power Input | | Electric | Stea m | Adia-batic | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | kBTU | kBTU | kBTU | kW | cfm/kW | kW | cfm/kW | kW | tons | kW | therm s | kW | therms |
| 31-Dec | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 39.9 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.9 | 44.0 | 2,980 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 17 | 127,545 | 67.5 | 67.5 | 67.5 | 39.9 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.9 | 44.0 | 2,980 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 18 | 127,545 | 67.5 | 67.5 | 67.5 | 40.6 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 40.6 | 44.0 | 2,979 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 19 | 127,545 | 67.5 | 67.5 | 67.5 | 40.3 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 40.3 | 44.0 | 2,979 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 20 | 127,545 | 67.5 | 67.5 | 67.5 | 39.4 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.4 | 44.0 | 2,978 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 21 | 127,545 | 67.5 | 67.5 | 67.5 | 39.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.7 | 44.0 | 2,977 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 22 | 127,545 | 67.5 | 67.5 | 67.5 | 39.9 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.9 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 23 | 127,545 | 67.5 | 67.5 | 67.5 | 38.8 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 38.8 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 24 | 127,545 | 67.5 | 67.5 | 67.5 | 37.6 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.6 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| Sum | | | | | | | 1,433 | 199 | 298 | 2,406 | 3,394 | | | | | ######## | 0 | 0 | 478,182 | | 204,428 | | ###### | | 0 | 0 | 0 | 0 |
| Ave | | 127,545 | 67.5 | 67.5 | 67.5 | 39.9 | 0.164 | 0.023 | 0.034 | 0.275 | 0.387 | 61,633 | 75.6 | 39.9 | 44.0 | 1,245 | 0 | 0 | 54.6 | 2,337 | 23.3 | 4,513 | 77.9 | 104 | 0.0 | 0.0 | 0.00 | 0.0 |
| Max | | 127,545 | 67.5 | 67.5 | 67.5 | 61.0 | | | | | | 127,545 | 89.6 | 61.0 | 44.0 | 3,047 | 0 | 0 | 54.6 | 2,337 | 46.5 | 7,022 | 101.1 | 254 | 0.0 | 0.0 | 0.00 | 0.0 |
| Min | | 127,545 | 67.5 | 67.5 | 67.5 | 3.4 | | | | | | 1,017 | 65.5 | 3.4 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 0.1 | 1,514 | 54.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |

# Cooling Tower Energy Use, Proposed

**Assumptions**

The proposed cooling towers are staged in tandem with the baseline chillers (number of active towers = number of active chillers).
The proposed cooling tower fan motors are two-speed (100% and 50%).

**Parameters**

| | | | |
|---|---|---|---|
| Chiller Condenser Water Temperature Setpoint | 80 | °F | Baseline |
| Cooling Tower Fan Motor Size | 30 | hp | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Cooling Tower Condenser Water Flow, Maximum | 2,600 | gpm | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Motor Load Factor at Full Speed | 90% | | Estimate |
| Fan Motor Efficiency | 92.5% | | Baseline |
| Fan Drive Efficiency | 95% | | Belt drive |
| Fan Power, Baseline Cooling Tower, 100% | 22.9 | kW | = 0.746 * motor size * load factor / (drive effic * motor effic) |
| Fan Power, Baseline Cooling Tower, 50% | 2.9 | kW | Fan Law Calculation |

**Hourly Calculations**

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 1-Jan | 1 | 33 | 247 | 1 | 46% | 247 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 2 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 3 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 4 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 5 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 6 | 37 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 7 | 36 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 8 | 36 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 9 | 37 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 10 | 37 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 1-Jan | 11 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 12 | 41 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 30-Jun | 13 | 62 | 253 | 1 | 46% | 253 | 75 | 80.0 | 58% | 13.4 | 22.9 | 13.4 | 22.9 |
| 30-Jun | 14 | 62 | 253 | 1 | 46% | 253 | 75 | 80.0 | 58% | 13.4 | 22.9 | 13.4 | 22.9 |
| 30-Jun | 15 | 63 | 253 | 1 | 46% | 253 | 75 | 80.0 | 60% | 13.8 | 22.9 | 13.8 | 22.9 |
| 30-Jun | 16 | 63 | 253 | 1 | 46% | 253 | 75 | 80.0 | 60% | 13.8 | 22.9 | 13.8 | 22.9 |
| 30-Jun | 17 | 63 | 253 | 1 | 46% | 253 | 75 | 80.0 | 60% | 13.8 | 22.9 | 13.8 | 22.9 |
| 30-Jun | 18 | 63 | 253 | | | | | | 60% | 13.8 | 22.9 | 13.8 | 22.9 |
| 30-Jun | 19 | 63 | 253 | | | | | | 60% | 13.8 | 22.9 | 13.8 | 22.9 |
| 30-Jun | 20 | 60 | 252 | | | | | | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 30-Jun | 21 | 58 | 252 | | | | | | 52% | 11.8 | 22.9 | 11.8 | 22.9 |
| 30-Jun | 22 | 59 | 105 | | | | | | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 30-Jun | 23 | 58 | 88 | | | | | | 52% | 11.8 | 22.9 | 11.8 | 22.9 |
| 30-Jun | 24 | 57 | 72 | 1 | 46% | 72 | 70 | 80.0 | 50% | 11.5 | 22.9 | 11.5 | 22.9 |
| 1-Jul | 1 | 55 | 55 | 1 | 46% | 55 | 70 | 80.0 | 48% | 2.7 | 2.9 | 2.7 | 2.9 |
| 1-Jul | 2 | 54 | 41 | 1 | 46% | 41 | 70 | 80.0 | 47% | 2.7 | 2.9 | 2.7 | 2.9 |
| 1-Jul | 3 | 54 | 33 | 1 | 46% | 33 | 70 | 80.0 | 47% | 2.7 | 2.9 | 2.7 | 2.9 |
| 1-Jul | 4 | 55 | 33 | 1 | 46% | 33 | 70 | 80.0 | 48% | 2.7 | 2.9 | 2.7 | 2.9 |
| 1-Jul | 5 | 55 | 47 | 1 | 46% | 47 | 70 | 80.0 | 48% | 2.7 | 2.9 | 2.7 | 2.9 |
| 1-Jul | 6 | 57 | 88 | 1 | 46% | 88 | 70 | 80.0 | 50% | 11.5 | 22.9 | 11.5 | 22.9 |
| 1-Jul | 7 | 59 | 252 | 1 | 46% | 252 | 70 | 80.0 | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 1-Jul | 8 | 59 | 252 | 1 | 46% | 252 | 70 | 80.0 | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 1-Jul | 9 | 59 | 252 | 1 | 46% | 252 | 70 | 80.0 | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 1-Jul | 10 | 60 | 253 | 1 | 46% | 253 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 1-Jul | 11 | 61 | 253 | 1 | 46% | 253 | 75 | 80.0 | 56% | 12.9 | 22.9 | 12.9 | 22.9 |
| 1-Jul | 12 | 63 | 253 | 1 | 46% | 253 | 75 | 80.0 | 60% | 13.8 | 22.9 | 13.8 | 22.9 |
| 31-Dec | 13 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 31-Dec | 14 | 41 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 15 | 43 | 248 | 1 | 46% | 248 | 60 | 80.0 | 41% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 16 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 17 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 18 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 19 | 41 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 20 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 21 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 22 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 23 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 24 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| Sum | | | | | | | | | | | | 32,664 | 53,438 |
| Ave | | 50 | 104 | 0.513 | 46% | 104 | 67 | 80.0 | 49% | 3.7 | 6.1 | 3.7 | 6.1 |
| Max | | 71 | 254 | 1 | 46% | 254 | 80 | 80.0 | 87% | 20.0 | 22.9 | 20.0 | 22.9 |
| Min | | 23 | 0 | 0 | 46% | 0 | 50 | 80.0 | 38% | 0.0 | 0.0 | 0.0 | 0.0 |

No. of hours in year that actual CW temp > 80: 0

# CHW Pump Energy Use, Proposed

**Template Name:** **CHW Pump Energy Model_v1.01**

**Assumptions**

There is one operating constant-speed primary CHW pump per active chiller.
All of the primary CHW pumps are identical.
There is one operating variable-speed secondary CHW pump.

**Results**

| | Proposed | Units |
|---|---|---|
| CHW Pump Energy Required | 116,663 | kWh/yr |
| Ave CHW Pump System Effic. | 68.6 | gpm/kW |

***Primary Pumps***

**Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T across evaporator. |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

***Secondary Pump***

**Input Parameters**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 650 | 610 | gpm | Nominal: 650.<br>Design: 254-ton peak load, 10F CHW delta-T. |
| Head | 100 | 100 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 70% | 70% | | Nominal: Baseline for 75 hp motor.<br>Design: Baseline for 75 hp motor. |
| Pump Motor Size | 125 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 94.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 98% | | | Secondary pumps are variable speed. |
| Secondary CHW Loop Delta-T | | 10 | F | Estimate. |

**Calculations**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 22.0 | hp | (flow * head) / (3960 * pump effic) |
| Pump VFD Input Power | | 17.7 | kW | 0.746 * hp / motor effic / VFD effic |

**Error Messages**

OK -- Primary Pump Motor is not undersized.
OK -- Secondary Pump Motor is not undersized.

**Hourly Analysis**

| Date | Hour | Total Cooling Load | No. of Chillers On | Total Primary CHW Flow | Total Primary Pump Power | Secondary Loop CHW Flow | Secondary Pump Power | Total CHW Pump Power | CHW Pump System Efficiency |
|---|---|---|---|---|---|---|---|---|---|
| | | tons | | gpm | kW | gpm | kW | kW | gpm/kW |
| 1-Jan | 1 | 247 | 1 | 1,200 | 12 | 594 | 17 | 29 | 61.0 |
| 1-Jan | 2 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 3 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 4 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 5 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 6 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 7 | 248 | 1 | 1,200 | 12 | 594 | 17 | 29 | 61.0 |
| 1-Jan | 8 | 248 | 1 | 1,200 | 12 | 594 | 17 | 29 | 61.0 |
| 1-Jan | 9 | 248 | 1 | 1,200 | 12 | 594 | 17 | 29 | 61.0 |
| 1-Jan | 10 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 11 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 12 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 30-Jun | 13 | 253 | 1 | 1,200 | 12 | 606 | 18 | 30 | 60.3 |
| 30-Jun | 14 | 253 | 1 | 1,200 | 12 | 606 | 18 | 30 | 60.3 |
| 30-Jun | 15 | 253 | 1 | 1,200 | 12 | 606 | 18 | 30 | 60.3 |
| 30-Jun | 16 | 253 | 1 | 1,200 | 12 | 607 | 18 | 30 | 60.3 |
| 30-Jun | 17 | 253 | 1 | 1,200 | 12 | 606 | 18 | 30 | 60.3 |
| 30-Jun | 18 | 253 | 1 | 1,200 | 12 | 606 | 18 | 30 | 60.3 |
| 30-Jun | 19 | 253 | 1 | 1,200 | 12 | 606 | 18 | 30 | 60.3 |
| 30-Jun | 20 | 252 | 1 | 1,200 | 12 | 605 | 18 | 30 | 60.4 |
| 30-Jun | 21 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.5 |
| 30-Jun | 22 | 105 | 1 | 1,200 | 12 | 252 | 5 | 17 | 85.0 |
| 30-Jun | 23 | 88 | 1 | 1,200 | 12 | 212 | 4 | 16 | 88.2 |
| 30-Jun | 24 | 72 | 1 | 1,200 | 12 | 172 | 3 | 15 | 91.3 |
| 1-Jul | 1 | 55 | 1 | 1,200 | 12 | 133 | 2 | 14 | 94.1 |
| 1-Jul | 2 | 41 | 1 | 1,200 | 12 | 98 | 1 | 14 | 96.1 |
| 1-Jul | 3 | 33 | 1 | 1,200 | 12 | 78 | 1 | 13 | 97.0 |
| 1-Jul | 4 | 33 | 1 | 1,200 | 12 | 78 | 1 | 13 | 97.0 |
| 1-Jul | 5 | 47 | 1 | 1,200 | 12 | 113 | 1 | 14 | 95.3 |
| 1-Jul | 6 | 88 | 1 | 1,200 | 12 | 212 | 4 | 16 | 88.2 |
| 1-Jul | 7 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.4 |
| 1-Jul | 8 | 252 | 1 | 1,200 | 12 | 605 | 18 | 30 | 60.4 |
| 1-Jul | 9 | 252 | 1 | 1,200 | 12 | 606 | 18 | 30 | 60.3 |
| 1-Jul | 10 | 253 | 1 | 1,200 | 12 | 607 | 18 | 30 | 60.3 |
| 1-Jul | 11 | 253 | 1 | 1,200 | 12 | 607 | 18 | 30 | 60.3 |
| 1-Jul | 12 | 253 | 1 | 1,200 | 12 | 608 | 18 | 30 | 60.2 |
| 31-Dec | 13 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 31-Dec | 14 | 248 | 1 | 1,200 | 12 | 596 | 17 | 29 | 60.9 |
| 31-Dec | 15 | 248 | 1 | 1,200 | 12 | 596 | 17 | 30 | 60.9 |
| 31-Dec | 16 | 248 | 1 | 1,200 | 12 | 596 | 17 | 30 | 60.9 |
| 31-Dec | 17 | 248 | 1 | 1,200 | 12 | 596 | 17 | 30 | 60.9 |
| 31-Dec | 18 | 248 | 1 | 1,200 | 12 | 596 | 17 | 29 | 60.9 |
| 31-Dec | 19 | 248 | 1 | 1,200 | 12 | 596 | 17 | 29 | 60.9 |
| 31-Dec | 20 | 248 | 1 | 1,200 | 12 | 596 | 17 | 29 | 60.9 |
| 31-Dec | 21 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 31-Dec | 22 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 31-Dec | 23 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 31-Dec | 24 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| Sum | | | | | 55,612 | | 61,050 | 116,663 | |
| Ave | | 104 | 0.513 | 616 | 6 | 249 | 7 | 13 | 68.6 |
| Max | | 254 | 1 | 1,200 | 12 | 609 | 18 | 30 | 97.9 |
| Min | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60.1 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# CHW Plant Energy Use, Proposed

**Assumptions**
All chillers are identical and rotated equally.
There is one operating constant-speed CW pump per active chiller.

| | | | |
|---|---|---|---|
| Electric Chiller Capacity | 500 | tons | Assumed. |
| Number of Electric Chillers | 3 | | Assumed. |
| Total Electric Chiller Capacity | 1,500 | tons | Chiller capacity times number of chillers. |
| Chilled Water Supply Temperature | 44 | F | Baseline. |

**Condenser Water Pump Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

**Results (Annual Totals)**

| | Proposed | Units |
|---|---|---|
| Total Annual Electric Use | 721,540 | kWh/yr |
| Summer Peak Electric Demand | 202 | kW |
| Annual Average Cooling Efficiency | 0.794 | kW/ton |

**Hourly Calculations**

| Date | Hour | Total Cooling Load | Chillers | | | | Cooling Tower Power Demand | CHW & CW Pump Power Demand | Total Cooling Plant Power Demand | Summer Peak Demand |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Chillers Operating | Chiller Load Factor | Chiller Effic. | Chiller Power Demand | | | | |
| | | tons | 0-3 | % | kW/ton | kW | kW | kW | kW | kW |
| 1-Jan | 1 | 247 | 1 | 49% | 0.56 | 138 | 2.2 | 42 | 182 | n/a |
| 1-Jan | 2 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 3 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 4 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 5 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 6 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 7 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 8 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 9 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 10 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 11 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 12 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 30-Jun | 13 | 253 | 1 | 51% | 0.54 | 136 | 13.4 | 42 | 192 | 201 |
| 30-Jun | 14 | 253 | 1 | 51% | 0.54 | 136 | 13.4 | 42 | 192 | 201 |
| 30-Jun | 15 | 253 | 1 | 51% | 0.54 | 136 | 13.8 | 42 | 192 | 201 |
| 30-Jun | 16 | 253 | 1 | 51% | 0.54 | 136 | 13.8 | 42 | 192 | 202 |
| 30-Jun | 17 | 253 | 1 | 51% | 0.54 | 136 | 13.8 | 42 | 192 | 201 |
| 30-Jun | 18 | 253 | 1 | 51% | 0.54 | 136 | 13.8 | 42 | 192 | 201 |
| 30-Jun | 19 | 253 | 1 | 51% | 0.54 | 136 | 13.8 | 42 | 192 | n/a |
| 30-Jun | 20 | 252 | 1 | 50% | 0.54 | 136 | 12.5 | 42 | 191 | n/a |
| 30-Jun | 21 | 252 | 1 | 50% | 0.54 | 136 | 11.8 | 42 | 190 | n/a |
| 30-Jun | 22 | 105 | 1 | 21% | 0.65 | 69 | 12.1 | 29 | 110 | n/a |
| 30-Jun | 23 | 88 | 1 | 18% | 0.79 | 70 | 11.8 | 28 | 110 | n/a |
| 30-Jun | 24 | 72 | 1 | 14% | 0.79 | 57 | 11.5 | 27 | 96 | n/a |
| 1-Jul | 1 | 55 | 1 | 11% | 0.79 | 44 | 2.7 | 27 | 73 | n/a |
| 1-Jul | 2 | 41 | 1 | 8% | 1.23 | 50 | 2.7 | 26 | 79 | n/a |
| 1-Jul | 3 | 33 | 1 | 7% | 1.23 | 40 | 2.7 | 26 | 68 | n/a |
| 1-Jul | 4 | 33 | 1 | 7% | 1.23 | 40 | 2.7 | 26 | 69 | n/a |
| 1-Jul | 5 | 47 | 1 | 9% | 1.23 | 58 | 2.7 | 26 | 87 | n/a |
| 1-Jul | 6 | 88 | 1 | 18% | 0.79 | 70 | 11.5 | 28 | 110 | n/a |
| 1-Jul | 7 | 252 | 1 | 50% | 0.54 | 136 | 12.1 | 42 | 190 | n/a |
| 1-Jul | 8 | 252 | 1 | 50% | 0.54 | 136 | 12.1 | 42 | 190 | n/a |
| 1-Jul | 9 | 252 | 1 | 50% | 0.54 | 136 | 12.1 | 42 | 190 | n/a |
| 1-Jul | 10 | 253 | 1 | 51% | 0.54 | 136 | 12.5 | 42 | 191 | n/a |
| 1-Jul | 11 | 253 | 1 | 51% | 0.54 | 136 | 12.9 | 42 | 192 | n/a |
| 1-Jul | 12 | 253 | 1 | 51% | 0.54 | 137 | 13.8 | 42 | 193 | n/a |
| 31-Dec | 13 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 14 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 15 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 183 | n/a |
| 31-Dec | 16 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 183 | n/a |
| 31-Dec | 17 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 183 | n/a |
| 31-Dec | 18 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 19 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 20 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 21 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 22 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 23 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 24 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| Sum | | 908,988 | | | | 516,600 | 32,664 | 172,275 | 721,540 | 141,154 |
| Ave | | 104 | 0.513 | 40% | 0.34 | 59 | 3.7 | 20 | 82 | 173 |
| Max | | 254 | 1 | 51% | 1.23 | 139 | 20.0 | 42 | 199 | 202 |
| Min | | 0 | 0 | 0% | 0.00 | 0 | 0.0 | 0 | 0 | 0 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# First Year Electric Cost

**Results**

| | Proposed |
|---|---|
| Annual Electric Use Charges | $870,418 |
| Annual Electric Demand Charges | $222,269 |
| Annual Electric Expense | $1,092,687 |

**Rate Schedule**

| | |
|---|---|
| Select current rate schedule | E-19A |
| Select voltage type | Secondary |

| | | Secondary | Primary | Transmission | **Secondary** |
|---|---|---|---|---|---|
| Identifier | Total Demand Rates | $/kW | $/kW | $/kW | $/kW |
| 1 | Peak Summer | 11.54 | 10.43 | 8.13 | 11.54 |
| 2 | Part-Peak Summer | 2.64 | 2.39 | 1.84 | 2.64 |
| 3 | Maximum Summer | 6.62 | 5.63 | 3.72 | 6.62 |
| 4 | Part-Peak Winter | 0.99 | 0.74 | - | 0.99 |
| 5 | Maximum Winter | 6.62 | 5.63 | 3.72 | 6.62 |
| Identifier | Total Energy Rates | $/kWh | $/kWh | $/kWh | $/kWh |
| 1 | Peak Summer | 0.13286 | 0.13251 | 0.09801 | 0.13286 |
| 2 | Part-Peak Summer | 0.09095 | 0.08912 | 0.07843 | 0.09095 |
| 3 | Off-Peak Summer | 0.07383 | 0.07040 | 0.06674 | 0.07383 |
| 4 | Part-Peak Winter | 0.08095 | 0.07653 | 0.07134 | 0.08095 |
| 5 | Off-Peak Winter | 0.07127 | 0.06700 | 0.06326 | 0.07127 |

These rates are applicable for the time period:
**Jan 1, 2008 to Present**

**Hourly Energy Rate Calculations**

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge Proposed |
|---|---|---|---|
| | | | $ |
| 1-Jan | 1 | 5 | $92.07 |
| 1-Jan | 2 | 5 | $92.10 |
| 1-Jan | 3 | 5 | $92.10 |
| 1-Jan | 4 | 5 | $92.10 |
| 1-Jan | 5 | 5 | $92.10 |
| 1-Jan | 6 | 5 | $92.09 |
| 1-Jan | 7 | 5 | $92.08 |
| 1-Jan | 8 | 5 | $92.08 |
| 1-Jan | 9 | 4 | $104.59 |
| 1-Jan | 10 | 4 | $104.60 |
| 1-Jan | 11 | 4 | $104.61 |
| 1-Jan | 12 | 4 | $104.62 |
| 30-Jun | 13 | 1 | $172.98 |
| 30-Jun | 14 | 1 | $172.99 |
| 30-Jun | 15 | 1 | $173.06 |
| 30-Jun | 16 | 1 | $173.07 |
| 30-Jun | 17 | 1 | $173.06 |
| 30-Jun | 18 | 1 | $173.05 |
| 30-Jun | 19 | 2 | $118.46 |
| 30-Jun | 20 | 2 | $118.30 |
| 30-Jun | 21 | 2 | $118.21 |
| 30-Jun | 22 | 3 | $91.90 |
| 30-Jun | 23 | 3 | $91.91 |
| 30-Jun | 24 | 3 | $90.83 |
| 1-Jul | 1 | 3 | $88.90 |
| 1-Jul | 2 | 3 | $89.34 |
| 1-Jul | 3 | 3 | $88.55 |
| 1-Jul | 4 | 3 | $88.56 |
| 1-Jul | 5 | 3 | $89.94 |
| 1-Jul | 6 | 3 | $91.88 |

**Hourly Demand Charge Calculations**

| Hourly Demand | Demand Charge by Rate Period | | | | |
|---|---|---|---|---|---|
| | Proposed | | | | |
| Proposed | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| kW | $ | $ | $ | $ | $ |
| 1,292 | | | $8,552 | | $8,552 |
| 1,292 | | | $8,555 | | $8,555 |
| 1,2 | | | $8,555 | | $8,555 |
| 1,2 | | | $8,555 | | $8,555 |
| 1,2 | | | $8,555 | | $8,555 |
| 1,2 | | | $8,554 | | $8,554 |
| 1,2 | | | $8,553 | | $8,553 |
| 1,2 | | | $8,553 | | $8,553 |
| 1,2 | | | $8,554 | $1,279 | $8,554 |
| 1,2 | | | $8,554 | $1,279 | $8,554 |
| 1,292 | | | $8,555 | $1,279 | $8,555 |
| 1,292 | | | $8,556 | $1,279 | $8,556 |
| 1,302 | $15,025 | | $8,619 | | $8,619 |
| 1,302 | $15,026 | | $8,620 | | $8,620 |
| 1,303 | $15,032 | | $8,623 | | $8,623 |
| 1,303 | $15,033 | | $8,624 | | $8,624 |
| 1,303 | $15,032 | | $8,623 | | $8,623 |
| 1,303 | $15,031 | | $8,623 | | $8,623 |
| 1,302 | | $3,439 | $8,622 | | $8,622 |
| 1,301 | | $3,434 | $8,611 | | $8,611 |
| 1,300 | | $3,431 | $8,604 | | $8,604 |
| 1,245 | | | $8,240 | | $8,240 |
| 1,245 | | | $8,241 | | $8,241 |
| 1,230 | | | $8,144 | | $8,144 |
| 1,204 | | | $7,971 | | $7,971 |
| 1,210 | | | $8,011 | | $8,011 |
| 1,199 | | | $7,940 | | $7,940 |
| 1,199 | | | $7,940 | | $7,940 |
| 1,218 | | | $8,064 | | $8,064 |
| 1,245 | | | $8,239 | | $8,239 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge | Hourly Demand | Demand Charge by Rate Period | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Proposed | Proposed | Proposed | | | | |
| | | | | | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| | | | $ | kW | $ | $ | $ | $ | $ |
| 1-Jul | 7 | 3 | $95.99 | 1,300 | | | $8,607 | | $8,607 |
| 1-Jul | 8 | 3 | $96.01 | 1,300 | | | $8,609 | | $8,609 |
| 1-Jul | 9 | 2 | $118.30 | 1,301 | | $3,434 | $8,611 | | $8,611 |
| 1-Jul | 10 | 2 | $118.36 | 1,301 | | $3,436 | $8,615 | | $8,615 |
| 1-Jul | 11 | 2 | $118.41 | 1,302 | | $3,437 | $8,619 | | $8,619 |
| 1-Jul | 12 | 2 | $118.51 | 1,303 | | $3,440 | $8,626 | | $8,626 |
| 31-Dec | 13 | 4 | $104.62 | 1,292 | | | $8,555 | $1,279 | $8,555 |
| 31-Dec | 14 | 4 | $104.63 | 1,292 | | | $8,556 | $1,280 | $8,556 |
| 31-Dec | 15 | 4 | $104.64 | 1,293 | | | $8,558 | $1,280 | $8,558 |
| 31-Dec | 16 | 4 | $104.63 | 1,293 | | | $8,557 | $1,280 | $8,557 |
| 31-Dec | 17 | 4 | $104.63 | 1,293 | | | $8,557 | $1,280 | $8,557 |
| 31-Dec | 18 | 4 | $104.63 | 1,292 | | | $8,556 | $1,280 | $8,556 |
| 31-Dec | 19 | 4 | $104.62 | 1,292 | | | $8,556 | $1,280 | $8,556 |
| 31-Dec | 20 | 4 | $104.62 | 1,292 | | | $8,556 | $1,279 | $8,556 |
| 31-Dec | 21 | 4 | $104.62 | 1,292 | | | $8,555 | $1,279 | $8,555 |
| 31-Dec | 22 | 5 | $92.10 | 1,292 | | | $8,555 | | $8,555 |
| 31-Dec | 23 | 5 | $92.10 | 1,292 | | | $8,555 | | $8,555 |
| 31-Dec | 24 | 5 | $92.10 | 1,292 | | | $8,555 | | $8,555 |
| | | Sum | $870,418 | 10,621,172 | | | | | |
| | | Ave | $99.36 | 1212.5 | $14,769 | $3,272 | $8,027 | $1,188 | $8,027 |
| | | Max | $173.98 | 1309.5 | $15,112 | $3,452 | $8,669 | $1,290 | $8,669 |
| | | Min | $80.44 | 1128.7 | $13,025 | $2,980 | $7,472 | $1,117 | $7,472 |

**Monthly Demand Charge Calculations**

| Month | Actual Demand Charge per Rate Period | | | | |
|---|---|---|---|---|---|
| | Proposed | | | | |
| | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| | $ | $ | $ | $ | $ |
| Jan | N/A | N/A | N/A | 1,281 | 8,565 |
| Feb | N/A | N/A | N/A | 1,281 | 8,564 |
| Mar | N/A | N/A | N/A | 1,290 | 8,625 |
| Apr | N/A | N/A | N/A | 1,290 | 8,624 |
| May | 15,047 | 3,442 | 8,632 | N/A | N/A |
| Jun | 15,061 | 3,443 | 8,646 | N/A | N/A |
| Jul | 15,108 | 3,452 | 8,667 | N/A | N/A |
| Aug | 15,112 | 3,451 | 8,669 | N/A | N/A |
| Sep | 15,046 | 3,438 | 8,632 | N/A | N/A |
| Oct | 15,024 | 3,434 | 8,626 | N/A | N/A |
| Nov | N/A | N/A | N/A | 1,281 | 8,625 |
| Dec | N/A | N/A | N/A | 1,290 | 8,625 |
| Sum | 90,398 | 20,660 | 51,871 | 7,712 | 51,628 |
| Ave | 15,066 | 3,443 | 8,645 | 1,285 | 8,605 |
| Max | 15,112 | 3,452 | 8,669 | 1,290 | 8,625 |
| Min | 15,024 | 3,434 | 8,626 | 1,281 | 8,564 |

# Annual Total Gas Energy Use

**Assumptions**
All gas use comes from the heating plant.

**Hourly Calculations**

| Date | Hour | Heating Plant Energy Use Proposed therms |
|---|---|---|
| 1-Jan | 1 | 0.00 |
| 1-Jan | 2 | 0.00 |
| 1-Jan | 3 | 0.00 |
| 1-Jan | 4 | 0.00 |
| 1-Jan | 5 | 0.00 |
| 1-Jan | 6 | 0.00 |
| 30-Jun | 15 | 0.00 |
| 30-Jun | 16 | 0.00 |
| 30-Jun | 17 | 0.00 |
| 30-Jun | 18 | 0.00 |
| 30-Jun | 19 | 0.00 |
| 30-Jun | 20 | 0.00 |
| 30-Jun | 21 | 0.00 |
| 30-Jun | 22 | 0.00 |
| 30-Jun | 23 | 0.00 |
| 30-Jun | 24 | 0.00 |
| 1-Jul | 1 | 0.00 |
| 1-Jul | 2 | 0.00 |
| 1-Jul | 3 | 0.00 |
| 1-Jul | 4 | 0.00 |
| 1-Jul | 5 | 0.00 |
| 1-Jul | 6 | 0.00 |
| 1-Jul | 7 | 0.00 |
| 1-Jul | 8 | 0.00 |
| 1-Jul | 9 | 0.00 |
| 1-Jul | 10 | 0.00 |
| 1-Jul | 11 | 0.00 |
| 1-Jul | 12 | 0.00 |
| 31-Dec | 13 | 0.00 |
| 31-Dec | 14 | 0.00 |
| 31-Dec | 15 | 0.00 |
| 31-Dec | 16 | 0.00 |
| 31-Dec | 17 | 0.00 |
| 31-Dec | 18 | 0.00 |
| 31-Dec | 19 | 0.00 |
| 31-Dec | 20 | 0.00 |
| 31-Dec | 21 | 0.00 |
| 31-Dec | 22 | 0.00 |
| 31-Dec | 23 | 0.00 |
| 31-Dec | 24 | 0.00 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| | |
|---|---|
| Sum | 0.00 |
| Ave | 0.00 |
| Max | 0.00 |
| Min | 0.00 |

# First Year Gas Cost

**Gas Use (therms)**

| | Proposed | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | 0 | | 0 |
| Feb | 0 | | 0 |
| Mar | 0 | | 0 |
| Apr | 0 | 0 | |
| May | 0 | 0 | |
| Jun | 0 | 0 | |
| Jul | 0 | 0 | |
| Aug | 0 | 0 | |
| Sep | 0 | 0 | |
| Oct | 0 | 0 | |
| Nov | 0 | | 0 |
| Dec | 0 | | 0 |
| Sum | 0 | 0 | 0 |
| Ave | 0 | 0 | 0 |
| Max | 0 | 0 | 0 |
| Min | 0 | 0 | 0 |

**Gas Cost**

| | Proposed | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | | | $0 |
| Feb | | | $0 |
| Mar | | | $0 |
| Apr | | $0 | |
| May | | $0 | |
| Jun | | $0 | |
| Jul | | $0 | |
| Aug | | $0 | |
| Sep | | $0 | |
| Oct | | $0 | |
| Nov | | | $0 |
| Dec | | | $0 |

Annual Totals: $0

# Life Cycle Cost

**Template:** **Life Cycle Cost_v2.0**

**General Notes**
Negative values are expenses, positive values are income or savings.

**Costs, in Year Zero dollars.**

| | Baseline | Proposed | Difference | Source |
|---|---|---|---|---|
| First Cost | | | -$50,800 | See Implementation Cost sheet. |
| Annual Electric Cost | -$1,187,233 | -$1,092,687 | $94,547 | See Electric Cost sheet. |
| Annual Gas Cost | $0 | $0 | $0 | See Gas Cost sheet. |
| Annual Energy Cost | -$1,187,233 | -$1,092,687 | $94,547 | Sum previous two lines. |
| Annual Material Cost | | | -$500 | Estimated incremental cost of AHU air filters. |
| Annual Labor Cost | | | -$2,000 | Estimate of incremental air handler maintenance cost. |

**Incentive**

| | | |
|---|---|---|
| Estimated total incentive for this project | $25,400 | See the Summary sheet. |

**Financial Parameters**

| | | |
|---|---|---|
| Cost of Borrowed Capital | 7.0% | Typical assumption. |
| Highest-Yielding Current Investment Opportunity | 8.0% | Typical assumption. |
| Discount Rate | 8.0% | Greater of previous two lines. |
| Inflation in Prices of Energy | | |
| Natural Gas Rate | 6.0% | Assumed. |
| Average Inflation of Electric Use and Electric Demand Rates | 3.0% | Assumed. |
| Escalation in Material Costs | 3.0% | Assumed. |
| Inflation in Price of Labor | 3.0% | Assumed. |

**Life Cycle Costs, Adjusted for Inflation**

| Year | Annual Energy Costs | | Differences | | | | |
|---|---|---|---|---|---|---|---|
| | Baseline | Proposed | Energy | Material | Labor | Total | |
| 0 | | | | | | -$50,800 | First Cost |
| 1 | -$1,222,850 | -$1,125,467 | $97,383 | -$515 | -$2,060 | $94,808 | |
| 2 | -$1,259,536 | -$1,159,231 | $100,304 | -$530 | -$2,122 | $97,652 | |
| 3 | -$1,297,322 | -$1,194,008 | $103,314 | -$546 | -$2,185 | $100,582 | |
| 4 | -$1,336,241 | -$1,229,828 | $106,413 | -$563 | -$2,251 | $103,599 | |
| 5 | -$1,376,329 | -$1,266,723 | $109,605 | -$580 | -$2,319 | $106,707 | |
| 6 | -$1,417,618 | -$1,304,725 | $112,893 | -$597 | -$2,388 | $109,908 | |
| 7 | -$1,460,147 | -$1,343,867 | $116,280 | -$615 | -$2,460 | $113,206 | |
| 8 | -$1,503,951 | -$1,384,183 | $119,769 | -$633 | -$2,534 | $116,602 | |
| 9 | -$1,549,070 | -$1,425,708 | $123,362 | -$652 | -$2,610 | $120,100 | |
| 10 | -$1,595,542 | -$1,468,479 | $127,063 | -$672 | -$2,688 | $123,703 | |
| 11 | -$1,643,408 | -$1,512,534 | $130,874 | -$692 | -$2,768 | $127,414 | |
| 12 | -$1,692,710 | -$1,557,910 | $134,801 | -$713 | -$2,852 | $131,236 | |
| 13 | -$1,743,492 | -$1,604,647 | $138,845 | -$734 | -$2,937 | $135,173 | |
| 14 | -$1,795,797 | -$1,652,786 | $143,010 | -$756 | -$3,025 | $139,229 | |
| 15 | -$1,849,670 | -$1,702,370 | $147,300 | -$779 | -$3,116 | $143,405 | |
| 16 | -$1,905,161 | -$1,753,441 | $151,719 | -$802 | -$3,209 | $147,708 | |
| 17 | -$1,962,315 | -$1,806,044 | $156,271 | -$826 | -$3,306 | $152,139 | |
| 18 | -$2,021,185 | -$1,860,226 | $160,959 | -$851 | -$3,405 | $156,703 | |
| 19 | -$2,081,820 | -$1,916,032 | $165,788 | -$877 | -$3,507 | $161,404 | |
| 20 | -$2,144,275 | -$1,973,513 | $170,762 | -$903 | -$3,612 | $166,246 | |

**Proposed Measure(s) vs Baseline**

| | | |
|---|---|---|
| Simple Payback | 0.3 | years |
| Relative Net Present Value | $1,110,601 | |
| Internal Rate of Return | 190% | |

# CHW AHUs with Air Side Economizing

## CEC Zone 12 (Sacramento)

# Annual Total Electric Energy Use, Proposed

**Assumptions**

This scenario assumes seven 500 kVa modules. The efficiencies for the modules are drawn from Powersmith data sheets. Where data points were not provided we have estimated values according to a standard transformer curve profile. We assume that the number, size, and efficiency of the modules are the same for the baseline and proposed case.

We assume that all active transformer modules are loaded to an equal percentage.

All transformers are assumed to be of the linear type.

The power factor is assumed to be 1.00 (kW = kVA).

Transformers are not located in an air-conditioned space, so they do not impose a cooling load.

The transformers serve the rack, UPS, lighting, and chilled water plant loads.

**Input Parameters**

| | | | |
|---|---|---|---|
| Transformer Module Size: | 500 | kVA | See Transformers sheet |

**Annual Energy Use**

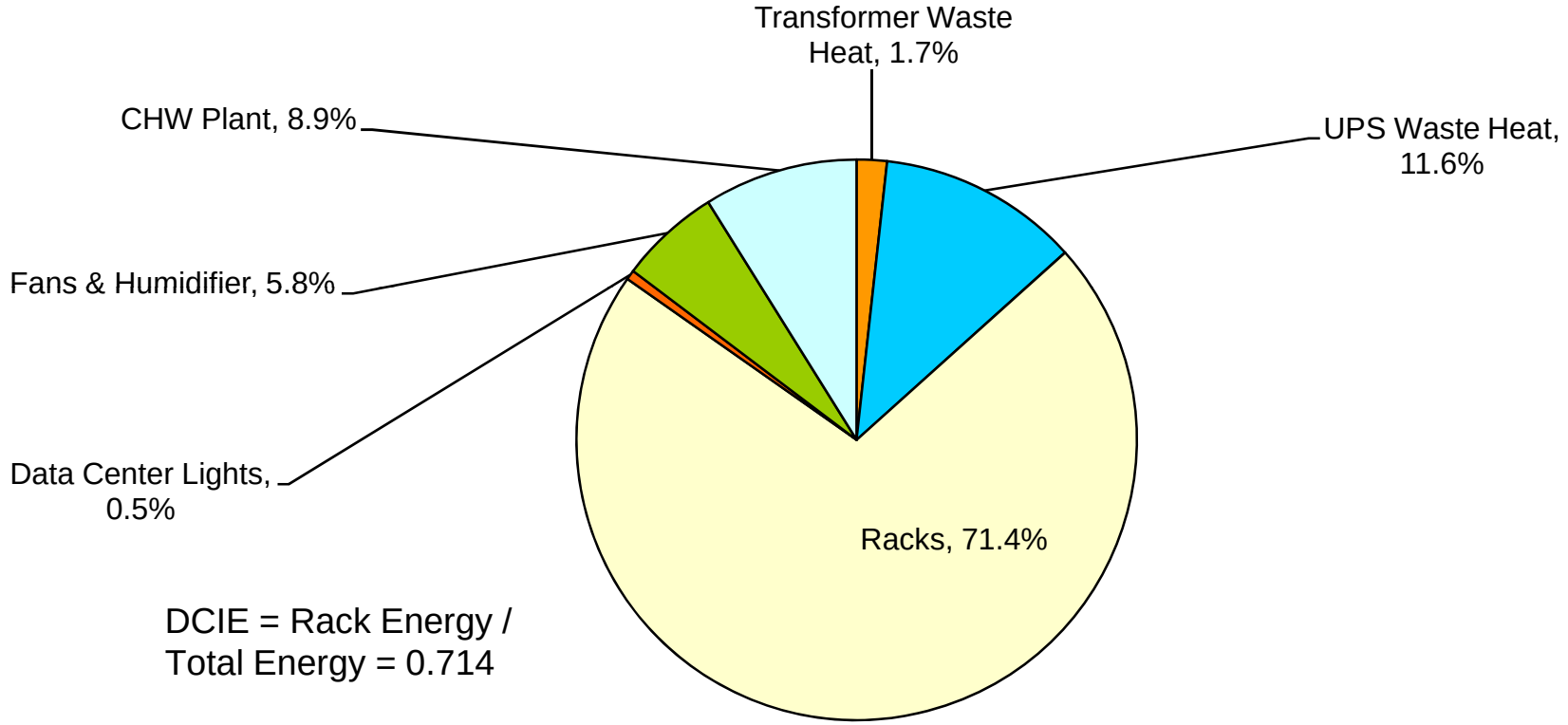
| System | Proposed | |
|---|---|---|
| | kWh/yr | Percent of Total |
| Transformer Waste Heat | 187,149 | 1.7% |
| UPS Waste Heat | 1,256,917 | 11.6% |
| Racks | 7,721,064 | 71.4% |
| Data Center Lights | 59,393 | 0.5% |
| Fans & Humidifier | 630,176 | 5.8% |
| CHW Plant | 960,664 | 8.9% |
| Total | 10,815,363 | 100.0% |

**Hourly Calculations**

| Date | Hour | Required Transformer Output Power | | | | | Transformer Modules | | | Transformer Total Input Power Demand | Trans-former Waste Heat | Peak Summer Power Demand |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | UPS Input Power | Data Center Lights | Fans and Humidifier | CHW Plant | Total | Quant. | Load Factor | Module Effic. | | | |
| | | kW | kW | kW | kW | kW | | % | % | kW | kW | kW |
| 1-Jan | 1 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 2 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 3 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 4 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 5 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 6 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 7 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,293 | 24 | n/a |
| 1-Jan | 8 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,293 | 24 | n/a |
| 1-Jan | 9 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,293 | 24 | n/a |
| 1-Jan | 10 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,293 | 24 | n/a |
| 1-Jan | 11 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 1-Jan | 12 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 30-Jun | 13 | 1,025 | 7 | 55 | 197 | 1,284 | 3 | 86% | 98.2% | 1,308 | 24 | 1,308 |
| 30-Jun | 14 | 1,025 | 7 | 55 | 197 | 1,283 | 3 | 86% | 98.2% | 1,307 | 24 | 1,307 |
| 30-Jun | 15 | 1,025 | 7 | 55 | 197 | 1,283 | 3 | 86% | 98.2% | 1,307 | 24 | 1,307 |
| 30-Jun | 16 | 1,025 | 7 | 55 | 197 | 1,283 | 3 | 86% | 98.2% | 1,307 | 24 | 1,307 |
| 30-Jun | 17 | 1,025 | 7 | 55 | 194 | 1,280 | 3 | 85% | 98.2% | 1,304 | 24 | 1,304 |
| 30-Jun | 18 | 1,025 | 7 | 55 | 192 | 1,278 | 3 | 85% | 98.2% | 1,302 | 24 | 1,302 |
| 30-Jun | 19 | 1,025 | 7 | 80 | 108 | 1,220 | 3 | 81% | 98.2% | 1,243 | 23 | n/a |
| 30-Jun | 20 | 1,025 | 7 | 80 | 93 | 1,205 | 3 | 80% | 98.2% | 1,228 | 22 | n/a |
| 30-Jun | 21 | 1,025 | 7 | 80 | 78 | 1,190 | 3 | 79% | 98.4% | 1,209 | 19 | n/a |
| 30-Jun | 22 | 1,025 | 7 | 80 | 0 | 1,112 | 3 | 74% | 98.5% | 1,129 | 17 | n/a |
| 30-Jun | 23 | 1,025 | 7 | 89 | 0 | 1,121 | 3 | 75% | 98.5% | 1,137 | 17 | n/a |
| 30-Jun | 24 | 1,025 | 7 | 98 | 0 | 1,130 | 3 | 75% | 98.4% | 1,148 | 18 | n/a |
| 1-Jul | 1 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 1-Jul | 2 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 1-Jul | 3 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 1-Jul | 4 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 1-Jul | 5 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 1-Jul | 6 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 1-Jul | 7 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 1-Jul | 8 | 1,025 | 7 | 96 | 0 | 1,128 | 3 | 75% | 98.4% | 1,146 | 18 | n/a |
| 1-Jul | 9 | 1,025 | 7 | 83 | 0 | 1,115 | 3 | 74% | 98.5% | 1,132 | 17 | n/a |
| 1-Jul | 10 | 1,025 | 7 | 80 | 63 | 1,175 | 3 | 78% | 98.4% | 1,194 | 19 | n/a |
| 1-Jul | 11 | 1,025 | 7 | 80 | 89 | 1,201 | 3 | 80% | 98.2% | 1,223 | 22 | n/a |
| 1-Jul | 12 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 31-Dec | 13 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 14 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 15 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 16 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 17 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 18 | 1,025 | 7 | 99 | 0 | 1,131 | 3 | 75% | 98.4% | 1,149 | 18 | n/a |
| 31-Dec | 19 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 20 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 21 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 22 | 1,025 | 7 | 55 | 182 | 1,268 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 23 | 1,025 | 7 | 55 | 182 | 1,268 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 24 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| Sum | | 8,977,981 | 59,393 | 630,176 | 960,664 | 10,628,215 | | | | 10,815,363 | 187,149 | 1,043,037 |
| Ave | | 1,025 | 7 | 72 | 110 | 1,213 | 3.00 | 81% | 98.3% | 1,235 | 21 | 1,278 |
| Max | | 1,025 | 7 | 101 | 202 | 1,288 | 3 | 86% | 98.5% | 1,312 | 24 | 1,312 |
| Min | | 1,025 | 7 | 55 | 0 | 1,112 | 3 | 74% | 98.2% | 1,129 | 17 | 1,129 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# Data Center Infrastructure Efficiency (DCIE)
# Proposed




DCIE = Rack Energy / Total Energy = 0.714

# Space Parameters

**Assumptions**
Chilled water CRAC values are based on the Liebert Deluxe System 3, Model 740C.

| | Proposed | Units | Sources |
|---|---|---|---|
| **Input Parameters** | | | |
| ***Space Dimensions*** | | | |
| Floor Area | 6,780 | sf | Email from Dave Shroyer, 10/13/08. |
| ***Occupancy Schedule*** | | | |
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | Datacenter assumed to operate 8,760 hours per year |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | Datacenter assumed to operate 8,760 hours per year |
| ***HVAC System Type & Setpoints*** | | | |
| Air Delivery System | VAV | | The proposed system uses VAV air handlers. |
| Return Air Drybulb Setpoint | 89.5 | °F | Selected to get a 22 deg-F delta-T, email from Rupa Ganguly on 9/30/08. |
| Supply Air Drybulb Setpoint (VAV Systems Only) | 67.5 | °F | Estimate from email from Rupa Ganguly on 9/30/08. |
| Supply Air Design Flow Rate (CAV Systems Only) | | cfm | Total air flow provided by selected number & size of CRAC units and expected total static pressure drop of open HACA arrangement. |
| Active Humidity Control? | no | | Humidity control is baseline practice. The proposed facility will have no active humidity control. |
| Drybulb Temp at RH Sensor Location | 89.5 | °F | Humidity sensor is assumed to be mounted on the data center ceiling. |
| Allowed Relative Humidity, Maximum | 100% | RH | Assumed based on no humidity control. |
| Allowed Relative Humidity, Minimum | 1% | RH | Assumed based on no humidity control. |
| CHWST Setpoint, Primary | 44 | °F | Baseline CHWST setpoint value. |
| CHWST Setpoint, Secondary | 44 | °F | We are not considering CHWST reset. |
| Adiabatic Humdifier Power Draw | 0.000 | kW/ (lb of H20/hr) | No adiabatic humidifier. |

| | Proposed | Units | Sources |
|---|---|---|---|
| ***Cooling Load*** | | | |
| Total Rack Load, Occupied | 881 | kW | Calculated from rack load of 130 W/sf, email from Dave Shroyer, 10/13/08. |
| Total Rack Load, Unoccupied | n/a | kW | Rack load does not vary with occupancy. |
| Average Lighting Density | 1.0 | W/sf | Typical value. |
| ***Ventilation Requirement*** | | | |
| Minimum Ventilation Requirement | 0.15 | cfm/sf | CA Title 24 requirement for office space. |
| ***Boiler Data*** | | | |
| HHW Boiler Efficiency | 82% | % | Baseline value. |
| Gas-fired Humidifier Efficiency | 76% | % | Baseline value. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| ***HVAC System Type & Setpoints*** | | | |
| Occupied Supply Air Drybulb | | °F | = RAT - Occupied Load / (1.08 * cfm) |
| Unoccupied Supply Air Drybulb | | °F | A datacenter is assumed always occupied. |
| Occupied Supply Air Flow Rate | 127,545 | cfm | = Load / (1.08 * Delta-T) |
| Unoccupied Suppllly Air Flow Rate | n/a | | A datacenter is assumed always occupied. |
| Air Side Delta-T | 22 | °F | Subtract |
| ***Cooling Load*** | | | |
| UPS Waste Heat | 0 | kW | From UPS calculation sheet. The UPS units are in conditioned space, so the UPS waste heat is a load on the cooling system. |
| Data Center Lights | 7 | kW | Average lighting density times space floor area. |
| Total Internal Load, Occupied | 888 | kW | Rack load, UPS waste heat, lights. |
| Total Internal Load, Occupied | 253 | tons | Convert to tons |
| Total Internal Load, Occupied | 3,030 | kBTU/hr | Convert to kBTU/hr |
| Average Internal Load Density, Occupied | 131 | W/sf | Divide by floor area |
| Total Internal Load, Unoccupied | n/a | kW | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | tons | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | kBTU/hr | A datacenter is assumed always occupied. |
| Average Internal Load Density, Unoccupied | n/a | W/sf | A datacenter is assumed always occupied. |
| ***Ventilation Requirement*** | | | |
| Min Allowed Ventilation Volumetric Air Flow Rate | 1,017 | cfm | Floor area times minimum ventilation requirement. |

# Weather Data

Source: California Energy Commission
Data Set: California Climate Zone 12 (CZ12RV2) - Sacramento

| Date | Hour | Outside Air | | | | | |
|---|---|---|---|---|---|---|---|
| | | Drybulb Temp. | Dewpoint Temp. | Relative Humidity | Atmospheric Pressure | Wetbulb Temp. | Enthalpy |
| | | °F | °F | % | psia | °F | BTU/lb |
| 1-Jan | 1 | 39.4 | 36.1 | 100% | 14.6 | 39.4 | 14.9 |
| 1-Jan | 2 | 40.3 | 37.6 | 97% | 14.6 | 39.9 | 15.2 |
| 1-Jan | 3 | 40.3 | 39.0 | 97% | 14.6 | 39.9 | 15.2 |
| 1-Jan | 4 | 40.3 | 40.3 | 96% | 14.6 | 39.8 | 15.1 |
| 1-Jan | 5 | 40.3 | 40.3 | 96% | 14.6 | 39.8 | 15.1 |
| 1-Jan | 6 | 40.3 | 40.3 | 97% | 14.6 | 39.9 | 15.2 |
| 1-Jan | 7 | 42.3 | 42.3 | 97% | 14.6 | 41.9 | 16.1 |
| 1-Jan | 8 | 43.3 | 43.3 | 97% | 14.6 | 42.9 | 16.6 |
| 1-Jan | 9 | 44 | | | | 43.7 | 17.0 |
| 1-Jan | 10 | 45 | | | | 44.7 | 17.5 |
| 1-Jan | 11 | 45 | | | | 44.9 | 17.6 |
| 1-Jan | 12 | 45 | | | | 44.9 | 17.6 |
| 30-Jun | 13 | 90 | | | | 69.8 | 33.9 |
| 30-Jun | 14 | 91 | | | | 69.2 | 33.4 |
| 30-Jun | 15 | 92 | | | | 68.7 | 33.0 |
| 30-Jun | 16 | 93.2 | 52.3 | 29% | 14.5 | 68.9 | 33.1 |
| 30-Jun | 17 | 88.9 | 53.2 | 29% | 14.5 | 65.9 | 30.7 |
| 30-Jun | 18 | 84.4 | 54.1 | 29% | 14.5 | 62.7 | 28.4 |
| 30-Jun | 19 | 76.5 | 51.4 | 32% | 14.5 | 58.1 | 25.2 |
| 30-Jun | 20 | 73.4 | 51.8 | 45% | 14.5 | 59.8 | 26.4 |
| 30-Jun | 21 | 70.3 | 51.8 | 50% | 14.5 | 58.7 | 25.6 |
| 30-Jun | 22 | 67.3 | 52.2 | 53% | 14.5 | 56.9 | 24.5 |
| 30-Jun | 23 | 63.7 | 49.1 | 57% | 14.5 | 54.8 | 23.1 |
| 30-Jun | 24 | 59.9 | 46.0 | 66% | 14.5 | 53.4 | 22.3 |
| 1-Jul | 1 | 56.3 | 49.6 | 64% | 14.5 | 49.9 | 20.3 |
| 1-Jul | 2 | 53.6 | 48.6 | 69% | 14.5 | 48.4 | 19.4 |
| 1-Jul | 3 | 52.2 | 48.0 | 71% | 14.5 | 47.4 | 18.9 |
| 1-Jul | 4 | 51.6 | 47.5 | 66% | 14.5 | 46.1 | 18.2 |
| 1-Jul | 5 | 51.8 | 48.7 | 68% | 14.5 | 46.6 | 18.5 |
| 1-Jul | 6 | 52.7 | 48.7 | 63% | 14.5 | 46.5 | 18.4 |
| 1-Jul | 7 | 56.1 | 50.2 | 59% | 14.6 | 48.8 | 19.6 |
| 1-Jul | 8 | 61.2 | 51.1 | 48% | 14.6 | 50.7 | 20.7 |
| 1-Jul | 9 | 64.9 | 52.0 | 40% | 14.6 | 51.8 | 21.3 |
| 1-Jul | 10 | 70.0 | 50.9 | 39% | 14.6 | 55.4 | 23.5 |
| 1-Jul | 11 | 73.9 | 52.0 | 30% | 14.5 | 55.7 | 23.6 |
| 1-Jul | 12 | 79.0 | 48.9 | 30% | 14.5 | 59.3 | 25.9 |
| 31-Dec | 13 | 56.8 | 29.8 | 53% | 14.7 | 48.2 | 19.3 |
| 31-Dec | 14 | 56.8 | 30.0 | 49% | 14.7 | 47.4 | 18.8 |
| 31-Dec | 15 | 56.8 | 30.0 | 53% | 14.7 | 48.2 | 19.3 |
| 31-Dec | 16 | 56.8 | 29.8 | 53% | 14.7 | 48.2 | 19.3 |
| 31-Dec | 17 | 52.3 | 29.3 | 69% | 14.7 | 47.3 | 18.8 |
| 31-Dec | 18 | 48.4 | 28.8 | 77% | 14.7 | 44.9 | 17.6 |
| 31-Dec | 19 | 43.3 | 27.3 | 86% | 14.7 | 41.5 | 15.9 |
| 31-Dec | 20 | 40.3 | 25.7 | 86% | 14.7 | 38.5 | 14.5 |
| 31-Dec | 21 | 37.9 | 24.8 | 89% | 14.7 | 36.6 | 13.7 |
| 31-Dec | 22 | 36.5 | 24.4 | 97% | 14.7 | 36.2 | 13.5 |
| 31-Dec | 23 | 36.7 | 23.9 | 95% | 14.7 | 36.1 | 13.5 |
| 31-Dec | 24 | 37.9 | 24.3 | 86% | 14.7 | 36.3 | 13.6 |
| | Ave | 59.5 | 45.6 | 68% | 14.5 | 52.1 | 22.0 |
| | Max | 103.5 | 66.7 | 100% | 14.8 | 97.2 | 67.7 |
| | Min | 26.8 | 16.5 | 10% | 14.2 | 26.2 | 9.4 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

# Transformer Data

## Proposed

**Parameters**

| | | |
|---|---|---|
| Size | 500 | kVA |

Values in blue are from NEMA Standard TP-1 Transformer Efficiency, Three Phase (Table 4.2). All other values are extrapolated.

| **Linear Efficiency vs. Load Factor** | |
|---|---|
| Load | Efficiency |
| 100% | 97.9% |
| 90% | 98.2% |
| 80% | 98.4% |
| 75% | 98.5% |
| 70% | 98.6% |
| 60% | 98.8% |
| 50% | 98.8% |
| 40% | 98.8% |
| 35% | 98.7% |
| 30% | 98.6% |
| 25% | 98.5% |
| 20% | 98.3% |
| 17% | 98.2% |
| 10% | 97.7% |

# Chiller Data

**Assumptions**
The same chillers are used in the baseline and proposed cases.
We set the chillers to the same size.

**Parameters**

| | Proposed | Units | Sources |
|---|---|---|---|
| Chiller Capacity | 500 | tons | Capacity selected to result in a total of three chillers, with appropriate safety and redundancy factors. |
| Condenser Water Temperature | 80 | °F | Typical value. |
| CHW Supply Temperature | 44 | °F | Typical value. |
| CW Flow Rate | 1,200 | gpm | Assumes a 10F CW delta-T when chiller is a maximum load. |

Values from Baseline Water-Cooled Chilled Water Plant Above 300 tons

| **Chiller Efficiency (kW/ton) at CHWS Temp = 44 F** | |
|---|---|
| Load | Condenser Water Temp (°F) |
| | 80 |
| 100% | 0.529 |
| 90% | 0.526 |
| 80% | 0.526 |
| 70% | 0.530 |
| 60% | 0.539 |
| 50% | 0.557 |
| 40% | 0.590 |
| 30% | 0.653 |
| 20% | 0.792 |
| 10% | 1.234 |

# Cooling Tower Fan Speed Lookup Tables, Proposed

| | |
|---|---|
| Cooling Tower Make & Model Used in Analysis | BAC 3482A |

The following lookup tables were created by drawing information from BAC's Cooling Tower Selection Software, Release 6.02 NA. The fan speeds are expressed in percent.

Fan speed depends on the load on the tower, the condenser water flow rate, the ambient wetbulb temperature, and the temperature of the condenser water leaving the tower (aka the cold condenser water temperature). The lowest fan speed the BAC software wil

**Tower Specifications at Nominal Conditions**

| | | |
|---|---|---|
| Ambient Wetbulb Temperature | 78 | deg F |
| Hot Condenser Water Temperature | 95 | deg F |
| Cold Condenser Water Temperature | 88.7 | deg F |
| Condenser Water Flow Rate, Maximum | 2,600 | gpm |
| Condenser Water Flow Rate, Minimum | 609 | gpm |
| Nominal Cooling Tower Capacity | 679 | tons |
| Cooling Tower Fan Motor Size | 30 | hp |

## 50% Maximum Flow = 1300 gpm

**0 tons, 1300 gpm**

All temperatures in deg F

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**50 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**100 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**150 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**200 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**250 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**300 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

# UPS Energy Calculation

| UPS System Parameters | Proposed | Units | Comments |
|---|---|---|---|
| **UPS Module Data** | | | |
| Total Rack Load | 881 | kW | From Space sheet. |
| Percentage of Load Served by UPS | 100% | % | We assume all racks are backed up. |
| UPS Load | 881 | kW | Rack load times percentage of load served by UPS. |
| Number of Modules | 5 | | Assumed. |
| Unit Capacity | 500 | kVA | Assumed. |
| Total UPS Capacity | 2,500 | kVA | Unit capacity * number of units |
| Load Factor | 35% | % | UPS load / UPS capacity |
| UPS Efficiency | 86% | % | From LBNL Datacenter UPS benchmarking study. |
| **Energy Use** | | | |
| Annual Energy Use | 8,977,981 | kWh/yr | UPS load / UPS efficiency * 8760 hours |
| Peak Demand | 1,025 | kW | UPS load / UPS efficiency |

# Proposed Heating & Cooling Load, Fan Energy, Energy Savings

**Template:** **Air Handler Energy Model_Recirculation with Economizer_v10.3**

**Input Parameters**

| | | | |
|---|---|---|---|
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | From the Space Parameters sheet. |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | From the Space Parameters sheet. |
| Air Delivery System: CAV or VAV? | VAV | | From the Space Parameters sheet. |
| Return Air Drybulb Setpoint | 89.5 | F | From the Space Parameters sheet. |
| Active Humidity Control? | no | | From the Space Parameters sheet. |
| Drybulb Temp at RH Sensor Location | 89.5 | F | From the Space Parameters sheet. |
| Allowed Relative Humidity, Maximum | 100% | RH | From the Space Parameters sheet. |
| Allowed Relative Humidity, Minimum | 1% | RH | From the Space Parameters sheet. |
| Min Allowed Ventilation Air Flow Rate | 1,017 | cfm | From the Space Parameters sheet. |
| CHWST Setpoint, Primary | 44 | F | From the Space Parameters sheet. |
| CHWST Setpoint during Reset | 44 | F | From the Space Parameters sheet. |
| Adiabatic Humidifier Power Draw | 0.000 | kW/(lb of H20/hr) | From the Space Parameters sheet. |

| | | | |
|---|---|---|---|
| Humidifier: 0=None, 1=Electric, 2=Steam, 3=Adiabatic | 0 | | No active humidification in the proposed case. |
| Cooling Plant Type: 1=CHW, 2=DX | 1 | | There is a chilled water plant in the proposed case. |
| CHWST Reset: 0=No, 1=Yes | 0 | | No CHWST in the proposed case. |
| Economizer? | yes | | Proposed design includes integrated economizing. |
| Economizer Drybulb Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Drybulb Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Drybulb Upper Lockout | 78 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Dewpoint Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Dewpoint Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Dewpoint Upper Lockout | 55 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Enthalpy Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Enthalpy Lower Lockout | 0 | BTU/lb | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Enthalpy Upper Lockout | 29.75 | BTU/lb | Email from Rupa Ganguly on 9/30/08. |
| Economizer Relative Humidity Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| RH Lower Lockout | 20% | % | Email from Rupa Ganguly on 9/30/08. |
| RH Upper Lockout | 80% | % | Email from Rupa Ganguly on 9/30/08. |

| Fan System Parameters | | Supply | Relief | Units | Sources |
|---|---|---|---|---|---|
| Fan Motor Size, Nominal | | 30 | 50 | hp | Sized in accordance with calculated brake horsepower, below. |
| Number of Fans | | 10 | 5 | | Arbitrary numbers selected for model. Assuming one supply fan per RAHU. |
| Fan Efficiency | | 63.8% | 67.5% | % | Baseline fan efficiencies for motor sizes indicated. |
| Fan Drive Efficiency | | 95% | 95% | % | Typical value for belt drive. |
| Fan Motor Efficiency | | 92.5% | 93.2% | % | Baseline efficiencies. |
| VFD Efficiency | | 98% | 98% | % | Supply and relief fans assumed to be equipped with VFDs. |
| Fan Motor and Drive in Airstream? | | 1 | n/a | 1=yes, 0=no | Assumption. |
| Econ. In Min. Pos. | Total Static Pressure Drop | 2.00 | 8.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | n/a | F | Calculated based on maximum fan motor output power. |
| Economizer Open | Total Static Pressure Drop | 2.00 | 1.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | n/a | F | Calculated based on maximum fan motor output power. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| Return Air Minimum Dewpoint | 0.0 | F | Dewpoint of return air when RH sensor is at minimum allowed RH. |
| Space Dewpoint at Maximum Allowed Space Humidity | 89.5 | | Corresponds to Space DB and Max Allowed RH. |
| Chilled Water Minimum Temperature Requirement | 64.5 | F | If the cooling system is CHW, the cooling coil is assumed to have a constant approach temperature of 3 deg F. |

| Fan System Parameters | Supply | Relief | Units | Comments |
|---|---|---|---|---|
| Fan Motor Output Power, Maximum | 4.9 | 8.5 | kW | Per fan motor. This is the maximum output brake power each fan motor is called upon to deliver. |
| Fan Motor Output Power, Maximum | 6.6 | 11.4 | hp | Per fan motor. Converted from kW to hp. |

**Error Messages**

OK - RH minimum does not require humidifier. No humidifier identified.
OK - Chilled Water Supply Temperature Setpoint is low enough to perform required sensible and latent cooling.
OK - Supply Fan Motor Size Exceeds Maximum Required Supply Fan Motor Output
OK - Relief Fan Motor Size Exceeds Maximum Required Relief Fan Motor Output

**Results (Annual Totals)**

| | Proposed | Units |
|---|---|---|
| Cooling Energy Extracted from Airstream | 14,924,779 | kBTU/yr |
| Heating Energy Added to Airstream | 0 | kBTU/yr |
| Humidifier Energy Added to Airstream | 0 | kBTU/yr |

| | Proposed | Units |
|---|---|---|
| Humidifier Energy Required | n/a | kWh/yr |
| | n/a | therms/yr |
| Fan Motor Energy Required | 630,176 | kWh/yr |

**Hourly Calculations**

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Energy Required to Sensibly Cool Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | | | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | Supply | | Relief | | Total Power Input | | Electric | Steam | Adia-batic | |
| | | | | | | | | | | | | | | | | | | | Total Power Input | Air Deliv. Effic. | Total Power Input | Air Deliv. Effic. | | | | | | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | kBTU | kBTU | kBTU | kW | cfm/kW | kW | cfm/kW | kW | tons | kW | therms | kW | therms |
| 1-Jan | 1 | 127,545 | 67.5 | 67.5 | 67.5 | 36.1 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 36.1 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 2 | 127,545 | 67.5 | 67.5 | 67.5 | 37.6 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.6 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 39.0 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.0 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 40.3 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 40.3 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 40.3 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 40.3 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 40.3 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 40.3 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 42.3 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 42.3 | 44.0 | 2,979 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 43.3 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 43.3 | 44.0 | 2,980 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 44.1 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 44.1 | 44.0 | 2,981 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 45.1 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 45.1 | 44.0 | 2,982 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 45.5 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 45.5 | 44.0 | 2,982 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 45.9 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.2 | 45.9 | 44.0 | 2,983 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 57.2 | 1 | 1 | 1 | 0 | 1 | 1,017 | 89.5 | 57.2 | 44.0 | 3,031 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 55.6 | 1 | 1 | 1 | 0 | 1 | 1,017 | 89.5 | 55.6 | 44.0 | 3,032 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 54.0 | 1 | 0 | 1 | 0 | 1 | 1,017 | 89.5 | 54.0 | 44.0 | 3,034 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 52.3 | 1 | 0 | 1 | 0 | 1 | 1,017 | 89.5 | 52.3 | 44.0 | 3,035 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 17 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | 1 | 0 | 1 | 0 | 1 | 1,017 | 89.5 | 53.2 | 44.0 | 3,030 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 18 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.5 | 54.1 | 44.0 | 3,025 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 19 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 76.5 | 51.4 | 44.0 | 1,234 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 103 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 20 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 73.4 | 51.8 | 44.0 | 813 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 68 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 21 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 70.3 | 51.8 | 44.0 | 391 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 33 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 22 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 67.3 | 52.2 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 23 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 118,555 | 65.5 | 49.1 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 34.3 | 3,460 | 88.9 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 24 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 103,415 | 65.5 | 46.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 43.4 | 2,380 | 98.0 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 1 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 92,201 | 65.5 | 49.6 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.3 | 1,993 | 100.8 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 2 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 85,267 | 65.5 | 48.6 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.5 | 1,835 | 101.1 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 48.0 | 0 | 0 | 0 | 0 | 0 | 81,979 | 65.5 | 48.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.2 | 1,775 | 100.8 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 47.5 | 0 | 0 | 0 | 0 | 0 | 80,810 | 65.5 | 47.5 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.0 | 1,756 | 100.6 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 48.7 | 0 | 0 | 0 | 0 | 0 | 81,196 | 65.5 | 48.7 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.1 | 1,762 | 100.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 48.7 | 0 | 0 | 0 | 0 | 0 | 83,182 | 65.5 | 48.7 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.3 | 1,796 | 100.9 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 50.2 | 0 | 0 | 0 | 0 | 0 | 91,704 | 65.5 | 50.2 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.3 | 1,980 | 100.9 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 51.1 | 0 | 0 | 0 | 0 | 0 | 108,013 | 65.5 | 51.1 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 41.3 | 2,613 | 95.9 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 52.0 | 0 | 0 | 0 | 0 | 0 | 124,637 | 65.5 | 52.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 28.7 | 4,346 | 83.3 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 50.9 | 0 | 0 | 0 | 0 | 0 | 127,545 | 70.0 | 50.9 | 44.0 | 342 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 28 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 52.0 | 0 | 0 | 0 | 0 | 0 | 127,545 | 73.9 | 52.0 | 44.0 | 887 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 74 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 48.9 | 1 | 0 | 0 | 0 | 1 | 1,017 | 89.4 | 48.9 | 44.0 | 3,019 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 29.8 | 0 | 0 | 0 | 0 | 0 | 93,726 | 65.5 | 29.8 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.1 | 2,035 | 100.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 30.0 | 0 | 0 | 0 | 0 | 0 | 93,726 | 65.5 | 30.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.1 | 2,035 | 100.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 30.0 | 0 | 0 | 0 | 0 | 0 | 93,726 | 65.5 | 30.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.1 | 2,035 | 100.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Energy Required to Sensibly Cool Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | | | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | Supply | | Relief | | | | | | | |
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | Total Power Input | Air Deliv. Effic. | Total Power Input | Air Deliv. Effic. | Total Power Input | | Electric | Stea m | Adia-batic | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | kBTU | kBTU | kBTU | kW | cfm/kW | kW | cfm/kW | kW | tons | kW | therm s | kW | therms |
| 31-Dec | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 29.8 | 0 | 0 | 0 | 0 | 0 | 93,726 | 65.5 | 29.8 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.1 | 2,035 | 100.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 17 | 127,545 | 67.5 | 67.5 | 67.5 | 29.3 | 0 | 0 | 0 | 0 | 0 | 82,376 | 65.5 | 29.3 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.2 | 1,782 | 100.8 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 18 | 127,545 | 67.5 | 67.5 | 67.5 | 28.8 | 0 | 0 | 0 | 0 | 0 | 74,443 | 65.5 | 28.8 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 44.7 | 1,666 | 99.3 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 19 | 127,545 | 67.5 | 67.5 | 67.5 | 27.3 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 27.3 | 44.0 | 2,980 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 20 | 127,545 | 67.5 | 67.5 | 67.5 | 25.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 25.7 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 21 | 127,545 | 67.5 | 67.5 | 67.5 | 24.8 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 24.8 | 44.0 | 2,974 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 22 | 127,545 | 67.5 | 67.5 | 67.5 | 24.4 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 24.4 | 44.0 | 2,972 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 23 | 127,545 | 67.5 | 67.5 | 67.5 | 23.9 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 23.9 | 44.0 | 2,972 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 24 | 127,545 | 67.5 | 67.5 | 67.5 | 24.3 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 24.3 | 44.0 | 2,974 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| Sum | | | | | | | 1,084 | 709 | 756 | 3,483 | 4,820 | | | | | ######## | 0 | 0 | 478,182 | | 151,995 | | ###### | | 0 | 0 | 0 | 0 |
| Ave | | 127,545 | 67.5 | 67.5 | 67.5 | 45.6 | 0.124 | 0.081 | 0.086 | 0.398 | 0.550 | 46,868 | 79.2 | 45.6 | 44.0 | 1,704 | 0 | 0 | 54.6 | 2,337 | 17.4 | 5,203 | 71.9 | 142 | 0.0 | 0.0 | 0.00 | 0.0 |
| Max | | 127,545 | 67.5 | 67.5 | 67.5 | 66.7 | | | | | | 127,545 | 89.6 | 66.7 | 44.0 | 3,046 | 0 | 0 | 54.6 | 2,337 | 46.5 | 7,022 | 101.1 | 254 | 0.0 | 0.0 | 0.00 | 0.0 |
| Min | | 127,545 | 67.5 | 67.5 | 67.5 | 16.5 | | | | | | 1,017 | 65.5 | 16.5 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 0.1 | 1,514 | 54.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |

# Cooling Tower Energy Use, Proposed

**Assumptions**

The proposed cooling towers are staged in tandem with the baseline chillers (number of active towers = number of active chillers).
The proposed cooling tower fan motors are two-speed (100% and 50%).

**Parameters**

| | | | |
|---|---|---|---|
| Chiller Condenser Water Temperature Setpoint | 80 | °F | Baseline |
| Cooling Tower Fan Motor Size | 30 | hp | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Cooling Tower Condenser Water Flow, Maximum | 2,600 | gpm | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Motor Load Factor at Full Speed | 90% | | Estimate |
| Fan Motor Efficiency | 92.5% | | Baseline |
| Fan Drive Efficiency | 95% | | Belt drive |
| Fan Power, Baseline Cooling Tower, 100% | 22.9 | kW | = 0.746 * motor size * load factor / (drive effic * motor effic) |
| Fan Power, Baseline Cooling Tower, 50% | 2.9 | kW | Fan Law Calculation |

**Hourly Calculations**

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 1-Jan | 1 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 2 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 3 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 4 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 5 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 6 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 7 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 8 | 43 | 248 | 1 | 46% | 248 | 60 | 80.0 | 41% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 9 | 44 | 248 | 1 | 46% | 248 | 60 | 80.0 | 41% | 2.4 | 2.9 | 2.4 | 2.9 |
| 1-Jan | 10 | 45 | 248 | 1 | 46% | 248 | 60 | 80.0 | 41% | 2.4 | 2.9 | 2.4 | 2.9 |
| 1-Jan | 11 | 45 | 249 | 1 | 46% | 249 | 60 | 80.0 | 41% | 2.4 | 2.9 | 2.4 | 2.9 |
| 1-Jan | 12 | 45 | 249 | 1 | 46% | 249 | 60 | 80.0 | 41% | 2.4 | 2.9 | 2.4 | 2.9 |
| 30-Jun | 13 | 70 | 253 | 1 | 46% | 253 | 80 | 80.0 | 83% | 19.0 | 22.9 | 19.0 | 22.9 |
| 30-Jun | 14 | 69 | 253 | 1 | 46% | 253 | 80 | 80.0 | 79% | 18.0 | 22.9 | 18.0 | 22.9 |
| 30-Jun | 15 | 69 | 253 | 1 | 46% | 253 | 80 | 80.0 | 79% | 18.0 | 22.9 | 18.0 | 22.9 |
| 30-Jun | 16 | 69 | 253 | 1 | 46% | 253 | 80 | 80.0 | 79% | 18.0 | 22.9 | 18.0 | 22.9 |
| 30-Jun | 17 | 66 | 252 | 1 | 46% | 252 | 80 | 80.0 | 68% | 15.6 | 22.9 | 15.6 | 22.9 |
| 30-Jun | 18 | 63 | 252 | | | | | | 60% | 13.8 | 22.9 | 13.8 | 22.9 |
| 30-Jun | 19 | 58 | 103 | | | | | | 52% | 11.8 | 22.9 | 11.8 | 22.9 |
| 30-Jun | 20 | 60 | 68 | | | | | | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 30-Jun | 21 | 59 | 33 | | | | | | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 30-Jun | 22 | 57 | 0 | | | | | | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 30-Jun | 23 | 55 | 0 | | | | | | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 30-Jun | 24 | 53 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 1 | 50 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 2 | 48 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 3 | 47 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 4 | 46 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 5 | 47 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 6 | 47 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 7 | 49 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 8 | 51 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 9 | 52 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 10 | 55 | 28 | 1 | 46% | 28 | 70 | 80.0 | 48% | 2.7 | 2.9 | 2.7 | 2.9 |
| 1-Jul | 11 | 56 | 74 | 1 | 46% | 74 | 70 | 80.0 | 49% | 2.8 | 2.9 | 2.8 | 2.9 |
| 1-Jul | 12 | 59 | 252 | 1 | 46% | 252 | 70 | 80.0 | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 31-Dec | 13 | 48 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 31-Dec | 14 | 47 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 15 | 48 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 16 | 48 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 17 | 47 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 18 | 45 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 19 | 41 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 20 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 21 | 37 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 31-Dec | 22 | 36 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 31-Dec | 23 | 36 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| 31-Dec | 24 | 36 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.2 | 2.9 | 2.2 | 2.9 |
| Sum | | | | | | | | | | | | 39,591 | 59,876 |
| Ave | | 52 | 142 | 0.640 | 46% | 142 | 69 | 81.2 | 50% | 4.5 | 6.8 | 4.5 | 6.8 |
| Max | | 97 | 254 | 1 | 46% | 254 | 999 | 999.0 | 98% | 22.5 | 22.9 | 22.5 | 22.9 |
| Min | | 26 | 0 | 0 | 46% | 0 | 50 | 80.0 | 0% | 0.0 | 0.0 | 0.0 | 0.0 |

No. of hours in year that actual CW temp > 80: 141

# CHW Pump Energy Use, Proposed

**Template Name:** **CHW Pump Energy Model_v1.01**

**Assumptions**
There is one operating constant-speed primary CHW pump per active chiller.
All of the primary CHW pumps are identical.
There is one operating variable-speed secondary CHW pump.

**Results**

| | Proposed | Units |
|---|---|---|
| CHW Pump Energy Required | 154,333 | kWh/yr |
| Ave CHW Pump System Effic. | 65.2 | gpm/kW |

***Primary Pumps***

**Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T across evaporator. |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

***Secondary Pump***

**Input Parameters**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 650 | 610 | gpm | Nominal:650.<br>Design: 254-ton peak load, 10F CHW delta-T. |
| Head | 100 | 100 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 70% | 70% | | Nominal: Baseline for 75 hp motor.<br>Design: Baseline for 75 hp motor. |
| Pump Motor Size | 75 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 94.1% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 98% | | | Secondary pumps are variable speed. |
| Secondary CHW Loop Delta-T | | 10 | F | Estimate. |

**Calculations**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 22.0 | hp | (flow * head) / (3960 * pump effic) |
| Pump VFD Input Power | | 17.8 | kW | 0.746 * hp / motor effic / VFD effic |

**Error Messages**
OK -- Primary Pump Motor is not undersized.
OK -- Secondary Pump Motor is not undersized.

**Hourly Analysis**

| Date | Hour | Total Cooling Load | No. of Chillers On | Total Primary CHW Flow | Total Primary Pump Power | Secondary Loop CHW Flow | Secondary Pump Power | Total CHW Pump Power | CHW Pump System Efficiency |
|---|---|---|---|---|---|---|---|---|---|
| | | tons | | gpm | kW | gpm | kW | kW | gpm/kW |
| 1-Jan | 1 | 248 | 1 | 1,200 | 12 | 595 | 17 | 30 | 60.8 |
| 1-Jan | 2 | 248 | 1 | 1,200 | 12 | 595 | 17 | 30 | 60.8 |
| 1-Jan | 3 | 248 | 1 | 1,200 | 12 | 595 | 17 | 30 | 60.8 |
| 1-Jan | 4 | 248 | 1 | 1,200 | 12 | 595 | 17 | 30 | 60.8 |
| 1-Jan | 5 | 248 | 1 | 1,200 | 12 | 595 | 17 | 30 | 60.8 |
| 1-Jan | 6 | 248 | 1 | 1,200 | 12 | 595 | 17 | 30 | 60.8 |
| 1-Jan | 7 | 248 | 1 | 1,200 | 12 | 596 | 17 | 30 | 60.8 |
| 1-Jan | 8 | 248 | 1 | 1,200 | 12 | 596 | 17 | 30 | 60.8 |
| 1-Jan | 9 | 248 | | | | | 17 | 30 | 60.8 |
| 1-Jan | 10 | 248 | | | | | 17 | 30 | 60.7 |
| 1-Jan | 11 | 249 | | | | | 17 | 30 | 60.7 |
| 1-Jan | 12 | 249 | | | | | 17 | 30 | 60.7 |
| 30-Jun | 13 | 253 | | | | | 18 | 30 | 60.2 |
| 30-Jun | 14 | 253 | 1 | 1,200 | 12 | 606 | 18 | 30 | 60.2 |
| 30-Jun | 15 | 253 | 1 | 1,200 | 12 | 607 | 18 | 30 | 60.2 |
| 30-Jun | 16 | 253 | 1 | 1,200 | 12 | 607 | 18 | 30 | 60.2 |
| 30-Jun | 17 | 252 | 1 | 1,200 | 12 | 606 | 18 | 30 | 60.2 |
| 30-Jun | 18 | 252 | 1 | 1,200 | 12 | 605 | 18 | 30 | 60.3 |
| 30-Jun | 19 | 103 | 1 | 1,200 | 12 | 247 | 5 | 17 | 85.4 |
| 30-Jun | 20 | 68 | 1 | 1,200 | 12 | 163 | 2 | 15 | 92.0 |
| 30-Jun | 21 | 33 | 1 | 1,200 | 12 | 78 | 1 | 13 | 97.0 |
| 30-Jun | 22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 30-Jun | 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 30-Jun | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 10 | 28 | 1 | 1,200 | 12 | 68 | 1 | 13 | 97.3 |
| 1-Jul | 11 | 74 | 1 | 1,200 | 12 | 177 | 3 | 15 | 90.9 |
| 1-Jul | 12 | 252 | 1 | 1,200 | 12 | 604 | 18 | 30 | 60.3 |
| 31-Dec | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 19 | 248 | 1 | 1,200 | 12 | 596 | 17 | 30 | 60.8 |
| 31-Dec | 20 | 248 | 1 | 1,200 | 12 | 595 | 17 | 30 | 60.8 |
| 31-Dec | 21 | 248 | 1 | 1,200 | 12 | 595 | 17 | 30 | 60.8 |
| 31-Dec | 22 | 248 | 1 | 1,200 | 12 | 594 | 17 | 29 | 60.8 |
| 31-Dec | 23 | 248 | 1 | 1,200 | 12 | 594 | 17 | 29 | 60.8 |
| 31-Dec | 24 | 248 | 1 | 1,200 | 12 | 595 | 17 | 30 | 60.8 |
| Sum | | | | | 69,290 | | 85,043 | 154,333 | |
| Ave | | 142 | 0.640 | 768 | 8 | 341 | 10 | 18 | 65.2 |
| Max | | 254 | 1 | 1,200 | 12 | 609 | 18 | 30 | 97.9 |
| Min | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60.0 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# CHW Plant Energy Use, Proposed

**Assumptions**
All chillers are identical and rotated equally.
There is one operating constant-speed CW pump per active chiller.

| | | | |
|---|---|---|---|
| Electric Chiller Capacity | 500 | tons | Assumed. |
| Number of Electric Chillers | 3 | | Assumed. |
| Total Electric Chiller Capacity | 1,500 | tons | Chiller capacity times number of chillers. |
| Chilled Water Supply Temperature | 44 | F | Baseline. |

**Condenser Water Pump Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

**Results (Annual Totals)**

| | Proposed | Units |
|---|---|---|
| Total Annual Electric Use | 960,664 | kWh/yr |
| Summer Peak Electric Demand | 202 | kW |
| Annual Average Cooling Efficiency | 0.772 | kW/ton |

**Hourly Calculations**

| Date | Hour | Total Cooling Load | Chillers | | | | Cooling Tower Power Demand | CHW & CW Pump Power Demand | Total Cooling Plant Power Demand | Summer Peak Demand |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Chillers Operating | Chiller Load Factor | Chiller Effic. | Chiller Power Demand | | | | |
| | | tons | 0-3 | % | kW/ton | kW | kW | kW | kW | kW |
| 1-Jan | 1 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 2 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 3 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 4 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 5 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 6 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 7 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 8 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 183 | n/a |
| 1-Jan | 9 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 183 | n/a |
| 1-Jan | 10 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 183 | n/a |
| 1-Jan | 11 | 249 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 183 | n/a |
| 1-Jan | 12 | 249 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 183 | n/a |
| 30-Jun | 13 | 253 | 1 | 51% | 0.54 | 136 | 19.0 | 42 | 197 | 201 |
| 30-Jun | 14 | 253 | 1 | 51% | 0.54 | 136 | 18.0 | 42 | 197 | 202 |
| 30-Jun | 15 | 253 | 1 | 51% | 0.54 | 136 | 18.0 | 42 | 197 | 202 |
| 30-Jun | 16 | 253 | 1 | 51% | 0.54 | 136 | 18.0 | 42 | 197 | 202 |
| 30-Jun | 17 | 252 | 1 | 50% | 0.54 | 136 | 15.6 | 42 | 194 | 201 |
| 30-Jun | 18 | 252 | 1 | 50% | 0.54 | 136 | 13.8 | 42 | 192 | 201 |
| 30-Jun | 19 | 103 | 1 | 21% | 0.65 | 67 | 11.8 | 29 | 108 | n/a |
| 30-Jun | 20 | 68 | 1 | 14% | 0.79 | 54 | 12.5 | 27 | 93 | n/a |
| 30-Jun | 21 | 33 | 1 | 7% | 1.23 | 40 | 12.1 | 26 | 78 | n/a |
| 30-Jun | 22 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 30-Jun | 23 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 30-Jun | 24 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 1 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 2 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 3 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 4 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 5 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 6 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 7 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 8 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 9 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 10 | 28 | 1 | 6% | 1.23 | 35 | 2.7 | 25 | 63 | n/a |
| 1-Jul | 11 | 74 | 1 | 15% | 0.79 | 59 | 2.8 | 28 | 89 | n/a |
| 1-Jul | 12 | 252 | 1 | 50% | 0.54 | 136 | 12.1 | 42 | 190 | n/a |
| 31-Dec | 13 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 14 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 15 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 16 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 17 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 18 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 19 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 183 | n/a |
| 31-Dec | 20 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 21 | 248 | 1 | 50% | 0.56 | 138 | 2.2 | 42 | 182 | n/a |
| 31-Dec | 22 | 248 | 1 | 50% | 0.56 | 138 | 2.2 | 42 | 182 | n/a |
| 31-Dec | 23 | 248 | 1 | 50% | 0.56 | 138 | 2.2 | 42 | 182 | n/a |
| 31-Dec | 24 | 248 | 1 | 50% | 0.56 | 138 | 2.2 | 42 | 182 | n/a |
| Sum | | 1,243,732 | | | | 697,450 | 39,591 | 223,623 | 960,664 | 137,487 |
| Ave | | 142 | 0.640 | 44% | 0.39 | 80 | 4.5 | 26 | 110 | 168 |
| Max | | 254 | 1 | 51% | 1.23 | 139 | 22.5 | 42 | 202 | 202 |
| Min | | 0 | 0 | 0% | 0.00 | 0 | 0.0 | 0 | 0 | 0 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# First Year Electric Cost

**Results**

| | Proposed |
|---|---|
| Annual Electric Use Charges | $884,265 |
| Annual Electric Demand Charges | $223,135 |
| Annual Electric Expense | $1,107,400 |

**Rate Schedule**

| | |
|---|---|
| Select current rate schedule | E-19A |
| Select voltage type | Secondary |

| | | Secondary | Primary | Transmission | **Secondary** |
|---|---|---|---|---|---|
| Identifier | Total Demand Rates | $/kW | $/kW | $/kW | $/kW |
| 1 | Peak Summer | 11.54 | 10.43 | 8.13 | 11.54 |
| 2 | Part-Peak Summer | 2.64 | 2.39 | 1.84 | 2.64 |
| 3 | Maximum Summer | 6.62 | 5.63 | 3.72 | 6.62 |
| 4 | Part-Peak Winter | 0.99 | 0.74 | - | 0.99 |
| 5 | Maximum Winter | 6.62 | 5.63 | 3.72 | 6.62 |
| Identifier | Total Energy Rates | $/kWh | $/kWh | $/kWh | $/kWh |
| 1 | Peak Summer | 0.13286 | 0.13251 | 0.09801 | 0.13286 |
| 2 | Part-Peak Summer | 0.09095 | 0.08912 | 0.07843 | 0.09095 |
| 3 | Off-Peak Summer | 0.07383 | 0.07040 | 0.06674 | 0.07383 |
| 4 | Part-Peak Winter | 0.08095 | 0.07653 | 0.07134 | 0.08095 |
| 5 | Off-Peak Winter | 0.07127 | 0.06700 | 0.06326 | 0.07127 |

These rates are applicable for the time period:
**Jan 1, 2008 to Present**

**Hourly Energy Rate Calculations**

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge Proposed |
|---|---|---|---|
| | | | $ |
| 1-Jan | 1 | 5 | $92.10 |
| 1-Jan | 2 | 5 | $92.11 |
| 1-Jan | 3 | 5 | $92.11 |
| 1-Jan | 4 | 5 | $92.11 |
| 1-Jan | 5 | 5 | $92.11 |
| 1-Jan | 6 | 5 | $92.11 |
| 1-Jan | 7 | 5 | $92.12 |
| 1-Jan | 8 | 5 | $92.12 |
| 1-Jan | 9 | 4 | $104.64 |
| 1-Jan | 10 | 4 | $104.65 |
| 1-Jan | 11 | 4 | $104.65 |
| 1-Jan | 12 | 4 | $104.65 |
| 30-Jun | 13 | 1 | $173.76 |
| 30-Jun | 14 | 1 | $173.63 |
| 30-Jun | 15 | 1 | $173.64 |
| 30-Jun | 16 | 1 | $173.65 |
| 30-Jun | 17 | 1 | $173.29 |
| 30-Jun | 18 | 1 | $173.02 |
| 30-Jun | 19 | 2 | $113.04 |
| 30-Jun | 20 | 2 | $111.65 |
| 30-Jun | 21 | 2 | $109.96 |
| 30-Jun | 22 | 3 | $83.33 |
| 30-Jun | 23 | 3 | $83.98 |
| 30-Jun | 24 | 3 | $84.75 |
| 1-Jul | 1 | 3 | $84.96 |
| 1-Jul | 2 | 3 | $84.98 |
| 1-Jul | 3 | 3 | $84.96 |
| 1-Jul | 4 | 3 | $84.95 |
| 1-Jul | 5 | 3 | $84.95 |
| 1-Jul | 6 | 3 | $84.97 |

**Hourly Demand Charge Calculations**

| Hourly Demand | Demand Charge by Rate Period | | | | |
|---|---|---|---|---|---|
| | Proposed | | | | |
| Proposed | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| kW | $ | $ | $ | $ | $ |
| 1,292 | | | $8,555 | | $8,555 |
| 1,292 | | | $8,556 | | $8,556 |
| 1,292 | | | $8,556 | | $8,556 |
| 1,292 | | | $8,556 | | $8,556 |
| 1,292 | | | $8,556 | | $8,556 |
| 1,292 | | | $8,556 | | $8,556 |
| 1,293 | | | $8,557 | | $8,557 |
| 1,293 | | | $8,557 | | $8,557 |
| 1,293 | | | $8,558 | $1,280 | $8,558 |
| 1,293 | | | $8,558 | $1,280 | $8,558 |
| 1,293 | | | $8,558 | $1,280 | $8,558 |
| 1,293 | | | $8,558 | $1,280 | $8,558 |
| | | | $8,658 | | $8,658 |
| | | | $8,652 | | $8,652 |
| | | | $8,652 | | $8,652 |
| | | | $8,652 | | $8,652 |
| | | | $8,635 | | $8,635 |
| | | | $8,621 | | $8,621 |
| | | $3,281 | $8,228 | | $8,228 |
| 1,228 | | $3,241 | $8,127 | | $8,127 |
| 1,209 | | $3,192 | $8,004 | | $8,004 |
| 1,129 | | | $7,472 | | $7,472 |
| 1,137 | | | $7,530 | | $7,530 |
| 1,148 | | | $7,599 | | $7,599 |
| 1,151 | | | $7,618 | | $7,618 |
| 1,151 | | | $7,620 | | $7,620 |
| 1,151 | | | $7,618 | | $7,618 |
| 1,151 | | | $7,617 | | $7,617 |
| 1,151 | | | $7,617 | | $7,617 |
| 1,151 | | | $7,619 | | $7,619 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge | Hourly Demand | Demand Charge by Rate Period | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Proposed | | | | |
| | | | Proposed | Proposed | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| | | | $ | kW | $ | $ | $ | $ | $ |
| 1-Jul | 7 | 3 | $84.97 | 1,151 | | | $7,619 | | $7,619 |
| 1-Jul | 8 | 3 | $84.60 | 1,146 | | | $7,585 | | $7,585 |
| 1-Jul | 9 | 2 | $102.94 | 1,132 | | $2,988 | $7,492 | | $7,492 |
| 1-Jul | 10 | 2 | $108.61 | 1,194 | | $3,152 | $7,905 | | $7,905 |
| 1-Jul | 11 | 2 | $111.24 | 1,223 | | $3,229 | $8,097 | | $8,097 |
| 1-Jul | 12 | 2 | $118.25 | 1,300 | | $3,433 | $8,607 | | $8,607 |
| 31-Dec | 13 | 4 | $93.14 | 1,151 | | | $7,617 | $1,139 | $7,617 |
| 31-Dec | 14 | 4 | $93.14 | 1,151 | | | $7,617 | $1,139 | $7,617 |
| 31-Dec | 15 | 4 | $93.14 | 1,151 | | | $7,617 | $1,139 | $7,617 |
| 31-Dec | 16 | 4 | $93.14 | 1,151 | | | $7,617 | $1,139 | $7,617 |
| 31-Dec | 17 | 4 | $93.16 | 1,151 | | | $7,618 | $1,139 | $7,618 |
| 31-Dec | 18 | 4 | $93.03 | 1,149 | | | $7,608 | $1,138 | $7,608 |
| 31-Dec | 19 | 4 | $104.63 | 1,293 | | | $8,557 | $1,280 | $8,557 |
| 31-Dec | 20 | 4 | $104.62 | 1,292 | | | $8,555 | $1,279 | $8,555 |
| 31-Dec | 21 | 4 | $104.60 | 1,292 | | | $8,554 | $1,279 | $8,554 |
| 31-Dec | 22 | 5 | $92.09 | 1,292 | | | $8,554 | | $8,554 |
| 31-Dec | 23 | 5 | $92.09 | 1,292 | | | $8,554 | | $8,554 |
| 31-Dec | 24 | 5 | $92.09 | 1,292 | | | $8,554 | | $8,554 |
| | | Sum | $884,265 | 10,815,363 | | | | | |
| | | Ave | $100.94 | 1234.6 | $14,754 | $3,240 | $8,173 | $1,196 | $8,173 |
| | | Max | $174.32 | 1312.1 | $15,141 | $3,462 | $8,686 | $1,294 | $8,686 |
| | | Min | $80.44 | 1128.7 | $13,025 | $2,980 | $7,472 | $1,117 | $7,472 |

**Monthly Demand Charge Calculations**

| Month | Actual Demand Charge per Rate Period | | | | |
|---|---|---|---|---|---|
| | Proposed | | | | |
| | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| | $ | $ | $ | $ | $ |
| Jan | N/A | N/A | N/A | 1,291 | 8,633 |
| Feb | N/A | N/A | N/A | 1,291 | 8,636 |
| Mar | N/A | N/A | N/A | 1,294 | 8,651 |
| Apr | N/A | N/A | N/A | 1,293 | 8,647 |
| May | 15,136 | 3,456 | 8,683 | N/A | N/A |
| Jun | 15,138 | 3,462 | 8,684 | N/A | N/A |
| Jul | 15,141 | 3,460 | 8,686 | N/A | N/A |
| Aug | 15,140 | 3,462 | 8,685 | N/A | N/A |
| Sep | 15,125 | 3,460 | 8,683 | N/A | N/A |
| Oct | 15,032 | 3,443 | 8,670 | N/A | N/A |
| Nov | N/A | N/A | N/A | 1,292 | 8,638 |
| Dec | N/A | N/A | N/A | 1,291 | 8,633 |
| Sum | 90,711 | 20,743 | 52,091 | 7,752 | 51,838 |
| Ave | 15,119 | 3,457 | 8,682 | 1,292 | 8,640 |
| Max | 15,141 | 3,462 | 8,686 | 1,294 | 8,651 |
| Min | 15,032 | 3,443 | 8,670 | 1,291 | 8,633 |

# Annual Total Gas Energy Use

**Assumptions**
All gas use comes from the heating plant.

**Hourly Calculations**

| Date | Hour | Heating Plant Energy Use Proposed therms |
|---|---|---|
| 1-Jan | 1 | 0.00 |
| 1-Jan | 2 | 0.00 |
| 1-Jan | 3 | 0.00 |
| 1-Jan | 4 | 0.00 |
| 1-Jan | 5 | 0.00 |
| 1-Jan | 6 | 0.00 |
| 1-Jan | | |
| 1-Jan | | |
| 1-Jan | | |
| 1-Jan | | |
| 1-Jan | | |
| 1-Jan | | |
| 30-Jun | | |
| 30-Jun | | |
| 30-Jun | 15 | 0.00 |
| 30-Jun | 16 | 0.00 |
| 30-Jun | 17 | 0.00 |
| 30-Jun | 18 | 0.00 |
| 30-Jun | 19 | 0.00 |
| 30-Jun | 20 | 0.00 |
| 30-Jun | 21 | 0.00 |
| 30-Jun | 22 | 0.00 |
| 30-Jun | 23 | 0.00 |
| 30-Jun | 24 | 0.00 |
| 1-Jul | 1 | 0.00 |
| 1-Jul | 2 | 0.00 |
| 1-Jul | 3 | 0.00 |
| 1-Jul | 4 | 0.00 |
| 1-Jul | 5 | 0.00 |
| 1-Jul | 6 | 0.00 |
| 1-Jul | 7 | 0.00 |
| 1-Jul | 8 | 0.00 |
| 1-Jul | 9 | 0.00 |
| 1-Jul | 10 | 0.00 |
| 1-Jul | 11 | 0.00 |
| 1-Jul | 12 | 0.00 |
| 31-Dec | 13 | 0.00 |
| 31-Dec | 14 | 0.00 |
| 31-Dec | 15 | 0.00 |
| 31-Dec | 16 | 0.00 |
| 31-Dec | 17 | 0.00 |
| 31-Dec | 18 | 0.00 |
| 31-Dec | 19 | 0.00 |
| 31-Dec | 20 | 0.00 |
| 31-Dec | 21 | 0.00 |
| 31-Dec | 22 | 0.00 |
| 31-Dec | 23 | 0.00 |
| 31-Dec | 24 | 0.00 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| | |
|---|---|
| Sum | 0.00 |
| Ave | 0.00 |
| Max | 0.00 |
| Min | 0.00 |

# First Year Gas Cost

**Gas Use (therms)**

| | Proposed | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | 0 | | 0 |
| Feb | 0 | | 0 |
| Mar | 0 | | 0 |
| Apr | 0 | 0 | |
| May | 0 | 0 | |
| Jun | 0 | 0 | |
| Jul | 0 | 0 | |
| Aug | 0 | 0 | |
| Sep | 0 | 0 | |
| Oct | 0 | 0 | |
| Nov | 0 | | 0 |
| Dec | 0 | | 0 |
| Sum | 0 | 0 | 0 |
| Ave | 0 | 0 | 0 |
| Max | 0 | 0 | 0 |
| Min | 0 | 0 | 0 |

**Gas Cost**

| | Proposed | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | | | $0 |
| Feb | | | $0 |
| Mar | | | $0 |
| Apr | | $0 | |
| May | | $0 | |
| Jun | | $0 | |
| Jul | | $0 | |
| Aug | | $0 | |
| Sep | | $0 | |
| Oct | | $0 | |
| Nov | | | $0 |
| Dec | | | $0 |

Annual Totals: $0

# Life Cycle Cost

**Template:** **Life Cycle Cost_v2.0**

**General Notes**
Negative values are expenses, positive values are income or savings.

**Costs, in Year Zero dollars.**

| | Baseline | Proposed | Difference | Source |
|---|---|---|---|---|
| First Cost | | | -$50,800 | See Implementation Cost sheet. |
| Annual Electric Cost | -$1,187,233 | -$1,107,400 | $79,833 | See Electric Cost sheet. |
| Annual Gas Cost | $0 | $0 | $0 | See Gas Cost sheet. |
| Annual Energy Cost | -$1,187,233 | -$1,107,400 | $79,833 | Sum previous two lines. |
| Annual Material Cost | | | -$500 | Estimated incremental cost of AHU air filters. |
| Annual Labor Cost | | | -$2,000 | Estimate of incremental air handler maintenance cost. |

**Incentive**

| | | |
|---|---|---|
| Estimated total incentive for this project | $25,400 | See the Summary sheet. |

**Financial Parameters**

| | | |
|---|---|---|
| Cost of Borrowed Capital | 7.0% | Typical assumption. |
| Highest-Yielding Current Investment Opportunity | 8.0% | Typical assumption. |
| Discount Rate | 8.0% | Greater of previous two lines. |
| Inflation in Prices of Energy | | |
| Natural Gas Rate | 6.0% | Assumed. |
| Average Inflation of Electric Use and Electric Demand Rates | 3.0% | Assumed. |
| Escalation in Material Costs | 3.0% | Assumed. |
| Inflation in Price of Labor | 3.0% | Assumed. |

**Life Cycle Costs, Adjusted for Inflation**

| Year | Annual Energy Costs | | Differences | | | | |
|---|---|---|---|---|---|---|---|
| | Baseline | Proposed | Energy | Material | Labor | Total | |
| 0 | | | | | | -$50,800 | First Cost |
| 1 | -$1,222,850 | -$1,140,622 | $82,228 | -$515 | -$2,060 | $79,653 | |
| 2 | -$1,259,536 | -$1,174,841 | $84,695 | -$530 | -$2,122 | $82,043 | |
| 3 | -$1,297,322 | -$1,210,086 | $87,236 | -$546 | -$2,185 | $84,504 | |
| 4 | -$1,336,241 | -$1,246,388 | $89,853 | -$563 | -$2,251 | $87,039 | |
| 5 | -$1,376,329 | -$1,283,780 | $92,548 | -$580 | -$2,319 | $89,650 | |
| 6 | -$1,417,618 | -$1,322,293 | $95,325 | -$597 | -$2,388 | $92,340 | |
| 7 | -$1,460,147 | -$1,361,962 | $98,185 | -$615 | -$2,460 | $95,110 | |
| 8 | -$1,503,951 | -$1,402,821 | $101,130 | -$633 | -$2,534 | $97,963 | |
| 9 | -$1,549,070 | -$1,444,906 | $104,164 | -$652 | -$2,610 | $100,902 | |
| 10 | -$1,595,542 | -$1,488,253 | $107,289 | -$672 | -$2,688 | $103,929 | |
| 11 | -$1,643,408 | -$1,532,901 | $110,508 | -$692 | -$2,768 | $107,047 | |
| 12 | -$1,692,710 | -$1,578,888 | $113,823 | -$713 | -$2,852 | $110,259 | |
| 13 | -$1,743,492 | -$1,626,254 | $117,238 | -$734 | -$2,937 | $113,566 | |
| 14 | -$1,795,797 | -$1,675,042 | $120,755 | -$756 | -$3,025 | $116,973 | |
| 15 | -$1,849,670 | -$1,725,293 | $124,377 | -$779 | -$3,116 | $120,482 | |
| 16 | -$1,905,161 | -$1,777,052 | $128,109 | -$802 | -$3,209 | $124,097 | |
| 17 | -$1,962,315 | -$1,830,363 | $131,952 | -$826 | -$3,306 | $127,820 | |
| 18 | -$2,021,185 | -$1,885,274 | $135,911 | -$851 | -$3,405 | $131,654 | |
| 19 | -$2,081,820 | -$1,941,833 | $139,988 | -$877 | -$3,507 | $135,604 | |
| 20 | -$2,144,275 | -$2,000,087 | $144,187 | -$903 | -$3,612 | $139,672 | |

**Proposed Measure(s) vs Baseline**

| | | |
|---|---|---|
| Simple Payback | 0.3 | years |
| Relative Net Present Value | $924,954 | |
| Internal Rate of Return | 160% | |

# CHW AHUs with Air Side Economizing

## CEC Zone 13 (Fresno)

# Annual Total Electric Energy Use, Proposed

**Assumptions**

This scenario assumes seven 500 kVa modules. The efficiencies for the modules are drawn from Powersmith data sheets. Where data points were not provided we have estimated values according to a standard transformer curve profile. We assume that the number, size, and efficiency of the modules are the same for the baseline and proposed case.

We assume that all active transformer modules are loaded to an equal percentage.

All transformers are assumed to be of the linear type.

The power factor is assumed to be 1.00 (kW = kVA).

Transformers are not located in an air-conditioned space, so they do not impose a cooling load.

The transformers serve the rack, UPS, lighting, and chilled water plant loads.

**Input Parameters**

| | | | |
|---|---|---|---|
| Transformer Module Size: | 500 | kVA | See Transformers sheet |

**Annual Energy Use**

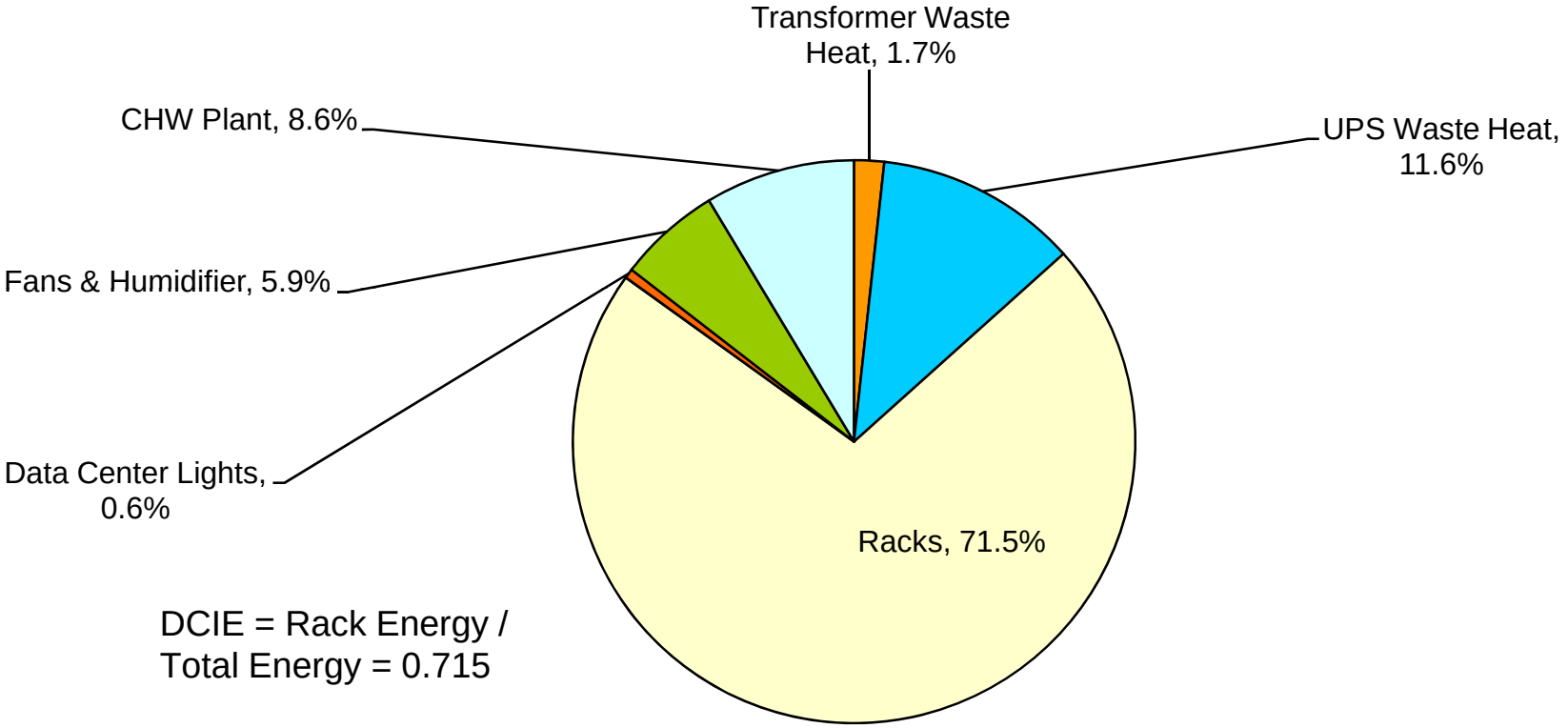
| System | Proposed | |
|---|---|---|
| | kWh/yr | Percent of Total |
| Transformer Waste Heat | 186,022 | 1.7% |
| UPS Waste Heat | 1,256,917 | 11.6% |
| Racks | 7,721,064 | 71.5% |
| Data Center Lights | 59,393 | 0.6% |
| Fans & Humidifier | 637,128 | 5.9% |
| CHW Plant | 931,040 | 8.6% |
| Total | 10,791,564 | 100.0% |

**Hourly Calculations**

| Date | Hour | Required Transformer Output Power | | | | | Transformer Modules | | | Transformer Total Input Power Demand | Trans-former Waste Heat | Peak Summer Power Demand |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | UPS Input Power | Data Center Lights | Fans and Humidifier | CHW Plant | Total | Quant. | Load Factor | Module Effic. | | | |
| | | kW | kW | kW | kW | kW | | % | % | kW | kW | kW |
| 1-Jan | 1 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 2 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 3 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 4 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 5 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 6 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 7 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 8 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 9 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 10 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 11 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 12 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 30-Jun | 13 | 1,025 | 7 | 55 | 195 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | 1,305 |
| 30-Jun | 14 | 1,025 | 7 | 55 | 194 | 1,281 | 3 | 85% | 98.2% | 1,305 | 24 | 1,305 |
| 30-Jun | 15 | 1,025 | 7 | 55 | 193 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | 1,303 |
| 30-Jun | 16 | 1,025 | 7 | 55 | 194 | 1,280 | 3 | 85% | 98.2% | 1,304 | 24 | 1,304 |
| 30-Jun | 17 | 1,025 | 7 | 55 | 194 | 1,280 | 3 | 85% | 98.2% | 1,304 | 24 | 1,304 |
| 30-Jun | 18 | 1,025 | 7 | 55 | 193 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | 1,303 |
| 30-Jun | 19 | 1,025 | 7 | 55 | 193 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | n/a |
| 30-Jun | 20 | 1,025 | 7 | 55 | 192 | 1,278 | 3 | 85% | 98.2% | 1,302 | 24 | n/a |
| 30-Jun | 21 | 1,025 | 7 | 55 | 191 | 1,277 | 3 | 85% | 98.2% | 1,301 | 24 | n/a |
| 30-Jun | 22 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 30-Jun | 23 | 1,025 | 7 | 80 | 105 | 1,217 | 3 | 81% | 98.2% | 1,239 | 23 | n/a |
| 30-Jun | 24 | 1,025 | 7 | 80 | 58 | 1,170 | 3 | 78% | 98.4% | 1,189 | 19 | n/a |
| 1-Jul | 1 | 1,025 | 7 | 83 | 0 | 1,115 | 3 | 74% | 98.5% | 1,132 | 17 | n/a |
| 1-Jul | 2 | 1,025 | 7 | 95 | 0 | 1,126 | 3 | 75% | 98.4% | 1,145 | 18 | n/a |
| 1-Jul | 3 | 1,025 | 7 | 98 | 0 | 1,129 | 3 | 75% | 98.4% | 1,147 | 18 | n/a |
| 1-Jul | 4 | 1,025 | 7 | 99 | 0 | 1,130 | 3 | 75% | 98.4% | 1,149 | 18 | n/a |
| 1-Jul | 5 | 1,025 | 7 | 99 | 0 | 1,130 | 3 | 75% | 98.4% | 1,149 | 18 | n/a |
| 1-Jul | 6 | 1,025 | 7 | 97 | 0 | 1,128 | 3 | 75% | 98.4% | 1,147 | 18 | n/a |
| 1-Jul | 7 | 1,025 | 7 | 84 | 0 | 1,116 | 3 | 74% | 98.5% | 1,133 | 17 | n/a |
| 1-Jul | 8 | 1,025 | 7 | 80 | 54 | 1,166 | 3 | 78% | 98.4% | 1,185 | 19 | n/a |
| 1-Jul | 9 | 1,025 | 7 | 80 | 86 | 1,198 | 3 | 80% | 98.4% | 1,217 | 19 | n/a |
| 1-Jul | 10 | 1,025 | 7 | 80 | 110 | 1,222 | 3 | 81% | 98.2% | 1,245 | 23 | n/a |
| 1-Jul | 11 | 1,025 | 7 | 55 | 191 | 1,278 | 3 | 85% | 98.2% | 1,301 | 24 | n/a |
| 1-Jul | 12 | 1,025 | 7 | 55 | 192 | 1,278 | 3 | 85% | 98.2% | 1,302 | 24 | n/a |
| 31-Dec | 13 | 1,025 | 7 | 100 | 0 | 1,132 | 3 | 75% | 98.4% | 1,150 | 18 | n/a |
| 31-Dec | 14 | 1,025 | 7 | 100 | 0 | 1,131 | 3 | 75% | 98.4% | 1,150 | 18 | n/a |
| 31-Dec | 15 | 1,025 | 7 | 99 | 0 | 1,131 | 3 | 75% | 98.4% | 1,149 | 18 | n/a |
| 31-Dec | 16 | 1,025 | 7 | 99 | 0 | 1,130 | 3 | 75% | 98.4% | 1,149 | 18 | n/a |
| 31-Dec | 17 | 1,025 | 7 | 55 | 184 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 31-Dec | 18 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 19 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 20 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 21 | 1,025 | 7 | 55 | 183 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 31-Dec | 22 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 23 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 31-Dec | 24 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| Sum | | 8,977,981 | 59,393 | 637,128 | 931,040 | 10,605,542 | | | | 10,791,564 | 186,022 | 1,053,063 |
| Ave | | 1,025 | 7 | 73 | 106 | 1,211 | 3.00 | 81% | 98.3% | 1,232 | 21 | 1,291 |
| Max | | 1,025 | 7 | 101 | 202 | 1,288 | 3 | 86% | 98.5% | 1,312 | 24 | 1,312 |
| Min | | 1,025 | 7 | 55 | 0 | 1,112 | 3 | 74% | 98.2% | 1,129 | 17 | 1,129 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# Data Center Infrastructure Efficiency (DCIE)
# Proposed




DCIE = Rack Energy / Total Energy = 0.715

# Space Parameters

**Assumptions**
Chilled water CRAC values are based on the Liebert Deluxe System 3, Model 740C.

| | Proposed | Units | Sources |
|---|---|---|---|
| **Input Parameters** | | | |
| ***Space Dimensions*** | | | |
| Floor Area | 6,780 | sf | Email from Dave Shroyer, 10/13/08. |
| ***Occupancy Schedule*** | | | |
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | Datacenter assumed to operate 8,760 hours per year |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | Datacenter assumed to operate 8,760 hours per year |
| ***HVAC System Type & Setpoints*** | | | |
| Air Delivery System | VAV | | The proposed system uses VAV air handlers. |
| Return Air Drybulb Setpoint | 89.5 | °F | Selected to get a 22 deg-F delta-T, email from Rupa Ganguly on 9/30/08. |
| Supply Air Drybulb Setpoint (VAV Systems Only) | 67.5 | °F | Estimate from email from Rupa Ganguly on 9/30/08. |
| Supply Air Design Flow Rate (CAV Systems Only) | | cfm | Total air flow provided by selected number & size of CRAC units and expected total static pressure drop of open HACA arrangement. |
| Active Humidity Control? | no | | Humidity control is baseline practice. The proposed facility will have no active humidity control. |
| Drybulb Temp at RH Sensor Location | 89.5 | °F | Humidity sensor is assumed to be mounted on the data center ceiling. |
| Allowed Relative Humidity, Maximum | 100% | RH | Assumed based on no humidity control. |
| Allowed Relative Humidity, Minimum | 1% | RH | Assumed based on no humidity control. |
| CHWST Setpoint, Primary | 44 | °F | Baseline CHWST setpoint value. |
| CHWST Setpoint, Secondary | 44 | °F | We are not considering CHWST reset. |
| Adiabatic Humdifier Power Draw | 0.000 | kW/ (lb of H20/hr) | No adiabatic humidifier. |

| | Proposed | Units | Sources |
|---|---|---|---|
| ***Cooling Load*** | | | |
| Total Rack Load, Occupied | 881 | kW | Calculated from rack load of 130 W/sf, email from Dave Shroyer, 10/13/08. |
| Total Rack Load, Unoccupied | n/a | kW | Rack load does not vary with occupancy. |
| Average Lighting Density | 1.0 | W/sf | Typical value. |
| ***Ventilation Requirement*** | | | |
| Minimum Ventilation Requirement | 0.15 | cfm/sf | CA Title 24 requirement for office space. |
| ***Boiler Data*** | | | |
| HHW Boiler Efficiency | 82% | % | Baseline value. |
| Gas-fired Humidifier Efficiency | 76% | % | Baseline value. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| ***HVAC System Type & Setpoints*** | | | |
| Occupied Supply Air Drybulb | | °F | = RAT - Occupied Load / (1.08 * cfm) |
| Unoccupied Supply Air Drybulb | | °F | A datacenter is assumed always occupied. |
| Occupied Supply Air Flow Rate | 127,545 | cfm | = Load / (1.08 * Delta-T) |
| Unoccupied Suppllly Air Flow Rate | n/a | | A datacenter is assumed always occupied. |
| Air Side Delta-T | 22 | °F | Subtract |
| ***Cooling Load*** | | | |
| UPS Waste Heat | 0 | kW | From UPS calculation sheet. The UPS units are in conditioned space, so the UPS waste heat is a load on the cooling system. |
| Data Center Lights | 7 | kW | Average lighting density times space floor area. |
| Total Internal Load, Occupied | 888 | kW | Rack load, UPS waste heat, lights. |
| Total Internal Load, Occupied | 253 | tons | Convert to tons |
| Total Internal Load, Occupied | 3,030 | kBTU/hr | Convert to kBTU/hr |
| Average Internal Load Density, Occupied | 131 | W/sf | Divide by floor area |
| Total Internal Load, Unoccupied | n/a | kW | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | tons | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | kBTU/hr | A datacenter is assumed always occupied. |
| Average Internal Load Density, Unoccupied | n/a | W/sf | A datacenter is assumed always occupied. |
| ***Ventilation Requirement*** | | | |
| Min Allowed Ventilation Volumetric Air Flow Rate | 1,017 | cfm | Floor area times minimum ventilation requirement. |

# Weather Data

Source: California Energy Commission
Data Set: California Climate Zone 13 (CZ13RV2) - Fresno

| Date | Hour | Outside Air | | | | | |
|---|---|---|---|---|---|---|---|
| | | Drybulb Temp. | Dewpoint Temp. | Relative Humidity | Atmospheric Pressure | Wetbulb Temp. | Enthalpy |
| | | °F | °F | % | psia | °F | BTU/lb |
| 1-Jan | 1 | 40.5 | 40.5 | 100% | 14.5 | 40.5 | 15.5 |
| 1-Jan | 2 | 40.6 | 40.6 | 100% | 14.5 | 40.6 | 15.6 |
| 1-Jan | 3 | 40.6 | 39.6 | 96% | 14.5 | 40.1 | 15.3 |
| 1-Jan | 4 | 39.6 | 38.7 | 97% | 14.5 | 39.2 | 14.9 |
| 1-Jan | 5 | 38.8 | 37.8 | 96% | 14.5 | 38.4 | 14.5 |
| 1-Jan | 6 | 38.8 | 37.8 | 96% | 14.5 | 38.4 | 14.5 |
| 1-Jan | 7 | 38.8 | 37.8 | 96% | 14.5 | 38.4 | 14.5 |
| 1-Jan | 8 | [illegible] | [illegible] | [illegible] | [illegible] | 38.4 | 14.5 |
| 1-Jan | 9 | [illegible] | [illegible] | [illegible] | [illegible] | 38.4 | 14.5 |
| 1-Jan | 10 | [illegible] | [illegible] | [illegible] | [illegible] | 39.2 | 14.9 |
| 1-Jan | 11 | [illegible] | [illegible] | [illegible] | [illegible] | 40.1 | 15.3 |
| 1-Jan | 12 | [illegible] | [illegible] | [illegible] | [illegible] | 42.9 | 16.7 |
| 30-Jun | 13 | [illegible] | [illegible] | [illegible] | [illegible] | 67.3 | 32.0 |
| 30-Jun | 14 | [illegible] | [illegible] | [illegible] | [illegible] | 66.3 | 31.2 |
| 30-Jun | 15 | 91.8 | 45.9 | 21% | 14.3 | 64.1 | 29.5 |
| 30-Jun | 16 | 93.7 | 47.8 | 21% | 14.3 | 65.4 | 30.5 |
| 30-Jun | 17 | 94.8 | 44.8 | 18% | 14.3 | 64.5 | 29.9 |
| 30-Jun | 18 | 92.8 | 45.9 | 20% | 14.3 | 64.3 | 29.7 |
| 30-Jun | 19 | 88.9 | 47.1 | 24% | 14.3 | 63.6 | 29.2 |
| 30-Jun | 20 | 85.5 | 46.0 | 25% | 14.3 | 61.7 | 27.8 |
| 30-Jun | 21 | 82.4 | 45.5 | 27% | 14.3 | 60.4 | 26.9 |
| 30-Jun | 22 | 79.2 | 45.5 | 30% | 14.3 | 59.3 | 26.1 |
| 30-Jun | 23 | 74.7 | 46.0 | 36% | 14.3 | 58.0 | 25.3 |
| 30-Jun | 24 | 69.6 | 46.9 | 44% | 14.3 | 56.4 | 24.3 |
| 1-Jul | 1 | 64.9 | 48.7 | 56% | 14.3 | 55.6 | 23.8 |
| 1-Jul | 2 | 61.7 | 49.3 | 64% | 14.3 | 54.6 | 23.2 |
| 1-Jul | 3 | 60.3 | 49.6 | 68% | 14.3 | 54.1 | 22.9 |
| 1-Jul | 4 | 59.4 | 49.5 | 70% | 14.3 | 53.7 | 22.6 |
| 1-Jul | 5 | 59.4 | 49.3 | 69% | 14.3 | 53.5 | 22.5 |
| 1-Jul | 6 | 60.8 | 49.8 | 67% | 14.3 | 54.4 | 23.0 |
| 1-Jul | 7 | 64.8 | 49.8 | 58% | 14.3 | 55.9 | 24.0 |
| 1-Jul | 8 | 68.7 | 49.6 | 51% | 14.3 | 57.5 | 25.0 |
| 1-Jul | 9 | 72.7 | 49.6 | 44% | 14.3 | 58.9 | 25.8 |
| 1-Jul | 10 | 76.6 | 48.6 | 37% | 14.3 | 59.8 | 26.5 |
| 1-Jul | 11 | 79.7 | 50.7 | 36% | 14.3 | 61.8 | 27.8 |
| 1-Jul | 12 | 83.7 | 50.7 | 32% | 14.3 | 63.2 | 28.9 |
| 31-Dec | 13 | 57.9 | 50.0 | 75% | 14.5 | 53.4 | 22.3 |
| 31-Dec | 14 | 58.5 | 50.9 | 76% | 14.5 | 54.1 | 22.7 |
| 31-Dec | 15 | 58.8 | 51.4 | 76% | 14.5 | 54.4 | 22.9 |
| 31-Dec | 16 | 59.4 | 52.3 | 78% | 14.5 | 55.3 | 23.5 |
| 31-Dec | 17 | 55.6 | 50.0 | 81% | 14.5 | 52.3 | 21.7 |
| 31-Dec | 18 | 52.0 | 47.5 | 85% | 14.5 | 49.6 | 20.1 |
| 31-Dec | 19 | 48.2 | 45.1 | 89% | 14.5 | 46.6 | 18.5 |
| 31-Dec | 20 | 46.2 | 43.2 | 89% | 14.5 | 44.7 | 17.5 |
| 31-Dec | 21 | 44.1 | 41.0 | 89% | 14.5 | 42.6 | 16.5 |
| 31-Dec | 22 | 42.1 | 39.0 | 89% | 14.5 | 40.7 | 15.6 |
| 31-Dec | 23 | 40.8 | 38.8 | 93% | 14.5 | 39.9 | 15.2 |
| 31-Dec | 24 | 40.5 | 38.7 | 93% | 14.5 | 39.6 | 15.1 |
| Ave | | 63.8 | 46.2 | 59% | 14.4 | 53.5 | 22.9 |
| Max | | 106.3 | 66.4 | 100% | 14.6 | 75.4 | 39.2 |
| Min | | 28.0 | 21.0 | 8% | 14.2 | 25.9 | 9.3 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

# Transformer Data

## Proposed

**Parameters**

| | | |
|---|---|---|
| Size | 500 | kVA |

Values in blue are from NEMA Standard TP-1 Transformer Efficiency, Three Phase (Table 4.2). All other values are extrapolated.

| **Linear Efficiency vs. Load Factor** | |
|---|---|
| Load | Efficiency |
| 100% | 97.9% |
| 90% | 98.2% |
| 80% | 98.4% |
| 75% | 98.5% |
| 70% | 98.6% |
| 60% | 98.8% |
| 50% | 98.8% |
| 40% | 98.8% |
| 35% | 98.7% |
| 30% | 98.6% |
| 25% | 98.5% |
| 20% | 98.3% |
| 17% | 98.2% |
| 10% | 97.7% |

# Chiller Data

**Assumptions**
The same chillers are used in the baseline and proposed cases.
We set the chillers to the same size.

**Parameters**

| | Proposed | Units | Sources |
|---|---|---|---|
| Chiller Capacity | 500 | tons | Capacity selected to result in a total of three chillers, with appropriate safety and redundancy factors. |
| Condenser Water Temperature | 80 | °F | Typical value. |
| CHW Supply Temperature | 44 | °F | Typical value. |
| CW Flow Rate | 1,200 | gpm | Assumes a 10F CW delta-T when chiller is a maximum load. |

Values from Baseline Water-Cooled Chilled Water Plant Above 300 tons

| **Chiller Efficiency (kW/ton) at CHWS Temp = 44 F** | |
|---|---|
| Load | Condenser Water Temp (°F) |
| | 80 |
| 100% | 0.529 |
| 90% | 0.526 |
| 80% | 0.526 |
| 70% | 0.530 |
| 60% | 0.539 |
| 50% | 0.557 |
| 40% | 0.590 |
| 30% | 0.653 |
| 20% | 0.792 |
| 10% | 1.234 |

# Cooling Tower Fan Speed Lookup Tables, Proposed

| | |
|---|---|
| Cooling Tower Make & Model Used in Analysis | BAC 3482A |

The following lookup tables were created by drawing information from BAC's Cooling Tower Selection Software, Release 6.02 NA. The fan speeds are expressed in percent.

Fan speed depends on the load on the tower, the condenser water flow rate, the ambient wetbulb temperature, and the temperature of the condenser water leaving the tower (aka the cold condenser water temperature). The lowest fan speed the BAC software wil

**Tower Specifications at Nominal Conditions**

| | | |
|---|---|---|
| Ambient Wetbulb Temperature | 78 | deg F |
| Hot Condenser Water Temperature | 95 | deg F |
| Cold Condenser Water Temperature | 88.7 | deg F |
| Condenser Water Flow Rate, Maximum | 2,600 | gpm |
| Condenser Water Flow Rate, Minimum | 609 | gpm |
| Nominal Cooling Tower Capacity | 679 | tons |
| Cooling Tower Fan Motor Size | 30 | hp |

## 50% Maximum Flow = 1300 gpm

**0 tons, 1300 gpm**

All temperatures in deg F

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**50 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**100 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**150 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**200 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**250 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**300 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

# UPS Energy Calculation

| UPS System Parameters | Proposed | Units | Comments |
|---|---|---|---|
| **UPS Module Data** | | | |
| Total Rack Load | 881 | kW | From Space sheet. |
| Percentage of Load Served by UPS | 100% | % | We assume all racks are backed up. |
| UPS Load | 881 | kW | Rack load times percentage of load served by UPS. |
| Number of Modules | 5 | | Assumed. |
| Unit Capacity | 500 | kVA | Assumed. |
| Total UPS Capacity | 2,500 | kVA | Unit capacity * number of units |
| Load Factor | 35% | % | UPS load / UPS capacity |
| UPS Efficiency | 86% | % | From LBNL Datacenter UPS benchmarking study. |
| **Energy Use** | | | |
| Annual Energy Use | 8,977,981 | kWh/yr | UPS load / UPS efficiency * 8760 hours |
| Peak Demand | 1,025 | kW | UPS load / UPS efficiency |

# Proposed Heating & Cooling Load, Fan Energy, Energy Savings

**Template:** **Air Handler Energy Model_Recirculation with Economizer_v10.3**

**Input Parameters**

| | | | |
|---|---|---|---|
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | From the Space Parameters sheet. |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | From the Space Parameters sheet. |
| Air Delivery System: CAV or VAV? | VAV | | From the Space Parameters sheet. |
| Return Air Drybulb Setpoint | 89.5 | F | From the Space Parameters sheet. |
| Active Humidity Control? | no | | From the Space Parameters sheet. |
| Drybulb Temp at RH Sensor Location | 89.5 | F | From the Space Parameters sheet. |
| Allowed Relative Humidity, Maximum | 100% | RH | From the Space Parameters sheet. |
| Allowed Relative Humidity, Minimum | 1% | RH | From the Space Parameters sheet. |
| Min Allowed Ventilation Air Flow Rate | 1,017 | cfm | From the Space Parameters sheet. |
| CHWST Setpoint, Primary | 44 | F | From the Space Parameters sheet. |
| CHWST Setpoint during Reset | 44 | F | From the Space Parameters sheet. |
| Adiabatic Humidifier Power Draw | 0.000 | kW/(lb of H20/hr) | From the Space Parameters sheet. |

| | | | |
|---|---|---|---|
| Humidifier: 0=None, 1=Electric, 2=Steam, 3=Adiabatic | 0 | | No active humidification in the proposed case. |
| Cooling Plant Type: 1=CHW, 2=DX | 1 | | There is a chilled water plant in the proposed case. |
| CHWST Reset: 0=No, 1=Yes | 0 | | No CHWST in the proposed case. |
| Economizer? | yes | | Proposed design includes integrated economizing. |
| Economizer Drybulb Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Drybulb Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Drybulb Upper Lockout | 78 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Dewpoint Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Dewpoint Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Dewpoint Upper Lockout | 55 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Enthalpy Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Enthalpy Lower Lockout | 0 | BTU/lb | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Enthalpy Upper Lockout | 29.75 | BTU/lb | Email from Rupa Ganguly on 9/30/08. |
| Economizer Relative Humidity Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| RH Lower Lockout | 20% | % | Email from Rupa Ganguly on 9/30/08. |
| RH Upper Lockout | 80% | % | Email from Rupa Ganguly on 9/30/08. |

| Fan System Parameters | | Supply | Relief | Units | Sources |
|---|---|---|---|---|---|
| Fan Motor Size, Nominal | | 30 | 50 | hp | Sized in accordance with calculated brake horsepower, below. |
| Number of Fans | | 10 | 5 | | Arbitrary numbers selected for model. Assuming one supply fan per RAHU. |
| Fan Efficiency | | 63.8% | 67.5% | % | Baseline fan efficiencies for motor sizes indicated. |
| Fan Drive Efficiency | | 95% | 95% | % | Typical value for belt drive. |
| Fan Motor Efficiency | | 92.5% | 93.2% | % | Baseline efficiencies. |
| VFD Efficiency | | 98% | 98% | % | Supply and relief fans assumed to be equipped with VFDs. |
| Fan Motor and Drive in Airstream? | | 1 | n/a | 1=yes, 0=no | Assumption. |
| Econ. In Min. Pos. | Total Static Pressure Drop | 2.00 | 8.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | n/a | F | Calculated based on maximum fan motor output power. |
| Economizer Open | Total Static Pressure Drop | 2.00 | 1.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | n/a | F | Calculated based on maximum fan motor output power. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| Return Air Minimum Dewpoint | 0.0 | F | Dewpoint of return air when RH sensor is at minimum allowed RH. |
| Space Dewpoint at Maximum Allowed Space Humidity | 89.5 | | Corresponds to Space DB and Max Allowed RH. |
| Chilled Water Minimum Temperature Requirement | 64.5 | F | If the cooling system is CHW, the cooling coil is assumed to have a constant approach temperature of 3 deg F. |

| Fan System Parameters | Supply | Relief | Units | Comments |
|---|---|---|---|---|
| Fan Motor Output Power, Maximum | 4.9 | 8.5 | kW | Per fan motor. This is the maximum output brake power each fan motor is called upon to deliver. |
| Fan Motor Output Power, Maximum | 6.6 | 11.4 | hp | Per fan motor. Converted from kW to hp. |

**Error Messages**

OK - RH minimum does not require humidifier. No humidifier identified.
OK - Chilled Water Supply Temperature Setpoint is low enough to perform required sensible and latent cooling.
OK - Supply Fan Motor Size Exceeds Maximum Required Supply Fan Motor Output
OK - Relief Fan Motor Size Exceeds Maximum Required Relief Fan Motor Output

**Results (Annual Totals)**

| | Proposed | Units |
|---|---|---|
| Cooling Energy Extracted from Airstream | 14,135,223 | kBTU/yr |
| Heating Energy Added to Airstream | 0 | kBTU/yr |
| Humidifier Energy Added to Airstream | 0 | kBTU/yr |

| | Proposed | Units |
|---|---|---|
| Humidifier Energy Required | n/a | kWh/yr |
| | n/a | therms/yr |
| Fan Motor Energy Required | 637,128 | kWh/yr |

**Hourly Calculations**

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Energy Required to Sensibly Cool Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | | | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | Supply | | Relief | | Total Power Input | | Electric | Steam | Adia-batic | |
| | | | | | | | | | | | | | | | | | | | Total Power Input | Air Deliv. Effic. | Total Power Input | Air Deliv. Effic. | | | | | | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | kBTU | kBTU | kBTU | kW | cfm/kW | kW | cfm/kW | kW | tons | kW | therms | kW | therms |
| 1-Jan | 1 | 127,545 | 67.5 | 67.5 | 67.5 | 40.5 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 40.5 | 44.0 | 2,977 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 2 | 127,545 | 67.5 | 67.5 | 67.5 | 40.6 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 40.6 | 44.0 | 2,977 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 39.6 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.6 | 44.0 | 2,977 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 38.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 38.7 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 37.8 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.8 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 37.8 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.8 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 37.8 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.8 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 37.8 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.8 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 37.8 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.8 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 38.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 38.7 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 39.6 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.6 | 44.0 | 2,977 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 42.4 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 42.4 | 44.0 | 2,980 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 54.9 | 1 | 0 | 1 | 0 | 1 | 1,017 | 89.5 | 54.9 | 44.0 | 3,031 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 50.7 | 1 | 0 | 1 | 0 | 1 | 1,017 | 89.5 | 50.7 | 44.0 | 3,034 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 45.9 | 1 | 0 | 0 | 0 | 1 | 1,017 | 89.5 | 45.9 | 44.0 | 3,033 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 47.8 | 1 | 0 | 1 | 0 | 1 | 1,017 | 89.5 | 47.8 | 44.0 | 3,035 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 17 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | 1 | 0 | 1 | 1 | 1 | 1,017 | 89.5 | 44.8 | 44.0 | 3,036 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 18 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.5 | 45.9 | 44.0 | 3,034 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 19 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.5 | 47.1 | 44.0 | 3,030 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 20 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.5 | 46.0 | 44.0 | 3,026 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 21 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.4 | 45.5 | 44.0 | 3,023 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 22 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.4 | 45.5 | 44.0 | 3,019 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 23 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 74.7 | 46.0 | 44.0 | 986 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 82 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 24 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 127,545 | 69.6 | 46.9 | 44.0 | 292 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 24 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 1 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 124,637 | 65.5 | 48.7 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 28.7 | 4,346 | 83.3 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 2 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0 | 110,111 | 65.5 | 49.3 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 40.2 | 2,740 | 94.8 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 49.6 | 0 | 0 | 0 | 0 | 0 | 104,688 | 65.5 | 49.6 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 42.9 | 2,439 | 97.5 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 49.5 | 0 | 0 | 0 | 0 | 0 | 101,562 | 65.5 | 49.5 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 44.1 | 2,301 | 98.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 49.3 | 0 | 0 | 0 | 0 | 0 | 101,562 | 65.5 | 49.3 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 44.1 | 2,301 | 98.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 49.8 | 0 | 0 | 0 | 0 | 0 | 106,658 | 65.5 | 49.8 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 42.0 | 2,538 | 96.6 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 49.8 | 0 | 0 | 0 | 0 | 0 | 123,730 | 65.5 | 49.8 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 29.6 | 4,182 | 84.2 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 49.6 | 0 | 0 | 0 | 0 | 0 | 127,545 | 68.7 | 49.6 | 44.0 | 168 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 14 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 49.6 | 0 | 0 | 0 | 0 | 0 | 127,545 | 72.7 | 49.6 | 44.0 | 714 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 59 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 48.6 | 0 | 0 | 0 | 0 | 0 | 127,545 | 76.6 | 48.6 | 44.0 | 1,259 | 0 | 0 | 54.6 | 2,337 | 25.6 | 4,982 | 80.2 | 105 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 50.7 | 1 | 0 | 0 | 0 | 1 | 1,017 | 89.4 | 50.7 | 44.0 | 3,020 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 50.7 | 1 | 0 | 0 | 0 | 1 | 1,017 | 89.5 | 50.7 | 44.0 | 3,024 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 252 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 50.0 | 0 | 0 | 0 | 0 | 0 | 96,931 | 65.5 | 50.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 45.5 | 2,132 | 100.1 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 50.9 | 0 | 0 | 0 | 0 | 0 | 98,617 | 65.5 | 50.9 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 45.0 | 2,189 | 99.6 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 51.4 | 0 | 0 | 0 | 0 | 0 | 99,774 | 65.5 | 51.4 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 44.7 | 2,231 | 99.3 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Energy Required to Sensibly Cool Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | | | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | Supply | | Relief | | | | | | | |
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | Total Power Input | Air Deliv. Effic. | Total Power Input | Air Deliv. Effic. | Total Power Input | | Electric | Steam | Adia-batic | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | kBTU | kBTU | kBTU | kW | cfm/kW | kW | cfm/kW | kW | tons | kW | therms | kW | therms |
| 31-Dec | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 52.3 | 0 | 0 | 0 | 0 | 0 | 101,562 | 65.5 | 52.3 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 44.1 | 2,301 | 98.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 17 | 127,545 | 67.5 | 67.5 | 67.5 | 50.0 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.2 | 50.0 | 44.0 | 2,993 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 18 | 127,545 | 67.5 | 67.5 | 67.5 | 47.5 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.2 | 47.5 | 44.0 | 2,989 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 19 | 127,545 | 67.5 | 67.5 | 67.5 | 45.1 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.2 | 45.1 | 44.0 | 2,985 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 20 | 127,545 | 67.5 | 67.5 | 67.5 | 43.2 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.2 | 43.2 | 44.0 | 2,983 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 21 | 127,545 | 67.5 | 67.5 | 67.5 | 41.0 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 41.0 | 44.0 | 2,981 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 22 | 127,545 | 67.5 | 67.5 | 67.5 | 39.0 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.0 | 44.0 | 2,978 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 23 | 127,545 | 67.5 | 67.5 | 67.5 | 38.8 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 38.8 | 44.0 | 2,977 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 24 | 127,545 | 67.5 | 67.5 | 67.5 | 38.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 38.7 | 44.0 | 2,977 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| Sum | | | | | | | 1,845 | 1,068 | 1,023 | 2,467 | 4,453 | | | | | ######## | 0 | 0 | 478,182 | | 158,947 | | ###### | | 0 | 0 | 0 | 0 |
| Ave | | 127,545 | 67.5 | 67.5 | 67.5 | 46.2 | 0.211 | 0.122 | 0.117 | 0.282 | 0.508 | 52,580 | 78.5 | 46.2 | 44.0 | 1,614 | 0 | 0 | 54.6 | 2,337 | 18.1 | 5,148 | 72.7 | 134 | 0.0 | 0.0 | 0.00 | 0.0 |
| Max | | 127,545 | 67.5 | 67.5 | 67.5 | 66.4 | | | | | | 127,545 | 89.6 | 66.4 | 44.0 | 3,049 | 0 | 0 | 54.6 | 2,337 | 46.5 | 7,022 | 101.1 | 254 | 0.0 | 0.0 | 0.00 | 0.0 |
| Min | | 127,545 | 67.5 | 67.5 | 67.5 | 21.0 | | | | | | 1,017 | 65.5 | 21.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 0.1 | 1,514 | 54.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |

# Cooling Tower Energy Use, Proposed

**Assumptions**

The proposed cooling towers are staged in tandem with the baseline chillers (number of active towers = number of active chillers).
The proposed cooling tower fan motors are two-speed (100% and 50%).

**Parameters**

| | | | |
|---|---|---|---|
| Chiller Condenser Water Temperature Setpoint | 80 | °F | Baseline |
| Cooling Tower Fan Motor Size | 30 | hp | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Cooling Tower Condenser Water Flow, Maximum | 2,600 | gpm | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Motor Load Factor at Full Speed | 90% | | Estimate |
| Fan Motor Efficiency | 92.5% | | Baseline |
| Fan Drive Efficiency | 95% | | Belt drive |
| Fan Power, Baseline Cooling Tower, 100% | 22.9 | kW | = 0.746 * motor size * load factor / (drive effic * motor effic) |
| Fan Power, Baseline Cooling Tower, 50% | 2.9 | kW | Fan Law Calculation |

**Hourly Calculations**

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 1-Jan | 1 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 2 | 41 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 3 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 4 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 5 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 6 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 7 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 8 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 9 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 10 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 11 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 12 | 43 | 248 | 1 | 46% | 248 | 60 | 80.0 | 41% | 2.3 | 2.9 | 2.3 | 2.9 |
| 30-Jun | 13 | 67 | 253 | 1 | 46% | 253 | 80 | 80.0 | 71% | 16.3 | 22.9 | 16.3 | 22.9 |
| 30-Jun | 14 | 66 | 253 | 1 | 46% | 253 | 80 | 80.0 | 68% | 15.6 | 22.9 | 15.6 | 22.9 |
| 30-Jun | 15 | 64 | 253 | 1 | 46% | 253 | 75 | 80.0 | 63% | 14.4 | 22.9 | 14.4 | 22.9 |
| 30-Jun | 16 | 65 | 253 | 1 | 46% | 253 | 75 | 80.0 | 65% | 15.0 | 22.9 | 15.0 | 22.9 |
| 30-Jun | 17 | 65 | 253 | 1 | 46% | 253 | 75 | 80.0 | 65% | 15.0 | 22.9 | 15.0 | 22.9 |
| 30-Jun | 18 | 64 | 253 | | | | | | 63% | 14.4 | 22.9 | 14.4 | 22.9 |
| 30-Jun | 19 | 64 | 252 | | | | | | 63% | 14.4 | 22.9 | 14.4 | 22.9 |
| 30-Jun | 20 | 62 | 252 | | | | | | 58% | 13.4 | 22.9 | 13.4 | 22.9 |
| 30-Jun | 21 | 60 | 252 | | | | | | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 30-Jun | 22 | 59 | 252 | | | | | | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 30-Jun | 23 | 58 | 82 | | | | | | 52% | 11.8 | 22.9 | 11.8 | 22.9 |
| 30-Jun | 24 | 56 | 24 | 1 | 46% | 24 | 70 | 80.0 | 49% | 2.8 | 2.9 | 2.8 | 2.9 |
| 1-Jul | 1 | 56 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 2 | 55 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 3 | 54 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 4 | 54 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 5 | 54 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 6 | 54 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 7 | 56 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 8 | 58 | 14 | 1 | 46% | 14 | 70 | 80.0 | 52% | 11.8 | 22.9 | 11.8 | 22.9 |
| 1-Jul | 9 | 59 | 59 | 1 | 46% | 59 | 70 | 80.0 | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 1-Jul | 10 | 60 | 105 | 1 | 46% | 105 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 1-Jul | 11 | 62 | 252 | 1 | 46% | 252 | 75 | 80.0 | 58% | 13.4 | 22.9 | 13.4 | 22.9 |
| 1-Jul | 12 | 63 | 252 | 1 | 46% | 252 | 75 | 80.0 | 60% | 13.8 | 22.9 | 13.8 | 22.9 |
| 31-Dec | 13 | 53 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 31-Dec | 14 | 54 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 15 | 54 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 16 | 55 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 17 | 52 | 249 | 1 | 46% | 249 | 65 | 80.0 | 45% | 2.6 | 2.9 | 2.6 | 2.9 |
| 31-Dec | 18 | 50 | 249 | 1 | 46% | 249 | 65 | 80.0 | 44% | 2.5 | 2.9 | 2.5 | 2.9 |
| 31-Dec | 19 | 47 | 249 | 1 | 46% | 249 | 65 | 80.0 | 42% | 2.4 | 2.9 | 2.4 | 2.9 |
| 31-Dec | 20 | 45 | 249 | 1 | 46% | 249 | 60 | 80.0 | 41% | 2.4 | 2.9 | 2.4 | 2.9 |
| 31-Dec | 21 | 43 | 248 | 1 | 46% | 248 | 60 | 80.0 | 41% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 22 | 41 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 23 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 31-Dec | 24 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| Sum | | | | | | | | | | | | 50,112 | 78,474 |
| Ave | | 54 | 134 | 0.637 | 46% | 134 | 69 | 80.0 | 53% | 5.7 | 9.0 | 5.7 | 9.0 |
| Max | | 75 | 254 | 1 | 46% | 254 | 85 | 85.0 | 98% | 22.5 | 22.9 | 22.5 | 22.9 |
| Min | | 26 | 0 | 0 | 46% | 0 | 50 | 80.0 | 38% | 0.0 | 0.0 | 0.0 | 0.0 |

No. of hours in year that actual CW temp > 80: 29

# CHW Pump Energy Use, Proposed

**Template Name:** **CHW Pump Energy Model_v1.01**

**Assumptions**

There is one operating constant-speed primary CHW pump per active chiller.
All of the primary CHW pumps are identical.
There is one operating variable-speed secondary CHW pump.

**Results**

| | Proposed | Units |
|---|---|---|
| CHW Pump Energy Required | 148,618 | kWh/yr |
| Ave CHW Pump System Effic. | 67.1 | gpm/kW |

***Primary Pumps***

**Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T across evaporator. |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

***Secondary Pump***

**Input Parameters**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 650 | 610 | gpm | Nominal: 650.<br>Design: 254-ton peak load, 10F CHW delta-T. |
| Head | 100 | 100 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 70% | 70% | | Nominal: Baseline for 75 hp motor.<br>Design: Baseline for 75 hp motor. |
| Pump Motor Size | 100 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 94.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 98% | | | Secondary pumps are variable speed. |
| Secondary CHW Loop Delta-T | | 10 | F | Estimate. |

**Calculations**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 22.0 | hp | (flow * head) / (3960 * pump effic) |
| Pump VFD Input Power | | 17.7 | kW | 0.746 * hp / motor effic / VFD effic |

**Error Messages**

OK -- Primary Pump Motor is not undersized.
OK -- Secondary Pump Motor is not undersized.

**Hourly Analysis**

| Date | Hour | Total Cooling Load | No. of Chillers On | Total Primary CHW Flow | Total Primary Pump Power | Secondary Loop CHW Flow | Secondary Pump Power | Total CHW Pump Power | CHW Pump System Efficiency |
|---|---|---|---|---|---|---|---|---|---|
| | | tons | | gpm | kW | gpm | kW | kW | gpm/kW |
| 1-Jan | 1 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 2 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 3 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 4 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 5 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 6 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 7 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 8 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 9 | 248 | | | | | 17 | 29 | 60.9 |
| 1-Jan | 10 | 248 | | | | | 17 | 29 | 60.9 |
| 1-Jan | 11 | 248 | | | | | 17 | 29 | 60.9 |
| 1-Jan | 12 | 248 | | | | | 17 | 30 | 60.9 |
| 30-Jun | 13 | 253 | | | | | 18 | 30 | 60.3 |
| 30-Jun | 14 | 253 | 1 | 1,200 | 12 | 607 | 18 | 30 | 60.3 |
| 30-Jun | 15 | 253 | 1 | 1,200 | 12 | 607 | 18 | 30 | 60.3 |
| 30-Jun | 16 | 253 | 1 | 1,200 | 12 | 607 | 18 | 30 | 60.3 |
| 30-Jun | 17 | 253 | 1 | 1,200 | 12 | 607 | 18 | 30 | 60.3 |
| 30-Jun | 18 | 253 | 1 | 1,200 | 12 | 607 | 18 | 30 | 60.3 |
| 30-Jun | 19 | 252 | 1 | 1,200 | 12 | 606 | 18 | 30 | 60.3 |
| 30-Jun | 20 | 252 | 1 | 1,200 | 12 | 605 | 18 | 30 | 60.4 |
| 30-Jun | 21 | 252 | 1 | 1,200 | 12 | 605 | 18 | 30 | 60.4 |
| 30-Jun | 22 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.4 |
| 30-Jun | 23 | 82 | 1 | 1,200 | 12 | 197 | 3 | 16 | 89.4 |
| 30-Jun | 24 | 24 | 1 | 1,200 | 12 | 58 | 1 | 13 | 97.6 |
| 1-Jul | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 8 | 14 | 1 | 1,200 | 12 | 34 | 0 | 13 | 97.9 |
| 1-Jul | 9 | 59 | 1 | 1,200 | 12 | 143 | 2 | 14 | 93.4 |
| 1-Jul | 10 | 105 | 1 | 1,200 | 12 | 252 | 5 | 17 | 85.0 |
| 1-Jul | 11 | 252 | 1 | 1,200 | 12 | 604 | 17 | 30 | 60.4 |
| 1-Jul | 12 | 252 | 1 | 1,200 | 12 | 605 | 18 | 30 | 60.4 |
| 31-Dec | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 17 | 249 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.7 |
| 31-Dec | 18 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.8 |
| 31-Dec | 19 | 249 | 1 | 1,200 | 12 | 597 | 17 | 30 | 60.8 |
| 31-Dec | 20 | 249 | 1 | 1,200 | 12 | 597 | 17 | 30 | 60.8 |
| 31-Dec | 21 | 248 | 1 | 1,200 | 12 | 596 | 17 | 30 | 60.9 |
| 31-Dec | 22 | 248 | 1 | 1,200 | 12 | 596 | 17 | 29 | 60.9 |
| 31-Dec | 23 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 31-Dec | 24 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| Sum | | | | | 68,968 | | 79,649 | 148,618 | |
| Ave | | 134 | 0.637 | 764 | 8 | 323 | 9 | 17 | 67.1 |
| Max | | 254 | 1 | 1,200 | 12 | 610 | 18 | 30 | 97.9 |
| Min | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60.1 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# CHW Plant Energy Use, Proposed

**Assumptions**
All chillers are identical and rotated equally.
There is one operating constant-speed CW pump per active chiller.

| | | | |
|---|---|---|---|
| Electric Chiller Capacity | 500 | tons | Assumed. |
| Number of Electric Chillers | 3 | | Assumed. |
| Total Electric Chiller Capacity | 1,500 | tons | Chiller capacity times number of chillers. |
| Chilled Water Supply Temperature | 44 | F | Baseline. |

**Condenser Water Pump Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

**Results (Annual Totals)**

| | Proposed | Units |
|---|---|---|
| Total Annual Electric Use | 931,040 | kWh/yr |
| Summer Peak Electric Demand | 202 | kW |
| Annual Average Cooling Efficiency | 0.790 | kW/ton |

**Hourly Calculations**

| Date | Hour | Total Cooling Load | Chillers | | | | Cooling Tower Power Demand | CHW & CW Pump Power Demand | Total Cooling Plant Power Demand | Summer Peak Demand |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Chillers Operating | Chiller Load Factor | Chiller Effic. | Chiller Power Demand | | | | |
| | | tons | 0-3 | % | kW/ton | kW | kW | kW | kW | kW |
| 1-Jan | 1 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 2 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 3 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 4 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 5 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 6 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 7 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 8 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 9 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 10 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 11 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 182 | n/a |
| 1-Jan | 12 | 248 | 1 | [illegible] | [illegible] | [illegible] | [illegible] | 42 | 183 | n/a |
| 30-Jun | 13 | 253 | 1 | 51% | 0.54 | 136 | 16.3 | 42 | 195 | 201 |
| 30-Jun | 14 | 253 | 1 | 51% | 0.54 | 136 | 15.6 | 42 | 194 | 202 |
| 30-Jun | 15 | 253 | 1 | 51% | 0.54 | 136 | 14.4 | 42 | 193 | 201 |
| 30-Jun | 16 | 253 | 1 | 51% | 0.54 | 136 | 15.0 | 42 | 194 | 202 |
| 30-Jun | 17 | 253 | 1 | 51% | 0.54 | 136 | 15.0 | 42 | 194 | 202 |
| 30-Jun | 18 | 253 | 1 | 51% | 0.54 | 136 | 14.4 | 42 | 193 | 202 |
| 30-Jun | 19 | 252 | 1 | 50% | 0.54 | 136 | 14.4 | 42 | 193 | n/a |
| 30-Jun | 20 | 252 | 1 | 50% | 0.54 | 136 | 13.4 | 42 | 192 | n/a |
| 30-Jun | 21 | 252 | 1 | 50% | 0.54 | 136 | 12.5 | 42 | 191 | n/a |
| 30-Jun | 22 | 252 | 1 | 50% | 0.54 | 136 | 12.1 | 42 | 190 | n/a |
| 30-Jun | 23 | 82 | 1 | 16% | 0.79 | 65 | 11.8 | 28 | 105 | n/a |
| 30-Jun | 24 | 24 | 1 | 5% | 1.23 | 30 | 2.8 | 25 | 58 | n/a |
| 1-Jul | 1 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 2 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 3 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 4 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 5 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 6 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 7 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 8 | 14 | 1 | 3% | 1.23 | 17 | 11.8 | 25 | 54 | n/a |
| 1-Jul | 9 | 59 | 1 | 12% | 0.79 | 47 | 12.1 | 27 | 86 | n/a |
| 1-Jul | 10 | 105 | 1 | 21% | 0.65 | 69 | 12.5 | 29 | 110 | n/a |
| 1-Jul | 11 | 252 | 1 | 50% | 0.54 | 136 | 13.4 | 42 | 191 | n/a |
| 1-Jul | 12 | 252 | 1 | 50% | 0.54 | 136 | 13.8 | 42 | 192 | n/a |
| 31-Dec | 13 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 14 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 15 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 16 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 17 | 249 | 1 | 50% | 0.56 | 139 | 2.6 | 42 | 184 | n/a |
| 31-Dec | 18 | 249 | 1 | 50% | 0.56 | 139 | 2.5 | 42 | 183 | n/a |
| 31-Dec | 19 | 249 | 1 | 50% | 0.56 | 139 | 2.4 | 42 | 183 | n/a |
| 31-Dec | 20 | 249 | 1 | 50% | 0.56 | 138 | 2.4 | 42 | 183 | n/a |
| 31-Dec | 21 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 183 | n/a |
| 31-Dec | 22 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 23 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 31-Dec | 24 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| Sum | | 1,177,935 | | | | 663,342 | 50,112 | 217,586 | 931,040 | 150,048 |
| Ave | | 134 | 0.637 | 42% | 0.40 | 76 | 5.7 | 25 | 106 | 184 |
| Max | | 254 | 1 | 51% | 1.23 | 139 | 22.5 | 42 | 202 | 202 |
| Min | | 0 | 0 | 0% | 0.00 | 0 | 0.0 | 0 | 0 | 0 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# First Year Electric Cost

**Results**

| | Proposed |
|---|---|
| Annual Electric Use Charges | $883,612 |
| Annual Electric Demand Charges | $222,800 |
| Annual Electric Expense | $1,106,411 |

**Rate Schedule**

| | |
|---|---|
| Select current rate schedule | E-19A |
| Select voltage type | Secondary |

| | | Secondary | Primary | Transmission | **Secondary** |
|---|---|---|---|---|---|
| Identifier | Total Demand Rates | $/kW | $/kW | $/kW | $/kW |
| 1 | Peak Summer | 11.54 | 10.43 | 8.13 | 11.54 |
| 2 | Part-Peak Summer | 2.64 | 2.39 | 1.84 | 2.64 |
| 3 | Maximum Summer | 6.62 | 5.63 | 3.72 | 6.62 |
| 4 | Part-Peak Winter | 0.99 | 0.74 | - | 0.99 |
| 5 | Maximum Winter | 6.62 | 5.63 | 3.72 | 6.62 |
| Identifier | Total Energy Rates | $/kWh | $/kWh | $/kWh | $/kWh |
| 1 | Peak Summer | 0.13286 | 0.13251 | 0.09801 | 0.13286 |
| 2 | Part-Peak Summer | 0.09095 | 0.08912 | 0.07843 | 0.09095 |
| 3 | Off-Peak Summer | 0.07383 | 0.07040 | 0.06674 | 0.07383 |
| 4 | Part-Peak Winter | 0.08095 | 0.07653 | 0.07134 | 0.08095 |
| 5 | Off-Peak Winter | 0.07127 | 0.06700 | 0.06326 | 0.07127 |

These rates are applicable for the time period:
**Jan 1, 2008 to Present**

**Hourly Energy Rate Calculations**

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge Proposed |
|---|---|---|---|
| | | | $ |
| 1-Jan | 1 | 5 | $92.10 |
| 1-Jan | 2 | 5 | $92.11 |
| 1-Jan | 3 | 5 | $92.11 |
| 1-Jan | 4 | 5 | $92.10 |
| 1-Jan | 5 | 5 | $92.10 |
| 1-Jan | 6 | 5 | $92.10 |
| 1-Jan | 7 | 5 | $92.10 |
| 1-Jan | 8 | 5 | $92.10 |
| 1-Jan | 9 | 4 | $104.60 |
| 1-Jan | 10 | 4 | $104.61 |
| 1-Jan | 11 | 4 | $104.62 |
| 1-Jan | 12 | 4 | $104.63 |
| 30-Jun | 13 | 1 | $173.39 |
| 30-Jun | 14 | 1 | $173.32 |
| 30-Jun | 15 | 1 | $173.14 |
| 30-Jun | 16 | 1 | $173.24 |
| 30-Jun | 17 | 1 | $173.25 |
| 30-Jun | 18 | 1 | $173.15 |
| 30-Jun | 19 | 2 | $118.51 |
| 30-Jun | 20 | 2 | $118.40 |
| 30-Jun | 21 | 2 | $118.30 |
| 30-Jun | 22 | 3 | $95.99 |
| 30-Jun | 23 | 3 | $91.51 |
| 30-Jun | 24 | 3 | $87.77 |
| 1-Jul | 1 | 3 | $83.56 |
| 1-Jul | 2 | 3 | $84.51 |
| 1-Jul | 3 | 3 | $84.71 |
| 1-Jul | 4 | 3 | $84.80 |
| 1-Jul | 5 | 3 | $84.80 |
| 1-Jul | 6 | 3 | $84.65 |

**Hourly Demand Charge Calculations**

| Hourly Demand | Demand Charge by Rate Period | | | | |
|---|---|---|---|---|---|
| | Proposed | | | | |
| Proposed | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| kW | $ | $ | $ | $ | $ |
| 1,292 | | | $8,555 | | $8,555 |
| 1,292 | | | $8,555 | | $8,555 |
| 1,292 | | | $8,555 | | $8,555 |
| 1,292 | | | $8,555 | | $8,555 |
| 1,[illegible] | | | $8,554 | | $8,554 |
| 1,[illegible] | | | $8,554 | | $8,554 |
| 1,[illegible] | | | $8,554 | | $8,554 |
| 1,[illegible] | | | $8,554 | | $8,554 |
| 1,[illegible] | | | $8,554 | $1,279 | $8,554 |
| 1,[illegible] | | | $8,555 | $1,279 | $8,555 |
| 1,292 | | | $8,555 | $1,279 | $8,555 |
| 1,293 | | | $8,557 | $1,280 | $8,557 |
| 1,305 | $15,060 | | $8,640 | | $8,640 |
| 1,305 | $15,054 | | $8,636 | | $8,636 |
| 1,303 | $15,039 | | $8,627 | | $8,627 |
| 1,304 | $15,047 | | $8,632 | | $8,632 |
| 1,304 | $15,048 | | $8,632 | | $8,632 |
| 1,303 | $15,039 | | $8,627 | | $8,627 |
| 1,303 | | $3,440 | $8,626 | | $8,626 |
| 1,302 | | $3,437 | $8,618 | | $8,618 |
| 1,301 | | $3,434 | $8,611 | | $8,611 |
| 1,300 | | | $8,607 | | $8,607 |
| 1,239 | | | $8,205 | | $8,205 |
| 1,189 | | | $7,870 | | $7,870 |
| 1,132 | | | $7,492 | | $7,492 |
| 1,145 | | | $7,578 | | $7,578 |
| 1,147 | | | $7,596 | | $7,596 |
| 1,149 | | | $7,604 | | $7,604 |
| 1,149 | | | $7,604 | | $7,604 |
| 1,147 | | | $7,590 | | $7,590 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge Proposed | Hourly Demand Proposed | Demand Charge by Rate Period Proposed: Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
|---|---|---|---|---|---|---|---|---|---|
| | | | $ | kW | $ | $ | $ | $ | $ |
| 1-Jul | 7 | 3 | $83.63 | 1,133 | | | $7,499 | | $7,499 |
| 1-Jul | 8 | 3 | $87.47 | 1,185 | | | $7,843 | | $7,843 |
| 1-Jul | 9 | 2 | $110.70 | 1,217 | | $3,213 | $8,058 | | $8,058 |
| 1-Jul | 10 | 2 | $113.24 | 1,245 | | $3,287 | $8,243 | | $8,243 |
| 1-Jul | 11 | 2 | $118.36 | 1,301 | | $3,436 | $8,615 | | $8,615 |
| 1-Jul | 12 | 2 | $118.43 | 1,302 | | $3,438 | $8,620 | | $8,620 |
| 31-Dec | 13 | 4 | $93.09 | 1,150 | | | $7,613 | $1,138 | $7,613 |
| 31-Dec | 14 | 4 | $93.06 | 1,150 | | | $7,610 | $1,138 | $7,610 |
| 31-Dec | 15 | 4 | $93.03 | 1,149 | | | $7,608 | $1,138 | $7,608 |
| 31-Dec | 16 | 4 | $92.98 | 1,149 | | | $7,604 | $1,137 | $7,604 |
| 31-Dec | 17 | 4 | $104.72 | 1,294 | | | $8,564 | $1,281 | $8,564 |
| 31-Dec | 18 | 4 | $104.69 | 1,293 | | | $8,562 | $1,280 | $8,562 |
| 31-Dec | 19 | 4 | $104.66 | 1,293 | | | $8,559 | $1,280 | $8,559 |
| 31-Dec | 20 | 4 | $104.65 | 1,293 | | | $8,558 | $1,280 | $8,558 |
| 31-Dec | 21 | 4 | $104.64 | 1,293 | | | $8,557 | $1,280 | $8,557 |
| 31-Dec | 22 | 5 | $92.11 | 1,292 | | | $8,556 | | $8,556 |
| 31-Dec | 23 | 5 | $92.11 | 1,292 | | | $8,555 | | $8,555 |
| 31-Dec | 24 | 5 | $92.10 | 1,292 | | | $8,555 | | $8,555 |
| | | Sum | $883,612 | 10,791,564 | | | | | |
| | | Ave | $100.87 | 1231.9 | $14,889 | $3,334 | $8,155 | $1,184 | $8,155 |
| | | Max | $174.35 | 1312.3 | $15,144 | $3,463 | $8,687 | $1,293 | $8,687 |
| | | Min | $80.44 | 1128.7 | $13,025 | $2,980 | $7,472 | $1,117 | $7,472 |

**Monthly Demand Charge Calculations**

| Month | Actual Demand Charge per Rate Period Proposed: Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
|---|---|---|---|---|---|
| | $ | $ | $ | $ | $ |
| Jan | N/A | N/A | N/A | 1,280 | 8,563 |
| Feb | N/A | N/A | N/A | 1,290 | 8,628 |
| Mar | N/A | N/A | N/A | 1,280 | 8,607 |
| Apr | N/A | N/A | N/A | 1,293 | 8,643 |
| May | 15,096 | 3,447 | 8,660 | N/A | N/A |
| Jun | 15,100 | 3,456 | 8,665 | N/A | N/A |
| Jul | 15,123 | 3,459 | 8,687 | N/A | N/A |
| Aug | 15,144 | 3,463 | 8,687 | N/A | N/A |
| Sep | 15,109 | 3,453 | 8,669 | N/A | N/A |
| Oct | 15,071 | 3,445 | 8,646 | N/A | N/A |
| Nov | N/A | N/A | N/A | 1,290 | 8,625 |
| Dec | N/A | N/A | N/A | 1,290 | 8,628 |
| Sum | 90,644 | 20,722 | 52,014 | 7,724 | 51,695 |
| Ave | 15,107 | 3,454 | 8,669 | 1,287 | 8,616 |
| Max | 15,144 | 3,463 | 8,687 | 1,293 | 8,643 |
| Min | 15,071 | 3,445 | 8,646 | 1,280 | 8,563 |

# Annual Total Gas Energy Use

**Assumptions**
All gas use comes from the heating plant.

**Hourly Calculations**

| Date | Hour | Heating Plant Energy Use Proposed therms |
|---|---|---|
| 1-Jan | 1 | 0.00 |
| 1-Jan | 2 | 0.00 |
| 1-Jan | 3 | 0.00 |
| 1-Jan | 4 | 0.00 |
| 1-Jan | 5 | 0.00 |
| 30-Jun | 13 | 0.00 |
| 30-Jun | 14 | 0.00 |
| 30-Jun | 15 | 0.00 |
| 30-Jun | 16 | 0.00 |
| 30-Jun | 17 | 0.00 |
| 30-Jun | 18 | 0.00 |
| 30-Jun | 19 | 0.00 |
| 30-Jun | 20 | 0.00 |
| 30-Jun | 21 | 0.00 |
| 30-Jun | 22 | 0.00 |
| 30-Jun | 23 | 0.00 |
| 30-Jun | 24 | 0.00 |
| 1-Jul | 1 | 0.00 |
| 1-Jul | 2 | 0.00 |
| 1-Jul | 3 | 0.00 |
| 1-Jul | 4 | 0.00 |
| 1-Jul | 5 | 0.00 |
| 1-Jul | 6 | 0.00 |
| 1-Jul | 7 | 0.00 |
| 1-Jul | 8 | 0.00 |
| 1-Jul | 9 | 0.00 |
| 1-Jul | 10 | 0.00 |
| 1-Jul | 11 | 0.00 |
| 1-Jul | 12 | 0.00 |
| 31-Dec | 13 | 0.00 |
| 31-Dec | 14 | 0.00 |
| 31-Dec | 15 | 0.00 |
| 31-Dec | 16 | 0.00 |
| 31-Dec | 17 | 0.00 |
| 31-Dec | 18 | 0.00 |
| 31-Dec | 19 | 0.00 |
| 31-Dec | 20 | 0.00 |
| 31-Dec | 21 | 0.00 |
| 31-Dec | 22 | 0.00 |
| 31-Dec | 23 | 0.00 |
| 31-Dec | 24 | 0.00 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| | |
|---|---|
| Sum | 0.00 |
| Ave | 0.00 |
| Max | 0.00 |
| Min | 0.00 |

# First Year Gas Cost

**Gas Use (therms)**

| | Proposed | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | 0 | | 0 |
| Feb | 0 | | 0 |
| Mar | 0 | | 0 |
| Apr | 0 | 0 | |
| May | 0 | 0 | |
| Jun | 0 | 0 | |
| Jul | 0 | 0 | |
| Aug | 0 | 0 | |
| Sep | 0 | 0 | |
| Oct | 0 | 0 | |
| Nov | 0 | | 0 |
| Dec | 0 | | 0 |
| Sum | 0 | 0 | 0 |
| Ave | 0 | 0 | 0 |
| Max | 0 | 0 | 0 |
| Min | 0 | 0 | 0 |

**Gas Cost**

| | Proposed | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | | | $0 |
| Feb | | | $0 |
| Mar | | | $0 |
| Apr | | $0 | |
| May | | $0 | |
| Jun | | $0 | |
| Jul | | $0 | |
| Aug | | $0 | |
| Sep | | $0 | |
| Oct | | $0 | |
| Nov | | | $0 |
| Dec | | | $0 |

Annual Totals: $0

# Life Cycle Cost

**Template:** **Life Cycle Cost_v2.0**

**General Notes**
Negative values are expenses, positive values are income or savings.

**Costs, in Year Zero dollars.**

| | Baseline | Proposed | Difference | Source |
|---|---|---|---|---|
| First Cost | | | -$50,800 | See Implementation Cost sheet. |
| Annual Electric Cost | -$1,187,233 | -$1,106,411 | $80,822 | See Electric Cost sheet. |
| Annual Gas Cost | $0 | $0 | $0 | See Gas Cost sheet. |
| Annual Energy Cost | -$1,187,233 | -$1,106,411 | $80,822 | Sum previous two lines. |
| Annual Material Cost | | | -$500 | Estimated incremental cost of AHU air filters. |
| Annual Labor Cost | | | -$2,000 | Estimate of incremental air handler maintenance cost. |

**Incentive**

| | | |
|---|---|---|
| Estimated total incentive for this project | $25,400 | See the Summary sheet. |

**Financial Parameters**

| | | |
|---|---|---|
| Cost of Borrowed Capital | 7.0% | Typical assumption. |
| Highest-Yielding Current Investment Opportunity | 8.0% | Typical assumption. |
| Discount Rate | 8.0% | Greater of previous two lines. |
| Inflation in Prices of Energy | | |
| Natural Gas Rate | 6.0% | Assumed. |
| Average Inflation of Electric Use and Electric Demand Rates | 3.0% | Assumed. |
| Escalation in Material Costs | 3.0% | Assumed. |
| Inflation in Price of Labor | 3.0% | Assumed. |

**Life Cycle Costs, Adjusted for Inflation**

| Year | Annual Energy Costs | | Differences | | | | |
|---|---|---|---|---|---|---|---|
| | Baseline | Proposed | Energy | Material | Labor | Total | |
| 0 | | | | | | -$50,800 | First Cost |
| 1 | -$1,222,850 | -$1,139,604 | $83,246 | -$515 | -$2,060 | $80,671 | |
| 2 | -$1,259,536 | -$1,173,792 | $85,744 | -$530 | -$2,122 | $83,092 | |
| 3 | -$1,297,322 | -$1,209,006 | $88,316 | -$546 | -$2,185 | $85,584 | |
| 4 | -$1,336,241 | -$1,245,276 | $90,966 | -$563 | -$2,251 | $88,152 | |
| 5 | -$1,376,329 | -$1,282,634 | $93,695 | -$580 | -$2,319 | $90,796 | |
| 6 | -$1,417,618 | -$1,321,113 | $96,505 | -$597 | -$2,388 | $93,520 | |
| 7 | -$1,460,147 | -$1,360,746 | $99,401 | -$615 | -$2,460 | $96,326 | |
| 8 | -$1,503,951 | -$1,401,569 | $102,383 | -$633 | -$2,534 | $99,216 | |
| 9 | -$1,549,070 | -$1,443,616 | $105,454 | -$652 | -$2,610 | $102,192 | |
| 10 | -$1,595,542 | -$1,486,924 | $108,618 | -$672 | -$2,688 | $105,258 | |
| 11 | -$1,643,408 | -$1,531,532 | $111,876 | -$692 | -$2,768 | $108,416 | |
| 12 | -$1,692,710 | -$1,577,478 | $115,232 | -$713 | -$2,852 | $111,668 | |
| 13 | -$1,743,492 | -$1,624,802 | $118,689 | -$734 | -$2,937 | $115,018 | |
| 14 | -$1,795,797 | -$1,673,546 | $122,250 | -$756 | -$3,025 | $118,469 | |
| 15 | -$1,849,670 | -$1,723,753 | $125,918 | -$779 | -$3,116 | $122,023 | |
| 16 | -$1,905,161 | -$1,775,465 | $129,695 | -$802 | -$3,209 | $125,683 | |
| 17 | -$1,962,315 | -$1,828,729 | $133,586 | -$826 | -$3,306 | $129,454 | |
| 18 | -$2,021,185 | -$1,883,591 | $137,594 | -$851 | -$3,405 | $133,338 | |
| 19 | -$2,081,820 | -$1,940,099 | $141,721 | -$877 | -$3,507 | $137,338 | |
| 20 | -$2,144,275 | -$1,998,302 | $145,973 | -$903 | -$3,612 | $141,458 | |

**Proposed Measure(s) vs Baseline**

| | | |
|---|---|---|
| Simple Payback | 0.3 | years |
| Relative Net Present Value | $937,428 | |
| Internal Rate of Return | 162% | |

# CHW AHUs with Air Side Economizing

## CEC Zone 3 (San Francisco)

# Annual Total Electric Energy Use, Proposed

**Assumptions**

This scenario assumes seven 500 kVa modules. The efficiencies for the modules are drawn from Powersmith data sheets. Where data points were not provided we have estimated values according to a standard transformer curve profile. We assume that the number, size, and efficiency of the modules are the same for the baseline and proposed case.

We assume that all active transformer modules are loaded to an equal percentage.

All transformers are assumed to be of the linear type.

The power factor is assumed to be 1.00 (kW = kVA).

Transformers are not located in an air-conditioned space, so they do not impose a cooling load.

The transformers serve the rack, UPS, lighting, and chilled water plant loads.

**Input Parameters**

| | | | |
|---|---|---|---|
| Transformer Module Size: | 500 | kVA | See Transformers sheet |

**Annual Energy Use**

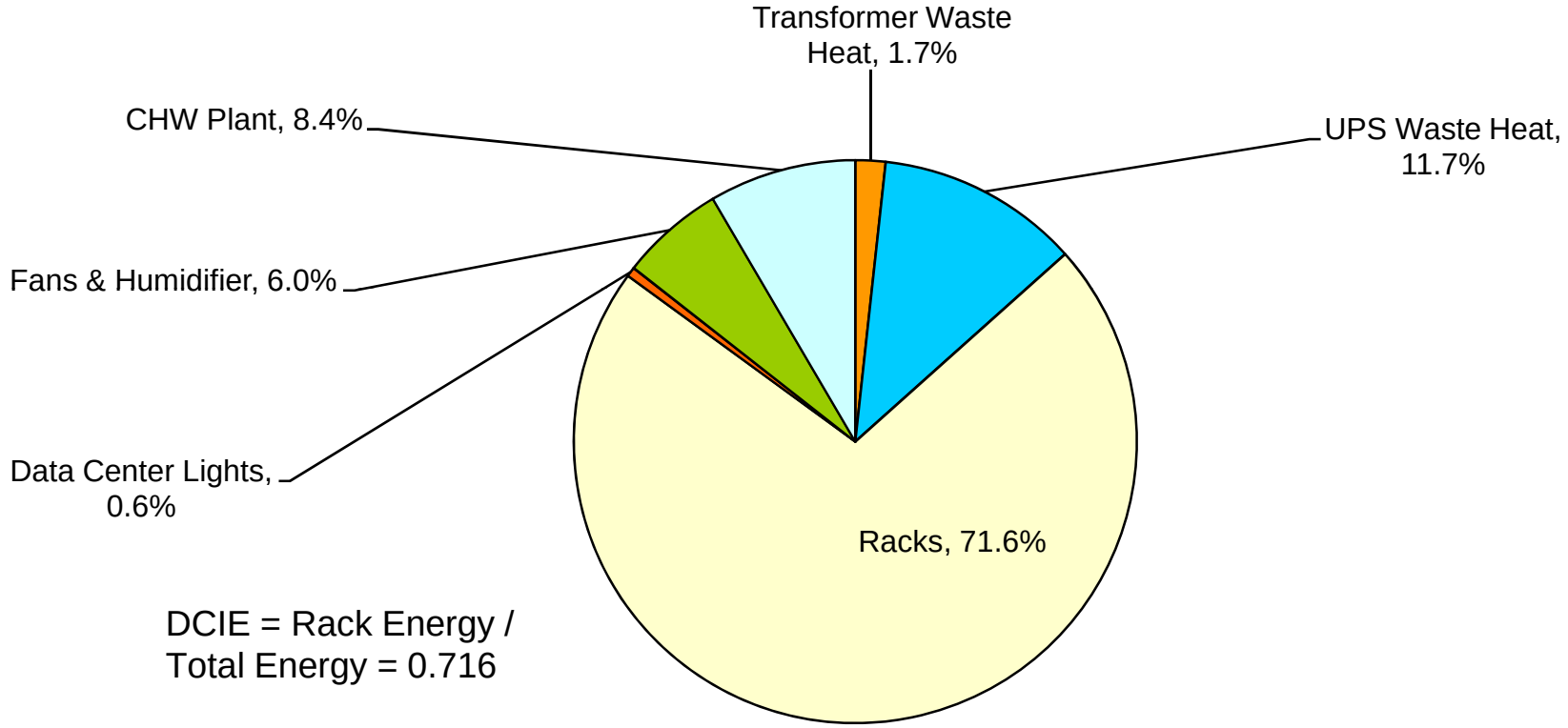
| System | Proposed | |
|---|---|---|
| | kWh/yr | Percent of Total |
| Transformer Waste Heat | 185,814 | 1.7% |
| UPS Waste Heat | 1,256,917 | 11.7% |
| Racks | 7,721,064 | 71.6% |
| Data Center Lights | 59,393 | 0.6% |
| Fans & Humidifier | 644,008 | 6.0% |
| CHW Plant | 909,930 | 8.4% |
| Total | 10,777,126 | 100.0% |

**Hourly Calculations**

| Date | Hour | Required Transformer Output Power | | | | | Transformer Modules | | | Transformer Total Input Power Demand | Trans-former Waste Heat | Peak Summer Power Demand |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | UPS Input Power | Data Center Lights | Fans and Humidifier | CHW Plant | Total | Quant. | Load Factor | Module Effic. | | | |
| | | kW | kW | kW | kW | kW | | % | % | kW | kW | kW |
| 1-Jan | 1 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 1-Jan | 2 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 3 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 4 | 1,025 | 7 | 55 | 182 | 1,269 | 3 | 85% | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 5 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 6 | 1,025 | 7 | 55 | [illegible] | [illegible] | [illegible] | [illegible] | 98.2% | 1,292 | 24 | n/a |
| 1-Jan | 7 | 1,025 | 7 | 97 | [illegible] | [illegible] | [illegible] | [illegible] | 98.4% | 1,146 | 18 | n/a |
| 1-Jan | 8 | 1,025 | 7 | 98 | [illegible] | [illegible] | [illegible] | [illegible] | 98.4% | 1,147 | 18 | n/a |
| 1-Jan | 9 | 1,025 | 7 | 99 | [illegible] | [illegible] | [illegible] | [illegible] | 98.4% | 1,148 | 18 | n/a |
| 1-Jan | 10 | 1,025 | 7 | 99 | [illegible] | [illegible] | [illegible] | [illegible] | 98.4% | 1,149 | 18 | n/a |
| 1-Jan | 11 | 1,025 | 7 | 101 | [illegible] | [illegible] | [illegible] | [illegible] | 98.4% | 1,151 | 18 | n/a |
| 1-Jan | 12 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 30-Jun | 13 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | 1,300 |
| 30-Jun | 14 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | 1,300 |
| 30-Jun | 15 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | 1,300 |
| 30-Jun | 16 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | 1,300 |
| 30-Jun | 17 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | 1,300 |
| 30-Jun | 18 | 1,025 | 7 | 55 | 189 | 1,276 | 3 | 85% | 98.2% | 1,299 | 24 | 1,299 |
| 30-Jun | 19 | 1,025 | 7 | 55 | 189 | 1,275 | 3 | 85% | 98.2% | 1,299 | 24 | n/a |
| 30-Jun | 20 | 1,025 | 7 | 55 | 193 | 1,279 | 3 | 85% | 98.2% | 1,303 | 24 | n/a |
| 30-Jun | 21 | 1,025 | 7 | 55 | 184 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 30-Jun | 22 | 1,025 | 7 | 55 | 184 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 30-Jun | 23 | 1,025 | 7 | 55 | 184 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 30-Jun | 24 | 1,025 | 7 | 55 | 184 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 1-Jul | 1 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 1-Jul | 2 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 1-Jul | 3 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 1-Jul | 4 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,294 | 24 | n/a |
| 1-Jul | 5 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 1-Jul | 6 | 1,025 | 7 | 55 | 183 | 1,270 | 3 | 85% | 98.2% | 1,293 | 24 | n/a |
| 1-Jul | 7 | 1,025 | 7 | 101 | 0 | 1,132 | 3 | 75% | 98.4% | 1,151 | 18 | n/a |
| 1-Jul | 8 | 1,025 | 7 | 99 | 0 | 1,130 | 3 | 75% | 98.4% | 1,148 | 18 | n/a |
| 1-Jul | 9 | 1,025 | 7 | 91 | 0 | 1,122 | 3 | 75% | 98.5% | 1,139 | 17 | n/a |
| 1-Jul | 10 | 1,025 | 7 | 55 | 190 | 1,276 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 1-Jul | 11 | 1,025 | 7 | 55 | 190 | 1,277 | 3 | 85% | 98.2% | 1,300 | 24 | n/a |
| 1-Jul | 12 | 1,025 | 7 | 55 | 191 | 1,277 | 3 | 85% | 98.2% | 1,301 | 24 | n/a |
| 31-Dec | 13 | 1,025 | 7 | 95 | 0 | 1,126 | 3 | 75% | 98.4% | 1,145 | 18 | n/a |
| 31-Dec | 14 | 1,025 | 7 | 97 | 0 | 1,129 | 3 | 75% | 98.4% | 1,147 | 18 | n/a |
| 31-Dec | 15 | 1,025 | 7 | 99 | 0 | 1,130 | 3 | 75% | 98.4% | 1,148 | 18 | n/a |
| 31-Dec | 16 | 1,025 | 7 | 100 | 0 | 1,131 | 3 | 75% | 98.4% | 1,150 | 18 | n/a |
| 31-Dec | 17 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 18 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 19 | 1,025 | 7 | 101 | 0 | 1,133 | 3 | 76% | 98.4% | 1,151 | 18 | n/a |
| 31-Dec | 20 | 1,025 | 7 | 100 | 0 | 1,132 | 3 | 75% | 98.4% | 1,150 | 18 | n/a |
| 31-Dec | 21 | 1,025 | 7 | 99 | 0 | 1,131 | 3 | 75% | 98.4% | 1,149 | 18 | n/a |
| 31-Dec | 22 | 1,025 | 7 | 98 | 0 | 1,130 | 3 | 75% | 98.4% | 1,148 | 18 | n/a |
| 31-Dec | 23 | 1,025 | 7 | 97 | 0 | 1,129 | 3 | 75% | 98.4% | 1,147 | 18 | n/a |
| 31-Dec | 24 | 1,025 | 7 | 97 | 0 | 1,128 | 3 | 75% | 98.4% | 1,147 | 18 | n/a |
| Sum | | 8,977,981 | 59,393 | 644,008 | 909,930 | 10,591,312 | | | | 10,777,126 | 185,814 | 1,029,819 |
| Ave | | 1,025 | 7 | 74 | 104 | 1,209 | 3.00 | 81% | 98.3% | 1,230 | 21 | 1,262 |
| Max | | 1,025 | 7 | 101 | 201 | 1,287 | 3 | 86% | 98.5% | 1,311 | 24 | 1,311 |
| Min | | 1,025 | 7 | 55 | 0 | 1,112 | 3 | 74% | 98.2% | 1,129 | 17 | 1,129 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# Data Center Infrastructure Efficiency (DCIE)
# Proposed




DCIE = Rack Energy / Total Energy = 0.716

# Space Parameters

**Assumptions**
Chilled water CRAC values are based on the Liebert Deluxe System 3, Model 740C.

| | Proposed | Units | Sources |
|---|---|---|---|
| **Input Parameters** | | | |
| ***Space Dimensions*** | | | |
| Floor Area | 6,780 | sf | Email from Dave Shroyer, 10/13/08. |
| ***Occupancy Schedule*** | | | |
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | Datacenter assumed to operate 8,760 hours per year |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | Datacenter assumed to operate 8,760 hours per year |
| ***HVAC System Type & Setpoints*** | | | |
| Air Delivery System | VAV | | The proposed system uses VAV air handlers. |
| Return Air Drybulb Setpoint | 89.5 | °F | Selected to get a 22 deg-F delta-T, email from Rupa Ganguly on 9/30/08. |
| Supply Air Drybulb Setpoint (VAV Systems Only) | 67.5 | °F | Estimate from email from Rupa Ganguly on 9/30/08. |
| Supply Air Design Flow Rate (CAV Systems Only) | | cfm | Total air flow provided by selected number & size of CRAC units and expected total static pressure drop of open HACA arrangement. |
| Active Humidity Control? | no | | Humidity control is baseline practice. The proposed facility will have no active humidity control. |
| Drybulb Temp at RH Sensor Location | 89.5 | °F | Humidity sensor is assumed to be mounted on the data center ceiling. |
| Allowed Relative Humidity, Maximum | 100% | RH | Assumed based on no humidity control. |
| Allowed Relative Humidity, Minimum | 1% | RH | Assumed based on no humidity control. |
| CHWST Setpoint, Primary | 44 | °F | Baseline CHWST setpoint value. |
| CHWST Setpoint, Secondary | 44 | °F | We are not considering CHWST reset. |
| Adiabatic Humdifier Power Draw | 0.000 | kW/ (lb of H20/hr) | No adiabatic humidifier. |

| | Proposed | Units | Sources |
|---|---|---|---|
| ***Cooling Load*** | | | |
| Total Rack Load, Occupied | 881 | kW | Calculated from rack load of 130 W/sf, email from Dave Shroyer, 10/13/08. |
| Total Rack Load, Unoccupied | n/a | kW | Rack load does not vary with occupancy. |
| Average Lighting Density | 1.0 | W/sf | Typical value. |
| ***Ventilation Requirement*** | | | |
| Minimum Ventilation Requirement | 0.15 | cfm/sf | CA Title 24 requirement for office space. |
| ***Boiler Data*** | | | |
| HHW Boiler Efficiency | 82% | % | Baseline value. |
| Gas-fired Humidifier Efficiency | 76% | % | Baseline value. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| ***HVAC System Type & Setpoints*** | | | |
| Occupied Supply Air Drybulb | | °F | = RAT - Occupied Load / (1.08 * cfm) |
| Unoccupied Supply Air Drybulb | | °F | A datacenter is assumed always occupied. |
| Occupied Supply Air Flow Rate | 127,545 | cfm | = Load / (1.08 * Delta-T) |
| Unoccupied Suppllly Air Flow Rate | n/a | | A datacenter is assumed always occupied. |
| Air Side Delta-T | 22 | °F | Subtract |
| ***Cooling Load*** | | | |
| UPS Waste Heat | 0 | kW | UPS waste heat is not part of cooling load. |
| Data Center Lights | 7 | kW | Average lighting density times space floor area. |
| Total Internal Load, Occupied | 888 | kW | Rack load, UPS waste heat, lights. |
| Total Internal Load, Occupied | 253 | tons | Convert to tons |
| Total Internal Load, Occupied | 3,030 | kBTU/hr | Convert to kBTU/hr |
| Average Internal Load Density, Occupied | 131 | W/sf | Divide by floor area |
| Total Internal Load, Unoccupied | n/a | kW | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | tons | A datacenter is assumed always occupied. |
| Total Internal Load, Unoccupied | n/a | kBTU/hr | A datacenter is assumed always occupied. |
| Average Internal Load Density, Unoccupied | n/a | W/sf | A datacenter is assumed always occupied. |
| ***Ventilation Requirement*** | | | |
| Min Allowed Ventilation Volumetric Air Flow Rate | 1,017 | cfm | Floor area times minimum ventilation requirement. |

# Weather Data

Source: California Energy Commission
Data Set: California Climate Zone 3 (CZ03RV2) - San Francisco

| Date | Hour | Outside Air | | | | | |
|---|---|---|---|---|---|---|---|
| | | Drybulb Temp. | Dewpoint Temp. | Relative Humidity | Atmospheric Pressure | Wetbulb Temp. | Enthalpy |
| | | °F | °F | % | psia | °F | BTU/lb |
| 1-Jan | 1 | 42.8 | 41.5 | 95% | 14.5 | 42.1 | 16.3 |
| 1-Jan | 2 | 41.5 | 39.7 | 93% | 14.5 | 40.6 | 15.6 |
| 1-Jan | 3 | 39.9 | 38.5 | 95% | 14.5 | 39.3 | 15.0 |
| 1-Jan | 4 | 39.0 | 37.9 | 96% | 14.5 | 38.5 | 14.6 |
| 1-Jan | 5 | 39.6 | 36.7 | 89% | 14.5 | 38.2 | 14.5 |
| 1-Jan | 6 | 42.1 | 37.8 | 85% | 14.5 | 40.1 | 15.3 |
| 1-Jan | 7 | 43.5 | 37.4 | 79% | 14.5 | 40.7 | 15.6 |
| 1-Jan | 8 | 45.1 | 37.2 | 74% | 14.5 | 41.5 | 16.0 |
| 1-Jan | 9 | 46 | | | | 42.2 | 16.3 |
| 1-Jan | 10 | 48 | | | | 42.9 | 16.6 |
| 1-Jan | 11 | 52 | | | | 44.3 | 17.3 |
| 1-Jan | 12 | 55 | | | | 45.7 | 18.0 |
| 30-Jun | 13 | 65 | | | | 59.6 | 26.2 |
| 30-Jun | 14 | 66 | | | | 60.1 | 26.5 |
| 30-Jun | 15 | 66 | | | | 60.4 | 26.7 |
| 30-Jun | 16 | 67.6 | 56.7 | 68% | 14.6 | 60.8 | 27.0 |
| 30-Jun | 17 | 65.8 | 56.3 | 71% | 14.6 | 59.8 | 26.3 |
| 30-Jun | 18 | 64.2 | 55.8 | 74% | 14.6 | 59.0 | 25.8 |
| 30-Jun | 19 | 62.1 | 55.0 | 78% | 14.6 | 57.8 | 25.0 |
| 30-Jun | 20 | 60.1 | 54.1 | 81% | 14.6 | 56.6 | 24.2 |
| 30-Jun | 21 | 58.8 | 53.8 | 83% | 14.6 | 55.8 | 23.7 |
| 30-Jun | 22 | 57.9 | 54.0 | 87% | 14.6 | 55.6 | 23.6 |
| 30-Jun | 23 | 56.8 | 53.8 | 89% | 14.6 | 54.9 | 23.2 |
| 30-Jun | 24 | 55.8 | 53.8 | 93% | 14.6 | 54.6 | 23.0 |
| 1-Jul | 1 | 54.7 | 49.3 | 82% | 14.6 | 51.6 | 21.3 |
| 1-Jul | 2 | 54.1 | 49.6 | 85% | 14.6 | 51.7 | 21.3 |
| 1-Jul | 3 | 54.1 | 49.8 | 85% | 14.5 | 51.7 | 21.3 |
| 1-Jul | 4 | 54.1 | 50.2 | 86% | 14.6 | 51.8 | 21.4 |
| 1-Jul | 5 | 54.1 | 49.5 | 84% | 14.6 | 51.5 | 21.2 |
| 1-Jul | 6 | 54.1 | 48.9 | 82% | 14.6 | 51.1 | 21.0 |
| 1-Jul | 7 | 56.5 | 50.5 | 80% | 14.6 | 53.0 | 22.0 |
| 1-Jul | 8 | 59.5 | 52.3 | 77% | 14.6 | 55.3 | 23.4 |
| 1-Jul | 9 | 63.1 | 54.5 | 73% | 14.6 | 57.8 | 25.0 |
| 1-Jul | 10 | 66.2 | 56.3 | 70% | 14.6 | 59.9 | 26.4 |
| 1-Jul | 11 | 68.4 | 57.4 | 68% | 14.6 | 61.4 | 27.5 |
| 1-Jul | 12 | 70.0 | 58.1 | 66% | 14.6 | 62.4 | 28.2 |
| 31-Dec | 13 | 61.7 | 44.6 | 53% | 14.6 | 52.3 | 21.5 |
| 31-Dec | 14 | 60.4 | 44.8 | 56% | 14.6 | 51.9 | 21.3 |
| 31-Dec | 15 | 59.5 | 45.0 | 58% | 14.6 | 51.5 | 21.1 |
| 31-Dec | 16 | 58.3 | 45.1 | 62% | 14.6 | 51.2 | 21.0 |
| 31-Dec | 17 | 56.3 | 43.3 | 62% | 14.6 | 49.5 | 20.0 |
| 31-Dec | 18 | 54.7 | 41.5 | 61% | 14.6 | 47.9 | 19.1 |
| 31-Dec | 19 | 53.4 | 40.5 | 61% | 14.6 | 46.8 | 18.6 |
| 31-Dec | 20 | 50.9 | 39.6 | 65% | 14.7 | 45.3 | 17.8 |
| 31-Dec | 21 | 48.7 | 39.0 | 69% | 14.7 | 44.0 | 17.1 |
| 31-Dec | 22 | 46.4 | 38.3 | 73% | 14.6 | 42.5 | 16.4 |
| 31-Dec | 23 | 44.8 | 36.0 | 71% | 14.6 | 40.7 | 15.6 |
| 31-Dec | 24 | 43.7 | 33.6 | 67% | 14.6 | 39.2 | 14.9 |
| Ave | | 57.4 | 49.0 | 75% | 14.6 | 52.7 | 22.1 |
| Max | | 90.9 | 68.4 | 100% | 14.8 | 72.7 | 36.6 |
| Min | | 34.2 | 11.1 | 16% | 14.3 | 29.7 | 10.8 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

# Transformer Data

## Proposed

**Parameters**

| | | |
|---|---|---|
| Size | 500 | kVA |

Values in blue are from NEMA Standard TP-1 Transformer Efficiency, Three Phase (Table 4.2). All other values are extrapolated.

| **Linear Efficiency vs. Load Factor** | |
|---|---|
| Load | Efficiency |
| 100% | 97.9% |
| 90% | 98.2% |
| 80% | 98.4% |
| 75% | 98.5% |
| 70% | 98.6% |
| 60% | 98.8% |
| 50% | 98.8% |
| 40% | 98.8% |
| 35% | 98.7% |
| 30% | 98.6% |
| 25% | 98.5% |
| 20% | 98.3% |
| 17% | 98.2% |
| 10% | 97.7% |

# Chiller Data

**Assumptions**
The same chillers are used in the baseline and proposed cases.
We set the chillers to the same size.

**Parameters**

| | Proposed | Units | Sources |
|---|---|---|---|
| Chiller Capacity | 500 | tons | Capacity selected to result in a total of three chillers, with appropriate safety and redundancy factors. |
| Condenser Water Temperature | 80 | °F | Typical value. |
| CHW Supply Temperature | 44 | °F | Typical value. |
| CW Flow Rate | 1,200 | gpm | Assumes a 10F CW delta-T when chiller is a maximum load. |

Values from Baseline Water-Cooled Chilled Water Plant Above 300 tons

| **Chiller Efficiency (kW/ton) at CHWS Temp = 44 F** | |
|---|---|
| Load | Condenser Water Temp (°F) |
| | 80 |
| 100% | 0.529 |
| 90% | 0.526 |
| 80% | 0.526 |
| 70% | 0.530 |
| 60% | 0.539 |
| 50% | 0.557 |
| 40% | 0.590 |
| 30% | 0.653 |
| 20% | 0.792 |
| 10% | 1.234 |

# Cooling Tower Fan Speed Lookup Tables, Proposed

| | |
|---|---|
| Cooling Tower Make & Model Used in Analysis | BAC 3482A |

The following lookup tables were created by drawing information from BAC's Cooling Tower Selection Software, Release 6.02 NA. The fan speeds are expressed in percent.

Fan speed depends on the load on the tower, the condenser water flow rate, the ambient wetbulb temperature, and the temperature of the condenser water leaving the tower (aka the cold condenser water temperature). The lowest fan speed the BAC software wil

**Tower Specifications at Nominal Conditions**

| | | |
|---|---|---|
| Ambient Wetbulb Temperature | 78 | deg F |
| Hot Condenser Water Temperature | 95 | deg F |
| Cold Condenser Water Temperature | 88.7 | deg F |
| Condenser Water Flow Rate, Maximum | 2,600 | gpm |
| Condenser Water Flow Rate, Minimum | 609 | gpm |
| Nominal Cooling Tower Capacity | 679 | tons |
| Cooling Tower Fan Motor Size | 30 | hp |

## 50% Maximum Flow = 1300 gpm

**0 tons, 1300 gpm**

All temperatures in deg F

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**50 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**100 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**150 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**200 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**250 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

**300 tons, 1300 gpm**

| Ambient Wetbulb Temp | Cold Condenser Water Temperature | | | | | | | | | | | | Minimum Cold Condenser Water Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | |
| 25 | | 100 | 80 | 67 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 45 |
| 26 | | | 83 | 69 | 58 | 49 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 27 | | | 86 | 70 | 59 | 50 | 46 | 39 | 38 | 34 | 33 | 33 | 50 |
| 28 | | | 89 | 72 | 60 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 29 | | | 92 | 74 | 61 | 51 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 30 | | | 95 | 76 | 63 | 52 | 47 | 40 | 38 | 34 | 33 | 33 | 50 |
| 31 | | | 98 | 78 | 64 | 53 | 48 | 40 | 38 | 34 | 33 | 33 | 50 |
| 32 | | | 100 | 80 | 65 | 53 | 48 | 41 | 39 | 34 | 33 | 33 | 50 |
| 33 | | | | 82 | 67 | 54 | 48 | 41 | 39 | 34 | 33 | 33 | 55 |
| 34 | | | | 85 | 68 | 55 | 49 | 41 | 39 | 34 | 33 | 33 | 55 |
| 35 | | | | 88 | 70 | 56 | 49 | 42 | 39 | 34 | 33 | 33 | 55 |
| 36 | | | | 91 | 71 | 57 | 50 | 42 | 39 | 34 | 33 | 33 | 55 |
| 37 | | | | 94 | 73 | 58 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 38 | | | | 97 | 76 | 60 | 51 | 43 | 39 | 34 | 33 | 33 | 55 |
| 39 | | | | 100 | 78 | 61 | 52 | 44 | 40 | 34 | 33 | 33 | 55 |
| 40 | | | | | 80 | 62 | 53 | 44 | 40 | 35 | 33 | 33 | 60 |
| 41 | | | | | 83 | 64 | 54 | 45 | 40 | 35 | 33 | 33 | 60 |
| 42 | | | | | 86 | 66 | 55 | 46 | 40 | 35 | 33 | 33 | 60 |
| 43 | | | | | 89 | 67 | 56 | 46 | 41 | 35 | 33 | 33 | 60 |
| 44 | | | | | 92 | 69 | 57 | 47 | 41 | 35 | 33 | 33 | 60 |
| 45 | | | | | 95 | 72 | 58 | 48 | 41 | 35 | 33 | 33 | 60 |
| 46 | | | | | 99 | 74 | 59 | 49 | 42 | 36 | 33 | 33 | 60 |
| 47 | | | | | | 76 | 61 | 50 | 42 | 36 | 33 | 33 | 65 |
| 48 | | | | | | 79 | 63 | 51 | 43 | 36 | 33 | 33 | 65 |
| 49 | | | | | | 82 | 64 | 52 | 43 | 36 | 33 | 33 | 65 |
| 50 | | | | | | 85 | 66 | 53 | 44 | 37 | 34 | 33 | 65 |
| 51 | | | | | | 88 | 68 | 55 | 45 | 37 | 34 | 33 | 65 |
| 52 | | | | | | 92 | 71 | 56 | 45 | 38 | 34 | 33 | 65 |
| 53 | | | | | | 96 | 73 | 58 | 46 | 38 | 34 | 33 | 65 |
| 54 | | | | | | | 76 | 59 | 47 | 38 | 34 | 33 | 70 |
| 55 | | | | | | | 79 | 61 | 48 | 39 | 35 | 33 | 70 |
| 56 | | | | | | | 82 | 63 | 49 | 40 | 35 | 33 | 70 |
| 57 | | | | | | | 86 | 65 | 50 | 40 | 35 | 33 | 70 |
| 58 | | | | | | | 90 | 67 | 52 | 41 | 36 | 33 | 70 |
| 59 | | | | | | | 94 | 70 | 53 | 42 | 36 | 33 | 70 |
| 60 | | | | | | | 99 | 72 | 55 | 43 | 37 | 33 | 70 |
| 61 | | | | | | | | 75 | 56 | 44 | 37 | 33 | 75 |
| 62 | | | | | | | | 78 | 58 | 45 | 38 | 34 | 75 |
| 63 | | | | | | | | 82 | 60 | 46 | 38 | 34 | 75 |
| 64 | | | | | | | | 85 | 63 | 47 | 39 | 34 | 75 |
| 65 | | | | | | | | 89 | 65 | 49 | 40 | 34 | 75 |
| 66 | | | | | | | | | 68 | 51 | 41 | 35 | 80 |
| 67 | | | | | | | | | 71 | 52 | 41 | 35 | 80 |
| 68 | | | | | | | | | 75 | 54 | 42 | 36 | 80 |
| 69 | | | | | | | | | 79 | 57 | 44 | 36 | 80 |
| 70 | | | | | | | | | 83 | 59 | 45 | 37 | 80 |
| 71 | | | | | | | | | 87 | 62 | 46 | 37 | 80 |
| 72 | | | | | | | | | 92 | 65 | 48 | 38 | 80 |
| 73 | | | | | | | | | 98 | 68 | 49 | 39 | 80 |
| 74 | | | | | | | | | | 72 | 51 | 40 | 85 |
| 75 | | | | | | | | | | 76 | 53 | 41 | 85 |
| 76 | | | | | | | | | | 81 | 55 | 42 | 85 |
| 77 | | | | | | | | | | 86 | 58 | 43 | 85 |
| 78 | | | | | | | | | | 91 | 61 | 44 | 85 |
| 79 | | | | | | | | | | 97 | 64 | 46 | 85 |
| 80 | | | | | | | | | | | 67 | 47 | 90 |
| 81 | | | | | | | | | | | 71 | 49 | 90 |
| 82 | | | | | | | | | | | 75 | 51 | 90 |
| 83 | | | | | | | | | | | 79 | 54 | 90 |
| 84 | | | | | | | | | | | | 56 | 95 |
| 85 | | | | | | | | | | | | 59 | 95 |
| 86 | | | | | | | | | | | | 63 | 95 |
| 87 | | | | | | | | | | | | 66 | 95 |
| 88 | | | | | | | | | | | | 70 | 95 |
| 89 | | | | | | | | | | | | | 999 |
| 90 | | | | | | | | | | | | | 999 |

# UPS Energy Calculation

| UPS System Parameters | Proposed | Units | Comments |
|---|---|---|---|
| **UPS Module Data** | | | |
| Total Rack Load | 881 | kW | From Space sheet. |
| Percentage of Load Served by UPS | 100% | % | We assume all racks are backed up. |
| UPS Load | 881 | kW | Rack load times percentage of load served by UPS. |
| Number of Modules | 5 | | Assumed. |
| Unit Capacity | 500 | kVA | Assumed. |
| Total UPS Capacity | 2,500 | kVA | Unit capacity * number of units |
| Load Factor | 35% | % | UPS load / UPS capacity |
| UPS Efficiency | 86% | % | From LBNL Datacenter UPS benchmarking study. |
| **Energy Use** | | | |
| Annual Energy Use | 8,977,981 | kWh/yr | UPS load / UPS efficiency * 8760 hours |
| Peak Demand | 1,025 | kW | UPS load / UPS efficiency |

# Proposed Heating & Cooling Load, Fan Energy, Energy Savings

**Template:** **Air Handler Energy Model_Recirculation with Economizer_v10.3**

**Input Parameters**

| | | | |
|---|---|---|---|
| Occupancy Start Time (6 = 06:00 = 6 am) | 0 | | From the Space Parameters sheet. |
| Occupancy Stop Time (20 = 20:00 = 8 pm) | 24 | | From the Space Parameters sheet. |
| Air Delivery System: CAV or VAV? | VAV | | From the Space Parameters sheet. |
| Return Air Drybulb Setpoint | 89.5 | F | From the Space Parameters sheet. |
| Active Humidity Control? | no | | From the Space Parameters sheet. |
| Drybulb Temp at RH Sensor Location | 89.5 | F | From the Space Parameters sheet. |
| Allowed Relative Humidity, Maximum | 100% | RH | From the Space Parameters sheet. |
| Allowed Relative Humidity, Minimum | 1% | RH | From the Space Parameters sheet. |
| Min Allowed Ventilation Air Flow Rate | 1,017 | cfm | From the Space Parameters sheet. |
| CHWST Setpoint, Primary | 44 | F | From the Space Parameters sheet. |
| CHWST Setpoint during Reset | 44 | F | From the Space Parameters sheet. |
| Adiabatic Humidifier Power Draw | 0.000 | kW/(lb of H20/hr) | From the Space Parameters sheet. |

| | | | |
|---|---|---|---|
| Humidifier: 0=None, 1=Electric, 2=Steam, 3=Adiabatic | 0 | | No active humidification in the proposed case. |
| Cooling Plant Type: 1=CHW, 2=DX | 1 | | There is a chilled water plant in the proposed case. |
| CHWST Reset: 0=No, 1=Yes | 0 | | No CHWST in the proposed case. |
| Economizer? | yes | | Proposed design includes integrated economizing. |
| Economizer Drybulb Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Drybulb Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Drybulb Upper Lockout | 78 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Dewpoint Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Dewpoint Lower Lockout | 0 | F | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Dewpoint Upper Lockout | 55 | F | Email from Rupa Ganguly on 9/30/08. |
| Economizer Enthalpy Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| Enthalpy Lower Lockout | 0 | BTU/lb | Assumed, no lower lockout, email from Rupa Ganguly on 9/30/08. |
| Enthalpy Upper Lockout | 29.75 | BTU/lb | Email from Rupa Ganguly on 9/30/08. |
| Economizer Relative Humidity Control? | yes | | Email from Rupa Ganguly on 9/30/08. |
| RH Lower Lockout | 20% | % | Email from Rupa Ganguly on 9/30/08. |
| RH Upper Lockout | 80% | % | Email from Rupa Ganguly on 9/30/08. |

| Fan System Parameters | | Supply | Relief | Units | Sources |
|---|---|---|---|---|---|
| Fan Motor Size, Nominal | | 30 | 50 | hp | Sized in accordance with calculated brake horsepower, below. |
| Number of Fans | | 10 | 5 | | Arbitrary numbers selected for model. Assuming one supply fan per RAHU. |
| Fan Efficiency | | 63.8% | 67.5% | % | Baseline fan efficiencies for motor sizes indicated. |
| Fan Drive Efficiency | | 95% | 95% | % | Typical value for belt drive. |
| Fan Motor Efficiency | | 92.5% | 93.2% | % | Baseline efficiencies. |
| VFD Efficiency | | 98% | 98% | % | Supply and relief fans assumed to be equipped with VFDs. |
| Fan Motor and Drive in Airstream? | | 1 | n/a | 1=yes, 0=no | Assumption. |
| Econ. In Min. Pos. | Total Static Pressure Drop | 2.00 | 8.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | n/a | F | Calculated based on maximum fan motor output power. |
| Economizer Open | Total Static Pressure Drop | 2.00 | 1.00 | in. w.g. | Typical value. |
| | Estimated SAT Increase | 2.0 | n/a | F | Calculated based on maximum fan motor output power. |

**Calculated Parameters**

| | | | |
|---|---|---|---|
| Return Air Minimum Dewpoint | 0.0 | F | Dewpoint of return air when RH sensor is at minimum allowed RH. |
| Space Dewpoint at Maximum Allowed Space Humidity | 89.5 | | Corresponds to Space DB and Max Allowed RH. |
| Chilled Water Minimum Temperature Requirement | 64.5 | F | If the cooling system is CHW, the cooling coil is assumed to have a constant approach temperature of 3 deg F. |

| Fan System Parameters | Supply | Relief | Units | Comments |
|---|---|---|---|---|
| Fan Motor Output Power, Maximum | 4.9 | 8.5 | kW | Per fan motor. This is the maximum output brake power each fan motor is called upon to deliver. |
| Fan Motor Output Power, Maximum | 6.6 | 11.4 | hp | Per fan motor. Converted from kW to hp. |

**Error Messages**

OK - RH minimum does not require humidifier. No humidifier identified.
OK - Chilled Water Supply Temperature Setpoint is low enough to perform required sensible and latent cooling.
OK - Supply Fan Motor Size Exceeds Maximum Required Supply Fan Motor Output
OK - Relief Fan Motor Size Exceeds Maximum Required Relief Fan Motor Output

**Results (Annual Totals)**

| | Proposed | Units |
|---|---|---|
| Cooling Energy Extracted from Airstream | 14,496,864 | kBTU/yr |
| Heating Energy Added to Airstream | 0 | kBTU/yr |
| Humidifier Energy Added to Airstream | 0 | kBTU/yr |

| | Proposed | Units |
|---|---|---|
| Humidifier Energy Required | n/a | kWh/yr |
| | n/a | therms/yr |
| Fan Motor Energy Required | 644,008 | kWh/yr |

**Hourly Calculations**

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Energy Required to Sensibly Cool Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | | | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | Supply | | Relief | | | | | | | |
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | Total Power Input | Air Deliv. Effic. | Total Power Input | Air Deliv. Effic. | Total Power Input | | Electric | Stea m | Adia-batic | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | kBTU | kBTU | kBTU | kW | cfm/kW | kW | cfm/kW | kW | tons | kW | therm s | kW | therms |
| 1-Jan | 1 | 127,545 | 67.5 | 67.5 | 67.5 | 41.5 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 41.5 | 44.0 | 2,979 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 2 | 127,545 | 67.5 | 67.5 | 67.5 | 39.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 39.7 | 44.0 | 2,978 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 38.5 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 38.5 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 37.9 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.9 | 44.0 | 2,975 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 36.7 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 36.7 | 44.0 | 2,976 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 37.8 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.1 | 37.8 | 44.0 | 2,978 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 248 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 37.4 | 0 | 0 | 0 | 0 | 0 | 66,574 | 65.5 | 37.4 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 42.0 | 1,586 | 96.6 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 37.2 | 0 | 0 | 0 | 0 | 0 | 69,005 | 65.5 | 37.2 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 42.9 | 1,608 | 97.5 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 36.9 | 0 | 0 | 0 | 0 | 0 | 71,924 | 65.5 | 36.9 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 43.9 | 1,637 | 98.5 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 36.7 | 0 | 0 | 0 | 0 | 0 | 74,770 | 65.5 | 36.7 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 44.8 | 1,670 | 99.4 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 36.0 | 0 | 0 | 0 | 0 | 0 | 81,585 | 65.5 | 36.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.1 | 1,768 | 100.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jan | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 35.1 | 0 | 0 | 0 | 0 | 0 | 90,244 | 65.5 | 35.1 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.4 | 1,944 | 101.0 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 55.9 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 55.9 | 44.0 | 3,004 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 56.1 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 56.1 | 44.0 | 3,005 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 56.3 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 56.3 | 44.0 | 3,006 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 56.7 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 56.7 | 44.0 | 3,006 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 17 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 56.3 | 44.0 | 3,004 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 18 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.3 | 55.8 | 44.0 | 3,003 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 19 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.3 | 55.0 | 44.0 | 3,000 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 20 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.3 | 54.1 | 44.0 | 2,998 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 21 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.3 | 53.8 | 44.0 | 2,997 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 22 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.2 | 54.0 | 44.0 | 2,996 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 23 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.2 | 53.8 | 44.0 | 2,995 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 30-Jun | 24 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.2 | 53.8 | 44.0 | 2,993 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 1 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.2 | 49.3 | 44.0 | 2,992 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 2 | 127,545 | 67.5 | 67.5 | 67.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1 | 1,017 | 89.2 | 49.6 | 44.0 | 2,992 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 3 | 127,545 | 67.5 | 67.5 | 67.5 | 49.8 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.2 | 49.8 | 44.0 | 2,992 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 4 | 127,545 | 67.5 | 67.5 | 67.5 | 50.2 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.2 | 50.2 | 44.0 | 2,992 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 5 | 127,545 | 67.5 | 67.5 | 67.5 | 49.5 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.2 | 49.5 | 44.0 | 2,992 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 6 | 127,545 | 67.5 | 67.5 | 67.5 | 48.9 | 0 | 0 | 0 | 1 | 1 | 1,017 | 89.2 | 48.9 | 44.0 | 2,992 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 249 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 7 | 127,545 | 67.5 | 67.5 | 67.5 | 50.5 | 0 | 0 | 0 | 0 | 0 | 92,704 | 65.5 | 50.5 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.2 | 2,006 | 100.8 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 8 | 127,545 | 67.5 | 67.5 | 67.5 | 52.3 | 0 | 0 | 0 | 0 | 0 | 102,172 | 65.5 | 52.3 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 43.9 | 2,326 | 98.5 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 9 | 127,545 | 67.5 | 67.5 | 67.5 | 54.5 | 0 | 0 | 0 | 0 | 0 | 116,126 | 65.5 | 54.5 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 36.2 | 3,209 | 90.8 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 10 | 127,545 | 67.5 | 67.5 | 67.5 | 56.3 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 56.3 | 44.0 | 3,005 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 250 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 11 | 127,545 | 67.5 | 67.5 | 67.5 | 57.4 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 57.4 | 44.0 | 3,007 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 1-Jul | 12 | 127,545 | 67.5 | 67.5 | 67.5 | 58.1 | 0 | 1 | 0 | 0 | 1 | 1,017 | 89.3 | 58.1 | 44.0 | 3,009 | 0 | 0 | 54.6 | 2,337 | 0.1 | 7,022 | 54.7 | 251 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 13 | 127,545 | 67.5 | 67.5 | 67.5 | 44.6 | 0 | 0 | 0 | 0 | 0 | 110,111 | 65.5 | 44.6 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 40.2 | 2,740 | 94.8 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 14 | 127,545 | 67.5 | 67.5 | 67.5 | 44.8 | 0 | 0 | 0 | 0 | 0 | 105,337 | 65.5 | 44.8 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 42.6 | 2,470 | 97.2 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 15 | 127,545 | 67.5 | 67.5 | 67.5 | 45.0 | 0 | 0 | 0 | 0 | 0 | 102,172 | 65.5 | 45.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 43.9 | 2,326 | 98.5 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |

All hours of the year are included in this analysis, but most are hidden in this printout for brevity.

| Date | Hour | Total Supply Air Flow | Supply Air Drybulb Temp | Return Air Max Allowable Dewpoint | Min Drybulb Temp of Air Leaving Cooling Coil | Return Air Actual Dew-point | Economizer Lockouts Based on Outside Air Condition | | | | | Volume of Outside Air | Mixed Air Condition Entering Cooling Coil | | CHWST | Energy Required to Sensibly Cool Mixed Air | Energy Required to Sensibly Heat Mixed Air | Energy Req'd to Humidify Mixed Air | Fan Power | | | | | Total Load on Cooling Plant | Humidifier Input Power | | | Heating Plant Gas Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Drybulb | Dew-point | Enthalpy | RH | Locked Out? | | Dry-bulb | Dew-point | | | | | Supply | | Relief | | Total Power Input | | Electric | Stea m | Adia-batic | |
| | | | | | | | | | | | | | | | | | | | Total Power Input | Air Deliv. Effic. | Total Power Input | Air Deliv. Effic. | | | | | | |
| | | cfm | F | F | F | F | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | 1=yes, 0=no | cfm | F | F | F | kBTU | kBTU | kBTU | kW | cfm/kW | kW | cfm/kW | kW | tons | kW | therm s | kW | therms |
| 31-Dec | 16 | 127,545 | 67.5 | 67.5 | 67.5 | 45.1 | 0 | 0 | 0 | 0 | 0 | 98,049 | 65.5 | 45.1 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 45.2 | 2,170 | 99.8 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 17 | 127,545 | 67.5 | 67.5 | 67.5 | 43.3 | 0 | 0 | 0 | 0 | 0 | 92,201 | 65.5 | 43.3 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.3 | 1,993 | 100.8 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 18 | 127,545 | 67.5 | 67.5 | 67.5 | 41.5 | 0 | 0 | 0 | 0 | 0 | 87,912 | 65.5 | 41.5 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.5 | 1,890 | 101.1 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 19 | 127,545 | 67.5 | 67.5 | 67.5 | 40.5 | 0 | 0 | 0 | 0 | 0 | 84,841 | 65.5 | 40.5 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 46.4 | 1,827 | 101.0 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 20 | 127,545 | 67.5 | 67.5 | 67.5 | 39.6 | 0 | 0 | 0 | 0 | 0 | 79,303 | 65.5 | 39.6 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 45.8 | 1,732 | 100.4 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 21 | 127,545 | 67.5 | 67.5 | 67.5 | 39.0 | 0 | 0 | 0 | 0 | 0 | 75,100 | 65.5 | 39.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 44.9 | 1,674 | 99.5 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 22 | 127,545 | 67.5 | 67.5 | 67.5 | 38.3 | 0 | 0 | 0 | 0 | 0 | 71,023 | 65.5 | 38.3 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 43.6 | 1,627 | 98.2 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 23 | 127,545 | 67.5 | 67.5 | 67.5 | 36.0 | 0 | 0 | 0 | 0 | 0 | 68,450 | 65.5 | 36.0 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 42.7 | 1,603 | 97.3 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| 31-Dec | 24 | 127,545 | 67.5 | 67.5 | 67.5 | 33.6 | 0 | 0 | 0 | 0 | 0 | 66,836 | 65.5 | 33.6 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 42.1 | 1,589 | 96.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |
| Sum | | | | | | | 146 | 1,757 | 267 | 3,535 | 4,811 | | | | | ######## | 0 | 0 | 478,182 | | 165,826 | | ###### | | 0 | 0 | 0 | 0 |
| Ave | | 127,545 | 67.5 | 67.5 | 67.5 | 49.0 | 0.017 | 0.201 | 0.030 | 0.404 | 0.549 | 43,753 | 78.7 | 49.0 | 44.0 | 1,655 | 0 | 0 | 54.6 | 2,337 | 18.9 | 4,952 | 73.5 | 138 | 0.0 | 0.0 | 0.00 | 0.0 |
| Max | | 127,545 | 67.5 | 67.5 | 67.5 | 67.5 | | | | | | 127,545 | 89.5 | 67.5 | 44.0 | 3,032 | 0 | 0 | 54.6 | 2,337 | 46.5 | 7,022 | 101.1 | 253 | 0.0 | 0.0 | 0.00 | 0.0 |
| Min | | 127,545 | 67.5 | 67.5 | 67.5 | 11.1 | | | | | | 1,017 | 65.5 | 11.1 | 44.0 | 0 | 0 | 0 | 54.6 | 2,337 | 0.1 | 1,524 | 54.7 | 0 | 0.0 | 0.0 | 0.00 | 0.0 |

# Cooling Tower Energy Use, Proposed

**Assumptions**

The proposed cooling towers are staged in tandem with the baseline chillers (number of active towers = number of active chillers).
The proposed cooling tower fan motors are two-speed (100% and 50%).

**Parameters**

| | | | |
|---|---|---|---|
| Chiller Condenser Water Temperature Setpoint | 80 | °F | Baseline |
| Cooling Tower Fan Motor Size | 30 | hp | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Cooling Tower Condenser Water Flow, Maximum | 2,600 | gpm | See Cooling Tower Fan Speed Lookup Tables sheet. |
| Motor Load Factor at Full Speed | 90% | | Estimate |
| Fan Motor Efficiency | 92.5% | | Baseline |
| Fan Drive Efficiency | 95% | | Belt drive |
| Fan Power, Baseline Cooling Tower, 100% | 22.9 | kW | = 0.746 * motor size * load factor / (drive effic * motor effic) |
| Fan Power, Baseline Cooling Tower, 50% | 2.9 | kW | Fan Law Calculation |

**Hourly Calculations**

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 1-Jan | 1 | 42 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 2 | 41 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 3 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 4 | 39 | 248 | 1 | 46% | 248 | 55 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 5 | 38 | 248 | 1 | 46% | 248 | 55 | 80.0 | 39% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 6 | 40 | 248 | 1 | 46% | 248 | 60 | 80.0 | 40% | 2.3 | 2.9 | 2.3 | 2.9 |
| 1-Jan | 7 | 41 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jan | 8 | 41 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jan | 9 | 42 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jan | 10 | 43 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jan | 11 | 44 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jan | 12 | 46 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 30-Jun | 13 | 60 | 250 | 1 | 46% | 250 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 30-Jun | 14 | 60 | 250 | 1 | 46% | 250 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 30-Jun | 15 | 60 | 250 | 1 | 46% | 250 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 30-Jun | 16 | 61 | 251 | 1 | 46% | 251 | 75 | 80.0 | 56% | 12.9 | 22.9 | 12.9 | 22.9 |
| 30-Jun | 17 | 60 | 250 | 1 | 46% | 250 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 30-Jun | 18 | 59 | 250 | | | | | [illegible] | 53% | 12.1 | 22.9 | 12.1 | 22.9 |
| 30-Jun | 19 | 58 | 250 | | | | | [illegible] | 52% | 11.8 | 22.9 | 11.8 | 22.9 |
| 30-Jun | 20 | 57 | 250 | | | | | [illegible] | 50% | 11.5 | 22.9 | 11.5 | 22.9 |
| 30-Jun | 21 | 56 | 250 | | | | | [illegible] | 49% | 2.8 | 2.9 | 2.8 | 2.9 |
| 30-Jun | 22 | 56 | 250 | | | | | [illegible] | 49% | 2.8 | 2.9 | 2.8 | 2.9 |
| 30-Jun | 23 | 55 | 250 | | | | | [illegible] | 48% | 2.7 | 2.9 | 2.7 | 2.9 |
| 30-Jun | 24 | 55 | 249 | 1 | 46% | 249 | 70 | 80.0 | 48% | 2.7 | 2.9 | 2.7 | 2.9 |
| 1-Jul | 1 | 52 | 249 | 1 | 46% | 249 | 65 | 80.0 | 45% | 2.6 | 2.9 | 2.6 | 2.9 |
| 1-Jul | 2 | 52 | 249 | 1 | 46% | 249 | 65 | 80.0 | 45% | 2.6 | 2.9 | 2.6 | 2.9 |
| 1-Jul | 3 | 52 | 249 | 1 | 46% | 249 | 65 | 80.0 | 45% | 2.6 | 2.9 | 2.6 | 2.9 |
| 1-Jul | 4 | 52 | 249 | 1 | 46% | 249 | 65 | 80.0 | 45% | 2.6 | 2.9 | 2.6 | 2.9 |
| 1-Jul | 5 | 51 | 249 | 1 | 46% | 249 | 65 | 80.0 | 45% | 2.6 | 2.9 | 2.6 | 2.9 |
| 1-Jul | 6 | 51 | 249 | 1 | 46% | 249 | 65 | 80.0 | 45% | 2.6 | 2.9 | 2.6 | 2.9 |
| 1-Jul | 7 | 53 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 8 | 55 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 9 | 58 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 1-Jul | 10 | 60 | 250 | 1 | 46% | 250 | 70 | 80.0 | 55% | 12.5 | 22.9 | 12.5 | 22.9 |
| 1-Jul | 11 | 61 | 251 | 1 | 46% | 251 | 75 | 80.0 | 56% | 12.9 | 22.9 | 12.9 | 22.9 |
| 1-Jul | 12 | 62 | 251 | 1 | 46% | 251 | 75 | 80.0 | 58% | 13.4 | 22.9 | 13.4 | 22.9 |
| 31-Dec | 13 | 52 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Date | Hour | Wet-bulb Temp | Total Load On Cooling Towers | Number of Towers Oper-ating | Each Tower | | | | | | | Tower Fan Power | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | CW Flow (% of Max) | Load on Cooling Tower | Min. Achiev. Cond. Water Temp for Current Load & Wetbulb | Actual Cond. Water Temp | Cooling Tower Fan Operating Point for Current Load, Wetbulb, and Cold Cond Water Temp | Ave. Hourly Fan Power | Peak Hourly Fan Power | Total Ave. Hourly Power | Total Peak Hourly Power |
| | | F | tons | | | tons | F | F | % | kW | kW | kW | kW |
| 31-Dec | 14 | 52 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 15 | 52 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 16 | 51 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 17 | 50 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 18 | 48 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 19 | 47 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 20 | 45 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 21 | 44 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 22 | 42 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 23 | 41 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| 31-Dec | 24 | 39 | 0 | 0 | n/a | 0 | n/a | 80.0 | n/a | 0.0 | 0.0 | 0.0 | 0.0 |
| Sum | | | | | | | | | | | | 33,434 | 53,369 |
| Ave | | 53 | 138 | 0.571 | 46% | 138 | 68 | 80.0 | 50% | 3.8 | 6.1 | 3.8 | 6.1 |
| Max | | 73 | 253 | 1 | 46% | 253 | 80 | 80.0 | 98% | 22.5 | 22.9 | 22.5 | 22.9 |
| Min | | 30 | 0 | 0 | 46% | 0 | 50 | 80.0 | 39% | 0.0 | 0.0 | 0.0 | 0.0 |

No. of hours in year that actual CW temp > 80: 0

# CHW Pump Energy Use, Proposed

**Template Name:** **CHW Pump Energy Model_v1.01**

**Assumptions**

There is one operating constant-speed primary CHW pump per active chiller.
All of the primary CHW pumps are identical.
There is one operating variable-speed secondary CHW pump.

**Results**

| | Proposed | Units |
|---|---|---|
| CHW Pump Energy Required | 145,283 | kWh/yr |
| Ave CHW Pump System Effic. | 61.9 | gpm/kW |

***Primary Pumps***

**Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T across evaporator. |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

***Secondary Pump***

**Input Parameters**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CHW Flow | 650 | 608 | gpm | Nominal: 650.<br>Design: 253-ton peak load, 10F CHW delta-T. |
| Head | 100 | 100 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 70% | 70% | | Nominal: Baseline for 75 hp motor.<br>Design: Baseline for 75 hp motor. |
| Pump Motor Size | 100 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 94.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 98% | | | Secondary pumps are variable speed. |
| Secondary CHW Loop Delta-T | | 10 | F | Estimate. |

**Calculations**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 21.9 | hp | (flow * head) / (3960 * pump effic) |
| Pump VFD Input Power | | 17.7 | kW | 0.746 * hp / motor effic / VFD effic |

**Error Messages**

OK -- Primary Pump Motor is not undersized.
OK -- Secondary Pump Motor is not undersized.

**Hourly Analysis**

| Date | Hour | Total Cooling Load | No. of Chillers On | Total Primary CHW Flow | Total Primary Pump Power | Secondary Loop CHW Flow | Secondary Pump Power | Total CHW Pump Power | CHW Pump System Efficiency |
|---|---|---|---|---|---|---|---|---|---|
| | | tons | | gpm | kW | gpm | kW | kW | gpm/kW |
| 1-Jan | 1 | 248 | 1 | 1,200 | 12 | 596 | 17 | 30 | 60.8 |
| 1-Jan | 2 | 248 | 1 | 1,200 | 12 | 596 | 17 | 30 | 60.8 |
| 1-Jan | 3 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 4 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 5 | 248 | 1 | 1,200 | 12 | 595 | 17 | 29 | 60.9 |
| 1-Jan | 6 | 248 | 1 | 1,200 | 12 | 596 | 17 | 30 | 60.8 |
| 1-Jan | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jan | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jan | 9 | 0 | | | | | 0 | 0 | n/a |
| 1-Jan | 10 | 0 | | | | | 0 | 0 | n/a |
| 1-Jan | 11 | 0 | | | | | 0 | 0 | n/a |
| 1-Jan | 12 | 0 | | | | | 0 | 0 | n/a |
| 30-Jun | 13 | 250 | | | | | 17 | 30 | 60.5 |
| 30-Jun | 14 | 250 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.5 |
| 30-Jun | 15 | 250 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.5 |
| 30-Jun | 16 | 251 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.5 |
| 30-Jun | 17 | 250 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.5 |
| 30-Jun | 18 | 250 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.6 |
| 30-Jun | 19 | 250 | 1 | 1,200 | 12 | 600 | 17 | 30 | 60.6 |
| 30-Jun | 20 | 250 | 1 | 1,200 | 12 | 600 | 17 | 30 | 60.6 |
| 30-Jun | 21 | 250 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.6 |
| 30-Jun | 22 | 250 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.6 |
| 30-Jun | 23 | 250 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.7 |
| 30-Jun | 24 | 249 | 1 | 1,200 | 12 | 599 | 17 | 30 | 60.7 |
| 1-Jul | 1 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.7 |
| 1-Jul | 2 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.7 |
| 1-Jul | 3 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.7 |
| 1-Jul | 4 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.7 |
| 1-Jul | 5 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.7 |
| 1-Jul | 6 | 249 | 1 | 1,200 | 12 | 598 | 17 | 30 | 60.7 |
| 1-Jul | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 1-Jul | 10 | 250 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.5 |
| 1-Jul | 11 | 251 | 1 | 1,200 | 12 | 601 | 17 | 30 | 60.5 |
| 1-Jul | 12 | 251 | 1 | 1,200 | 12 | 602 | 17 | 30 | 60.5 |
| 31-Dec | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| 31-Dec | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | n/a |
| Sum | | | | | 61,808 | | 83,475 | 145,283 | |
| Ave | | 138 | 0.571 | 685 | 7 | 331 | 10 | 17 | 61.9 |
| Max | | 253 | 1 | 1,200 | 12 | 606 | 18 | 30 | 97.9 |
| Min | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60.2 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# CHW Plant Energy Use, Proposed

**Assumptions**
All chillers are identical and rotated equally.
There is one operating constant-speed CW pump per active chiller.

| | | | |
|---|---|---|---|
| Electric Chiller Capacity | 500 | tons | Assumed. |
| Number of Electric Chillers | 3 | | Assumed. |
| Total Electric Chiller Capacity | 1,500 | tons | Chiller capacity times number of chillers. |
| Chilled Water Supply Temperature | 44 | F | Baseline. |

**Condenser Water Pump Input Parameters (per Pump)**

| Parameter | Nominal | Design | Units | Comments |
|---|---|---|---|---|
| CW Flow | 1,750 | 1,200 | gpm | Nominal: 1750.<br>Design: 500-ton chiller, 10F CHW delta-T |
| Head | 30 | 30 | ft | Nominal: Estimate.<br>Design: Estimate. |
| Pump Efficiency | 60% | 60% | | Nominal: Baseline for 20 hp motor.<br>Design: Baseline for 20 hp motor. |
| Pump Motor Size | 20 | | hp | Selected to meet calculated hp requirement shown below. |
| Pump Motor Efficiency | 91.4% | | | Baseline efficiency. |
| Pump Motor VFD Efficiency | 100% | | | Primary pumps are constant speed, no VFD. |

**Calculations (per Pump)**

| | | | | |
|---|---|---|---|---|
| Pump Brake Power | | 15.2 | hp | (flow * head) / (3960 * pump effic) |
| Pump Motor Input Power | | 12.4 | kW | 0.746 * hp / motor effic / VFD effic |

**Results (Annual Totals)**

| | Proposed | Units |
|---|---|---|
| Total Annual Electric Use | 909,930 | kWh/yr |
| Summer Peak Electric Demand | 204 | kW |
| Annual Average Cooling Efficiency | 0.753 | kW/ton |

**Hourly Calculations**

| Date | Hour | Total Cooling Load | Chillers | | | | Cooling Tower Power Demand | CHW & CW Pump Power Demand | Total Cooling Plant Power Demand | Summer Peak Demand |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Chillers Operating | Chiller Load Factor | Chiller Effic. | Chiller Power Demand | | | | |
| | | tons | 0-3 | % | kW/ton | kW | kW | kW | kW | kW |
| 1-Jan | 1 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 2 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 3 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 4 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 5 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 6 | 248 | 1 | 50% | 0.56 | 138 | 2.3 | 42 | 182 | n/a |
| 1-Jan | 7 | 0 | 0 | | | | | 0 | 0 | n/a |
| 1-Jan | 8 | 0 | 0 | | | | | 0 | 0 | n/a |
| 1-Jan | 9 | 0 | 0 | | | | | 0 | 0 | n/a |
| 1-Jan | 10 | 0 | 0 | | | | | 0 | 0 | n/a |
| 1-Jan | 11 | 0 | 0 | | | | | 0 | 0 | n/a |
| 1-Jan | 12 | 0 | 0 | | | | | 0 | 0 | n/a |
| 30-Jun | 13 | 250 | 1 | 50% | 0.54 | 135 | 12.5 | 42 | 190 | 200 |
| 30-Jun | 14 | 250 | 1 | 50% | 0.54 | 135 | 12.5 | 42 | 190 | 200 |
| 30-Jun | 15 | 250 | 1 | 50% | 0.54 | 135 | 12.5 | 42 | 190 | 200 |
| 30-Jun | 16 | 251 | 1 | 50% | 0.54 | 135 | 12.9 | 42 | 190 | 200 |
| 30-Jun | 17 | 250 | 1 | 50% | 0.54 | 135 | 12.5 | 42 | 190 | 200 |
| 30-Jun | 18 | 250 | 1 | 50% | 0.54 | 135 | 12.1 | 42 | 189 | 200 |
| 30-Jun | 19 | 250 | 1 | 50% | 0.54 | 135 | 11.8 | 42 | 189 | n/a |
| 30-Jun | 20 | 250 | 1 | 50% | 0.56 | 139 | 11.5 | 42 | 193 | n/a |
| 30-Jun | 21 | 250 | 1 | 50% | 0.56 | 139 | 2.8 | 42 | 184 | n/a |
| 30-Jun | 22 | 250 | 1 | 50% | 0.56 | 139 | 2.8 | 42 | 184 | n/a |
| 30-Jun | 23 | 250 | 1 | 50% | 0.56 | 139 | 2.7 | 42 | 184 | n/a |
| 30-Jun | 24 | 249 | 1 | 50% | 0.56 | 139 | 2.7 | 42 | 184 | n/a |
| 1-Jul | 1 | 249 | 1 | 50% | 0.56 | 139 | 2.6 | 42 | 183 | n/a |
| 1-Jul | 2 | 249 | 1 | 50% | 0.56 | 139 | 2.6 | 42 | 183 | n/a |
| 1-Jul | 3 | 249 | 1 | 50% | 0.56 | 139 | 2.6 | 42 | 183 | n/a |
| 1-Jul | 4 | 249 | 1 | 50% | 0.56 | 139 | 2.6 | 42 | 183 | n/a |
| 1-Jul | 5 | 249 | 1 | 50% | 0.56 | 139 | 2.6 | 42 | 183 | n/a |
| 1-Jul | 6 | 249 | 1 | 50% | 0.56 | 139 | 2.6 | 42 | 183 | n/a |
| 1-Jul | 7 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 8 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 9 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 1-Jul | 10 | 250 | 1 | 50% | 0.54 | 135 | 12.5 | 42 | 190 | n/a |
| 1-Jul | 11 | 251 | 1 | 50% | 0.54 | 135 | 12.9 | 42 | 190 | n/a |
| 1-Jul | 12 | 251 | 1 | 50% | 0.54 | 135 | 13.4 | 42 | 191 | n/a |
| 31-Dec | 13 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 14 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 15 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 16 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 17 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 18 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 19 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 20 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 21 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 22 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 23 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| 31-Dec | 24 | 0 | 0 | n/a | - | 0 | 0.0 | 0 | 0 | n/a |
| Sum | | 1,208,072 | | | | 669,406 | 33,434 | 207,091 | 909,930 | 124,049 |
| Ave | | 138 | 0.571 | 48% | 0.33 | 76 | 3.8 | 24 | 104 | 152 |
| Max | | 253 | 1 | 51% | 1.23 | 139 | 22.5 | 42 | 201 | 204 |
| Min | | 0 | 0 | 0% | 0.00 | 0 | 0.0 | 0 | 0 | 0 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

# First Year Electric Cost

**Results**

| | Proposed |
|---|---|
| Annual Electric Use Charges | $881,099 |
| Annual Electric Demand Charges | $222,731 |
| Annual Electric Expense | $1,103,830 |

**Rate Schedule**

| | |
|---|---|
| Select current rate schedule | E-19A |
| Select voltage type | Secondary |

| | | Secondary | Primary | Transmission | **Secondary** |
|---|---|---|---|---|---|
| Identifier | Total Demand Rates | $/kW | $/kW | $/kW | $/kW |
| 1 | Peak Summer | 11.54 | 10.43 | 8.13 | 11.54 |
| 2 | Part-Peak Summer | 2.64 | 2.39 | 1.84 | 2.64 |
| 3 | Maximum Summer | 6.62 | 5.63 | 3.72 | 6.62 |
| 4 | Part-Peak Winter | 0.99 | 0.74 | - | 0.99 |
| 5 | Maximum Winter | 6.62 | 5.63 | 3.72 | 6.62 |
| Identifier | Total Energy Rates | $/kWh | $/kWh | $/kWh | $/kWh |
| 1 | Peak Summer | 0.13286 | 0.13251 | 0.09801 | 0.13286 |
| 2 | Part-Peak Summer | 0.09095 | 0.08912 | 0.07843 | 0.09095 |
| 3 | Off-Peak Summer | 0.07383 | 0.07040 | 0.06674 | 0.07383 |
| 4 | Part-Peak Winter | 0.08095 | 0.07653 | 0.07134 | 0.08095 |
| 5 | Off-Peak Winter | 0.07127 | 0.06700 | 0.06326 | 0.07127 |

These rates are applicable for the time period:
**Jan 1, 2008 to Present**

**Hourly Energy Rate Calculations**

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge Proposed |
|---|---|---|---|
| | | | $ |
| 1-Jan | 1 | 5 | $92.12 |
| 1-Jan | 2 | 5 | $92.11 |
| 1-Jan | 3 | 5 | $92.10 |
| 1-Jan | 4 | 5 | $92.10 |
| 1-Jan | 5 | 5 | $92.10 |
| 1-Jan | 6 | 5 | $92.11 |
| 1-Jan | 7 | 5 | $81.71 |
| 1-Jan | 8 | 5 | $81.78 |
| 1-Jan | 9 | 4 | $92.97 |
| 1-Jan | 10 | 4 | $93.04 |
| 1-Jan | 11 | 4 | $93.15 |
| 1-Jan | 12 | 4 | $93.17 |
| 30-Jun | 13 | 1 | $172.69 |
| 30-Jun | 14 | 1 | $172.69 |
| 30-Jun | 15 | 1 | $172.69 |
| 30-Jun | 16 | 1 | $172.75 |
| 30-Jun | 17 | 1 | $172.69 |
| 30-Jun | 18 | 1 | $172.62 |
| 30-Jun | 19 | 2 | $118.13 |
| 30-Jun | 20 | 2 | $118.51 |
| 30-Jun | 21 | 2 | $117.69 |
| 30-Jun | 22 | 3 | $95.53 |
| 30-Jun | 23 | 3 | $95.52 |
| 30-Jun | 24 | 3 | $95.52 |
| 1-Jul | 1 | 3 | $95.50 |
| 1-Jul | 2 | 3 | $95.50 |
| 1-Jul | 3 | 3 | $95.50 |
| 1-Jul | 4 | 3 | $95.50 |
| 1-Jul | 5 | 3 | $95.50 |
| 1-Jul | 6 | 3 | $95.50 |

**Hourly Demand Charge Calculations**

| Hourly Demand | Demand Charge by Rate Period | | | | |
|---|---|---|---|---|---|
| | Proposed | | | | |
| Proposed | Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
| kW | $ | $ | $ | $ | $ |
| 1,293 | | | $8,557 | | $8,557 |
| 1,292 | | | $8,556 | | $8,556 |
| 1,292 | | | $8,555 | | $8,555 |
| 1,292 | | | $8,555 | | $8,555 |
| [illegible] | | | $8,555 | | $8,555 |
| [illegible] | | | $8,556 | | $8,556 |
| [illegible] | | | $7,589 | | $7,589 |
| [illegible] | | | $7,596 | | $7,596 |
| [illegible] | | | $7,603 | $1,137 | $7,603 |
| [illegible] | | | $7,608 | $1,138 | $7,608 |
| [illegible] | | | $7,618 | $1,139 | $7,618 |
| 1,151 | | | $7,620 | $1,139 | $7,620 |
| 1,300 | $14,999 | | $8,604 | | $8,604 |
| 1,300 | $15,000 | | $8,605 | | $8,605 |
| 1,300 | $15,000 | | $8,605 | | $8,605 |
| 1,300 | $15,005 | | $8,608 | | $8,608 |
| 1,300 | $14,999 | | $8,604 | | $8,604 |
| 1,299 | $14,994 | | $8,601 | | $8,601 |
| 1,299 | | $3,429 | $8,598 | | $8,598 |
| 1,303 | | $3,440 | $8,626 | | $8,626 |
| 1,294 | | $3,416 | $8,566 | | $8,566 |
| 1,294 | | | $8,566 | | $8,566 |
| 1,294 | | | $8,565 | | $8,565 |
| 1,294 | | | $8,565 | | $8,565 |
| 1,294 | | | $8,563 | | $8,563 |
| 1,294 | | | $8,563 | | $8,563 |
| 1,294 | | | $8,563 | | $8,563 |
| 1,294 | | | $8,563 | | $8,563 |
| 1,293 | | | $8,563 | | $8,563 |
| 1,293 | | | $8,563 | | $8,563 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| Day | Hour | Current Rate Period (see rate tab for details) | Electric Energy Charge Proposed | Hourly Demand Proposed | Demand Charge by Rate Period Proposed: Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
|---|---|---|---|---|---|---|---|---|---|
| | | | $ | kW | $ | $ | $ | $ | $ |
| 1-Jul | 7 | 3 | $84.96 | 1,151 | | | $7,618 | | $7,618 |
| 1-Jul | 8 | 3 | $84.79 | 1,148 | | | $7,603 | | $7,603 |
| 1-Jul | 9 | 2 | $103.63 | 1,139 | | $3,008 | $7,543 | | $7,543 |
| 1-Jul | 10 | 2 | $118.21 | 1,300 | | $3,431 | $8,605 | | $8,605 |
| 1-Jul | 11 | 2 | $118.26 | 1,300 | | $3,433 | $8,608 | | $8,608 |
| 1-Jul | 12 | 2 | $118.31 | 1,301 | | $3,434 | $8,612 | | $8,612 |
| 31-Dec | 13 | 4 | $92.66 | 1,145 | | | $7,578 | $1,133 | $7,578 |
| 31-Dec | 14 | 4 | $92.86 | 1,147 | | | $7,594 | $1,136 | $7,594 |
| 31-Dec | 15 | 4 | $92.97 | 1,148 | | | $7,603 | $1,137 | $7,603 |
| 31-Dec | 16 | 4 | $93.07 | 1,150 | | | $7,611 | $1,138 | $7,611 |
| 31-Dec | 17 | 4 | $93.16 | 1,151 | | | $7,618 | $1,139 | $7,618 |
| 31-Dec | 18 | 4 | $93.18 | 1,151 | | | $7,620 | $1,140 | $7,620 |
| 31-Dec | 19 | 4 | $93.17 | 1,151 | | | $7,620 | $1,139 | $7,620 |
| 31-Dec | 20 | 4 | $93.12 | 1,150 | | | $7,615 | $1,139 | $7,615 |
| 31-Dec | 21 | 4 | $93.04 | 1,149 | | | $7,609 | $1,138 | $7,609 |
| 31-Dec | 22 | 5 | $81.83 | 1,148 | | | $7,601 | | $7,601 |
| 31-Dec | 23 | 5 | $81.76 | 1,147 | | | $7,594 | | $7,594 |
| 31-Dec | 24 | 5 | $81.71 | 1,147 | | | $7,590 | | $7,590 |
| | | Sum | $881,099 | 10,777,126 | | | | | |
| | | Ave | $100.58 | 1230.3 | $14,614 | $3,266 | $8,144 | $1,180 | $8,144 |
| | | Max | $174.21 | 1311.2 | $15,131 | $3,449 | $8,680 | $1,291 | $8,680 |
| | | Min | $80.44 | 1128.7 | $13,025 | $2,980 | $7,472 | $1,117 | $7,472 |

**Monthly Demand Charge Calculations**

| Month | Actual Demand Charge per Rate Period Proposed: Peak Summer | Part-Peak Summer | Max Summer | Part-Peak Winter | Max Winter |
|---|---|---|---|---|---|
| | $ | $ | $ | $ | $ |
| Jan | N/A | N/A | N/A | 1,290 | 8,628 |
| Feb | N/A | N/A | N/A | 1,290 | 8,631 |
| Mar | N/A | N/A | N/A | 1,291 | 8,634 |
| Apr | N/A | N/A | N/A | 1,291 | 8,670 |
| May | 15,089 | 3,442 | 8,656 | N/A | N/A |
| Jun | 15,131 | 3,448 | 8,680 | N/A | N/A |
| Jul | 15,081 | 3,446 | 8,651 | N/A | N/A |
| Aug | 15,079 | 3,444 | 8,650 | N/A | N/A |
| Sep | 15,100 | 3,449 | 8,662 | N/A | N/A |
| Oct | 15,078 | 3,444 | 8,650 | N/A | N/A |
| Nov | N/A | N/A | N/A | 1,290 | 8,628 |
| Dec | N/A | N/A | N/A | 1,281 | 8,628 |
| Sum | 90,558 | 20,672 | 51,949 | 7,734 | 51,818 |
| Ave | 15,093 | 3,445 | 8,658 | 1,289 | 8,636 |
| Max | 15,131 | 3,449 | 8,680 | 1,291 | 8,670 |
| Min | 15,078 | 3,442 | 8,650 | 1,281 | 8,628 |

# Annual Total Gas Energy Use

**Assumptions**
All gas use comes from the heating plant.

**Hourly Calculations**

| Date | Hour | Heating Plant Energy Use Proposed therms |
|---|---|---|
| 1-Jan | 1 | 0.00 |
| 1-Jan | 2 | 0.00 |
| 1-Jan | 3 | 0.00 |
| 1-Jan | 4 | 0.00 |
| 1-Jan | 5 | 0.00 |
| 1-Jan | 6 | 0.00 |
| 30-Jun | 14 | 0.00 |
| 30-Jun | 15 | 0.00 |
| 30-Jun | 16 | 0.00 |
| 30-Jun | 17 | 0.00 |
| 30-Jun | 18 | 0.00 |
| 30-Jun | 19 | 0.00 |
| 30-Jun | 20 | 0.00 |
| 30-Jun | 21 | 0.00 |
| 30-Jun | 22 | 0.00 |
| 30-Jun | 23 | 0.00 |
| 30-Jun | 24 | 0.00 |
| 1-Jul | 1 | 0.00 |
| 1-Jul | 2 | 0.00 |
| 1-Jul | 3 | 0.00 |
| 1-Jul | 4 | 0.00 |
| 1-Jul | 5 | 0.00 |
| 1-Jul | 6 | 0.00 |
| 1-Jul | 7 | 0.00 |
| 1-Jul | 8 | 0.00 |
| 1-Jul | 9 | 0.00 |
| 1-Jul | 10 | 0.00 |
| 1-Jul | 11 | 0.00 |
| 1-Jul | 12 | 0.00 |
| 31-Dec | 13 | 0.00 |
| 31-Dec | 14 | 0.00 |
| 31-Dec | 15 | 0.00 |
| 31-Dec | 16 | 0.00 |
| 31-Dec | 17 | 0.00 |
| 31-Dec | 18 | 0.00 |
| 31-Dec | 19 | 0.00 |
| 31-Dec | 20 | 0.00 |
| 31-Dec | 21 | 0.00 |
| 31-Dec | 22 | 0.00 |
| 31-Dec | 23 | 0.00 |
| 31-Dec | 24 | 0.00 |

All the hours in the year are included in this analysis, but most of them are hidden in this printout for brevity.

| | |
|---|---|
| Sum | 0.00 |
| Ave | 0.00 |
| Max | 0.00 |
| Min | 0.00 |

# First Year Gas Cost

**Gas Use (therms)**

| | Proposed | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | 0 | | 0 |
| Feb | 0 | | 0 |
| Mar | 0 | | 0 |
| Apr | 0 | 0 | |
| May | 0 | 0 | |
| Jun | 0 | 0 | |
| Jul | 0 | 0 | |
| Aug | 0 | 0 | |
| Sep | 0 | 0 | |
| Oct | 0 | 0 | |
| Nov | 0 | | 0 |
| Dec | 0 | | 0 |
| Sum | 0 | 0 | 0 |
| Ave | 0 | 0 | 0 |
| Max | 0 | 0 | 0 |
| Min | 0 | 0 | 0 |

**Gas Cost**

| | Proposed | | |
|---|---|---|---|
| | All | Summer | Winter |
| Jan | | | $0 |
| Feb | | | $0 |
| Mar | | | $0 |
| Apr | | $0 | |
| May | | $0 | |
| Jun | | $0 | |
| Jul | | $0 | |
| Aug | | $0 | |
| Sep | | $0 | |
| Oct | | $0 | |
| Nov | | | $0 |
| Dec | | | $0 |

Annual Total: $0

# Life Cycle Cost

**Template:** **Life Cycle Cost_v2.0**

**General Notes**
Negative values are expenses, positive values are income or savings.

**Costs, in Year Zero dollars.**

| | Baseline | Proposed | Difference | Source |
|---|---|---|---|---|
| First Cost | | | -$50,800 | See Implementation Cost sheet. |
| Annual Electric Cost | -$1,187,233 | -$1,103,830 | $83,403 | See Electric Cost sheet. |
| Annual Gas Cost | $0 | $0 | $0 | See Gas Cost sheet. |
| Annual Energy Cost | -$1,187,233 | -$1,103,830 | $83,403 | Sum previous two lines. |
| Annual Material Cost | | | -$500 | Estimated incremental cost of AHU air filters. |
| Annual Labor Cost | | | -$2,000 | Estimate of incremental air handler maintenance cost. |

**Incentive**

| | | |
|---|---|---|
| Estimated total incentive for this project | $25,400 | See the Summary sheet. |

**Financial Parameters**

| | | |
|---|---|---|
| Cost of Borrowed Capital | 7.0% | Typical assumption. |
| Highest-Yielding Current Investment Opportunity | 8.0% | Typical assumption. |
| Discount Rate | 8.0% | Greater of previous two lines. |
| Inflation in Prices of Energy | | |
| Natural Gas Rate | 6.0% | Assumed. |
| Average Inflation of Electric Use and Electric Demand Rates | 3.0% | Assumed. |
| Escalation in Material Costs | 3.0% | Assumed. |
| Inflation in Price of Labor | 3.0% | Assumed. |

**Life Cycle Costs, Adjusted for Inflation**

| Year | Annual Energy Costs | | Differences | | | | |
|---|---|---|---|---|---|---|---|
| | Baseline | Proposed | Energy | Material | Labor | Total | |
| 0 | | | | | | -$50,800 | First Cost |
| 1 | -$1,222,850 | -$1,136,945 | $85,905 | -$515 | -$2,060 | $83,330 | |
| 2 | -$1,259,536 | -$1,171,054 | $88,482 | -$530 | -$2,122 | $85,830 | |
| 3 | -$1,297,322 | -$1,206,185 | $91,136 | -$546 | -$2,185 | $88,404 | |
| 4 | -$1,336,241 | -$1,242,371 | $93,870 | -$563 | -$2,251 | $91,057 | |
| 5 | -$1,376,329 | -$1,279,642 | $96,687 | -$580 | -$2,319 | $93,788 | |
| 6 | -$1,417,618 | -$1,318,031 | $99,587 | -$597 | -$2,388 | $96,602 | |
| 7 | -$1,460,147 | -$1,357,572 | $102,575 | -$615 | -$2,460 | $99,500 | |
| 8 | -$1,503,951 | -$1,398,299 | $105,652 | -$633 | -$2,534 | $102,485 | |
| 9 | -$1,549,070 | -$1,440,248 | $108,822 | -$652 | -$2,610 | $105,560 | |
| 10 | -$1,595,542 | -$1,483,456 | $112,086 | -$672 | -$2,688 | $108,726 | |
| 11 | -$1,643,408 | -$1,527,959 | $115,449 | -$692 | -$2,768 | $111,988 | |
| 12 | -$1,692,710 | -$1,573,798 | $118,912 | -$713 | -$2,852 | $115,348 | |
| 13 | -$1,743,492 | -$1,621,012 | $122,480 | -$734 | -$2,937 | $118,808 | |
| 14 | -$1,795,797 | -$1,669,643 | $126,154 | -$756 | -$3,025 | $122,372 | |
| 15 | -$1,849,670 | -$1,719,732 | $129,939 | -$779 | -$3,116 | $126,044 | |
| 16 | -$1,905,161 | -$1,771,324 | $133,837 | -$802 | -$3,209 | $129,825 | |
| 17 | -$1,962,315 | -$1,824,463 | $137,852 | -$826 | -$3,306 | $133,720 | |
| 18 | -$2,021,185 | -$1,879,197 | $141,987 | -$851 | -$3,405 | $137,731 | |
| 19 | -$2,081,820 | -$1,935,573 | $146,247 | -$877 | -$3,507 | $141,863 | |
| 20 | -$2,144,275 | -$1,993,641 | $150,634 | -$903 | -$3,612 | $146,119 | |

**Proposed Measure(s) vs Baseline**

| | | |
|---|---|---|
| Simple Payback | 0.3 | years |
| Relative Net Present Value | $969,992 | |
| Internal Rate of Return | 167% | |

# APPENDIX G:
# Contract Task 2.3.1 Low Pressure Drop Guidelines

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# Data Center Best Practices

This is one of several Best Practices Guidelines for data centers. Each paper addresses a different aspect of data center energy use. When designing a new facility these different aspects are typically ranked in terms of potential impact on energy use, and addressed in order. When evaluating an existing facility, the greatest energy saving opportunities may lie anywhere. Both of these issues are not addressed here. This paper deals with the single aspect of low pressure drop air distribution.

# Low Pressure Drop Air Distribution

Most data center cooling systems rely on air movement to remove heat from the IT equipment and transport it out of the data center space. In order to design and operate a data center that uses energy efficiently, it is important to examine the power required to move cooling air. The power draw of the fans that move the air depends largely on the resistance that the air flow encounters, often referred to as "pressure drop". Along with the fan energy benefits, low pressure drop design also results in a quieter system, in many cases alleviating the need to introduce duct silencers into the air system. The elimination of duct silencers also decreases pressure drop in its own right.

## Data Centers vs Office Space

Data center cooling load densities are usually at least ten times as high as those found in offices, and can be up to one hundred times greater. Data center loads tend to be constant year-round, while office space loads cycle with daily and weekly business activity. High cooling loads in general require higher air flows, so efforts to reduce air flow resistance in data centers pay off much more rapidly than they do in office spaces.

Data center cooling systems are almost always designed with some redundant cooling capacity. In cases where a chilled water plant and variable speed fans are used, this redundant capacity can operate to reduce face velocity and energy cost - two air handlers at 50% volume use far less power than single unit at 100% capacity.

## New Construction and Retrofit

This paper is organized to address both new construction and retrofit applications. Low pressure drop is most easily achieved when it is given priority in the design of a new data center facility, but there are typically many opportunities to reduce pressure drop in existing facilities.

## Fan System Efficiency

To facilitate comparisons between data centers of different sizes, we can use the following fan system efficiency metric:

$$\frac{\text{Volumetric Air Delivery Rate (cubic feet per minute)}}{\text{Fan System Power draw (kW)}}$$

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This metric tells us how many cubic feet of air per minute are being delivered for each 1 kW of fan power. It can refer to a specific moment in time, or it can be averaged over a given time interval.

An alternative metric is Watts/cfm, which is essentially the reciprocal of cfm/kW:

$$\text{Watts/cfm} = 1000 / (\text{cfm/kW})$$

This metric tells us how many Watts of fan power are required to deliver each cubic foot per minute of air. We use cfm/kW in the remainder of this paper.

The results of data center benchmarking studies give us the following approximate ranges:

| Fan System Efficiency Ranges (cfm/kW) | Relative Performance |
|---|---|
| Less than 1,200 | Poor |
| 1,200 to 2,000 | Typical |
| Greater than 2,000 | Good |

## How to Measure Fan System Efficiency in an Existing Data Center

To determine fan efficiency in an existing facility, we need to measure the power draw of the fans and the rate of air delivered by the fans. If a Test and Balance (TAB) has been performed in the past and the facility has not changed significantly since then, the TAB report may already include the fan power and air flow information. If new measurements are required and all the fans are constant speed, spot checks of a few units may be sufficient to obtain a reasonably close measurement. A spot check should also be adequate if the air delivery system is variable volume but the load is relatively constant. If the air system is variable volume and the load varies, the best approach is to measure the fan power and air flow over an extended period

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## Efficiency Improvements

The remainder of this paper describes methods for reducing the pressure drop and increasing the efficiency of the air delivery system.

### Step 1: Reduce Air Flow

Before determining how efficiently a given volume of air can be delivered to a data center, it is more productive to ask, "What is the minimum air flow needed to meet the cooling demand?" This is because, in general, the fan power requirement falls more rapidly when air flow is reduced than it does when improving the pressure drop characteristics of the delivery path for the original amount of air.

Minimizing air flow may appear to be a counterintuitive strategy, as we commonly associate higher air flows with increased cooling. Data centers are often constrained by the amount of cooling that the HVAC system can provide, so it is natural to seek more air flow. The key is to pursue *effective* cooling. In an ideal system, the air flow delivered by the cooling system matches the air flow moved by the IT equipment fans, and there is strict separation between supply and return air flows: all the cooling air passes through the IT equipment, with no bypass and no recirculation, before returning to the cooling coil.

Strategies for reducing air flow are addressed in the Best Practices Guideline titled Air Management.

### Step 2: Low Pressure Drop, High Fan Efficiency

Once we have minimized the needed air flow, the efficiency of air delivery is governed by only two things:

- The resistance to flow along the entire air distribution path, typically quantified as inches of water column, also known as inches of water gauge (in. w.g).
- The mechanical efficiency of the fan system (fan motor, fan drive, and the fan itself), typically expressed in percentages (%).

There are many opportunities for increased efficiency in the fan system components, but they are not the main focus of this paper. The rest of this paper deals mostly with methods of reducing resistance to air flow.

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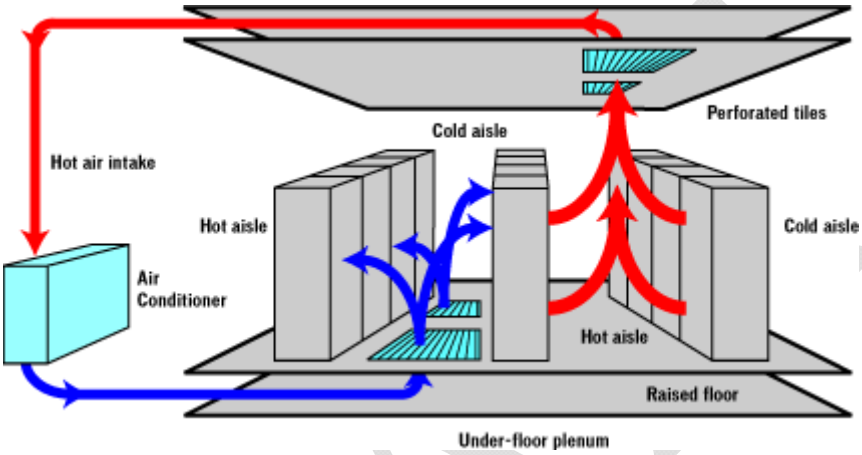
## Air Distribution Path

For organizational purposes, we can break up the air distribution path in to four parts:

A. Air Handlers
B. Plenums, Ducts, and Dampers
C. Air Management Measures
D. IT Equipment




For new designs, attention should be given to reducing the pressure drop of all parts of the system, but especially the air handler, which typically imposes the largest pressure drop in a data center cooling system and is the most difficult to modify after the system is built.

The greatest energy efficiency opportunities in existing facilities can reside in any part of the system: direct measurement of pressure drops in the different parts will reveal the best opportunities.

| | |
|---|---|
| External Static Pressure (ESP) | The resistance to air flow imposed by all portions of the air delivery system that are external to the air handler – plenums, ducts, dampers, air management devices, and the IT equipment itself. |
| Internal Static Pressure (ISP) | The resistance to air flow imposed by all the components inside the air handler. |
| Total Static Pressure (TSP) | = ISP + ESP |

## A. Air Handlers

| *General Type* | *Remarks* |
|---|---|
| Built-up Air Handlers | This typically refers to air handlers that use chilled water (CHW) coils and are designed to fit the space and needs of a particular project. These offer the most design flexibility. |
| Packaged Air Handlers or AC Units | The term "air handler" typically refers to a unit that uses a CHW coil, and "AC" refers to a unit with an on-board direct-expansion (DX) cooling system. These units can be installed inside the building or on the exterior. |
| Computer Room Air Conditioners (CRACs) or Computer Room Air Handlers (CRAHs) | CRACs = DX, CRAHs = CHW. These are designed specifically for data center cooling, and are usually offered with self-contained controls and a humidity control option.<br>CRACs & CRAHs typically have a low internal pressure drop at nominal air flow (1.0 to 1.5 in. w.g.) compared to typical AHUs and AC units at nominal air flow (2.0 to 2.5 in. w.g. is common in units serving office space). |
| In-Row Cooling Units | These are a type of CRAH whose form factor is the same as the IT equipment cabinets. These units are designed to supply cool air only to the nearest IT cabinets, and to immediately retrieve the warm IT exhaust air. This short air circulation loop does not mix with air outside the cabinets. |

"Air handler" is used throughout this paper as a generic term for all the types of units listed in the above table, as the principles governing low air-side pressure drop design apply to all of them.

**When designing a new data center facility, aim for a low air-side pressure drop from the beginning.**

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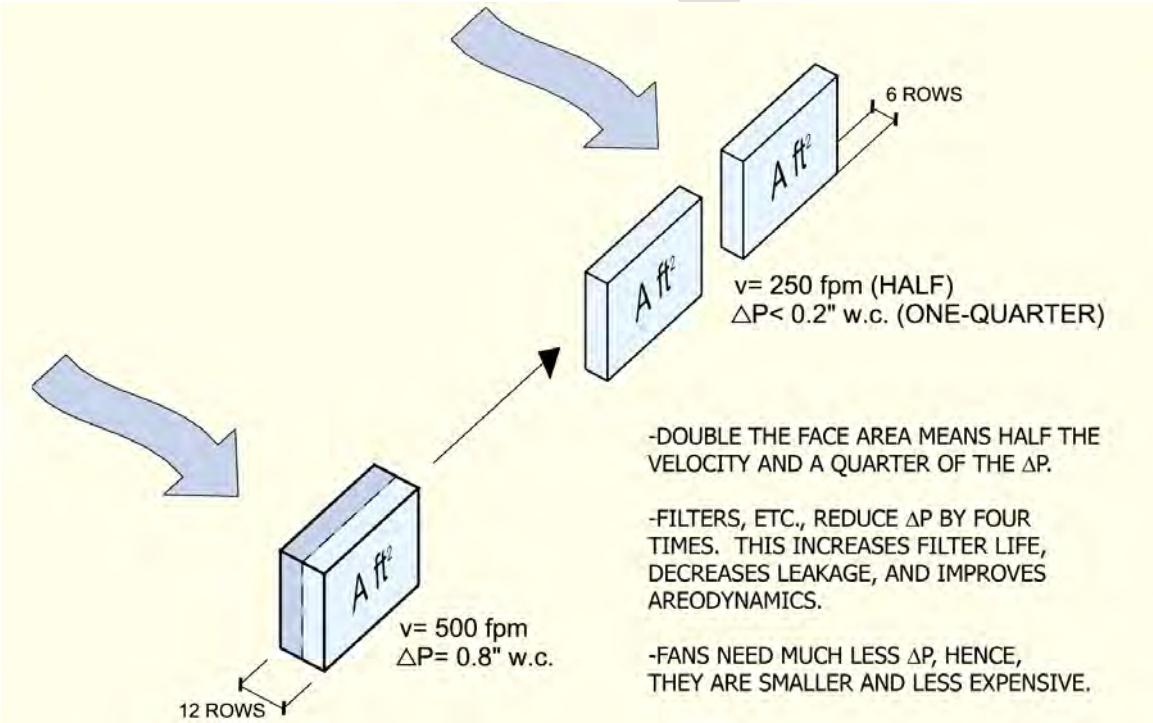
Air Handler Internal Pressure Drop

The internal resistance of an air handler is determined by its cross-sectional area and the resistance of its individual components:

*Face Velocity*

Face velocity is simply the speed of the air moving through the air handler (averaged across the full area, or "face" of the air filters, cooling coil, and other components. The nominal face velocity is the air speed when the fan is running at maximum speed and the air handler is subject to the nominal external static pressure (ESP) specified by the air handler manufacturer. A long-exercised rule of thumb for design in the HVAC industry is to specify a face velocity of 500 feet per minute (fpm), but this is more an absolute maximum velocity set to avoid blowing condensation droplets off the coil into the downstream system. It has been found to typically be a poor economical design point for most 8,760 hour per year operation facilities, such as datacenters.

Reducing face velocity is the most effective way to reduce fan power draw.




**New Construction**

**Specify a low face velocity air handler (350 fpm or less).** The fan power requirement decreases approximately as the square of the velocity decrease, all other factors held equal. For example, a 20% reduction in face velocity will yield about 36% fan energy savings.

The standard arguments against this approach are 1) high first cost, and 2) excessive space requirements.

Cost:

A. The coil has more area but fewer rows, as the load it needs to serve is still the same. The coil cost increase should be minimal.
B. The fan motor size can often be reduced. This means a smaller motor starter or VFD, smaller wires, and smaller circuit capacity. It is critical that the cost benefits of smaller fans on the electrical system be evaluated. In some cases, the generator and/or building transformer sizes can be reduced significantly offsetting the air handler cost. There is often a 'sweet spot,' the face velocity that allows for the next smaller motor size to be used or that permits dropping a circuit breaker and wire size.
C. More filters are required, but they will load up more slowly, as the air volume is still the same. The filter change interval can be increased proportionally.

For these reasons, the cost increase of an "oversized" air handler is often negligible.

Excessive Space Requirements:

A. Modest increases in size give the desired result. Consider an example air handler with an 8' x 8' cross-section at 500 fpm. To achieve 400 fpm, we need only expand to 9' x 9', or 8' x 10'.

***CRACs and CRAHs***

CRAC and CRAH manufacturers typically offer their units in a range of cooling capacities. The size of the cabinet varies with capacity, but usually not as much: a given cabinet size will be used for several different capacities. If possible, select the largest possible cabinet size for the needed capacity.

If the design calls for CHW units with variable-speed fans, another strategy is to oversize the nominal cooling capacity. The fans can run slower to meet the actual cooling load, resulting in lower face velocity.

**Existing Facilities**

It is usually impractical to alter the face velocity of existing, working air handlers. Consider upsizing air handlers when they reach the end of their service life.

*Redundancy*

Almost always, data centers are designed with surplus cooling and air flow capacity for the purpose of redundancy.

If the existing air handlers use chilled water and have variable speed fans (or if a new system is specified as such), operate all the air handlers simultaneously. This will reduce

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face velocity and energy cost. For example, two air handlers at 50% air flow use far less fan power than single unit at 100% flow.

*Air Filters*

**New Construction**

If the supply fan will be equipped with a VFD, low pressure drop filters will allow the fan to deliver a given volume of air with a lower energy requirement. For constant speed fans, lower pressure drop filters will allow a greater volume of air to be delivered with the same fan energy.

Typical air handler designs use 1" thick pleated prefilters and 15" deep bag filters with pressure drops of 0.4 in. w.g. and 0.7 in. w.g. at design flow, respectively. Bag filters are usually rated for 80% of design flow in a VAV system, meaning their actual pressure drop at maximum flow can be 20 - 50% higher than the rated value.

The pressure drop among filters of the same efficiency can vary significantly. Holding the media effectiveness constant, filter pressure drop (proportional to the fan power required to overcome the filter) is reduced as the media area increases.

**Select prefilters and final filters with the lowest available pressure drop at 100% design flow.** Achieving this typically requires the use of 2" - 4" deep pre-filters and 20" deep micropleated final filters. Micropleated filters do not rely on the air flow to support the media as bag filters do - this usually gives them an advantage in variable air flow systems. With micropleats, the filters can safely be selected at 100% design flow and they can be deeper without requiring support loops for the filter pockets and risking pocket-to-pocket contact that can rob bag filters of effective surface area and drive up pressure drop.

**Existing Facilities**

**Switch to lower pressure drop filters.**

Switching filters is simple if lower pressure drop filters are available with the required filtration effectiveness and the same physical dimensions as the existing filters. But lower pressure drop filters are usually deeper and require deeper mounting frames. The practicality and cost effectiveness of retrofitting filter mounting frames must be addressed case by case.

If the air handler fan is equipped with a variable speed drive, reducing the air filter pressure drop will allow a given amount of air to be delivered at a slower fan speed. If the supply fan is constant speed, lower pressure drop air filters will increase the amount of air delivered, with little or no effect on fan power. If there are large number of existing, constant fan speed air handlers, switching to low pressure drop air filters may allow one or more air handlers to be shut off and yet still deliver the original volume of air.

**Change filters regularly.**



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Air filter pressure drop increases as the filter loads up with particles. In a CAV system, progressively less air is delivered for each kW of fan power. In a VAV system, the fan must work harder to deliver a given amount of air. Changing the filters regularly will help ensure long-term air delivery efficiency.

**Change filters more frequently.**
Consider replacing the air filters even more frequently than the filter manufacturer recommends. Weigh the fan energy savings against the expense of filter replacement (including labor) to determine if this is a cost-effective measure.

*Fans*

**New Construction**
**Specify a high efficiency fan.**
High efficiency fans have lower resistance to air flow. "Off-the-shelf" air handlers typically come with a standard fan, but most manufacturers are willing to substitute a different fan upon request. More efficient fans are typically larger in diameter, have a higher quality of manufacture, and cost more. Efficiency improvements on the order of 5% to 10% are usually possible, depending on the standard fan originally specified. The increased first cost is typically repaid many times over the operating lifetime of the air handler. If the fan motor can be downsized in the design, the payback may be immediate.

**Existing Facilities**
Retrofitting a high efficiency fan to an existing air handler is not always practical. High efficiency fans are typically larger in diameter, and therefore will often not fit in the air handler. The ability to retrofit must be examined case-by-case.

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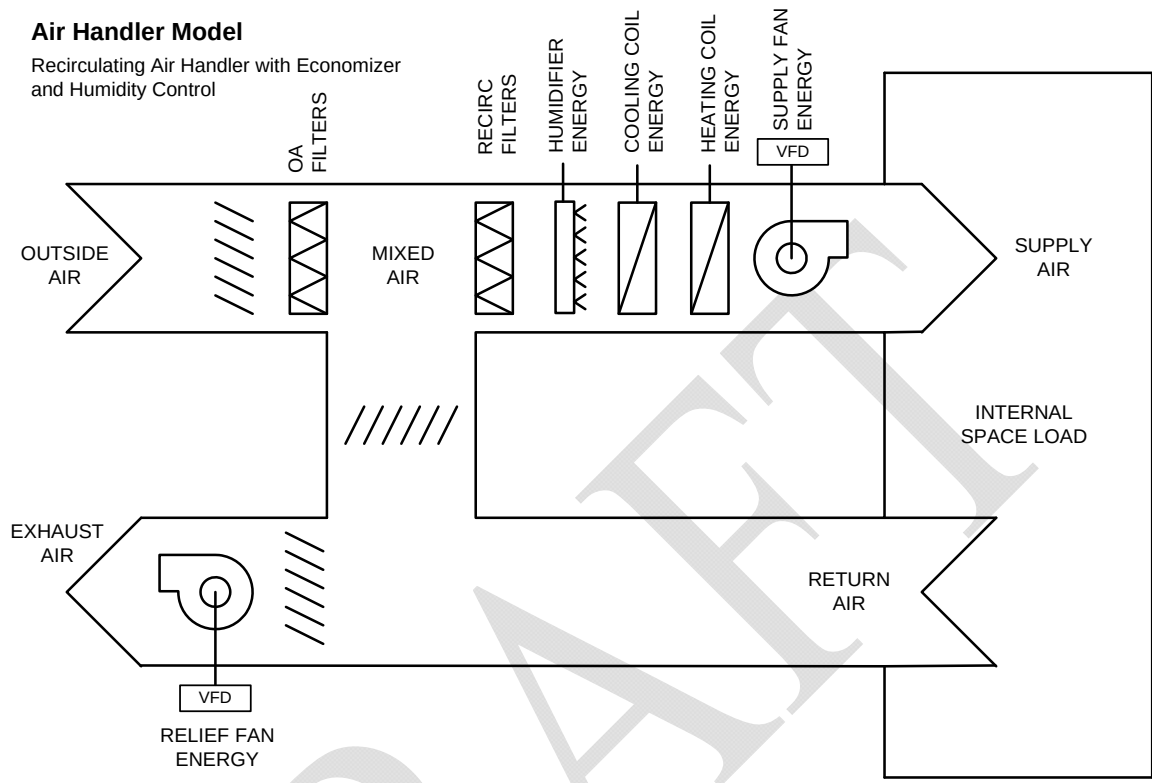


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**<u>New Construction</u>**

**Specify a low pressure drop economizer.**

It is easier to select a low pressure drop economizer in a built-up air handler system, as there is more flexibility in sizing and placement of the economizer dampers. Packaged units with built-in economizers do not have this flexibility, but the designer does have the option of over sizing the air handler at running the fan at lower speed.

**Place Filters Strategically.**

Refer to the diagram above. It shows two sets of filters – one in the recirculation path, and another dedicated to outside air. If the filter banks are set up in this manner it will minimize filter pressure drop. The recirculation set can be relatively light duty, as they only need to deal with particles generated within the data center and the few that manage to get through the outside air filters. The outside air filters can be more robust to deal with outside air conditions. These require more fan energy, but only when the economizer is open.

Retrofit: The difficulty of adding a new filter bank to an existing set-up will vary from one project to the next.

**Existing Facilities**
It is typically not cost effective to replace an existing economizer with a lower pressure drop design.

**Consider a low pressure drop design when the existing unit reaches the end of its service life.**

**Maintain economizer in good working condition.**
Check that the economizer is controlled correctly and that it opens and closes fully.

*Coils, Humidifier*

**New Construction**
**Select CHW coils with a low air-side pressure drop.**
Bear in mind this may have to be traded off against an increased water-side pressure drop and the associated increased CHW pump power requirement, but typically the air side fan energy cost far outweighs the pumping energy cost since water has a far higher heat-carrying capacity.

**Design the data center to not need a humidifier.**
For example, increase the acceptable humidity range and design for a higher supply air temperature. Accomplishing this will remove the air-side pressure drop of the humidifier and is possible in many climates.

**Design air delivery system to not need silencers.**
A low pressure drop design is inherently quieter. Silencers are not always specified as part of a standard data center air delivery system, but making sure they are not included will drop the first cost and the pressure drop.

**Existing Facilities**
**Remove unneeded air handler components.**
In existing air handlers, remove any unused coils. For example, a heating coil should not be needed in an air handler dedicated to data center space.

**Remove the humidifier if it is not needed.**

**Remove any unneeded air silencers.**

## B. Plenums, Ducts, and Dampers

Data centers with low load densities and cooled by CRACs or CRAHs typically have little in the way of ducts or dampers. A supply plenum under a raised floor with perforated floor tiles is common. This is typically a low pressure drop design.

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As load densities increase, more effective cooling of the IT equipment is needed. This is accomplished through air management measures. These measures typically add more pressure drop.

A common first step is to arrange the IT cabinets in alternately-facing rows, forming "hot" and "cold" aisles. The perforated floor tiles are placed only in the cold aisles.

Higher densities call for an overhead return plenum, with openings above the hot aisles and short vertical ducts from the plenum to the CRAC/CRAH return openings.

In the highest density data centers, the aisles are completely enclosed to minimize any potential mixing of supply and return air, creating a true heat exhaust.

Air handlers not located in the data center space itself typically deliver and retrieve air via a duct or plenum system. This system may include manual balancing dampers to ensure that the appropriate amount of air is delivered to each supply point.

VAV boxes may be appropriate when a variation in load is expected, (across the data center floor, over time, or both) such as in a co-location facility, but add significantly to the pressure drop of the system and add an additional point of failure. If VAV operation is required, pressure-dependent boxes (without the integral air flow station) are lower pressure drop, less prone to failure, and appropriate for low pressure drop supply systems; a low pressure drop supply system has relatively low fluctuations in the supply mains pressure and therefore can often eliminate the complexity of pressure independent supply devices.

## Plenums

### *Raised Floor*

**New Construction**

**Specify a tall plenum.**

If implementing a raised floor system, design for a tall, unobstructed under floor space. Obstructions are typically caused by communication and power cables, fire suppression systems, and chilled water pipes. Standards for installation of utilities under the floor should clearly call out maximum allowed blockage to ensure maintenance of even air flow to minimize pressure drop and prevent balancing problems.

Down flow CRACs and CRAHs installed on a low-height raised floor result in a sudden change in air velocity (direction) as the air impacts the slab. This serves no useful purpose yet requires additional fan motor energy. Turning vanes reduce this energy cost, but the velocity of the air under the floor should be minimized to prevent room air being drawn into the under floor plenum near the air handlers due to the venturi effect.

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**Optimize placement of perforated floor tiles.**
A non-zero pressure drop must be maintained in the floor plenum to promote uniform air delivery through the perforated floor tiles. The number of tiles and the size of perforations need to be optimized to deliver the required amount of air in the appropriate places with the lowest practical pressure drop.

**Distribute the CRACs/CRAHs around the space.**
Avoid placing them all on one side of the space.

**Existing Facilities**
It is typically impractical to change the floor height in an existing datacenter, but measures to reduce air flow obstructions are often cost-effective.
**Remove or reduce obstructions to air flow in floor and ceiling plenums.**

**Institute a program to regularly optimize the placement of perforated floor tiles. A rolling survey which verifies every row once a year is appropriate for most facilities with moderate turnover.**

**Eliminate air flow through unintended paths.**
Raised floor systems often have cable cutouts, partial tiles under the IT cabinets, or air gaps around pipe penetrations. Sealing these will reduce the air flow requirement.

*Ceiling Plenum*

The opportunities for reduced pressure drop in a ceiling plenums are much the same as for the raised floor plenum. Increasing the height of a ceiling plenum (i.e., lowering the drop ceiling) is typically more practical than raising the height of a raised floor.

Ducts

**New Construction**
**Minimize the duct system.**
CRAC/CRAH solutions have minimal duct systems (or none at all), but they do not offer the benefit of air-side economizing and typically use relatively small fans and compact configurations that offer lower performance than larger fans and air handlers. (Sometimes a separate, custom economizer can be constructed).

Data centers typically have high cooling loads and require a large amount of air. To minimize the economizer duct system, locate the data center on the top floor or adjacent to an exterior wall, and place the air handlers as close to the data center as possible.

**Optimize the duct system design.**
The duct system should have short, straight runs, large diameter ducts with smooth inner surfaces (avoid flex duct), large-radius bends if bends are needed, and appropriate

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relative branch sizes. If one branch is undersized, the duct supply pressure must be increased and the other branches throttled in order to deliver the required air flow through the undersized branch. This wastes fan energy. The duct system should be designed with the energy cost associated with 8,760 hour annual operation in mind – the operating cost is roughly triple an office space duct of the same air flow and the first cost versus operating cost part of the sizing equation should be evaluated accordingly.

**Existing Facilities**

It is typically impractical to entirely rebuild an existing duct system. If measurements reveal that the existing duct system imposes a high pressure drop, it is possible the source of the air flow resistance is localized and can be resolved by modifying only the offending portion of the duct system.

Dampers

*Balancing Dampers*

The purpose of a balancing damper is to increase the pressure drop, or throttle, one branch of an air distribution system. Minimize the need for this.

**New Construction and Existing Facilities**

During air-side balancing, select a main duct pressure setpoint that results in at least one air path not being throttled at all.

*Variable Air Volume (VAV) Boxes*

VAV boxes allow zone thermostats to automatically regulate the amount of cooling air the zone receives. There are two basic types of VAV box, in terms of air flow regulation: Pressure Dependent (PD), and Pressure Independent (PI).

In a PD box, the damper position is simply a response to the thermostat signal. The amount of air provided by the box is determined by the pressure in the duct serving the box. The damper continues to open until the thermostat is satisfied.

A PI box contains a sensor that measures actual air flow through the box. Thus, even when the duct supply pressure varies the box can deliver a known air volume in response to the thermostat signal. The air flow sensor requires a non-zero pressure drop in order to work properly. If the duct supply pressure is too low or the VAV box is too large, the sensor won't operate reliably.

**New Construction**

**Are VAV boxes really needed?**

If the data center load distribution is expected to be relatively stable across zones in the space and relatively constant over time, a constant air volume system may be more appropriate. Eliminating the VAV boxes will reduce pressure drop, as well as expense

and complexity. A very low pressure drop ducting system, where the pressure at the supply of all the VAV boxes would vary by no more than 10% across the expected operating flow rates, has little need of pressure independent supply devices. If a VAV system is appropriate, optimize the size of the VAV boxes and equip them with sensitive air flow sensors.

**Design for lowest practical main duct pressure setpoint.**
The duct pressure setpoint has to be high enough to allow the VAV boxes to work properly, but setting it higher than this wastes fan energy.

**Existing Facilities**
**Are VAV boxes really needed?**
See this same item under New Construction, above.

**Do the existing VAV boxes support a low pressure drop design?**
Are they appropriately sized? If the existing boxes are PD, will trading them out for PI units allow the supply air pressure to be reduced? If the existing boxes are PI, will trading out their air flow sensors for more sensitive ones allow a reduced supply air pressure?

**Reduce main supply duct pressure setpoint.**
If the existing design will still work reliably with a lower pressure setpoint, reduce it.

## C. Air Management Measures

Air management measures such as those described previously under "Plenums, Ducts and Dampers" allow a reduced air flow to serve a given load, but they also increase the pressure drop for a given air flow. In general, if the percent decrease in air flow is greater than the percent increase in pressure drop, the net energy efficiency gain will be positive.

**New Construction**
**Place IT cabinets in straight, uninterrupted rows.**
Placing IT cabinets in straight rows with no gaps, and blanking panels for unused rack slots, will reduce opportunities for cooling air to bypass the IT equipment and IT exhaust air to recirculate to the IT equipment intakes.

**Implement a Hot Aisle/Cold Aisle arrangement.**
To promote effective cooling, alternate the orientation of every row of IT cabinets to form alternating hot and cold aisles: this will allow a wider differential between supply and return air, which in turn will allow a lower air flow to serve the given load. This translates in to fan energy savings.

**Line up CRACs/CRAHs with IT cabinet rows.**

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Ideally, supply air should be delivered directly to the cold aisles, and return air collected directly from hot aisles. Whether or not the CRACs/CRAHs are ducted, orienting them to minimize air travel distance and changes in direction will help promote low pressure drop.

**Existing Facilities**

It is usually not practical or cost effective to rearrange IT cabinets that are in use, or to rearrange CRACs/CRAHs.

**Maintain unbroken rows of IT cabinets.**

Institute a program of creating and maintaining unbroken rows of cabinets. Fill in gaps with unused cabinets if needed, and seal unused rack slots with blanking panels. Ideally, the only viable air path through the IT cabinets should be through the IT equipment itself.

## D. IT Equipment

Most IT equipment contains one or more internal cooling fans that draw air through the device. To ensure each device receives adequate cooling, remove obstructions to both the intake and exhaust paths.

**New Construction**

**Implement consistent air flow paths.**

Most IT rack equipment is designed to draw cooling air in the front and reject it out the back, but there are exceptions. For example, some cabinet designs draw air in the front and reject it out the top. Select IT equipment to have a uniform, low pressure drop air flow path and to allow complete separation of supply and return air.

**Remove solid IT cabinet doors.**

Many IT cabinets are offered with glass doors, with narrow perforated panels at the sides to admit air. Specify cabinets without doors. If security is an issue, specify fully perforated doors.

**Route IT cables out of air flow path.**

Often there are a large number of communication cables to be attached to IT equipment. Select IT cabinet solutions that offer a way to route the cables in such a way as to interfere as little as possible with air flow.

**Existing Facilities**

**Remove solid IT cabinet doors.**

Remove glass doors from cabinets or replace them with fully perforated doors.

**Cable management.**

Institute a cable management to improve and maintain unobstructed air flow through IT equipment.

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### General Maintenance

**Keep the entire air distribution system clean.**
Dirt and dust that accumulates on surfaces will increase the pressure drop of the distribution system and also degrade the efficiency of the fan.

**Repair air leaks.**
Leaks increase the air flow requirement and therefore the fan power requirement.

## Related Practices

Air Management
Centralized Air Handling
Air-side Economizer
Direct Liquid Cooling of Racks

## Resources

ASHRAE Publications
http://www.ashrae.org/publications/

Critical Facilities Roundtable
http://www.cfroundtable.org/

Green Grid
http://www.thegreengrid.org/home

Lawrence Berkeley Lab: High Performance Buildings for High Tech Industries
http://hightech.lbl.gov/htindex.html

Pacific Gas & Electric: High Technology Facilities
http://www.pge.com/hightech/

Silicon Valley Leadership Group: Data Center Efficiency Project
http://svlg.net/campaigns/datacenter/

US Department of Energy: "Save Energy Now" Program
http://www1.eere.energy.gov/industry/saveenergynow/partnering_data_centers.html

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# APPENDIX H:
# Contract Task 2.3.2 Update Best Practices

By: S. Greenberg

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PG&E Design Guidelines Sourcebook AC-DC Power Distribution for Data Centers Best Practice Guide

## AC-DC Power Distribution

Power distribution efficiency in data centers is an area of significant potential improvement relative to typical practice. There is a huge range of existing and possible efficiencies, but typical existing centers have efficiencies in the 60% range, and efficiencies in the 85% range are possible, resulting in over 25% savings (Ton, 2008).

Efficiency improvements result in obvious operating cost savings due to the direct savings in reduced distribution system losses. There are also first-cost savings, since downstream efficiencies allow the sizing of the upstream equipment to be progressively smaller. And there are first and operating cost savings in the cooling system that can be smaller because there is less heat to remove, since the distribution system losses all end up as heat.

The opportunities for improving power distribution efficiency can be put into three categories: using best available technologies in the traditional alternating current (AC) configuration, using best available technologies in non-traditional AC configurations, and using best available technologies in a direct current (DC) configuration.

### *Principles*

The typical data center does power distribution at two or more voltages of alternating current (AC). Because energy for short-term power backup is often stored in batteries, which are direct current (DC), and because the IT equipment operates on DC power, there are typically additional conversions (AC to DC, DC to AC, and AC to DC again).

**What comprises a typical data center power distribution system?**

- Simply put, the power distribution system in the data center has components that provide the following functions. Distribution in the typical existing data center is then briefly described for each function. Except where noted all of the distribution is done with AC. See Figure 1.
    - Converting the voltage supplied by the utility to a suitable voltage for the IT loads. Typically this is done with medium-voltage to “low voltage” (600V or less, usually 480V in the U.S.) transformers. The

480V is then converted using another stage of step down from 480V to 208/120V; often this conversion is done in a power distribution unit or PDU, which typically also contains some filtering, monitoring, and branch-circuit over-current protection via circuit breakers.

- Providing protection against power quality problems, ranging from spikes, through swells and sags, all the way to complete power failure (blackouts). This function is typically provided by Uninterruptible Power Supplies (UPSs) in conjunction with standby generators. There are a variety of UPS configurations; see “UPS Systems” chapter for more information.
- Converting the power delivered to the rack to DC for use by the IT equipment. Typically this is done in the first stage of the power supplies built into the IT equipment.
- Connecting the components via power cables, sometimes with bus bars as well.
- Overcurrent protection, typically using at least one level of circuit breakers at each voltage level

- Note that the efficiency numbers cited in this guide include the overall efficiency of the distribution system from the 480VAC (or other voltage after conversion from the medium voltage supplied by the utility) up to and including the IT equipment power supply (known as the PSU or power supply unit) and not including the final DC/DC conversion typically from 12VDC to various lower voltages. Even though there may be opportunities in the medium-voltage transformer, and in the final DC/DC stage, they are not quantitatively addressed in this guide.

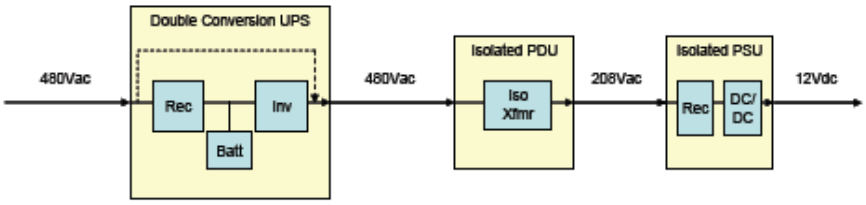


Figure 1. Typical power distribution system. “Rec” is AC/DC rectifier; “Inv” is DC/AC inverter; “Xfrmr” is transformer. Source: Green Grid 2008.

**Efficiencies of typical equipment:**
The configuration, basic efficiency, and loading characteristics of typical data center power distribution results in the following efficiencies (Pratt).

| UPS Efficiency | Transformer Efficiency | Power Supply Efficiency | System Efficiency |
|---|---|---|---|
| 88% | 93% | 79% | 65% |

The **UPS** is typically a double-conversion unit, meaning that all of the power flowing through it is first converted from AC to DC, with the DC bus connected to a set of batteries for back-up power, and then converted from DC back to AC.

This fact, and the typical load at below 40% of rating (necessitated by these constraints: if one UPS fails, a redundant unit can back it up; and with 80% of the full-load rating allowed per the National Electrical Code for continuous operation), often results in real-world efficiencies lower than shown, which is for a single set of power distribution equipment. There is significant variation in these values depending on several variables, but they can be considered representative, especially for comparison with the other schemes discussed in this guide. See the UPS chapter for more information.

The **transformer** efficiency (480VAC to 208/120VAC, often in a PDU) is typical for a unit over a reasonable range of loading. At light loads, the overall losses decrease, but the no-load (constant) losses become a larger and larger fraction of the input, with resulting efficiency penalties. Note that the efficiency of the transformer itself is typically in the 97-99% range, but the losses in the distribution cables are also included in this number.

The **power supply** efficiency is typical of existing IT equipment. It has a stage to convert AC to DC, a filtering/power factor correction stage, and a DC/DC converter stage (typically from the bus voltage of 380VDC to 12VDC for direct use or further regulation all the way down to under 2VDC). A typical number is shown.

The overall **system** efficiency is simply the product of the three.

**Best Practice for a traditional AC distribution system**

Even without changing the basic configuration of the power distribution system, there are significant efficiency opportunities compared to typical practice.

The following efficiencies are representative of a system that uses the same basic components and configuration as the typical data center, but with each part selected for high efficiency (Pratt):

| **UPS Efficiency** | **Transformer Efficiency** | **Power Supply Efficiency** | **System Efficiency** |
|---|---|---|---|
| 98% | 94% | 89% | 82% |

The **UPS** is either a line-interactive or a delta-conversion design. Either of these configurations pass through AC power that is acceptable and only convert DC (typically from batteries) to AC as needed to meet power quality requirements. The AC to DC conversion is typically only to keep the batteries float-charged. See the UPS chapter for more information.

The **transformer** efficiency (480VAC to 208/120VAC, often in a PDU) is selected for higher efficiency, and cable sizing is optimized to reduce losses consistent with minimizing total cost of ownership.

The **power supply** is a high-efficiency unit available in new IT equipment. It is the same basic configuration as the typical supply, but with higher efficiency components and circuit design. It goes beyond the 80Plus specification (see http://www.80plus.org/). See the Power Supply chapter for more information.

The overall **system** efficiency is simply the product of the three.

**Best Practice for a non-traditional AC distribution system**

An alternative to the traditional AC distribution is one in which the second (480V-208/120V) transformer is eliminated, and all IT equipment is served with voltages in the range of 230 to 277 volts, depending on the scheme. There are several possible ways to do this, including (but not limited to) 1. using a double-conversion UPS with an input of 480V and an output of 400/230 volts; 2. a line-interactive UPS operating at 480/277 volts, and 3. using a 400/230-volt transformer at the building entrance in lieu of 480/277. See Figure 2. In much of the world, 400V 3-phase power (with 230V phase-to-neutral; sometimes cited at the slightly higher 415/240) is the norm; the 230 volts can be used directly by the same IT equipment that uses the US-standard 208V. If the 277-volt scheme is used, servers would need to be refitted with suitable power supplies, since the standard units are rated to directly use voltages only up to 250V. (Green Grid 2007)

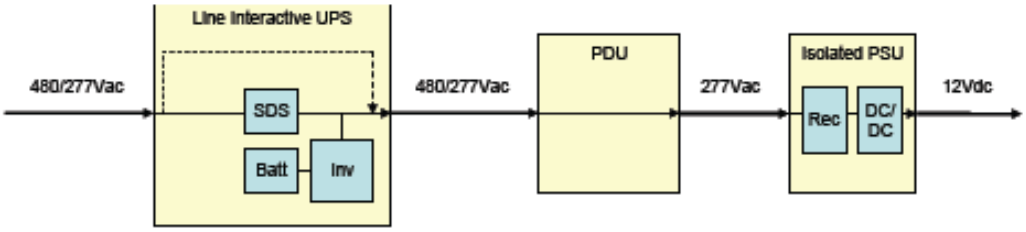


Figure 2. Non-traditional AC power distribution system. “Rec” is AC/DC rectifier; “Inv” is DC/AC inverter; “SDS” is static disconnect switch. Source: Green Grid 2008.

The following efficiencies are representative of a system that uses either scheme 2 or 3 above, avoiding the double-conversion UPS. (Pratt):

| UPS Efficiency | Transformer Efficiency | Power Supply Efficiency | System Efficiency |
|---|---|---|---|
| 98% | 97% | 89% | 85% |

The **UPS** is either a line-interactive or a delta-conversion design. Either of these configurations passes through AC power that is acceptable and only converts DC (typically from batteries) as needed to meet power quality requirements. The AC

to DC conversion is typically only to keep the batteries float-charged. See the UPS chapter for more information.

The **transformer** efficiency here is just the cabling losses, since there is no transformer.

The **power supply** is a high-efficiency unit available in new IT equipment. It is the same basic configuration as the typical supply, but with higher efficiency components and circuit design. It goes beyond the 80Plus specification (see http://www.80plus.org/). See the Power Supply chapter for more information.

The overall **system** efficiency is simply the product of the three.

**Best Practice for a DC distribution system**

Another alternative to the traditional AC distribution is one in which all IT equipment is served with DC voltage. There are several possible ways to do this, with the two most-common schemes of 1. 48VDC to the IT equipment, with AC-DC conversion done at the rack level, and 2. 380VDC to the IT equipment, with AC-DC conversion done centrally and 380VDC distribution from the central AC-DC converters and UPS equipment to the racks. Note that there are various alternative schemes to these, including central 48VDC and rack-level 380VDC, but the two noted seem to be the most promising. Scheme 1 is already available, since most IT equipment manufacturers make equipment for the telecommunications industry, where 48VDC has been the standard for decades. Scheme 2, which takes advantage of the 380VDC bus in standard IT equipment power supplies, promises to have the highest overall efficiency and the fewest number of components, with likely first cost, operating cost, and reliability advantages. However, not all of the parts required (in particular, plugs, and receptacles, including for cords and power strips, plus server power supplies) have standard, commonly available configurations. See Figure 3.

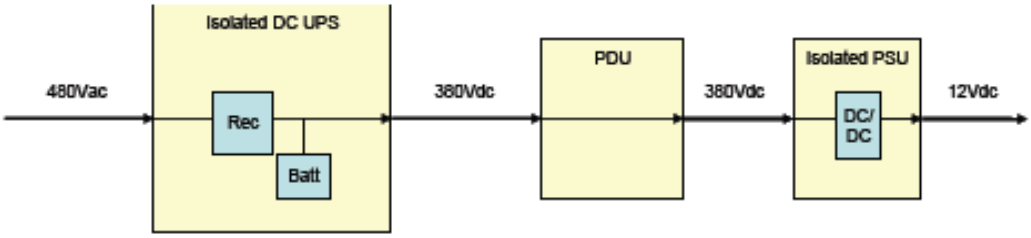


Figure 3: DC distribution schematic, with central DC power conversion and 380VDC to racks. Source: Green Grid 2008.

The following efficiencies are representative of a system that uses 380VDC centrally produced and distributed to the racks (Pratt):

| UPS Efficiency | Transformer Efficiency | Power Supply Efficiency | System Efficiency |
|---|---|---|---|

| | | | |
|---|---|---|---|
| 97% | 97% | 93% | 88% |

The **UPS** is simply an AC-DC converter and battery set. Note that with this simple configuration, the voltage will fluctuate from a value at the float charge level of the batteries (somewhat higher than 380V) to significantly lower than 380V in the event of a power failure and depleted batteries. This range should not adversely affect the IT equipment, since the IT power supplies regulate these input voltages typically to 12VDC and below.

The **transformer** efficiency here is just the cabling losses, since there is no transformer.

The **power supply** is a high-efficiency unit available in new IT equipment. The AC-DC conversion stage is eliminated, since the 380-volt DC is used directly by the DC-DC converter. This supply can be made available from several manufacturers (Ton, 2008).

The overall **system** efficiency is simply the product of the three.

## *Approach*

**Consider the level of redundancy required.** Remember that distribution losses can increase dramatically at high (e.g. 2N) levels of redundancy, and first costs rise as well. Consider that in many cases the entire data center is backed up by another center, and use that overall redundancy to reduce the redundancy level required in each center.

**Scrutinize rated versus real power usage.** Use the numbers from the ASHRAE thermal report (rather than the nameplate power) and establish diversity factors to allow more right-sized distribution equipment to be used. Also beware of cascading safety factors that tend to result in grossly oversized equipment.

**Specify and demand high-efficiency components.** As noted above, there are high-efficiency versions of all of the basic components of the distribution system. Often the added cost is small, and in any case the selection of higher efficiency equipment tends to be very cost-effective when the total cost of ownership is considered. Many manufacturers can easily supply higher efficiency, but won't bother unless there is a clear demand.

**Push internal and external organizations to use the highest possible efficiency scheme.** A high-efficiency conventional distribution system can save significant power, energy, and money. However, unconventional schemes (AC and ultimately DC) can save progressively more. With willingness and commitment within the data center builder-owner-operator community, remaining

hurdles with codes, standards, and IT equipment can be overcome to achieve the higher levels of efficiency, economy, and reliability.

**Remember the "law of large numbers".** Simply put, the law of large numbers is the fact that a small fraction of a large number is still a large number. So, when comparing distribution options, remember that even a small increase in efficiency yields large savings in operating cost, because data center energy use is so large.

## Major Points

- Each approach has advantages and disadvantages. The easiest to implement, using conventional components and configurations, yields the lowest efficiencies of the different best-practice schemes. The higher-efficiency schemes involve non-standard designs, equipment, and components, requiring more design effort, and in some cases, efforts to update codes and standards.
- Existing data center power distribution systems have large opportunities for improvement. Typical existing system efficiencies are in the low- to mid-60% range, with best in class systems achieving efficiencies in the low to high 80% range, with resulting savings typically over 20%.
- The best efficiencies are achieved by reducing the number of conversions, which require non-typical configurations. This is true for the non-conventional AC, and even more so for the DC schemes.
- Some configurations require non-standard components, which are unlikely to be widely available until there is demonstrated demand—a bit of a "chicken and egg" problem. These include connectors for the DC schemes and IT equipment with suitable power supplies for the 277-volt AC and 380-volt DC schemes.
- The level of redundancy required can have a significant impact on loading and thus efficiency.
- Since the efficiency of each component in the system varies with load, and the shapes of these curves vary with different manufacturers and configurations, it is important to get and use the specific curves for the equipment under consideration, and analyze the system as it will be loaded, in order to make valid comparisons for a specific application.
- While the direct energy and dollar savings are only in the power delivery chain to the IT equipment, the % savings can approximately be applied to the entire data center, since the cooling system will be proportionately unloaded by the more-efficient power distribution.
- Compounded first-cost savings can be realized by taking advantage of increased downstream efficiency to down-size the upstream components, as well as the cooling system.

## *Case studies*

In 2006, the Lawrence Berkeley National Laboratory coordinated a study funded by the California Energy Commission to evaluate the potential for DC power distribution in a data center (Ton, 2008). The study was hosted at Sun Microsystems in Newark, California and used side-by-side comparison of IT equipment powered by conventional AC and by 380-volt DC. This study demonstrated that "DC delivery systems are viable, can be 20% or more efficient than current AC delivery systems, be more reliable, and potentially cost less in the long run". The savings ranged from about 5% to about 28%, with the lower numbers representing the difference between "best in class" AC and the demonstration DC configuration, and the higher numbers the difference between "typical" AC and the demonstration DC configuration.

## *Related Chapters*

UPS Systems
Power Supply Efficiency
Self-Generation

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Green Grid. " Qualititative Analysis of Power Distribution Configurations for Data Centers." White Paper #4, Rev 2007-0, December 2007. http://www.thegreengrid.org/gg_content/TGG_Qualitative_Analysis.pdf

Pratt, A., P. Kumar, K. Bross, and "Powering Compute Platforms in High Efficiency Data Centers." Presentation by Intel, no date.

## *Resources*

*IEEE Standard 1100-2005 – Recommended Practice for Powering and Grounding Electronic Equipment*. Commonly known as the IEEE Emerald Book.

ASHRAE *Best Practices for Datacom Facility Energy Efficiciency*, 2008

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## Data Center Best Practices

This is one of several Best Practices Guidelines for data centers. Each paper addresses a different aspect of data center energy use. When designing a new facility, the design team typically investigates different potential energy-saving measures and ranks them in terms of potential impact and cost effectiveness. When evaluating an existing facility, the greatest energy saving opportunities may lie anywhere. These issues (identifying and ranking all potential energy-saving measures) are not addressed here. This paper deals with the narrower topic of efficient, variable-speed chilled water pumping.

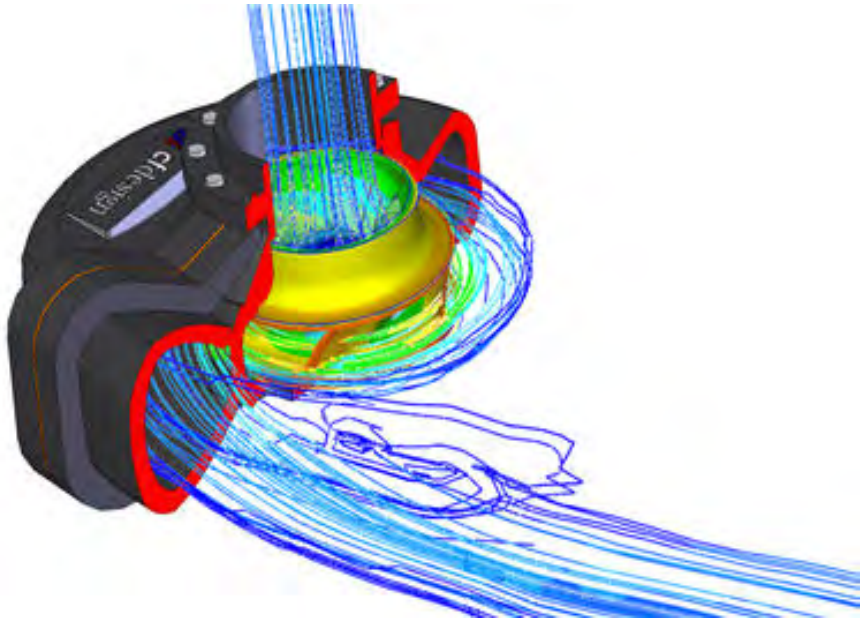


Figure 1: Graphic representation of centrifugal pump dynamics.

## Variable Speed Pumping

While variable speed pumping configurations can be applied to several different hydronic systems, including chilled water, condenser water, hot water, and process fluids, this paper concentrates only on variable flow pumping for chilled water systems. Heating water and process fluid pumping are not common in data center facilities, and variable flow condenser water strategies are beyond the scope of this paper.

### *Data Centers vs Office Space*

Data Centers are often located in facilities that also include offices or other types of commercial space. While the data center represents a relatively high, continuous, internally-generated cooling load, commercial space cooling requirements vary according to occupancy schedules, outside weather conditions, and, to a lesser extent, internal loading caused by office equipment, lighting, and other power draws.

In facilities where a central chilled water plant is shared by both the intermittent commercial cooling load and the continuous data center cooling load, the overall load on the chilled water plant can vary widely. These facilities are particularly well-suited for the load-matching capabilities of variable speed chilled water pumping.

## *Basic Pumping Configurations*

### Primary-Secondary Chilled Water Pumping

In a primary-secondary pumping system, primary loops maintain flow through the chillers, while a second ("secondary") loop conveys water from the primary loop to the cooling load (chilled water coils), and then dumps the warmed water back into the primary loop, for heat rejection at the chiller condenser.

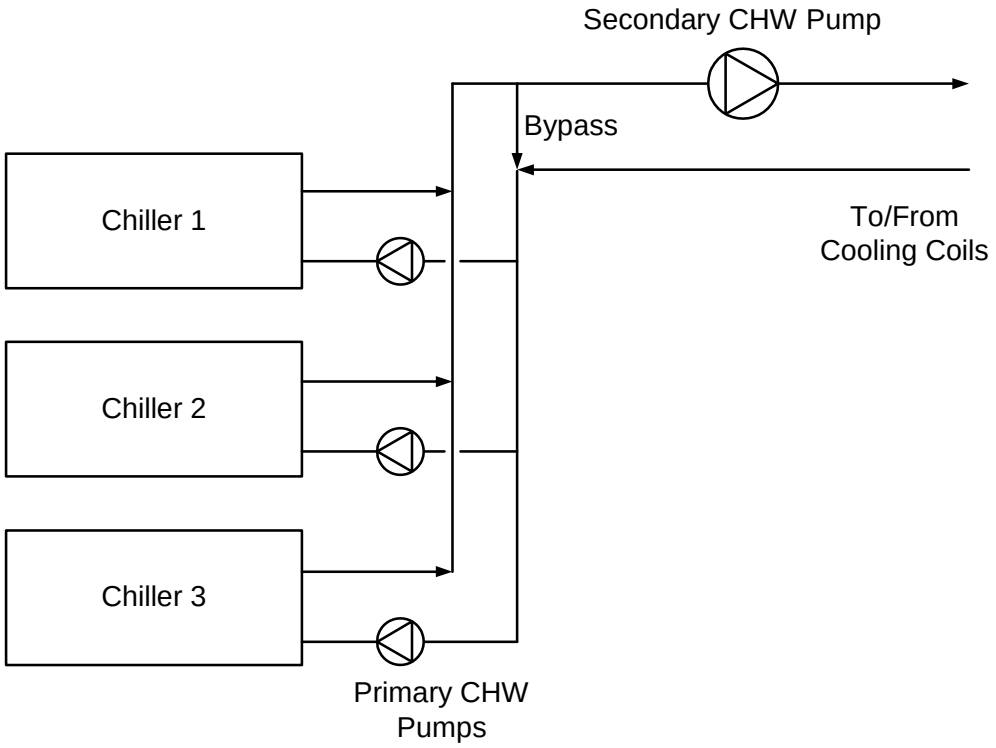



Fig. 2: Primary-Secondary Chilled Water Pumping

Third (tertiary), fourth (quaternary), and even more loops are possible on large, highly distributed systems. This paper addresses only primary/secondary systems.

#### Primary Loops

The primary loops ensure a constant, peak-load-equivalent flow rate through the evaporator barrel of each operating chiller. The primary pumps are typically constant speed, and staged with their respective chiller. When the secondary loop is flowing at the same rate as the primary loop(s), the flow in the bypass is zero.

The secondary loop can be constant flow or variable flow. If it is variable flow, and flowing at less than the rate of the primary loop(s), the bypass leg allows the unused primary flow to return directly to the chiller(s).

If not guarded against, it may be possible to have larger flow in the secondary loop than the total primary flow. This allows chilled water returning from the load to enter the chilled water supply stream without passing through the chillers. This degrades the cooling capacity of the system and should be avoided.

## Constant Flow Secondary Loop

A constant-flow secondary loop can serve a constant load or a variable load.

### Constant Load

A constant flow secondary loop may be appropriate if the chiller plant is expected to serve a constant load for the majority of its operating lifetime. This is a rare circumstance.

### Variable Load

Chilled water systems are typically designed to accommodate a variable cooling load. If the secondary loop is designed as constant flow, load variation is addressed with 3-way valves at the cooling coils. A 3-way valve is able to bypass chilled water flow not needed for cooling, which still allows for a constant volume of water to flow through the valve even though only a portion of it actually reaches the chilled water coil to do active cooling. As the cooling demand at a coil decreases, more water bypasses the coil.

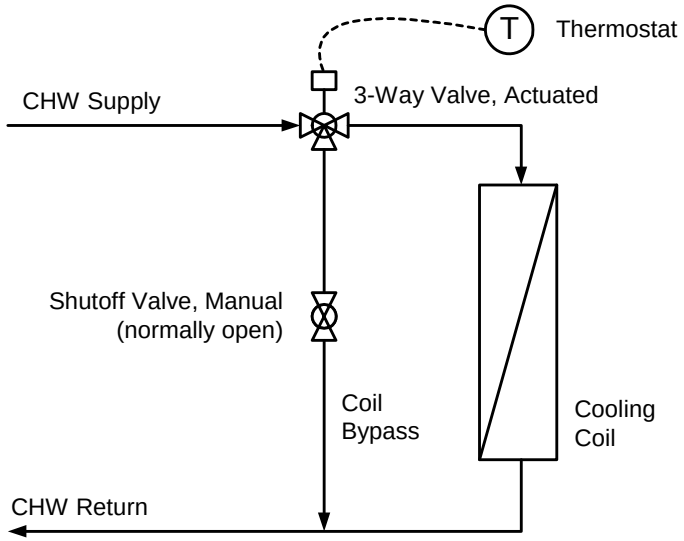


Fig. 3: Cooling Coil with 3-Way Valve and Bypass

This type of design wastes pump energy, as it moves the same amount of water through the system regardless of cooling demand.

## Variable Flow Secondary Loop

In a variable flow secondary loop, the chilled water flow varies in response to the cooling load. The cooling coils are equipped with 2-way valves. As the cooling demand at a coil decreases, the valve closes and increases the resistance to flow. There is no bypass around the coil.

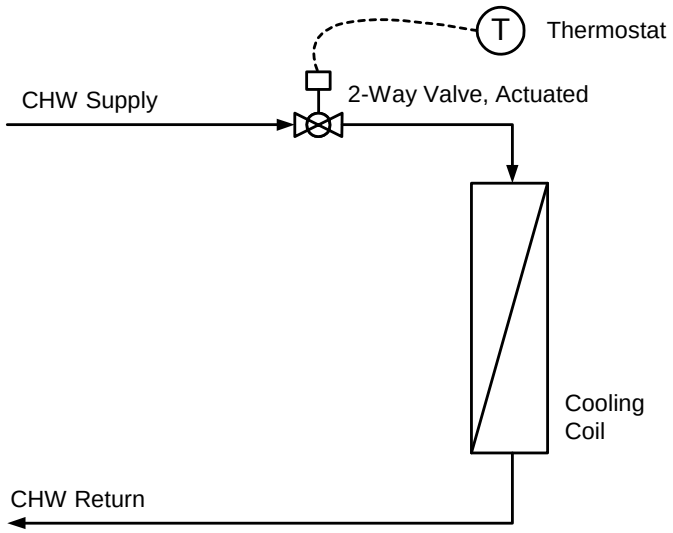



Fig. 4: Cooling Coil with 2-Way Valve

There are two basic ways to control the flow:

**"Ride the Pump Curve"**
This solution simply allows the pressure to rise in the chilled water pipes as the coil valves close. The pump motor, even though it continues to operate at constant speed, typically draws less power as the pressure rises and the flow decreases. There are two drawbacks to this:

- The pump motor power demand is still greater when "riding the curve" than it would be for a variable-speed pump control scheme.
- The further away the pump operates from its nominal pressure/flow condition, the less efficient the pump is.

**Variable Frequency Drive**
A variable frequency drive (VFD) placed on the pump motor can be configured to maintain a constant pressure at a selected point in the chilled water distribution system, by varying the speed of the pump when coil valve positions change. This control scheme reduces the required pumping power and also retains pumping efficiency across a wide range of speeds.

Placing the pressure sensor at the most "hydraulically remote" coil in the chilled water system allows the pumps to deliver just enough pressure to satisfy the entire system without over-pumping. The most hydraulically remote coil is the one that receives the lowest pressure. This is usually, but not always, the coil that is the greatest distance from the pump.

A VFD allows for oversizing of the pumps for future capacity without an efficiency penalty.

## Primary-Only Chilled Water Pumping

A primary-only pumping system consists of only one "loop," i.e. the water flows through the chiller, out to the load, through the chilled water coils, and back to the chiller.

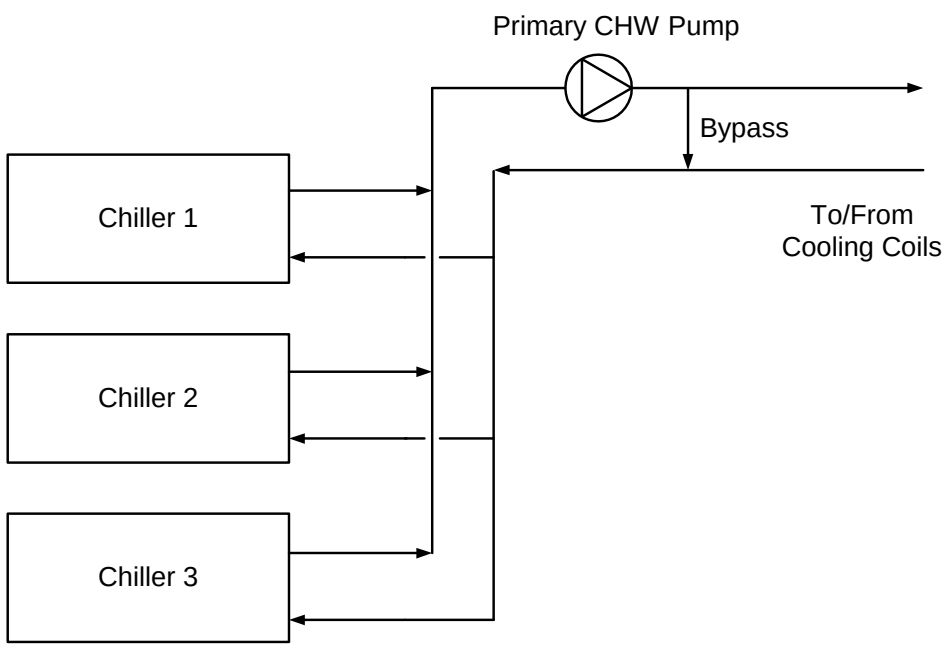



Fig. 5: Primary-Only Chilled Water Pumping

### Advantages

A primary-only system offers several advantages over the primary-secondary configuration:

- More efficient chiller operation. With variable chilled water flow through the chiller evaporator, the chiller can operate at its design chilled water temperature difference ("delta-T") even during part-load conditions. Traditional chiller design maintains a constant flow through the evaporator, which inevitably results in the delta-T (the difference between the warm water entering the chiller versus the chilled water leaving the chiller) being directly proportional to the load. A 50% load will result in a delta-T that is 50% of the design value. This type of operation results in an unnecessary pump power requirement and often leads to inefficient chiller staging control, with an additional chiller (and condenser water pumps and towers) being staged on before the operating units are fully loaded.
- There are fewer pumps, therefore fewer potential points of failure and increased reliability.
- Fewer pumps results in lower first cost.
- The controls for a primary-only system are simpler, although, just as in a primary-secondary system, staging must be done properly.

The (PG&E? LBNL?) Best Practice Guideline "Cooling Plant Optimization" has further information on this subject.

A primary-only loop design can be constant flow or variable flow.

## Constant Flow Primary-Only Loop

A primary-only loop can serve a constant load or a variable load.

### Constant Load

A constant flow primary-only loop may be appropriate if the chiller plant is expected to serve a constant load for the majority of its operating lifetime. This is a rare circumstance.

### Variable Load

Chilled water systems are typically designed to accommodate a variable cooling load. If the primary loop is designed as constant flow, load variation is addressed with 3-way valves at the cooling coils. A 3-way valve is able to bypass chilled water flow not needed for cooling, which still allows for a constant volume of water to flow through the valve even though only a portion of it actually reaches the chilled water coil to do active cooling. As the cooling demand at a coil decreases, more water bypasses the coil.

This type of design wastes pump energy, as it moves the same amount of water through the system regardless of cooling demand.

### Variable Flow Primary-Only Loop

In a variable flow primary-only loop, the chilled water flow varies in response to the cooling load. The cooling coils are equipped with 2-way valves. As the cooling demand at a coil decreases, the valve closes and increases the resistance to flow.

There are two basic ways to control the flow to the cooling coils. These are described under "Variable Flow Secondary Loop" in the preceding section.

However, whatever the flow demand is at the cooling coils, the chiller evaporator barrels must be served with a certain minimum continuous flow of chilled water. This is provided by means of the bypass indicated in Fig. 5.

The bypass is a critical component, so redundancy is appropriate. A balance valve in the bypass may also be appropriate to ensure it can never pass more than the design bypass flow.

A main objective of the primary-only pumping configuration is to minimize pump power. Therefore, evaluating potential chiller selections for their minimum chilled water flow capability is appropriate.

Even with limited chilled water turndown capability at the chiller, the primary-only configuration saves energy by reducing the typical operating pressure drop. Sending water through the bypass is lower pressure drop than pushing it through the entire facility loop and bypassing it at the coil. A primary-only loop also has a lower first cost and fewer points of potential failure than a primary-secondary system.

A stable, reliable flow meter is important for bypass control. Full-bore magnetic is the best technology for this critical application. A less expensive and less accurate alternative is to use the chilled water pressure drop across the chiller evaporator barrel to control the bypass to maintain minimum flow. Many chillers come equipped with a chilled water pressure sensor across the evaporator for use as an internal low-flow alarm point, so this signal may be already available to the control system.

## *New Construction and Retrofit*

For new construction, a primary-only chilled water loop can be easily designed for the plant. It is also generally not difficult to retrofit an existing, primary/secondary plant. See "Convert Primary/Secondary Chilled Water Pumping System to Primary-Only" under Efficiency Improvements, below.

## *Pumping System Efficiency*

To allow comparisons between data centers of different sizes, we can use the following pump system efficiency metric:

$$\frac{\text{Volumetric Water Delivery Rate (gallons per minute)}}{\text{Pump System Power draw (kW)}}$$

This metric tells us how many gallons of water per minute (gpm) are delivered for each 1 kW of pump power. An alternative metric is Watts/gpm, which is essentially the reciprocal of gpm/kW (with a conversion from kW to W):

$$\text{Watts/gpm} = 1000 / (\text{gpm/kW})$$

This metric tells us how many Watts of pump power are required to deliver each gallon per minute of water.

The metric gpm/kW is used in the remainder of this paper.

Pumping efficiency can vary widely depending on the configuration of the system. For example, if the chilled water plant is dedicated to the data center (a concentrated load) and located nearby, we expect the pumping efficiency to be relatively high. If the plant serves several uses (a distributed and diffuse load) and is located at some distance from the loads, we expect the efficiency to be lower.

## *How to Measure Pump System Efficiency in An Existing Data Center*

To determine a pump system's efficiency, we need to measure two things:

- The power draw of the pump motor(s).
- The total flow through the pump(s).

### Pump Power Draw

This is best done with a meter that measures true kW. An amp meter does not reveal the motor's power factor, which is often less than 1.0.

### Flow Rate

If a flow meter that sees the desired flow is already installed in the system and its reading is trustworthy, use the data.

If the control system does not provide the needed reading, there are two basic ways to measure the flow.

1. Determine the pump speed, impeller diameter, and measure the pressure drop across the pump. The flow rate can then be read from the pump manufacturer's speed/impeller diameter/pressure/flow diagram (the "pump curve"). If the pump is constant speed and the loop it serves is constant flow, a single measurement should suffice. If the flow rate and/or the pump speed varies, looking up a series of flow rates can become laborious.

2. Use a non-invasive, clamp-on flowmeter. This type of meter typically uses ultrasound to determine the flow rate in the pipe. Once this meter is set up, it will provide a continuous readout of the flow rate.

Coincident power and flow measurements can then be used to determine the gpm/kW.

## *Efficiency Improvements*

The remainder of this paper describes methods for implementing variable flow chilled water pumping and increasing the efficiency of the chilled water distribution system.

## Reduce the Average Rate of Chilled Water Flow to the Load

Regardless of whether the distribution system that serves chilled water to the load is constant flow or variable flow, reducing the average flow rate reduces the required pumping power. For a distribution system of fixed geometry (valve openings not changing), the power required by a pump is proportional to approximately the cube of the flow rate through the pump. For example, if the flow is reduced by 20%, the power is reduced by approximately (1.00 - 0.20)^3, or 50%.
However, the chilled water loop is only one of a series of linked loops in the total cooling system. For a given cooling load, reducing the chilled water flow rate will increase the difference between the supply and return chilled water temperatures (the chilled water "delta-T"). This in turn has implications for the power requirement of the air distribution system and the chillers. The chilled water pump power savings must be balanced against the potential resultant power increases in these other components.

**New Construction**

Minimize the design chilled water flow rate to the load, but not at the expense of increased air flow through the cooling coils. Transporting heat by water is typically much more efficient than transporting heat by air due to the much greater heat capacity of water, so reductions in air flow are typically more cost-effective than reductions in chilled water flow.

Reducing the chilled water flow rate requires a higher chilled water delta-T to handle a given load. To avoid a negative impact on fan energy, design for a relatively high supply air temperature, and an even higher return air temperature.

**Existing Facilities**

To a large degree, the air and water temperature setpoints selected during the design of a cooling system dictate most of the other parameters: the air and water flow rates, the size of the cooling coils, the chiller specifications, and more. Data center cooling systems are almost always designed with excess capacity in order to provide redundancy and accommodate future growth, so there is usually some flexibility in the choice of setpoints in an existing system.

Whether or not turning down the chilled water flow rate in an existing system leads to net energy savings for the whole system must be examined case by case.

## Design for Efficient Variable Chilled Water Flow

Once the chilled water flow rate is optimized, the efficiency of delivering that flow rate is governed mainly by three things:

- The configuration of the chilled water distribution system (number of loops, number of pumps, constant speed vs. variable speed pumps)
- The pressure drop of the chilled water distribution system (how resistant is the system to the given flow?)
- The efficiency of the pump system (VFDs, motors, and pumps)

Variable chilled water flow systems are standard modern design practice. To maximize variable flow chilled water pumping efficiency, adopt the following design elements:

### Primary-Only Chilled Water Loop

See “Implement Primary-Only Variable Flow Chilled Water Pumping”, below.

### True Variable Speed Pumping

Avoid designs that control flow rate simply by modulating the valves at the cooling coils and allowing the pump to “ride its curve”.

It is also important to differentiate between a multi-speed motor, and a single-speed motor fitted with a variable frequency drive (VFD), also known as a variable speed drive (VSD). Multi-speed (most often two-speed) motors are inherently inefficient and are not recommended for use in variable flow pumping applications. VFDs enable a motor to modulate smoothly from full speed to virtually zero.

Fig. 6: Variable Frequency Drives (VFDs) and Electric Motors.

### Low Pressure Drop

See the “Low Pressure Drop” section, below.

### High Efficiency Pump System

See the “Pump System Efficiency” section, below.

## Convert Existing System from Constant Flow to Variable Flow

Unless the chilled water distribution system is optimized for a completely constant cooling load, converting from constant flow to variable flow will result in pump energy savings whenever the load is less than the peak design load (all other factors held equal).

If the cooling coils in an existing primary/secondary system are equipped with shut-off valves in the coil bypass as shown in Fig. 3, converting to a variable flow system is relatively simple:

1. Equip the secondary pump(s) with a VFD.
2. Install a chilled water differential pressure sensor across the most hydraulically remote cooling coil, connect the pressure signal to the VFD, and select an initial pressure differential setpoint to be maintained via the pump speed.
3. Close all the shutoff valves in the cooling coil bypass legs.
4. Test and balance the system.

If there are no shutoff valves in the coil bypass legs then the bypasses will have to be disabled by other means, but otherwise the procedure is the same.

## Implement Primary-Only Variable Flow Chilled Water Pumping

In recent years, chiller designs have evolved to be more tolerant of variable chilled water flow through the evaporator. As a result, primary-only variable flow chilled water

pumping has become more common. This arrangement eliminates the secondary chilled water pumps and typically results in energy savings. Chillers still have minimum allowable evaporator chilled water flow rates, so the control system must monitor and ensure these rates.

For chiller flow measurement, a full-bore magnetic flowmeter (Danfoss Magflo or similar) is recommended. This type of meter has a relatively high first cost, but it adds no pressure drop and it is accurate and stable. For a lower cost flow measurement method, the pressure drop across each chiller evaporator barrel can be calibrated to flow and successfully used as a fixed-orifice flow meter.

The additional cost of this measure is in the VFDs, sensors and controls. Cost savings are realized by the elimination of the per-chiller CHW pumps (called primary CHW pumps in the primary/secondary CHW pumping scheme).

Energy savings from this measure arise in two ways:

1. If the chilled water flow through the chiller can be reduced as the cooling load decreases, less pump power is required to move chilled water through the chiller evaporator. This difference is most pronounced in a single-chiller system. It becomes less noticeable as the number of chillers increases, as the number of operating chillers can be more closely matched to the load.
2. Variable chilled water flow through the chiller evaporator allows the chiller to maintain an optimum chilled water delta-T across the evaporator, which in turn yields more efficient chiller operation for the given load.

## Convert Primary/Secondary Chilled Water Pumping System to Primary-Only

Converting an existing primary/secondary system to primary-only is not difficult. It offers the advantage of fewer potential failure points, but whether measure this saves energy or not depends on several factors:

- The variability of load. If the load is constant and the operating chillers are at a high load factor, the chilled water flow rate distribution and delta-T across the evaporators in the existing primary/secondary system and the proposed primary-only system will be similar, with similar energy requirements. If the load varies significantly, the primary-only system can be expected to save energy.
- How tolerant are the existing chillers of a turndown of chilled water through the evaporators? If they are not tolerant, the energy savings will be minimal.

## Low Pressure Drop

Minimizing the resistance to flow imposed by the chilled water distribution system translates directly to a reduced pumping energy requirement.

**New Construction**

**Design a Low Pressure Drop Chilled Water Distribution System**
Select a chiller with a low chilled water pressure drop through the evaporator. Specify large diameter pipes, straight runs, large radius bends, wyes instead of tees, and properly sized valves.

**Specify Suction Diffusers Only Where Needed**
Suction diffusers on pump inlets serve to straighten out the water flow before it enters the pump. While this helps avoid the drop in pump efficiency that accompanies turbulent inlet flow, it comes at the cost of increased pressure drop. A more efficient arrangement is to lay out the piping, wherever possible, to provide a straight section of pipe at the pump inlet that is at least ten pipe diameters in length. This is normally sufficient to straighten out the flow and can often be worked into the design with no pressure drop penalty.

**Eliminate Triple Duty Throttling Valves from the Design**
Triple duty valves (TDVs) are typically located near pumps, and provide shutoff, throttling, and check (one-way flow) functions in a single unit. Two pressure ports are provided, one on either end of the valve, to determine the flow rate that results from different throttling positions. Using the pressure drop across the valve to determine flow rate does not work properly unless a significant pressure drop is developed -- but this is precisely what we wish to avoid if we want to minimize pumping energy. Balancing the flow of the system near the pump is not a good choice in terms of energy use. For example, a Bell & Gossett model 3DS-10S triple duty valve that is 80% open at design flow adds about 5.5 feet w.g. of pressure drop. Assuming $0.10/kWh, the pressure drop due to the triple duty valve would account for roughly $2,000 to $3,000 in annual pumping electrical costs (continuous duty). Even at 100% open it generates a constant parasitic pressure drop of over 4 ft. w.g.

TDVs use a very high pressure drop globe valve to allow for throttling of the pump to prevent overpumping. While throttling does reduce pump energy use slightly, it is significantly more efficient to eliminate the throttling valve's pressure drop entirely:

a) Balance the system flow at the far end of the distribution system; and,
b) Either have the pump impeller trimmed to match the load when balancing is performed; or,
c) Equip the pump motor with a VFD and control flow by varying the pump speed (VFDs are often a small premium over a standard motor starter and offer greater flexibility). Throttling valves are redundant on speed controlled (VFD) pumps.

Do not use any globe or other high pressure drop type of valve for pump throttling. Use a low pressure drop check valve and a butterfly valve for shutoff and isolation purposes. To match the pump flow to design, have the actual loop pressure drop at design flow measured during balance. The pump impeller should be trimmed to match the actual loop pressure drop at design flow, plus a small safety factor to account for future fouling.

**Eliminate Flow Control Valves and Circuit Setters from the Design**
Flow control valves and circuit setters serve the same purpose -- they limit flow by imposing a restriction. The pump has to work against this restriction.

These valves traditionally serve two purposes: They limit the maximum flow through a component and they provide a flow measurement point. This functionality is typically not necessary in a water distribution system that uses DDC (Direct Digital Control), even in multiple-building critical facilities. Unless the component is undersized or assigned an unobtainable setpoint, the control valve will automatically throttle it as necessary. Modern DDC control valves sized properly for the system can provide both control and this automatic balance function. To allow for future spot fixes, the addition of one more pressure port can provide the ability to spot balance components using the shutoff valves for balance where required. To determine flow, pressure taps can be installed on either side of the 2-way control valve. Then the flow can be determined by reading the pressure across these taps and then consulting the CV table supplied by the valve manufacturer. A less reliable method of determining the design flow point that requires only the two pressure ports typically installed is to compare the pressure drop across the component to the manufacturer's design pressure drop submittal data. The appropriate CHW pressure setpoint to provide the minimum needed flow to all coils at design conditions is also determined during balancing. Once this value is known the pump impeller can be trimmed as required, or the pump speed can be set by VFD.

**Design an Efficient Pipe Layout for Pumps**
It is not uncommon to see a lot of right angles in piping as it approaches and leaves a pump. In some cases this is unavoidable due to space restrictions. When the designer has flexibility, the pressure drop of the piping can be greatly reduced by a thoughtful layout. This provides built-in, permanent pump energy savings. Long-radius elbows should be used wherever possible to keep the pressure drop low.

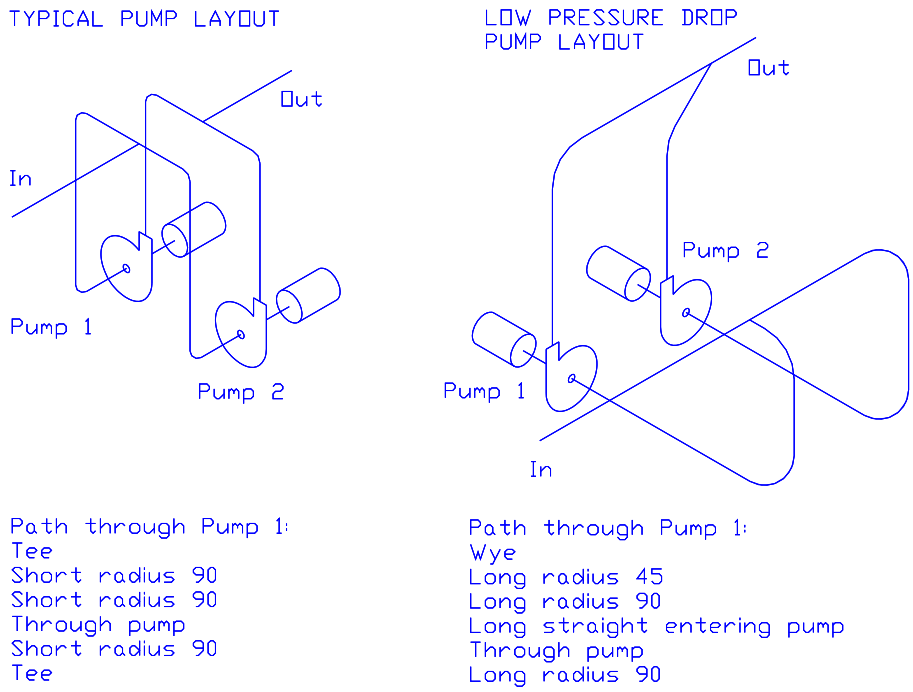



Fig 7: Low Pressure Drop Pump Layout

**Select a Low Chilled Water Supply Pressure Setpoint**

This measure applies equally to constant flow or variable flow systems. During the test and balance phase of construction, make sure that the chilled water pumping pressure setpoint is not set any higher than is needed to ensure adequate flow through all of the cooling coils at the peak design load.

**Specify a Chilled Water Pumping Delta-P Setpoint Reset Control Sequence**

Standard control system design calls for the chilled water pump serving the chilled water distribution system to maintain a constant pressure at a given location (usually at the most remote cooling coil), regardless of the current cooling load. The pressure setpoint is set to a value that ensures adequate flow through all the coils under the highest possible load condition. Under lower load conditions the coils require lower flow rates and the pressure needed to supply the flow is also much lower. With constant pressure control, the CHW control valves at the coils are required to throttle closed to prevent overflowing the coil at low loads. When all the coil control valves are operating at a partially closed throttling position, it is because the chilled water pump is supplying more pressure than is necessary. Rather than maintaining a constant pressure across the chilled water loop, the pressure setpoint can be lowered during periods of low load. The usual method is to continuously poll the control valves on the loop for their position. The highest valve position is then used as an input to a control loop that resets the chilled water loop pressure setpoint down until the maximum valve position equals 85% - 90% open. This control approach continuously optimizes the setpoint to reduce energy usage and, in some

extreme cases, even noise by reducing the throttling required during low load periods. The chilled water pump pressure setpoint is essentially self-balancing and continuously optimized to the system's operating conditions. This measure assumes a variable pumping chilled water system is already implemented, either a variable flow primary-only system or a more typical primary-secondary system with variable secondary loop. The controls cost is sensitive to whether the controls contractor has implemented this type of system before, ie whether or not they already have a "canned" routine available for the control.

## Existing Facilities

### Reduce the Pressure Drop of the Chilled Water Distribution System

It is typically not practical to replace an entire chilled water distribution system. However, it is often the case that the high pressure drop of an existing system is due to a small number of localized problems, such as sharp bends, short sections of small diameter pipe, undersized valves, and so forth. It may be possible to rectify these problems in a cost effective manner.

### Remove Suction Diffusers

Any pump served by a straight inlet pipe that is at least 10 pipe diameters in length is unlikely to need a suction diffuser. Removing the diffuser will reduce pressure drop.

### Remove Triple Duty Throttling Valves

Any situation requiring such severe pump throttling that a high pressure drop globe-type valve (as used in a triple duty valve) is required (i.e., control is being compromised due to valves being overpressurized to the point of chatter), indicates significant pump oversizing. This justifies actually correcting the pump size, i.e., trimming the impeller or even changing the pump out entirely for one sized to fit the actual system.

### Remove Flow Control Valves and Circuit Setters

Refer to "Eliminate Flow Control Valves and Circuit Setters from the Design" in the previous section.

### Reduce the Chilled Water Supply Pressure Setpoint

This measure applies equally to constant flow or variable flow systems. The chilled water supply pressure setpoint may currently be set higher than necessary. This can occur for several reasons -- improper initial balancing; overestimation of peak load; load growth projections were too aggressive; changes were made to the distribution system but it wasn't rebalanced; etc.

A pressure setpoint that is higher than necessary can cause the chilled water pump motor to draw more power than is necessary. Optimizing the setpoint for current conditions can save energy, particularly in systems where the CHW pump is continuously active.

### Add a Chilled Water Pumping Delta-P Setpoint Reset Control Sequence

If there is a significant variability in the load, this control sequence will likely save pumping energy. Refer to "Specify a Chilled Water Pumping Delta-P Setpoint Reset Control Sequence" in the previous section for implementation suggestions.

**Trim Pump Impeller and Open Triple Duty Valve**
Water flow is typically balanced by imposing a flow restriction via a balancing valve (one of three functions of a triple-duty valve). Fully opening the balancing valve and trimming the pump impeller to provide the desired flow will save energy.

An alternative to trimming the impeller is to add a VFD to the pump motor. If constant flow is required, the pump speed can be manually adjusted through the VFD to achieve the desired flow.

**Remove Strainers after Commissioning**
Chilled water pump strainers are appropriate during the commissioning phase of a new system, to trap any large objects accidentally left in the chilled water loop and prevent damage to the pumps. After commissioning, the strainers may be removed to reduce pressure drop. The chilled water loop is a closed system, so new objects are not likely to be introduced unless or until the system is physically altered. There is a small risk that the failure of a valve or other component will introduce fragments to the flow, but the likelihood of this should be weighed against the ongoing cost of the pump energy required to overcome the pressure drop of the strainers.

## Pump System Efficiency

**New Construction**

**Install High Efficiency Pumps**
A thorough search of available pumps for a particular application usually reveals a wide range of efficiencies. It is critical that minimum pump efficiency – the efficiency of the pump itself, not just the motor – be explicitly stated on the mechanical equipment schedule to ensure that it is noted as a requirement for any substitution requests. Spending the time to do the research and then selecting the most efficient pump is usually a cost-effective activity.

**Install Premium Efficiency Pump Motors**
More efficient motors translate directly to energy savings.

**Specify an Untrimmed Impeller, Use a VFD to Limit Pump Speed, Match the Pump Motor Size to the Design Flow Rate**
An alternative to baseline practice is to retain the full impeller size and use a VFD to limit the maximum pump speed to the value that provides the design flow. Note that while the impeller is untrimmed, the pump must still be selected to operate at its peak efficiency point at turndown. This is done by scaling the design conditions up to the untrimmed impeller point using the Pump Power Law (the same method pump manufactures use to translate a single efficiency curve test for a pump at 1800 rpm to

1180 rpm, for example). Most pumps are already available in differing motor speeds, and comparisons of curves for a single pump at 1800 rpm and 1180 rpm will quickly show that lower speeds do not adversely impact efficiency. This selection approach ensures that there are no losses due to operating at points other than the nominal operating point and will yield the highest possible efficiency. Losses in the VFD are minimal compared to the efficiency improvement that can be realized in the pump as long as the VFD and motor are sized to the operating power (not the full speed operating power requirement). The pump motor is selected to provide the necessary power to produce the design flow.

This approach does have reliability implications that should be considered, and may be deemed appropriate only for pump systems with N+1 redundancy. In particular, note that the pump motor VFD can no longer be put on bypass, or the motor will overheat and trip off. Modern VFD's are robust and reliable, so the lack of bypass capability is becoming less of a concern. Cost concerns must be evaluated on a job by job basis, but frequently a quality VFD is only marginally more costly than a good quality motor starter. Significant flexibility is gained from having additional pump capacity available with a simple motor and drive replacement (or by turning up the speed, even into the service factor in a temporary, emergency situation).

**Existing Facilities**

Evaluate the same measures as for New Construction. In addition:

**Optimize the Number of Pumps Running in a Bank of Variable-Speed Pumps**

Some installations have a bank of variable-speed pumps plumbed in parallel, where it is often the case that more than one pump is active at a time.

Given the interaction of the pump flow vs pressure characteristics, the pump efficiency curve, and the pump operating speed, it is not always obvious what number of operating pumps minimizes the energy use of the pump bank as a whole.

This is best investigated by simply commanding all the pumps on, recording the total pump motor kW, and then taking successive pumps off line and recording the new total kW each time. If the flow demand varies significantly over time, each test should be run for an appropriate amount of time. Note that a check valve on each pump is necessary to prevent backflow through non-operating pumps in the array.

## Related Practices

### Cooling Plant Optimization

## Resources

ASHRAE Publications
http://www.ashrae.org/publications/

Critical Facilities Roundtable
http://www.cfroundtable.org/

Green Grid
http://www.thegreengrid.org/home

Lawrence Berkeley Lab: High Performance Buildings for High Tech Industries
http://hightech.lbl.gov/htindex.html

Pacific Gas & Electric: High Technology Facilities
http://www.pge.com/hightech/

Silicon Valley Leadership Group: Data Center Efficiency Project
http://svlg.net/campaigns/datacenter/

US Department of Energy: "Save Energy Now" Program
http://www1.eere.energy.gov/industry/saveenergynow/partnering_data_centers.html

# Evaporative Cooling

Evaporative cooling is an alternative to conventional compressor-type cooling systems. Evaporative cooling systems have been used to condition facilities since before refrigerated cooling was invented. In general, there are two types of evaporative cooling techniques: indirect and direct. The indirect approach removes sensible energy, only, from the air stream with an exchanger that has the air stream flow on one side of a coil or a plate and water inside the tubes or on the other side of the plate. The direct approach removes energy from the air stream adiabatically (using the heat of vaporization of water) by adding moisture to the air stream. These approaches can be combined with an outside air economizer to provide cooling and humidification that displaces energy from a conventional compressor-type HVAC system in a data center.

## *Principles*

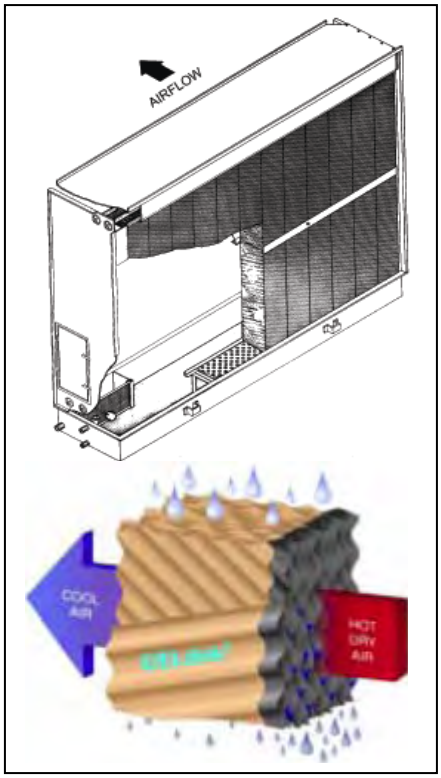
### Why use evaporative cooling?

- Using evaporative cooling should not be based solely on the ability to **replace** mechanical cooling but should be considered as an opportunity to **displace** refrigerated (so-called mechanical) cooling or humidification energy. Evaporative cooling is also referred to as adiabatic cooling or wet-bulb economizer cooling.

### Types of evaporative cooling:

- **Direct:** A direct evaporative cooler is comprised of a recirculated water source that is evaporated by the supply air stream consequently absorbing heat from the supply air (heat of vaporization), thus cooling the air stream. Usually, the recirculated water is passed over an extended surface, or media that is located in the supply air stream to a space requiring temperature and humidity conditioning. Alternately, water can be sprayed in the supply air stream by using high pressure air, or pumping pressure, to atomize a non-recirculated water source. Direct evaporative cooling can be justified on the basis of enhancing outside-air economizer operation, eliminating the need for a humidification system, reducing humidification energy used in conjunction with heat recovery, and controlling the temperature of a space independent of controlling its humidity. Direct evaporative cooling for both make-

**Figure 1**

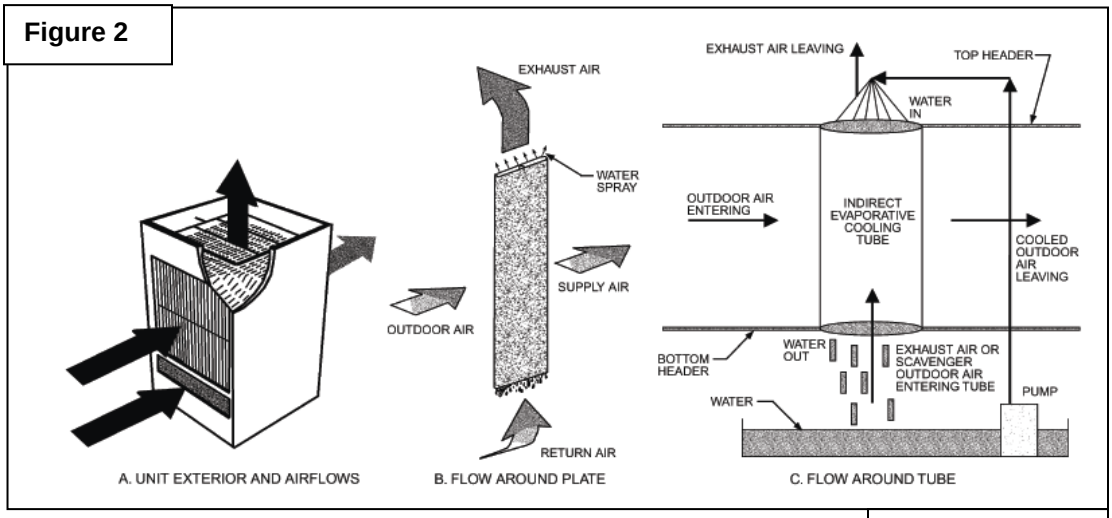



*Courtesy: ASHRAE & UC Davis WCEC*

Knebel, 1997] [Brown, 1990; Brown, 1993] [Mills, et al]

- **Indirect:** An air-side indirect evaporative cooler is usually comprised of a standard finned-tube heat exchanger connected with piping to a cooling tower via a plate-and-frame heat exchanger for heat rejection. Water cooled in the tower is circulated through the exchanger with water on the "other side" of the exchanger being circulated to an air-side coil in the air handling unit (AHU) to cool the supply air stream. Accordingly, mechanical cooling is displaced by indirect atmospheric thermodynamic exchange. Indirect evaporative cooling is applicable in a data center because there is a large process equipment-cooling load and the HVAC system operates on a continuous basis. Indirect evaporative cooling will only be effective where the difference between outdoor dry-bulb and wet-bulb remains high (13°F (7.2°C) or more) for the majority of the cooling hours. The concept is usually not applicable when the difference between dry-bulb and wet-bulb is small (12°F (6.7°C) or less) for the majority of the cooling hours. See Figure 2. (Brown (1990) & 1992 [Brown, 1993].).

**Figure 2**



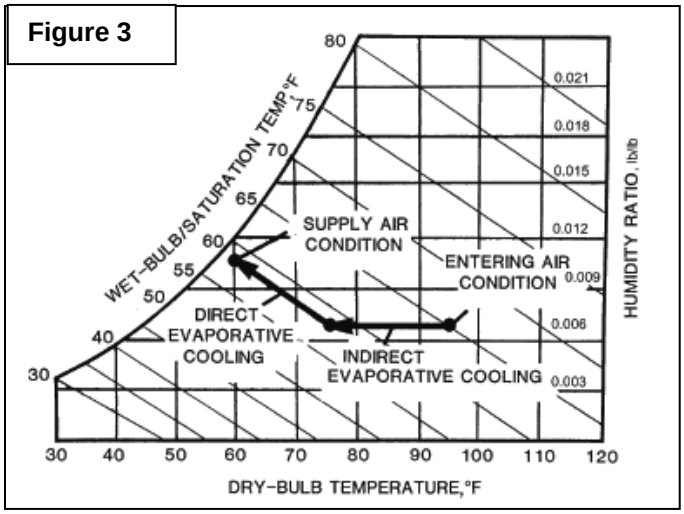

*Courtesy: ASHRAE*

In a water-side indirect evaporative cooling system, the heat rejection scheme is identical to the air-side indirect evaporative cooler. However, heat is removed from a chilled water loop rather than from the supply air stream with an integrated plate-and-frame heat exchanger. Consequently, refrigerated cooling is displaced in the returning cooling water loop from central AHUs or computer room air handling units (CRAHs). According to Tschudi, 2006, "Water-side economizers utilizing evaporative cooling (usually provided by cooling towers) can be used to indirectly produce

chilled water to cool a data center when outdoor conditions are mild or at night. This 'free cooling' is best suited to climates with wet-bulb temperatures lower than 55°F (12.8 °C) for 3,000 or more hours a year. Free cooling can improve the efficiency of a chilled-water plant by lowering chilled-water approach temperature (i.e., pre-cooling chilled water before it enters a chiller) or eliminate the need for compressor cooling, depending on the outdoor conditions and overall system design. With free cooling, chilled-water-plant consumption can be reduced by up to 75 percent, with related improvements in reliability and maintenance through reductions in chiller operation."

- **Two-stage:** Typically, a two-stage evaporative cooling system combines a direct evaporative cooler downstream of an indirect evaporative cooler. The two coolers can be combined in a myriad of arrangements to increase energy efficiency. The greater the range of allowable humidity in the data center, the greater the energy savings. As an energy-reduction example using a more conventional chiller system, this approach can consume as little as two-thirds of the energy necessary to provide a range of 40 to 45 percent R.H. See Figure 3. [Brown, 1992; Brown, 1993; Brown, 1990]

**Figure 3**




*Courtesy: ASHRAE*

**Hitting the target:**
At minimum, each data center conditioning system design needs to have accommodated the following three aspects to "bracket the target":

1. **Server supply (inlet) air temperature:** Use ASHRAE's guidelines for cold-aisle supply air temperature from the *Thermal Guidelines for Data Processing Equipment* to gain more current information to help you "hit the target." Using outdated temperature and humidity guidelines will waste energy and, perhaps more importantly, oversize the environmental conditioning system for the data center, increasing first costs and provide an inefficient system. Similarly, overly "tight" temperature and humidity requirements will result in unnecessary energy expenditures. See Figure 4

2. **Supply air cooling:** Following the most current ASHRAE guidelines, an outside air economizer can be used when outside supply air is < 80.6°F (27°C) DB. When outside air supply is > 80.6°F (27°C) DB, some form of

cooling will be required to meet ASHRAE recommendations (See Figure 5). The following should be considered:

- Achieving recommended ASHRAE range **with** humidity control: Use direct evaporative cooling when outside supply air is > 80.6°F (27°C) DB but < 59°F (15°C) WB. Use indirect evaporative cooling when outside supply air is > 59°F (15°C) WB but < 59°F (15°C) DP. Use refrigerated cooling when outside supply air is > 59°F (15°C) DP. Use direct evaporative cooling when outside supply air is <41.9°F (5.5°C) DP to add moisture (note that some reheating may be required; use data center return air for reheat).
- Achieving recommended ASHRAE range **without** humidity control: Use direct evaporative cooling when outside supply air is > 80.6°F (27°C) DB but < 80.6°F (27°C) WB. Use refrigerated cooling when outside supply air is > 80.6°F (27°C) WB.

**Figure 4**

Recommended conditions at the inlet to IT equipment: recently revised by ASHRAE

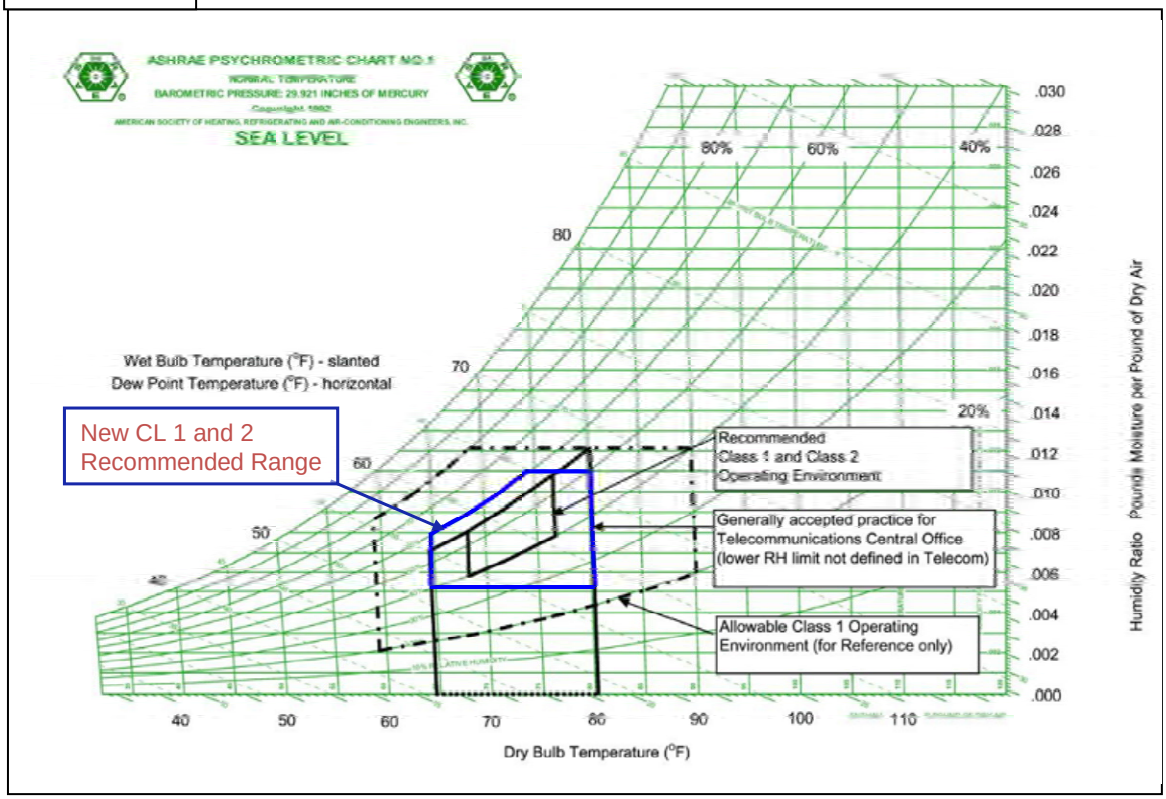
| | 2004 Version | 2008 Version |
|---|---|---|
| Low End Temperature | 20°C (68 °F) | 18°C (64.4 °F) |
| High End Temperature | 25°C (77 °F) | 27°C (80.6 °F) |
| Low End Moisture | 40% Relative Humidity | 5.5°C Dew Point (41.9 °F) |
| High End Moisture | 55% Relative Humidity | 60% Relative Humidity & 15°C Dew Point (59 °F Dew Point) |

*Courtesy: ASHRAE*

3. **Facility and server operational limitations:** Realistically, data center facility HVAC systems will not provide sufficiently precise supply air temperature control to always meet, but never exceed, the upper limit current ASHRAE guidelines. Therefore, a margin of safety is suggested that revises the target supply air temperature to 77°F ( 25°C) DB, instead of 80.6°F (27°C) DB, noted above. In addition, depending on the server's design/manufacturer, an internal cooling fan(s) will switch on when the supply air inlet temperature exceeds a pre-determined limit, usually 77°F (25°C) DB. This operational mode is less efficient than providing supply air cool enough to negate internal fan operation and should be avoided.

Therefore, this pre-determined limit must be determined and not exceeded by the data center's supply (inlet) air temperature.

**Figure 5**




**Humidity control may be unnecessary:**

- According to Greenberg, "Data center design often introduces potential inefficiencies when it comes to humidity. Tight humidity control is a carryover from old mainframe and tape storage eras and generally can be relaxed or eliminated for many locations. Data centers attempting tight humidity control were found to be simultaneously humidifying and dehumidifying in many of the benchmarking case studies. This can take the form of either: inadvertent dehumidification at cooling coils that run below the dew point of the air, requiring re-humidification to maintain desired humidity levels; or some computer-room air-handling or air-conditioning units (independently controlled) intentionally operating in dehumidification mode while others humidify."
- Intel has recently performed tests with elevated inlet temperatures and no humidity control to data centers operated in New Mexico. To perform the test, Intel created two data centers, a "control center" with warehouse-grade direct expansion air conditioning equipment, and the "test center" with air economizers. They were housed in a trailer in a temperate desert (steppe) climate that ranged from 64F to 92F DB with generally low relative humidity and ran between October 2007 and August 2008. Accordingly, "…there was no attempt to control humidity and there was

minimal filtering of incoming air. The inside temperature was below 90 degrees 91 percent of the time,…" and "…they saw no consistent increase in server failure rates as a result of the greater variation in temperature and humidity."

## *Approach*

**Review recommendations and resolve supply air conditions:** Compare ASHRAE and server manufacturer's recommendations.

**Evaluate climate:** Evaporative cooling works in almost every climate during some part of a day or a season. However, high relative humidity or high wet bulb temperatures may limit operation. Determine number of days anticipated evaporative cooling system can be used in your climate zone using psychometric chart for your altitude and weather data, usually typical meteorological year (TMY) for your climate zone.

**Right-size evaporative cooling system:** Evaluate the "Cooling Capture Efficiency" of the cooling system. This efficiency compares the delivered cooling, $Q_{del}$, to the theoretical maximum cooling, $Q_{max}$. $Q_{del}$ is calculated by multiplying the mass-flow of the air being cooled by the change in temperature (or enthalpy). $Q_{max}$ is calculated by multiplying the mass of the water being evaporated (usually expressed in gallons) by its heat of vaporization.

Include variable speed drives (VSDs) on supply, return and exhaust fans to perform efficiently at part-load operation; to accommodate filter loading, and to maintain data center room pressure control.

**Review control sequences and devices:** Consider control system flexibility and integration with any existing energy monitoring and control system (EMCS). Ascertain control device durability and repeatability. Note that the majority of available humidity sensors are noted for their inaccuracy and "drifting" over time.

**Determine maintenance support:** Does your facility have the staff and expertise to maintain an evaporative cooling system? Consider a service contract; out-sourcing maintenance may be necessary.

**Calculate value of displaced refrigeration cooling:** In simple-payback calculation to justify use on economics, include maintenance costs for each system being compared.

**Prepare for commissioning and hand-off:** Ensure your facilities staff is prepared to maintain the evaporative cooling system. Support the facilities hand-off by providing training. When appropriate, let a service contractor maintain the evaporative cooling system. Maintenance can be an easy issue when a cooling tower is already being maintained at your site; the issues are nearly identical.

## Major Points

**Installing either a custom-designed, built-up air handling unit (AHU) or pre-packaged AHU:**

Each approach has advantages and disadvantages. With a built-up AHU, the features and capacity can be customized for your data center. Design fees will be incurred and the AHU will likely cost more per delivered unit of airflow. Pre-packaged AHUs are available with many features and will shorten design time. However, not every built-up AHU is created equally, so performance guarantees should be specified and startup commissioning should be included with the purchase.

**Water treatment:**

- Review water treatment methods to limit production and to remove total dissolved solids (TDS). Particulate removal from the direct evaporative cooler sump can be achieved with bleed-off or flushing. Measuring total dissolved solids remotely can ensure your system will be well maintained, especially when connected to the EMCS.
- Chemical treatment regimes require continuous care and interface; a service contract may provide an economical approach. Treatment is required to: limit scale; control pH; hold dissolved solids in suspension; inhibit algae, slime, and bacterial growth. Note that, when used in supply air streams, some biocides may harm evaporative media and have offensive or harmful off-gassing; use only approved biocides for this application. There has been reported success for treating water in cooling towers by using pulse-power technology; this technology should be reviewed for your situation.
- Note that all of these issues are routinely handled in maintaining a chiller's cooling tower, which may already be used at your facility. If so, it is a simple matter to extend care of the evaporative cooling system and its sump to the existing maintenance method.

**AHU design features:**

The following is a brief list of some particular design features that the system designer should consider carefully:

- **Wetted media:** The evaporative cooling media required to adiabatically evaporate water needs to be both efficient and durable. Improved designs and materials are available that resist scaling and deterioration. Expect efficiencies of 90 percent evaporation with 12 inch-deep media at 400 FPM face velocity and a 0.14 inch WG pressure drop.
- **Fan and Coil placement:**
  There is some continuing unresolved discussion regarding cooling coil placement in the air stream. Consider the following two approaches:

  1) Brown (1993) points out that placement of the fan upstream from the cooling coil and evaporative cooler has two energy advantages. In cooling

mode, fan heat enhances operation of the cooling coil, and, in heating mode, the same fan heat is used to provide humidification energy and to displace preheat energy input. In addition compared to the approach noted by Scofield below, to first sensibly cool the supply air, before using the evaporative cooler, allows cooling "dry" supply air more precisely to a set-point temperature. Then, adding moisture as a second step reduces refrigerated cooling energy necessary to remove moisture. (See discussion noted below.)

2) Conversely according to Scofield, placing the refrigeration coil last in the direction of airflow provides three benefits:

- Cold condensate from the coil drains into the DEC sump reducing makeup water requirements and recovering some of the latent cooling effect.
- Leaving air off the coil is effectively saturated so that room DP temperature (absolute humidity) is the same as the DB temperature.
- In arid climates where ambient conditions are often below the room DP, refrigeration requirements may be reduced by 15% to 17% compared to a system where the cooling coil is located upstream of the rigid media DEC.

- **Controls:** Monitoring, measurement, output devices must be evaluated carefully. Consider using "averaging" dry-bulb temperature sensors. Wet-bulb monitoring devices can be unreliable, inaccurate, and are subject to "drift." Dampers and their actuators must be clearly specified to ensure reliable, repeatable operation. Use damper positioning devices with feedback to building management system (BMS). Monitor differential pressure of data center with respect to exterior environment (such as a hallway) to ensure a positive pressure is maintained. Maintain at least a +0.02 inch W.G. differential pressure relative to "outside" of the data center. Balance the supply and exhaust (return) fan airflows with variable speed drives (VSDs) to provide the noted positive pressure differential. Note that as supply air filters load, the fans will necessarily need to change speed; include EMCS programming sequences to achieve this speed change.
- **Construction materials:** Review materials for media and sump reservoir and other wetted surfaces, such as mist eliminators that may be required

**Maintenance:**

As noted above, maintenance will be an issue to ensure an efficiently performing evaporative cooling system. Consider whether your existing facilities staff can support the system because regular visits will be required. You may have to contract for outside support.

The ASHRAE Handbook HVAC Systems and Equipment, Chapter 40, Evaporative Air-Cooling Equipment recommends the following precautions

and maintenance procedures to improve cooler performance, reduce microbial growth and musty odors, and prolong equipment life:

- Run fans after turning off water until the media completely dries.
- Thoroughly clean and flush the entire cooling water loop regularly (minimum monthly). Disinfect before and after cleaning.
- Avoid dead-end piping, low spots, and other areas in the water distribution system where water may stagnate during shutdown.
- Obtain and maintain the best available mist elimination technology, especially when using misters and air washers.
- Do not locate the evaporative cooler inlet near a cooling tower outlet.
- Maintain system bleed-off and/or purge consistent with makeup water quality.
- Maintain system cleanliness. Deposits from calcium carbonate, minerals, and nutrients may contribute to growth of molds, slime, and other microbes annoying to building occupants.
- Develop a maintenance checklist, and follow it on a regular basis.
- Consult the equipment or media manufacturer for more detailed assistance in water system maintenance and treatment.

## *Case studies*

## *Related Chapters*

Air-side Economizer
Centralized Air Handling
Free Cooling via Water-side Economizer
Humidification Control Alternatives

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## *Resources*

ASHRAE *Thermal Guidelines for Data Processing Equipment* , 2008

# APPENDIX I:
# Contract Task 2.3.3 Commissioning Strategies

**Building Commissioning:**
***A Golden Opportunity for Reducing Energy Costs and Greenhouse-Gas Emissions***
***(Draft of 19 Feb 2009***

Evan Mills, Ph.D.
Lawrence Berkeley National Laboratory

**Executive Summary**

**Commissioning: The Stealth Energy Saving Strategy**

- Fig: Roth et al. estimate of national cost of commercial-buildings top 13 faults ($3-$17 billion/year savings potential)

**What Commissioning Is (and Is Not)**

- Intro/definitions/context
- Commissioning as risk management
    - Fig: Cross-section of building illustrating Cx definition and relationship to the rest of energy efficiency

**Quantifying Commissioning**

- Cost-benefit issues & methods, data sources, and description of the database/sample
    - Fig: US Map (vary densities?) – which states we have projects from
    - Fig: Data Completeness of our database
    - Fig: Cost definitions [how to characterize Cx costs and benefits]
    - Table: Suare footage of our projects by R/Cx provider

**The Impact of Commissioning: A Golden Opportunity for Saving Energy, Money, and Greenhouse Gas Emissions**

- Core of report: savings [energy/cost/carbon]
    - Fig: Reasons given for commissioning our projects – pie chart
    - Fig: Perceived non-energy benefits for our projects – pie chart
    - Table: Interventions matrix – summary of deficiencies and measures
    - Figs: Benchmarks of energy/cost savings metrics – whisker diagrams
    - Fig: Cost vs $ savings (with payback rays) – scatter plot
    - Fig: Pre-EUI vs savings (with % savings rays) – scatter plot
    - Fig: Cx as % of construction cost - scatter
    - Fig: Cost of conserved carbon – ranked bar chart (95% are negative CCC)
    - Fig: Commissioning investment return – other indicators of profitability (using real-estate standard method called “cash-on-cash return”

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- Fig: Central plants from UC/CSU (asking for Karl Brown's permission on this)
- Table: Comparisions to other studies (for reference/reality-check)

**High-Tech Facilities: The Commissioning Mother Lode**

Capital Cost Savings can Eclipse Energy Savings

Two Tales of One Building

- Comparing the savings of Commissioning (new) and then a year Retrocommissioning the same building (The Molecular Foundry at LBNL)
    - Table: Cx versus RCx costs and benefits for same building
    - Figure: Payback times by intervention
    - Box: Case study of large capital cost savings through chiller downsizing at MFL

**Trust, but Verify**

- Persistence for 36 projects
- Monitoring-based commissioning
    - Figs (2): Persistence– updated story on persistence (35 projects)
    - MBCx concept

**Building on Success (Conclusions/Challenges)**

- Conclusions/Needs identified at 2008 NCBC "Town Meeting"

**References**

Appendices (if any)

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# Benchmarking Analysis of UC/CSU/IOU Monitoring-Based Commissioning Projects – Phase 1

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Public Interest Energy Research (PIER)

Technology Demonstration Program

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## Executive Summary

Buildings rarely perform as intended, with the result that energy use is often higher than anticipated. Building commissioning has emerged as a strategy for remedying this problem in non-residential buildings. Complementing traditional hardware-based energy savings strategies, commissioning is a process of verifying performance and design intent and correcting deficiencies. Through an evaluation of a series of field projects, this report explores the efficacy of an emerging refinement of this practice, known as monitoring-based commissioning (MBCx). MBCx incorporates three components: 1) Installation of permanent energy information systems (EIS) and diagnostic tools at the whole-building and sub-system level; 2) Retro-commissioning based on the information from these tools; and 3) On-going commissioning of buildings to ensure efficient operations. MBCx is thus a measurement-based paradigm which affords better risk-management and also helps to identify problems and opportunities that are missed with periodic commissioning.

The analysis presented in this report is based on in-depth benchmarking of a portfolio of MBCx energy savings for 21 buildings located throughout the University of California and California State University systems. We developed a quality-control/quality-assurance a quality-assurance process for gathering and evaluating raw data from project sites and then selected a number of metrics to use for project benchmarking and evaluation, including normalizations for weather and climate, adjustments for central plant performance, and consideration of differences in building types. We performed a cost-benefit analysis of the resulting dataset, and provided comparisons to prior commissioning project experience.

A total of 1851 deficiency-intervention combinations were identified in the course of commissioning the projects described in this report. The most common location of deficiencies was in air-handling and distributions systems (29% of the total), followed by HVAC equipment (24%) and then lighting (18%). The most common intervention was calibration (20% of the total), followed by start/stop (18%), and modifying setpoints (11%).

From these interventions flowed significant and highly cost-effective energy savings For the MBCx cohort, source energy savings of 22 kBTU/sf-year (10%) were achieved, with a range of 2% to 25%. Median electricity savings were 1.9 kWh/ft2-year (9%), with a range of 1 to 17%. Peak electrical demand savings were 0.2 W/ft2-year (4%), with a range of 3% to 11%.

The aggregate commissioning cost for the 21 projects was $2.9 million. We observed a range of $0.37 to 1.62/ft2, with a median value of $1.00/ft2 for buildings that implemented MBCx projects. Median energy cost savings were $0.25/ft2, for a median simple payback time of 2.5 years. Significant and cost-

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effective energy savings were thus obtained. The greatest absolute energy savings and shortest payback times were achieved in the subset of laboratory-type facilities.

While impacts varied from project to project, we find MBCx to be a highly cost-effective means of obtaining significant program-level energy savings across a variety of building types. Energy savings are expected to be more robust and persistent for MBCx projects than for conventionally commissioned ones. Impacts of future programs can be maximized by benchmarking energy use and targeting the commissioning towards particularly energy-intensive facilities such as laboratories.

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# Introduction

## Context – A growing interest in measured energy performance

Buildings rarely perform as intended, with the result that energy use is often higher initially, or over time, than anticipated by the design and engineering estimates of savings. In recent years, building commissioning (see Box on terminology) has emerged as a highly cost-effective quality control and quality assurance strategy for remedying this problem in non-residential buildings. Complementing traditional hardware-based energy savings strategies, commissioning is a process of verifying performance and design intent and correcting deficiencies. A prior "meta-analysis" of 224 diverse buildings across the United States found median savings of 15% and payback times well under one year [Mills et al. 2004].

Meanwhile, there are many strong drivers towards a measurement-based paradigm for evaluating the performance of energy-efficiency projects, including commissioning. Current paradigms based on stipulated or estimated energy savings invite significant uncertainty and thus risk of under-attainment of goals. Shifting to a measurement-based strategy affords better risk-management and also helps to identify problems and opportunities that are missed when only engineering estimates are used. We know from prior research [Mills et al. 2005] that retro-commissioning is vulnerable to persistence problems, and thus is a particularly good candidate for a measurement-based approach. Furthermore, certain commissioning opportunities cannot even be identified without the use of measurement.

While commissioning on the one hand offers a means of managing performance risks associated with conventional "bricks and mortar" energy efficiency projects, it, too is vulnerable to risks – especially in the absence of a measurement and verification process. Jump [2007] notes the following array of risks faced by various stakeholders:

- Risks to Owner:
  - Savings not delivered, no return on investment
  - No ability to track actual savings
  - Savings do not last
    - "Soft" measures that can be and often are defeated
- EE Program Risks:
  - Program's claimed savings do not stand up to third party review
  - Savings lifetimes are short
  - Negative impact on program realization rates
- Risk to Regulatory Agencies:
  - Unreliable basis for program planning and accurate forecasting

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California policies and laws such as the California Global Warming Solutions Act of 2006 (AB 32) and non-residential energy benchmarking (AB1103) combined with the trend towards voluntary and mandatory markets for verifiable carbon trading and offsets will create a growing demand for verifiable energy and carbon reductions, as well as new metering and sensor technologies that make it easier and more productive to meter. There is also more research and evidence [Petersen, et al. 2007] showing that user behavior and motivation to reduce energy use is influenced by feedback on actual building performance. The growing interest in benchmarking also dovetails strongly with measurement-based analysis and opportunity assessment. For example, AB1103 will require that all California non-residential buildings provide a performance rating of their operational energy performance at the time of sale or lease. Many public sector buildings are being required to benchmark on a continuous basis, with goals to reduce energy use annually. New tools and methods are emerging in support of the growing interest in benchmarking [Mills et al. 2007; Mathew et al. 2007].

## Monitoring-based Commissioning (MBCx)

Monitoring based commissioning (MBCx) combines ongoing building energy system monitoring with standard retro-commissioning (RCx) practices to provide substantial, persistent, energy savings [Brown et al. 2006]. There are three primary streams of additional energy savings from MBCx relative to traditional RCx (see Figure 1):

1. Savings from persistence and optimization of savings from RCx thanks to early identification of deficiencies through metering and trending. Several studies have shown that RCx savings can degrade without an explicit effort to monitor and maintain them [Mills et al. 2005, Bourassa, Piette, and Motegi 2004].

2. Savings from measures identified through metering and trending during the initial commissioning effort i.e. measures unlikely to be found from RCx alone. Haves et al. [2008] provide several example of such measures, e.g. poor control of chilled water distribution to air handlers; unnecessary chiller operation due to disabled chiller lockout; poor VAV zone control due to inoperative actuators on air dampers and hot water valves.

3. Continually identified new measures. By virtue of the continuous nature of the monitoring, MBCx can identify new problems that emerge after the initial retro-commissioning investigation stage, such as equipment cycling and excessive simultaneous heating and cooling.

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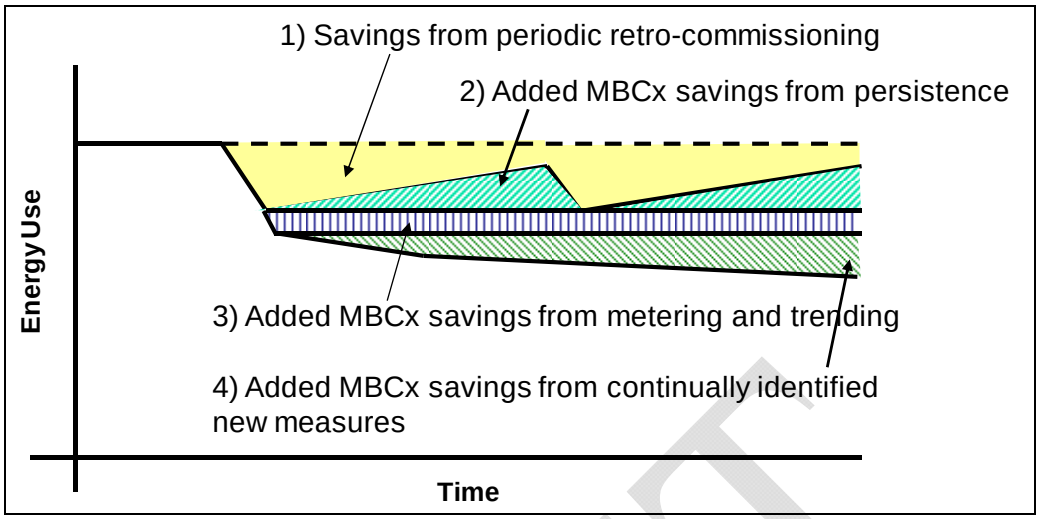


*Figure 1. MBCx provides three streams of additional energy savings relative to RCx. Need to update chart*

**Commissioning Terminology**

There has been a proliferation of terms used to describe various categories of commissioning activities. These include commissioning, new-construction commissioning, retro-commissioning, existing-buildings commissioning, re-commissioning, continuous commissioning, and monitoring-based commissioning. There do not appear to be any universally accepted definitions for these terms or for the scope of activities they represent. To distinguish MBCx from other types of commissioning for the purposes of this discussion, we define these terms as follows:

New-construction commissioning: Single-instance commissioning of the systems in a newly constructed building (or major building addition), applied from project inception to initial occupancy.

Retro-commissioning (RCx) [or existing-buildings commissioning]: Single-instance commissioning of systems in an existing building.

Re-commissioning: Periodic commissioning of systems in an existing building to ensure that systems are operating as intended.

Continuous Commissioning (CCx): This term has been registered (SM) by Texas A&M University (TAMU), who defines it as "an ongoing process to resolve operating problems, improve comfort, optimize energy use and identify retrofits for existing commercial and institutional buildings and central plant facilities."

Monitoring-Based Commissioning (MBCx): This refers to the approach in the UC/CSU/IOU partnership. It involves three elements: 1) Installation of Energy Information Systems/Building Diagnostics; 2) Retro-commissioning; and 3)

Ongoing commissioning using the metered and monitored data.

As noted in Brown et al. [2006], MBCx builds on a significant body of research and experience from the field. In the 1990s, research and development on building monitoring and diagnostics included an approach employing extensive permanent energy system monitoring. This capability was shown to enable building operators to identify previously unrecognized dysfunction and energy waste [Piette et al 2000]. Also in the 1990s, Texas A&M University was prominent among those pioneering the practice of building retro-commissioning, with an emphasis on monitoring for baseline determination and diagnostics [Claridge et al. 2000]. Early in this decade, some early adopters on university campuses spontaneously combined these concepts in their energy management programs, establishing part of the model for development of the MBCx program [Haves et al. 2005].

## UC/CSU/IOU MBCx Program Overview

The University of California (UC), California State University (CSU), and Investor-Owned Utility (IOU) Energy Efficiency Partnership is a California-wide energy efficiency program that establishes a permanent framework for a long-term, comprehensive energy management program at the 33 UC and CSU campuses served by California's four large IOUs (PG&E, SDG&E, SCE and SoCalGas) [UC/CSU/IOU EEP 2007]. The program employs three key strategies to meet its goals: 1) energy efficiency retrofits; 2) monitoring based commissioning (MBCx) for retrofitted and non-retrofitted buildings; and 3) training and education. The Partnership is funded by California's investor owned utility customers through Public Goods Charges (PGC), and administered by the utility companies under the auspices of the California Public Utilities Commission.

The Partnership has self-identified itself as an "innovative" program with all three elements supported by the California Energy Commission's Public Interest Energy Research Program (PIER). The retrofit component is supported by demonstration of PIER R&D products on participating campuses [Johnson, Bourassa, and Seaman 2008]. This has led to scaled-up proposals for deployment of these technologies with Partnership and campus funding. Course development for the training and education program was enhanced by the inclusion of the latest PIER program findings and technology information.

Development of the MBCx approach was enhanced by PIER program support [Piette, Khalsa, and Haves 2000]. The deployment of MBCx in the Partnership first received PIER support in the form of a campus case studies and needs assessments report [Haves et al 2005], them by an evaluation of EIS Architectures

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for MBCx implementation [Haves and Watson 2005]. The effort being reported on here developed and applied benchmarking methods to analyze and evaluate the performance of the first phase of campus MBCx projects. A new project will update the 2003 survey of web-based EIS systems that could be used in conjunction with MBCx [Motegi et al 2003].

The MBCx program represented $xx million of the total program budget and was performed on 37 building projects and 9 plant systems, representing over seven million gross square feet. It has three components:

- Installation of permanent energy information systems (EIS) and diagnostic tools, at the whole-building and sub-system level including both hardware (meters), as well as software to analyze and display data. Telemetry and trending software are brought to bear to support the use of raw data generated by the monitoring infrastructure.
- Retro-commissioning of selected buildings and plants based on the information from the EIS and other tools.
- Ongoing commissioning of buildings to ensure persistently efficient operations.

All three components are implemented by a team including campus facilities staff, working with commissioning agents supplied by the program. The campus facilities staff also received training to implement the MBCx program.

The program is also significant in that it is the first time that the California Public Utilities Commission has funded commissioning or the utilization of energy-monitoring and feedback as strategies for achieving statewide energy savings goals. The MBCx program is being administered by the California Institute for Energy Efficiency (CIEE) and Newcomb Anderson and McCormick (NAM). PECI was contracted to provide additional expertise for data analysis and research.

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# MBCx Benchmarking Project Overview

## Motivation and Objectives

Benchmarking methods and tools can, in principle, inform and address several areas that are important to the UC/CSU/IOU MBCx Program. Following are examples of the role that can be played by benchmarking, as well as questions that framed the research described in this report:

- Project screening: The MBCx program screens and selects projects for funding based on several criteria, including projected savings, projected costs and payback times, qualifications of implementation team, equity across different campuses, etc. Benchmarking could be used to check the reasonableness of baselines, savings, costs and payback, taking into account building type, location, and other characteristics.

- Ultimately, does the use of benchmarking for project screening improve the overall performance of the MBCx portfolio?

- Post-completion project evaluation:

- Which metrics are the key predictors of success? These could then be used to inform the screening process for the next phase of projects.

- Performance of MBCx projects relative to other commissioning projects:

- How do MBCx projects perform relative to the cohort of projects documented in the LBNL commissioning meta-analysis database (Mills et al 2004)?

- Does MBCx yield a different set of efficiency measures?

- Data quality and uncertainty:

- What are the protocols used to account for missing data or poor data quality?

- Normalization:

- What are the appropriate ways to normalize for building type, climate, weather and other factors? What are the appropriate methods to normalize and account for the buildings served by central utilities versus those that aren't?

- Cross-over to other programs:

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- How can the data from the MBCx program be used to inform related efforts such as California-wide benchmarking efforts?

### Scope of Work

In order to explore these areas further, LBNL was commissioned by the UC/CSU/IOU partnership to pursue two broad objectives:

- Develop practical benchmarking processes that can be implemented given existing constraints in terms of UC/CSU staff time, skills, and data availability.
- Conduct a benchmarking analysis of the results from the first phase of projects.

Task 1. Benchmarking methods

1a. Develop a quality assurance (QA) checklist for data provided by sites, prior to and after completion of project implementation

1b. Develop a practical benchmarking process that can be used to screen projects during selection, and evaluate their performance after completion.

Task 2. Benchmarking analysis of Phase-1 projects

2a. Assist NAM in developing QA'd dataset of Phase-1 projects, using the QA checklist developed in task 1a.

2b. Analyze and benchmark QA'd project data using benchmarking process developed in Task 1b.

2c. Compare outcomes to those of non-MBCx projects

These tasks were performed largely in parallel, with interim results from each task iteratively informing the other. Section 3 describes the results of Task 1, and Section 4 describes the results from Task 2.

# Benchmarking Methods

### Data Quality Assurance Checklist

Data collected on site for benchmarking is error-prone for several reasons, including outdated or non-existent building drawings and specifications, lack of EIS systems for energy data, lack of staff time and expertise to collect and review data, lack of motivation or incentives to ensure data quality for benchmarking, deviation from pre-defined data definitions, etc. These issues are widespread in

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the building industry, and are likely to remain so for the foreseeable future. Benchmarking processes need to take these factors into account and cannot assume good data quality.

Quality assurance can, of course, be performed at various levels, depending on the desired level of assurance and resources available. A comprehensive and robust quality assurance process would include independent on-site verification of data. This was beyond the scope of this project and arguably may not even be necessary. Rather, the intent here was to conduct some basic "sanity checks" that highlight irregularities that could then be explored further with the site as needed. It is recommended that these simple checks carried out for all future phases of the project. In some cases, they can be built into the data reporting forms to prevent erroneous input. Table 1 indicates simple QA checks that we performed for various data items, and recommendations for how to execute the QA checks. In almost all cases, the QA will require a technical reviewer to evaluate reasonableness. The benchmarking results in Section 4 can be used to aid this process. In a few cases, the QA check can be automated within the reporting form, which would flag errors at the time of input. Many of the QA checks require metrics calculated from the reported data. This also can be automated within the database.

*Table 1. Simple QA checks for MBCx project data. Need to add pointers to relevant charts from section 4*

| Data Item(s) | QA Check(s) | QA Execution |
|---|---|---|
| All descriptive fields (free form text) | Ensure that text is in appropriate field | Technical Reviewer |
| Building Area | Is it reasonable by order of magnitude? | Technical reviewer |
| | Calculate difference between proposal and final report? If yes, is it explained? | Calculation in database; Technical reviewer |
| Area with 100% OA | Calculate lab area ratio. Is it reasonable based on building description? | Calculation in database; Technical reviewer |
| Number of fume hoods. | Calculate # hoods/ 5000 gsf. Is it reasonable based on building description? (Refer to benchmarking chart) | Calculation in database; Technical Reviewer |
| Building electricity: baseline, post-retrofit | Ensure non-zero value | Auto validation in report form |
| | Calculate building kWh/gsf. Is it reasonable? | Calculation in database; Technical reviewer |

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| Data Item(s) | QA Check(s) | QA Execution |
|---|---|---|
| | Calculate % savings. Is magnitude reasonable based on description of ECM? | Calculation in database; Technical reviewer |
| Building on-peak electricity: baseline, post-retrofit | Ensure non-zero value | Auto validation in report form |
| | Calculate ratio of on-peak to total. Is it reasonable? | Calculation in database; Technical reviewer |
| | Calculate % savings. Is magnitude reasonable based on description of ECM? | Calculation in database; Technical reviewer |
| Building natural gas: baseline, post-retrofit | Ensure non-zero value if building served by natural gas, and vice versa | Auto validation in report input form (report should explicitly ask if there is building natural gas) |
| | Calculate building BTU/gsf. Is it reasonable? | Calculation in database; Technical reviewer |
| | Calculate % savings. Is magnitude reasonable based on description of ECM? | Calculation in database; Technical reviewer |
| Central plant steam/hotwater: baseline, post-retrofit | Ensure non-zero value if building served by central plant steam/hotwater, and vice versa | Auto validation in report input form (report should explicitly ask if there is central plant steam/hot water) |
| | Calculate steam/hotwater BTU/gsf. Is it reasonable? | Calculation in database; Technical reviewer |
| | Calculate % savings. Is magnitude reasonable based on description of ECM? | Calculation in database; Technical reviewer |
| Central plant chilled water: baseline, post-retrofit | Ensure non-zero value if building served by central plant chilled water, and vice versa | Auto validation in report input form (report should explicitly ask if there is central plant chilled water) |
| | Calculate chilled water ton-hr/gsf. Is it reasonable? | Calculation in mastersheet; Technical reviewer |
| | Calculate % savings. Is magnitude reasonable based on description of ECM? | Calculation in mastersheet; Technical reviewer |
| Max 15 min. demand: baseline, post-retrofit | Ensure non-zero value | Auto validation in report form |
| | Calculate W/sf. Is it reasonable? | Calculation in mastersheet; Technical reviewer |
| Central plant electricity | If non-zero, ensure building served by central plant chilled water generated from | Auto validation in report form |

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| Data Item(s) | QA Check(s) | QA Execution |
|---|---|---|
| savings | electric chillers | |
| | Calculate implied efficiency (kW/ton) for electric chillers. Is it reasonable? | Calculation in mastersheet; Technical reviewer |
| Central plant natural gas savings | If non-zero, ensure building served by central plant steam/hot water or gas-driven chillers | Auto validation in report form |
| | Calculate implied efficiency (BTU output/ BTUinput) for boilers. Is it reasonable? | Calculation in mastersheet; Technical reviewer |
| Metering and monitoring costs: Contracted out, in-house | Ensure that one or both fields are non-zero, and that zero value indicates no cost (and not missing data) | Auto validation in report input form (report should explicitly ask if metering was in-house and/or contracted out) |
| | Calculate total metering $/gsf. Is it reasonable? | Calculation in mastersheet; Technical reviewer |
| Baseline and Cx costs: Contracted out, in-house | Ensure that one or both fields are non-zero, and that zero value indicates no cost (and not missing data) | Auto validation in report input form (report should explicitly ask if baseline and Cx was in-house and/or contracted out) |
| | Calculate total baseline and Cx $/gsf. Is it reasonable? | Calculation in mastersheet; Technical reviewer |

These QA checks identified over 20 items in the Phase 1 projects data that required further investigation, many of which resulted in corrections to the reported data.

## Benchmarking Approach – Metrics and Data

As noted earlier, there are two primary applications of benchmarking in the MBCx program:

- Proposal screening
- Post-completion evaluation

Toward this end, we developed a set of metrics based on the analysis framework developed for the Cx Meta-analysis (Mills et al. 2005), with some additional metrics for portfolio level analysis and diagnostics. Table 2 lists the metrics and their application for proposal screening and post-completion evaluation. Note that many of these metrics are used for data QA during both proposal screening and post-completion evaluation.

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Three data sets were used for benchmarking the MBCx projects:

1. MBCx portfolio i.e. comparison across the MBCx project portfolio itself
2. Cx Meta-analysis – all data points, which includes over 100 projects across the US.
3. Cx Meta-analysis – West coast cohort which includes a subset of projects in California, Oregon, and Washington.

*Table 2. Benchmarking metrics for MBCx proposal screening and post-completion evaluation*

| Metrics | Proposal screening | Post-complete evaluation | Available in Cx Meta-Analysis? |
|---|---|---|---|
| ***Baseline*** | | | |
| Source energy kBTU/sf-yr | √ | | √ |
| Electricity kWh/sf-yr | √ | | √ |
| Peak elec kWh/sf-yr | √ | | |
| Fuel kBTU/sf-yr | √ | | √ |
| Historical vs. revised[1] Elec kWh/sf-yr | | √ | |
| Historical vs. revised[1] Peak kWh/sf-yr | | √ | |
| Historical vs. revised[1] Fuel kWh/sf-yr | | √ | |
| ***Savings*** | | | |
| Electricity %, kWh/sf-yr | √ | √ | √ |
| Bldg Elec %, kWh/sf-yr | √ | | |
| Peak elec %, kWh/sf-yr | √ | √ | [2] |
| Bldg Peak %, kWh/sf-yr | √ | | [2] |
| Fuel %, kBTU/sf-yr | √ | √ | √ |
| Bldg Fuel %, kBTU/sf-yr | √ | | √ |
| Chilled water % | √ | √ | √ |
| Hot water/steam % | √ | √ | √ |

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| | | | |
|---|---|---|---|
| Total source %, kBTU/sf-yr | √ | √ | √ |
| Total site %, kBTU/sf-yr | √ | √ | √ |
| Total cost $/sf-yr | √ | √ | √ |
| # Deficiencies | | √ | √ |
| # Measures | | √ | √ |
| Proposed vs. reported Elec kWh/sf-yr | | √ | |
| Proposed vs. reported Peak kWh/sf-yr | | √ | |
| Proposed vs. reported Fuel kBTU/sf-yr | | √ | |
| ***Implementation Costs*** | | | |
| Simple payback (yrs) | √ | √ | √ |
| Project cost $/sf | √ | | √ |
| Metering cost (% of total) | | √ | [3] |

Notes:

1. "Revised" refers to the baseline after the installation of any metering equipment
2. Power densities only
3. Includes related category called "Verification & Persistence Tracking"

## Special Considerations

A key to meaningful benchmarking is defining the appropriate peer group against which the subject building should be compared. In this project, we considered building type, climate and weather, and utilities/services provided and whether or not a given building is served by a central plant. We suggest a hierarchical classification scheme that allows classification at different levels of granularity based on data availability i.e. while it is generally preferable to benchmark with a classification that is as fine-grained as possible, data limitations may require a more coarse classification.

### Building type classification

Building type classification is a key issue in energy benchmarking. There is no standard way to classify non-residential buildings in the US. Figure 2 shows the classification in the CBECS database [EIA 2003] and the CEUS database [CEC 2006]). CEUS has a two- tier classification that is more fine-grained, with 62 sub-types.

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| CBECS classification | |
|---|---|
| Education | Office |
| Food Sales | Public Assembly |
| Food Service | Public Order and Safety |
| Health Care | Religious Worship |
| Inpatient | Service |
| Outpatient | Warehouse and Storage |
| Lodging | Other |
| Mercantile | Vacant |
| Retail (Other Than Mall) | |
| Enclosed and Strip Malls | |

| CEUS classification | |
|---|---|
| Office | Education |
| Administration and management | Daycare or Preschool |
| Financial/Legal | Elementary School |
| Insurance/Real Estate | Middle / Secondary School |
| Data Processing/Computer Center | College or University |
| Assorted/Multi-tenant | Vocational or Trade School |
| Lab/R&D Facility | Lodging |
| Software Development | Hotel |
| Government Services | Motel |
| Other Office | Resort |
| Food Service | Other Lodging |
| Fast Food or Self Service | Public Assembly |
| Specialty/Novelty Food Service | Religious Assembly (worship only) |

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- Table Service
- Bar/Tavern/Nightclub/Other
- Other Food Service

Food Stores

- Supermarkets
- Small General Grocery
- Specialty/Ethnic Grocery
- Convenience Store
- Liquor Store
- Other Food Store

Retail

- Department / Variety Store
- Retail Warehouse/Clubs
- Shop in Enclosed Mall
- Shop in Strip Mall
- Auto Sales
- Other Retail Store

Warehouse

- Refrigerated Warehouse
- Unconditioned Warehouse, High Bay
- Unconditioned Warehouse, Low Bay
- Conditioned Warehouse, High Bay
- Conditioned Warehouse, Low Bay

Healthcare

- Hospital
- Nursing Home
- Medical/Dental Office
- Religious Assembly (mixed use)
- Health/Fitness Center
- Movie Theaters
- Theater / Performing Arts
- Library / Museum
- Conference/Convention Center
- Community Center
- Other Recreational/Public Assembly

Services

- Gas Station / Auto Repair
- Gas Station With Convenience Store
- Repair (Non-Auto)
- Other Service Shop

Miscellaneous

- Assembly / Light Mfg.
- Police / Fire Stations
- Post Office

Other Unlisted Type

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| |
|---|
| Clinic/Outpatient Care<br><br>Medical/Dental Lab |

*Figure 2. Building type classification in CBECS and CEUS.*

Both CBECS and CEUS have the type "College or University" but do not provide further sub categories for the large diversity of types of buildings that are found on college and university campuses (although some of these building types, such as administrative offices are represented separately).

At the top level, buildings are simply classified as 'complex' (i.e. energy intensive) or 'non-complex' (i.e. not energy-intensive). This classification was also used in developing benchmarks for design loads for the UC Merced campus (Brown et al. 2002). Table 3 shows the proposed classification as well as the corresponding building types in CEUS and CBECS. Buildings that are mixed use could be classified based on predominant type or simply as "mixed".

*Table 3. Suggested building-type classification for Campuses in MBCx Program*

| Building Type | Related CEUS building type (* indicates aggregate type) | Related CBECS building type (* indicates aggregate type) |
|---|---|---|
| Complex | - | - |
| Laboratories | Lab/R&D Facility | Laboratory |
| Dense lab | - | - |
| Light lab | - | - |
| Healthcare | Healthcare* | Healthcare* |
| In-patient | Hospital; Nursing home | Out-patient healthcare |
| Out-patient | Clinic/Outpatient care | In-patient healthcare |
| Food Sales | Convenience Store | Food sales |
| Food Service | Fast food or self service | Food service |
| Non-Complex | | |
| Office | Office (non-medical)* | Office |

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| | | |
|---|---|---|
| Classroom | - | - |
| Library | Library/Museum | - |
| Dormitories | - | - |
| Retail | Other retail store | Retail other than mall |
| Sports facilities | Health/Fitness center | - |
| Warehouse (ex. refrigerated) | Warehouse* (ex. refrigerated) | Non-refrigerated warehouse |
| Conditioned | Conditioned warehouse | Non-refrigerated warehouse |
| Unconditioned | Unconditioned warehouse* | Non-refrigerated warehouse |

Given the limited number of data points for the current analysis, it was only possible to define use separate cohorts for 'Laboratories' and 'Non-Complex'.

*Laboratory sub-types: Dense vs. light:*

Given their high energy intensity and prevalence in colleges and universities, laboratories are an especially significant building type for this program. Furthermore, since this building type is more diverse compared to other building types, we explored the possibility of further sub-categorizing laboratories as "dense" or "light" to improve comparability in benchmarking.

There are three key factors that individually or in combination can be used to characterize lab intensity:

- Lab area ratio (ratio of area requiring 100% outside air to the total building area)
- Fume hood density
- Laboratory equipment plug load intensity

Ideally, the benchmarking process for laboratories should normalize for these three parameters. The rigor with which this is done would depend on the purpose of benchmarking. For first order screening, we propose simple threshold criteria, as follows:

A laboratory may be categorized as "dense" if it meets one or more of the following criteria:

- Lab area ratio greater than 0.5. This is the approximately the median value for lab area ratio in the Labs21 database (http://labs21.lbl.gov/).



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- Fume hood density greater than 0.75/ 1000 sf gross building area. This roughly corresponds to the threshold value above which ventilation rates become fume hood driven. The calculation and assumptions for this value are as follows: General exhaust requirements range from 1.0 to 1.3 cfm/sf of lab area. A six-foot fume hood is typically 1200 cfm at full flow, and therefore 1 fume hood / 1000 sf of lab area would result in 1.2 cfm/sf. So 1 fume hood/1000 sf of lab area is a threshold for a fume hood driven lab, assuming no sash management. Since the minimum flow for fume hoods is typically about a ¼ of full flow, the threshold with perfect sash management would be 4 fume hoods/ 1000 sf. of lab area. Since sash management is generally average to poor, we assume 1.5 fume hoods/1000 sf of lab area as threshold for a fume hood-driven lab. Assuming 0.5 lab area ratio this translates into 0.75 fume hoods / 1000 sf of gross building area.

- Plug load intensity: Since quantitative data (equipment W/sf) is unlikely to be available, a qualitative judgment should be made based on the usage of the laboratory i.e. labs that that are equipment intensive (e.g. laser labs) should be characterized as dense labs.

Each of the labs in the present analysis was classified as dense or light based on this approach, although data gaps and quality precluded rigor in this classification. The limited number of data points also precluded the use of separate dense and light lab cohorts for the benchmarking analysis.

### Climate and weather normalization

Climate normalization refers to the normalization for differences in climate across different geographical locations. This allows buildings in different climate zones to be compared to each other. Weather normalization refers to the normalization for differences in weather from one year to another in the same location. Depending on the intent of the benchmarking either or both climate and weather normalization may be required. The extent to which normalization matters and therefore the rigor with which it should be done depends on the purpose of the benchmarking analysis. To be done rigorously, normalization requires an adequate data set for regression analysis. In particular, weather normalization typically requires monthly data energy use data. In the context of MBCx, where benchmarking is primarily being used for project screening and post-completion evaluation, it could be argued that a rigorous regression-based analysis may not be worth the additional data collection requirements and loss of transparency inherent in regression-based approaches. There are some additional considerations that support this view:

- Since the phase-1 MBCx projects were executed within the same time frame, weather normalization (i.e. accounting for year-to-year differences)

is largely not an issue for comparing projects within a given phase. Note however, that the savings for each MBCx project were normalized to account for differences in baseline and post-retrofit conditions.

- A regression-based analysis of weather normalization for various EPA laboratory buildings [Mathew 2007] showed very strong correlations between energy use and monthly average temperatures. Despite these strong correlations, year-to-year differences in weather were not significant enough to affect conclusions about the impact of savings.

- Piette et al. [REF forthcoming from MAP] suggest that accounting for variations in climate may not be that critical for non-laboratory buildings in many regions of California.

Nevertheless, to the extent that regression-based normalization can improve the quality of benchmarking at a reasonable "cost" (in terms of data requirements and analysis time) it should continue to be an option – especially as more data is obtained from future phases of the MBCx program.

For the present, we recommend using a climate zone classification to compare buildings in similar climates. There are two options: a) DOE national classification; and b) California Title 24 climate zones.

The DOE climate zone classification was developed by Pacific Northwest National Laboratory, and has been adopted by several by ASHRAE [Briggs et al. 2002], the International Energy Conservation Code (IECC), the Labs21 benchmarking tool, and others. This classification has 15 major climate zones for the United States, based on temperature and humidity, and assigns a climate zone for each county and territory in the US (Figure 3).

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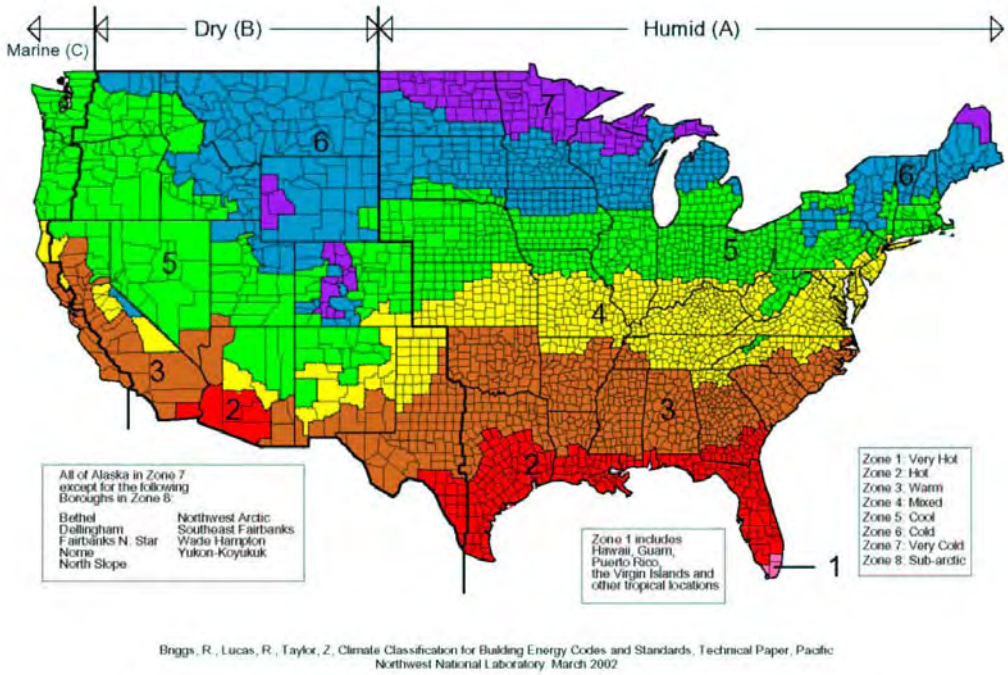


*Figure 3. DOE climate zone classification*

There are three relevant zones for the UC/CSU system:

- Warm Marine (Zone 3C)
- Warm Dry (Zone 3B)
- Mixed Marine (Zone 4C)

Since the DOE classifications are based on county, some adjustments are needed for counties that have significant microclimates. The warm dry region (3B) includes the central valley and the south coast (Los Angeles, San Diego). If using this classification, we recommend a separate Warm Dry Coastal sub-region to include UCLA, UC Irvine, UC San Diego, CSU Dominguez Hills and CSU Long Beach.

The California Title 24 Climate classification, with 16 climate zones for California, offers much more resolution than the DOE classification. The EnergyIQ benchmarking tool (http://EnergyIQ.lbl.gov), which builds on the CEUS database, provides an aggregated version with seven climate regions (a further level of resolution, while technically possible, was not available for reasons related to data

confidentiality). In the present analysis, the limited number of data points precluded the use of separate cohorts based on climate zone.

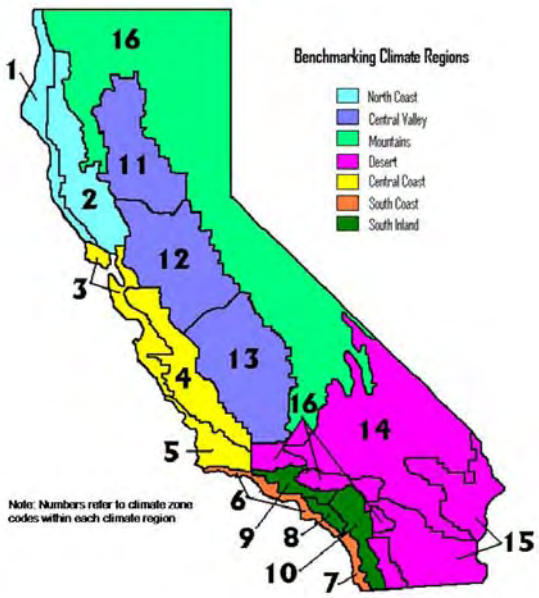


*Figure 4. California climate zones and regions*

## Comparing buildings with and without central plant services

Buildings in the benchmarking peer-group may have any combination of building utilities and central plant systems that serve these utilities, as listed in Table 4.

*Table 4. List of building utilities and plant systems*

| Building utilities | Plant systems |
|---|---|
| Electricity | Electric chillers |
| Natural gas | Gas-fired chillers |
| Other Fuel | Cogeneration |
| Plant chilled water | Thermal Energy Storage |
| Plant steam | Boilers |
| Plant hot water | |
| Plant condenser water | |

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Depending on the purpose of the benchmarking analysis, the following approach is recommended for computing the energy use of plant utilities in plant-served buildings:

- To assess and compare buildings in terms of their energy efficiency *at the building*, use uniform efficiency rates for plant utilities, as indicated in Table 5.

*Table 5. Standard efficiency rates for central plant utilities*

| Central Plant Utility | Efficiency |
|---|---|
| Chilled Water | 1.0 kW/ton |
| Steam | 80% |
| Hot water | 80% |
| Condenser water | ???? |

- To compare the cost-effectiveness and report energy and cost savings on completed projects, use reported (i.e. "actual") efficiency rates for plant utilities. This is the approach used for comparison to the meta analysis.

# Benchmarking Results from Phase 1 MBCx Projects

## Summary of Portfolio Results

Table 6 summarizes the overall performance of the 24 Phase-1 MBCx projects in terms of key savings and cost metrics. This set of projects is a subset of the overall portfolio of the MBCx Phase-1 program in that it excludes projects that had capital retrofits and/or central plant projects. However, it does include three MBCx projects that received funding but which were not implemented. As a result of including these zero-savings projects in the analysis, the portfolio results are more conservative than if they were to be excluded. For each metric, three different values are presented: median; project average (obtained from averaging the values of the metric for all projects); and aggregate (obtained from computing the metric at the portfolio level i.e. essentially a weighted average). For comparison, Table 6 also shows the values of the savings metrics for the two meta-analysis cohorts i.e. all projects, and west coast projects only.

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*Table 6. Overall performance of MBCx phase -1 projects*

| Savings/Cost Metric | MBCx Phase-1 projects<br><br>median/proj avg/ aggregate | Cx Meta Analysis [5]<br><br>median/proj avg | Cx Meta Analysis [5]<br>CA/OR/WA Only<br>median/proj avg |
|---|---|---|---|
| Total source energy savings % | 10% / 9% / 10%<br>(N=24/24/22) [1] | 13% / 16% (N=46) | 8% / 9% (N=24) |
| Total site energy savings % | 11% / 11% / 11%<br>(N=24/24/22)[1] | 15% / 19% (N=46) | 8% / 9% (N=24) |
| Simple Payback Period | 2.2 / N/A / 2.1 (N=21/24) [2,3] | 1.0 / 2.1 (N=98) | 1.5 / 2.7 (N=36) |
| Electricity savings % | 9% / 8% / 9%<br>(N=24/24/22) [1] | 9% / 11% (N=46) | |
| Peak electricity savings % | 5%/ 6% / 6%<br>(N=23/23/21) [1] | 2% / 7% (N= 3) | |
| Fuel savings % | 9% / 15% / 13%<br>(N=24/24/22) [1] | 6% / 13% (N=19) | |
| Chilled water savings % | 17% / N/A / 22% (N=10) [4] | | |
| Hot water/Steam savings % | 12% / 23% / 18% (N=13) | | |
| Total Thermal | | 36% / 37% (N=16) | |

Notes:

1. The number of data points for the aggregate value is less than the number of data points for median and project average because baseline data were not available for two of the un-implemented projects, and therefore they were excluded for calculating the aggregate values.

2. Project average was not calculated for simple pay back because the portfolio includes zero-savings projects for which simple payback could not be calculated.

3. The second value of N refers to the number of data points for the aggregate value. The number of data points for the median is lower because it excludes the zero savings projects, for which simple payback cannot be calculated.

4. One project resulted in a large shift of energy use from the building to the plant, rendering the average of values for chilled water meaningless.

5. Values for Meta-analysis include the subset with weather-normalized data, and assume the same energy prices and electric-conversion heat rate adopted for the MBCx analysis.

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## Detailed Results

We analyzed and compared performance among the MBCx cohort. In addition, we compare the cohort as a whole to the outcomes of other retro-commissioning projects that have been analyzed as part of the Lawrence Berkeley National Laboratory database of commissioning and retro-commissioning costs and benefits. We refer to this as the "LBNL Meta-Analysis Database".

This analysis seeks to normalize diverse retro-commissioning data to standard energy prices, and correct for inflation so that projects costs and savings in various years can be more readily compared. Per the discussion of defining meaningful peer groups for benchmarking and analysis purposes, we adopted the following conventions and normalizations:

- Building types: To distinguish among services, we provide separate analyses for laboratory facilities and other (less energy intensive) facilities.
- Weather and climate: Weather-normalization is achieved by short-term monitoring of energy and actual weather and then scaling to annual values based on normalization per long-term data. For climate normalization, we compare non-laboratory MBCx projects to other retro-commissioned projects in the states of California, Oregon, and Washington. Due to lack of data from CA/OR/WA climates, for laboratory-type spaces we compare those in the MBCx sample to other labs wherever they occur in the U.S. (predominantly at Texas A&M University).
- Central plant utilities: We used reported (i.e. "actual") efficiency rates for plant utilities.
- Economics: We use standardized commercial energy prices, and inflation-correct all cost data to 2007 levels.

## Deficiencies and Interventions

We applied a framework for tabulating the deficiencies identified and corresponding interventions (measures) implemented to correct them. This framework was previously used in the LBNL meta-analysis (Mills et al. 2005) with refinements and clarifications for the present version.

A total of 1851 deficiency-intervention combinations were identified in the course of retro-commissioning the 21 UC/CSU projects described in this report (Table 7 and key in Appendix B). The most common location of deficiencies was in air-handling and distributions systems (29% of the total), followed by HVAC equipment (24%) and then lighting (18%). The most common intervention was calibration (20% of the total), followed by start/stop (18%), and modifying

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setpoints (11%). From interventions flowed significant and highly cost-effective energy savings.

The highest frequency of deficiencies – measured in terms of number per unit of floor area-- was in HVAC and lighting systems (Figure 5). The most frequent measures were adjustment of start/stop and calibration (Figure 6).

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*Table 7. Deficiencies and Interventions in MBCx Projects. Shaded cells are the highest totals and top-10 combinations*

| | | Commissioning Measures Implemented | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Design, Installation, Retrofit, Replacement | | | | Operations & Control | | | | | | | | | Maintenance | | | | | total | (%) |
| | | Design change | Installation modifications | Retrofit/equipment replacement | Other | Implement advanced reset | Start/Stop (environmentally determined) | Scheduling (occupancy determined) | Modify setpoint | Equipment staging | Modify sequence of operations | Loop tuning | Behavior modification/manual changes to operations | Other | Calibration | Mechanical fix | Heat transfer maintenance | Filtration maintenance | Other | | |
| Component being Commissioned | | D1 | D2 | D3 | D4 | OC1 | OC2 | OC3 | OC4 | OC5 | OC6 | OC7 | OC8 | OC9 | M1 | M2 | M3 | M4 | M5 | | |
| HVAC (combined heating and cooling) | V | 2 | 2 | 1 | 0 | 27 | 25 | 12 | 47 | 0 | 45 | 33 | 16 | 0 | 97 | 123 | 0 | 7 | 0 | 437 | 23.6% |
| Cooling plant | C | 2 | 27 | 2 | 0 | 12 | 4 | 0 | 8 | 3 | 15 | 3 | 0 | 3 | 29 | 5 | 2 | 0 | 1 | 116 | 6.3% |
| Heating plant | H | 0 | 22 | 2 | 1 | 19 | 15 | 13 | 26 | 19 | 20 | 14 | 13 | 0 | 13 | 6 | 1 | 0 | 2 | 186 | 10.0% |
| Air handling & distribution | A | 6 | 0 | 0 | 1 | 65 | 12 | 27 | 125 | 9 | 78 | 64 | 10 | 2 | 79 | 38 | 9 | 9 | 0 | 534 | 28.8% |
| Terminal units | T | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 6 | 5 | 0 | 0 | 150 | 26 | 0 | 0 | 14 | 206 | 11.1% |
| Lighting | L | 1 | 1 | 1 | 0 | 1 | 286 | 49 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 342 | 18.5% |
| Envelope | E | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0.2% |
| Plug loads | P | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0.2% |
| Facility-wide (e.g. EMCS or utility related | F | 0 | 0 | 0 | 4 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 12 | 0.6% |
| Other | O | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 0.6% |
| Total | | 11 | 52 | 6 | 6 | 124 | 342 | 105 | 211 | 31 | 176 | 119 | 48 | 9 | 368 | 198 | 12 | 16 | 17 | **1851** | |

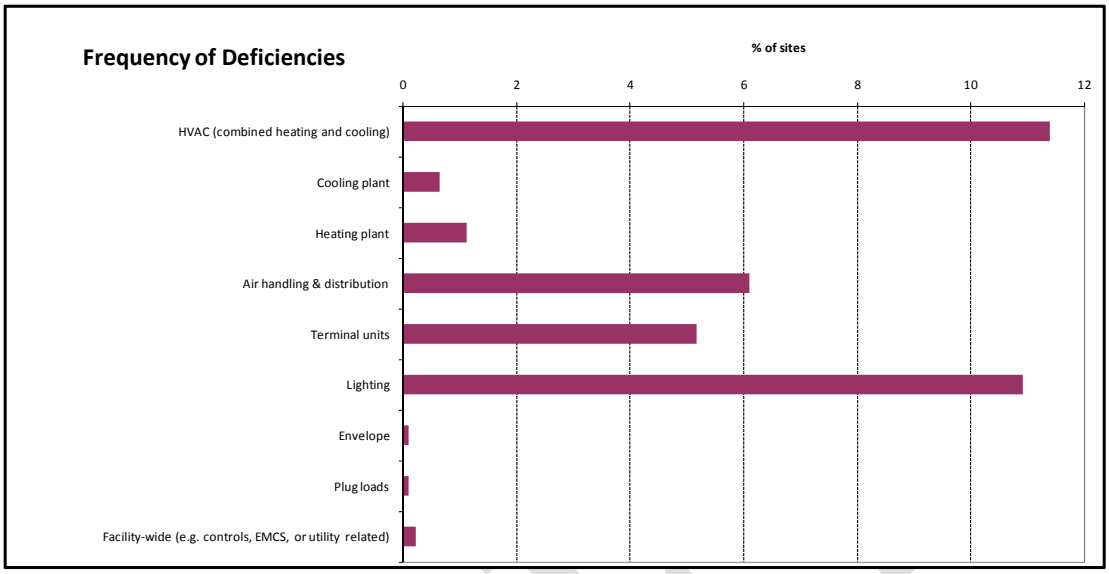


*Figure 5. Frequency of deficiencies found through MBCx*

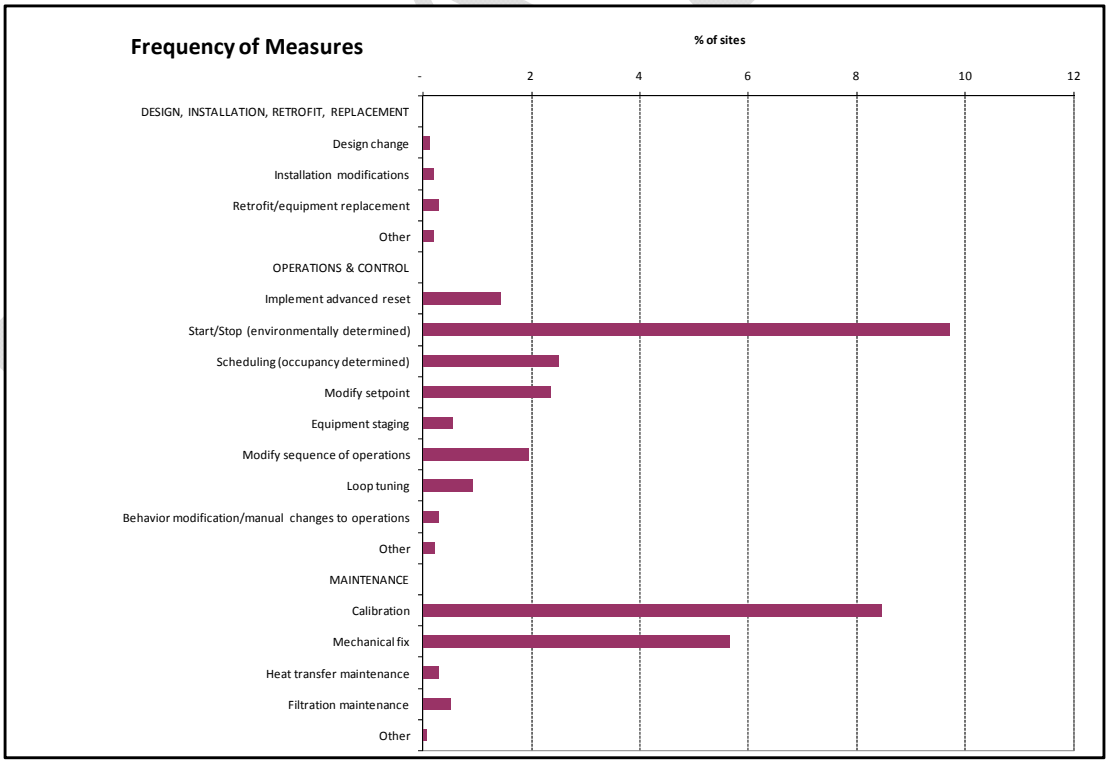


*Figure 6. Frequency of measures implemented in MBCx projects*

### Benchmarking analysis of energy use, costs, and savings

Table presents the benchmarking analysis of various energy use, cost and savings metrics. The analysis includes comparison to the meta-analysis, using the cohorts as defined in the introduction to this section 4.2. Note that this analysis divides the dataset into more cohorts than the portfolio summary analysis provided in Table 6. Additionally, this analysis excluded three MBCx projects that received funding but which were not implemented.

For the MBCx cohort, source energy savings of 22 kBTU/sf-year (10%) were achieved, with a range of 2% to 25%. Median electricity savings were 1.9 kWh/ft2-year (9%), with a range of 1to 17%. Peak electrical demand savings were 0.2 W/ft2-year (4%), with a range of 3% to 11%.

The aggregate commissioning cost for the 21 projects (26 buildings; 3.4 million square feet) analyzed was $2.9 million. We observed a range of $0.37 to 1.62/ft2, with a median value of $1.00 for buildings that implemented MBCx projects. Median energy cost savings were $0.25/ft2, for a median simple payback time of 2.5 years. Significant and cost-effective energy savings were thus obtained. The greatest absolute energy savings and shortest payback times were achieved in the subset of laboratory-type facilities.

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*Table 8. Benchmark outcomes for Meta-Analysis (MA) and Monitoring-Based Commissioning (MBCx) for full samples and for climate- and building-type cohorts (median values).*

| | All Sites | | By Climate | | By Building Type | |
|---|---|---|---|---|---|---|
| **Sample** | MA* | MBCx** | MA - non-Lab | MBCx - non-Lab | MA - Lab | MBCx - Lab |
| Location | US | CA | CA/OR/WA | CA | US | CA |
| Number of projects | 84 | 21 | 36 | 14 | 13 | 12 |
| Number of buildings | 128 | 26 | 72 | 9 | 15 | 12 |
| Median building size (square feet, sf) | 154,000 | 121,214 | 197,953 | 117,607 | 139,361 | 106,592 |
| **Total Source Energy** | | | | | | |
| Pre-cx (kBTU/sf, source) | 323 | 335 | 231 | 189 | 543 | 534 |
| Savings (kBTU/sf, source) | 31 | 24 | 15 | 18 | 119 | 40 |
| Savings (%) | 12% | 11% | 9% | 10% | 16% | 12% |
| **Building Electricity** | | | | | | |
| Pre-cx (kWh/sf-year) | 23 | 21 | 16 | 14 | 29 | 35 |
| Savings (kWh/sf-year) | 1.7 | 1.6 | 1.2 | 0.9 | 1.5 | 1.7 |
| Savings (%) | 8% | 7% | 9% | 8% | 5% | 6% |
| **Building Peak Power** | | | | | | |
| Pre-CX | 4.2 | 3.7 | 4.2 | 2.7 | | 4.4 |
| Savings | 0.5 | 0.2 | 0.1 | 0.3 | | 0.2 |
| Savings | 2% | 4% | 9% | 8% | | 3% |
| **Building Fuel** | | | | | | |
| Pre-cx (kBTU/sf, source) | 89 | 153 | 89 | 50 | | 195 |
| Savings (kBTU/sf, source) | 7 | 12 | 3 | 2 | | 20 |
| Savings (%) | 9% | 7% | 5% | 5% | | 10% |
| **Central Thermal*** ** | | | | | | |
| Pre-cx (kBTU/sf, source) | 211 | | | | 388 | |
| Savings (kBTU/sf, source) | 56 | | | | 142 | |
| Savings (%) | 32% | | | | 24% | |
| **Central Hot Water** | | | | | | |
| Pre-cx (kBTU/sf, source) | | 42 | | 19 | | 68 |
| Savings (kBTU/sf, source) | | 8 | | 8 | | 16 |
| Savings (%) | | 25% | | 36% | | 23% |
| **Central Steam** | | | | | | |
| Pre-cx (kBTU/sf, source) | | 98 | | 24 | | 213 |
| Savings (kBTU/sf, source) | | 32 | | 2 | | 41 |
| Savings (%) | | 19% | | 12% | | 19% |
| **Central Chilled Water** | | | | | | |
| Pre-cx (kBTU/sf, source) | | 45 | | 27 | | 95 |
| Savings (kBTU/sf, source) | | 8 | | 6 | | 9 |
| Savings (%) | | 19% | | 29% | | 16% |
| **Economics** | | | | | | |
| Project costs ($/sf) | $ 0.29 | $ 1.00 | $ 0.24 | $ 0.72 | $ 0.31 | $ 1.15 |
| Cost savings ($/sf) | $ 0.33 | $ 0.32 | $ 0.16 | $ 0.22 | $ 1.65 | $ 0.46 |
| Simple payback time (years) | 0.6 | 2.5 | 1.4 | 2.7 | 0.1 | 1.9 |

Values should not be compared between rows as the number of datapoints in each subset varies in many cases.
The following assumptions and normalization factors are applied in normalizing data to 2007 price levels, and to reflect CA conditior
Commercial-sector energy prices: $0.10/kWh; natural gas price $10.00/MBTU (Notes to table 1 in Brown et al. 2006).
Peak demand savings valued at $120/kW.
Labor cost index. June 2007 values. (Engineering News Record, McGraw-Hill).
GDP deflator: All values adjusted to 2007 currency levels.
Heat rate for electric power production 9,215 BTU of source energy input per kilowatt-hour generated.
Note: Assumed energy prices and heat rates reflect California conditions. In other published reviews of the MA data, assumptions are reflective of national conditions are used.
* Analysis using subset of projects with weather-normalized energy data
** MBCx cohort excludes three projects that were funded but not implemented.
*** For MA, energy use in central plant is broken out into hot water, steam, and chilled water.plant conversion losses. All centrally prepared energy is counted at the point of delivery to the building, i.e. excluding plant conversion losses.

We compared the outcomes for the MBCx cohort with those for the LBNL Meta-analysis, disaggregating the analysis by climate and building type (Figure 7 a&b). The disaggregation of impacts highlights the importance of examining peer groups. Although small in number, the more energy-intensive buildings skew most

values upwards for the all-inclusive sample. In particular, pre-commissioning energy intensities and savings were higher among lab than non-lab facilities. Examining the subgroups also narrows the observed variance in results (particularly for non-lab facilities).

The samples were quite consistent in terms of building source energy intensities prior to commissioning. The median building size was smaller for the MBCx cohort. The MBCx lab facilities were more electricity intensive than their counterparts in the Meta-analysis.

Across the MBCx sample, monitoring costs were much higher proportion of the total than for the comparison group, representing 40% of total. Some projects in the national meta-analysis sample also involved a degree of monitoring (up to 47%, characterized as "verification and persistent tracking), but the median value for the 31 Meta-analysis projects for which we have data is only 2%. Sites that hosted the UC/CSU MBCx program also tend to be thinly metered, as they are usually on campuses that are centrally metered, with individual buildings often not having the building level metering emphasized by the MBCx concept. Thus, particularly high investments in new metering were required at these sites. In addition, many of the campuses have chilled water, hot water, and/or steam distribution systems. Building-level metering ("BTU meters") for these energy streams has significant costs that are higher than for stand-alone buildings (e.g. steam or hot water metering can be more expensive than gas metering, chilled water metering is in addition to electricity metering).

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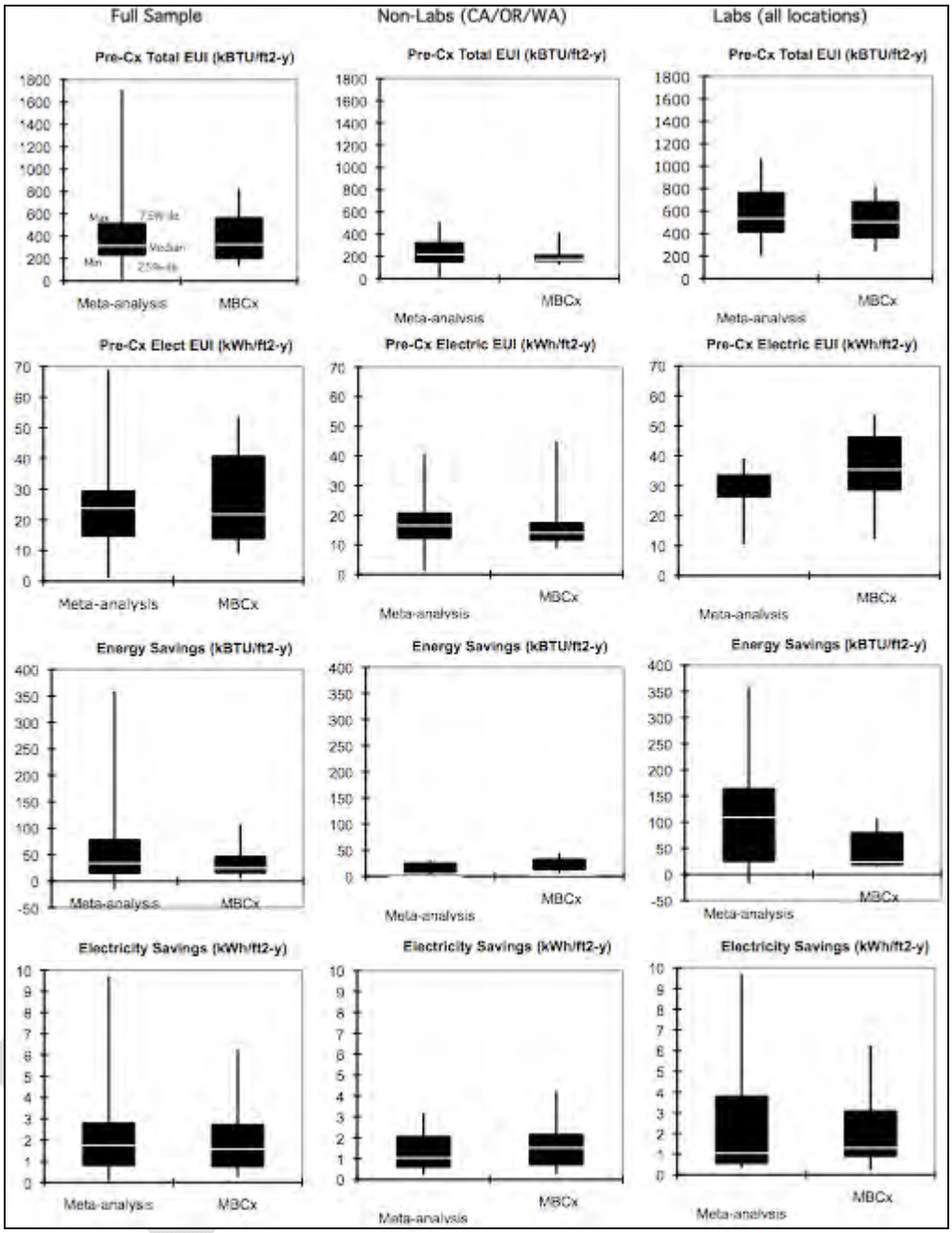


*Figure 7. (a) Portfolio comparison of MBCx and meta-analysis in terms of preCx EUI, pre-Cx electrical EUI, energy savings, and electricity savings for three cohorts: full sample (left column);non-lab buildings in CA/OR/WA (middle column); and labs in all locations (right column). Need to fix formatting and median lines*

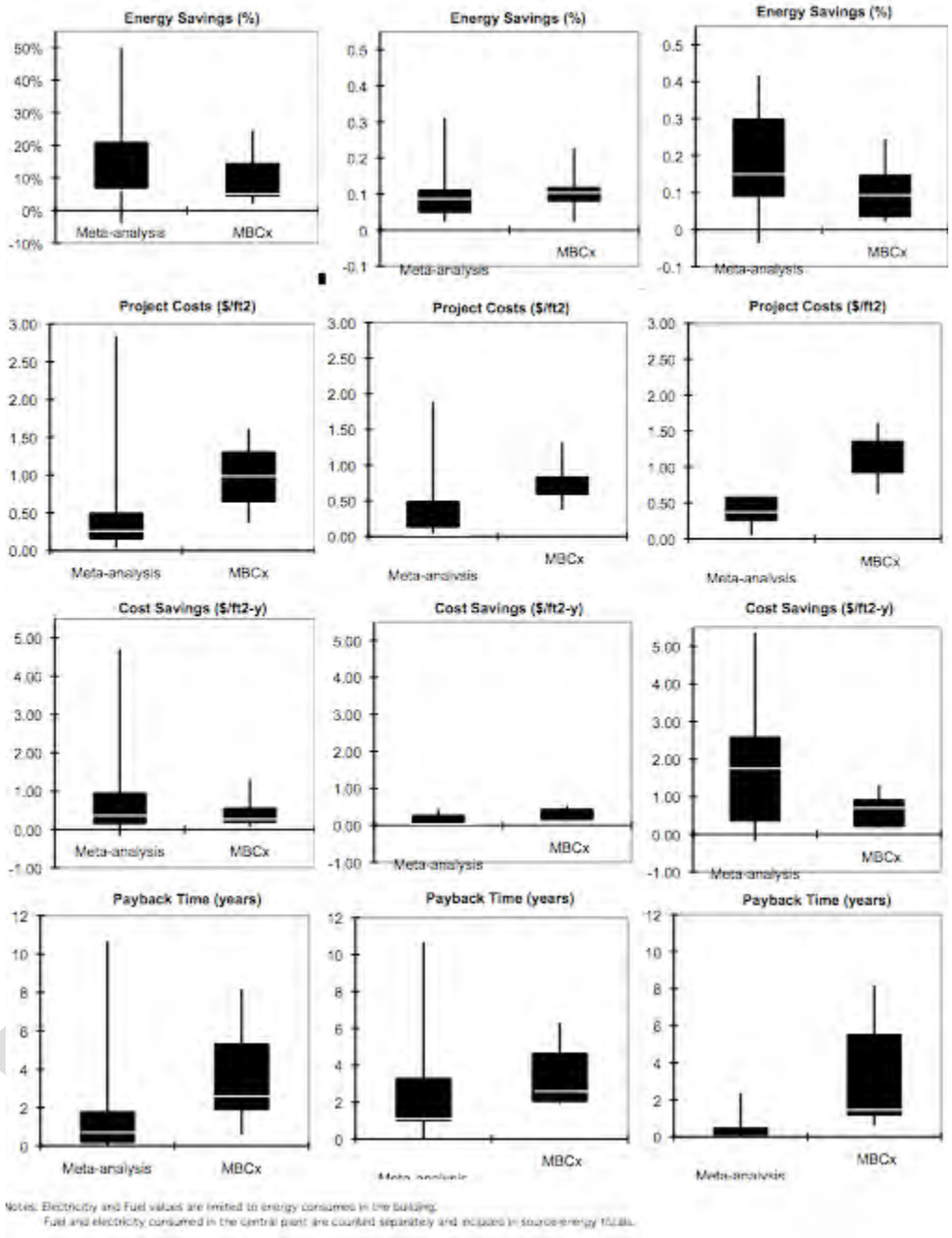


*Figure 7 (b). Portfolio comparison of MBCx and meta-analysis in terms of energy savings %, project costs, cost savings, and payback times for three cohorts: full sample (left column);non-lab buildings in CA/OR/WA (middle column); and labs in all locations (right column)* *Need to fix formatting and median lines*

Figure 8 through Figure 14 benchmark at the individual project level the energy and demand intensities prior to the retro-commissioning activity versus savings attributable to MBCx. The individual peer groups defined in figures xxxa - xxxr are used here as well, and indicated in the figures to facilitate comparisons. Laboratory-type facilities consistently stand out as having relatively high pre-project energy use as well as subsequent savings. Where comparable data are available, the MBCx projects are compared with projects from the LBNL meta-analysis database. Similar qualitative patterns of savings emerge for both data sets.

While the scatter is significant, most of the comparisons suggest that targeting high-EUI projects would improve the likelihood of attaining high savings. Particularly high savings were obtained from hot water, chilled water, and steam provided to the buildings by central plants.

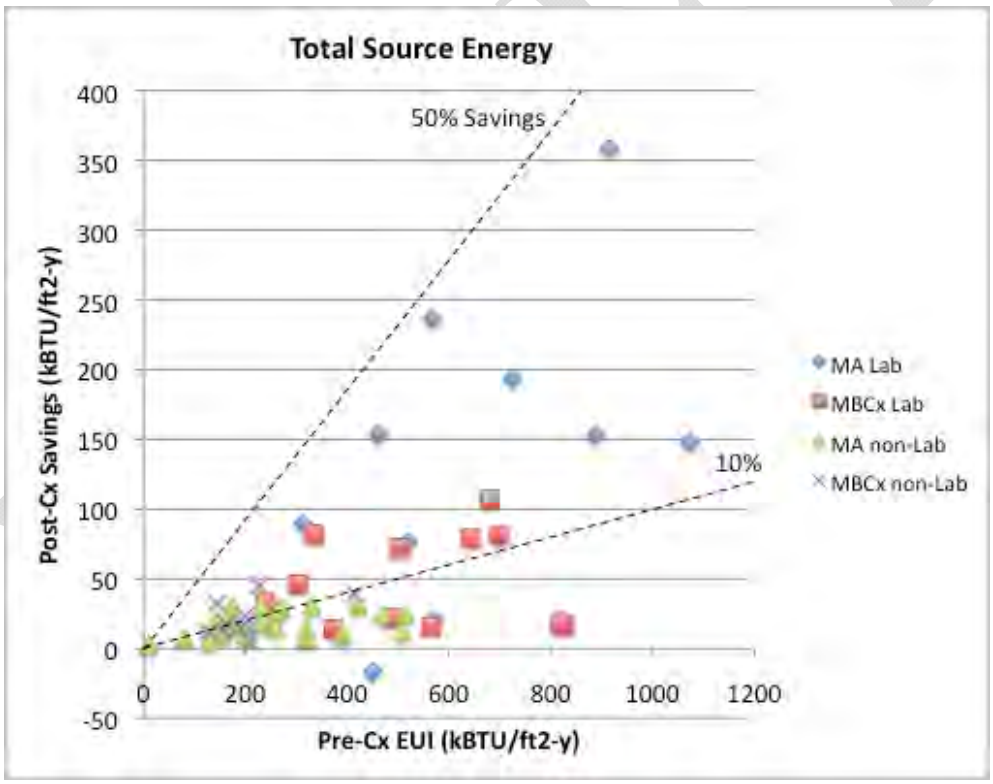


*Figure 8. Total source energy pre-Cx energy use intensity vs. post-Cx savings*

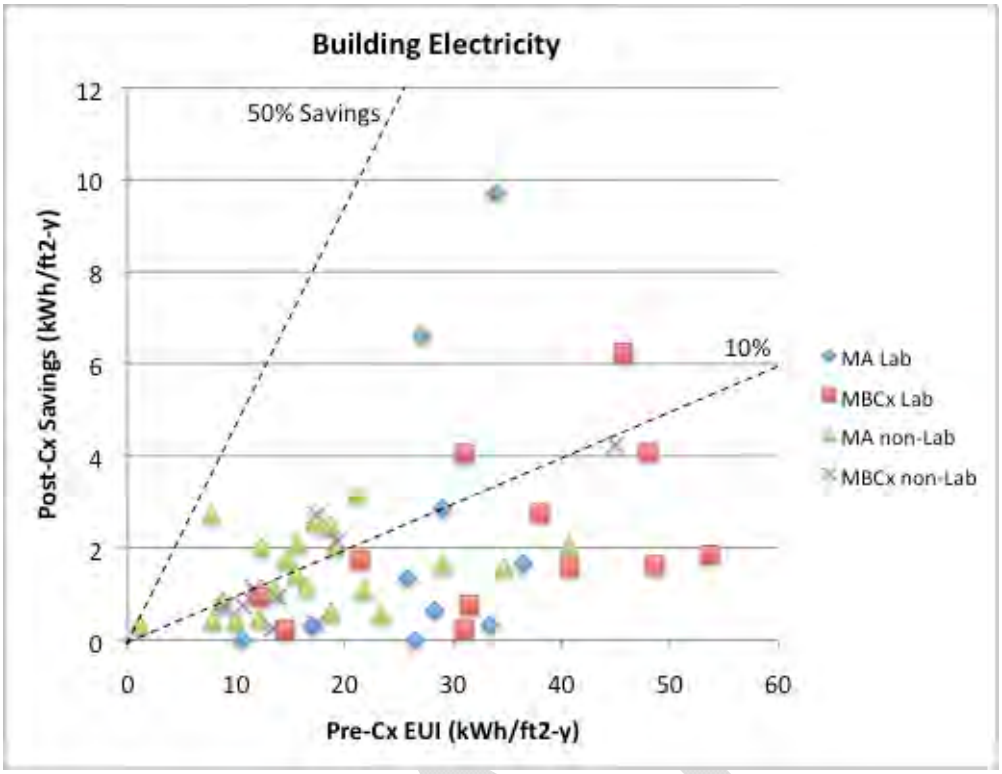


*Figure 9. Building electricity pre-Cx energy use intensity vs. post-Cx savings*

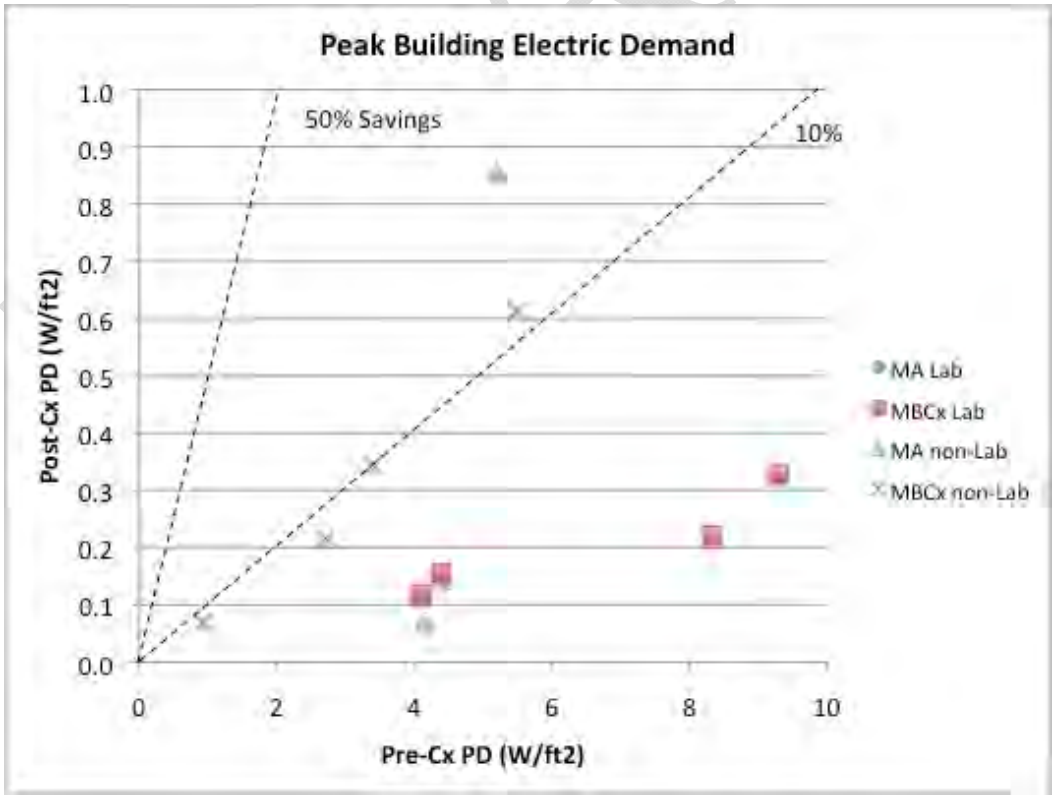


*Figure 10. Peak building electric demand pre-Cx power density vs. post-Cx savings*

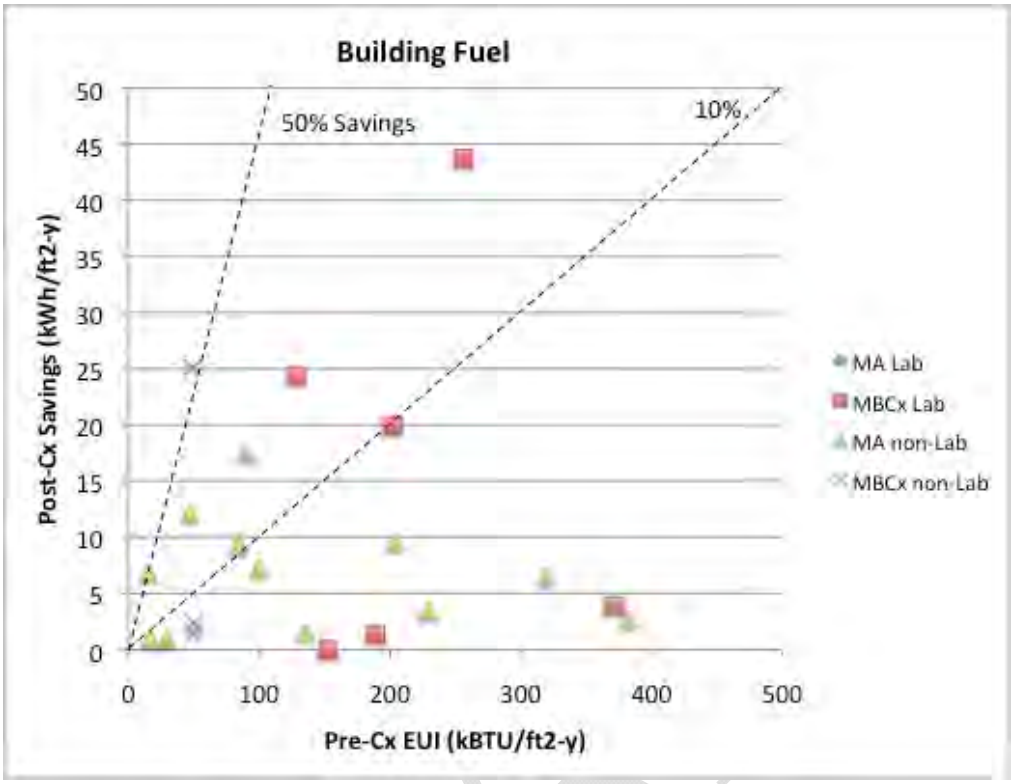


*Figure 11. Building fuel pre-Cx energy use intensity vs. post-Cx savings*

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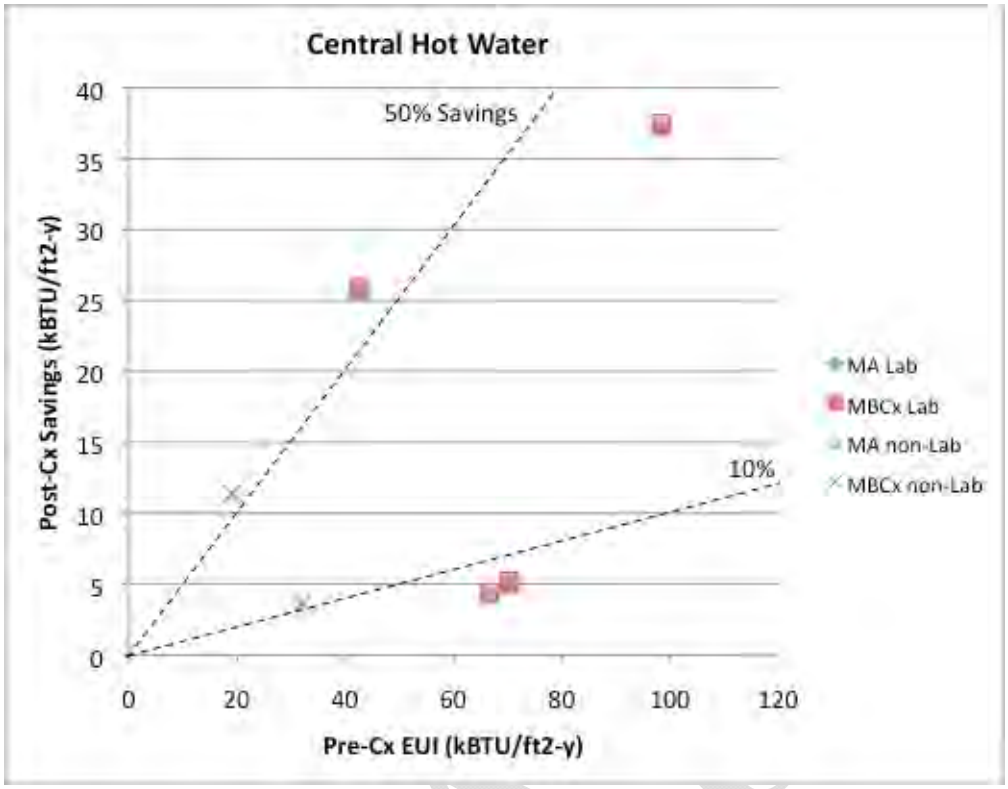


*Figure 12. Central plant hot water pre-Cx energy use intensity vs. post-Cx savings*

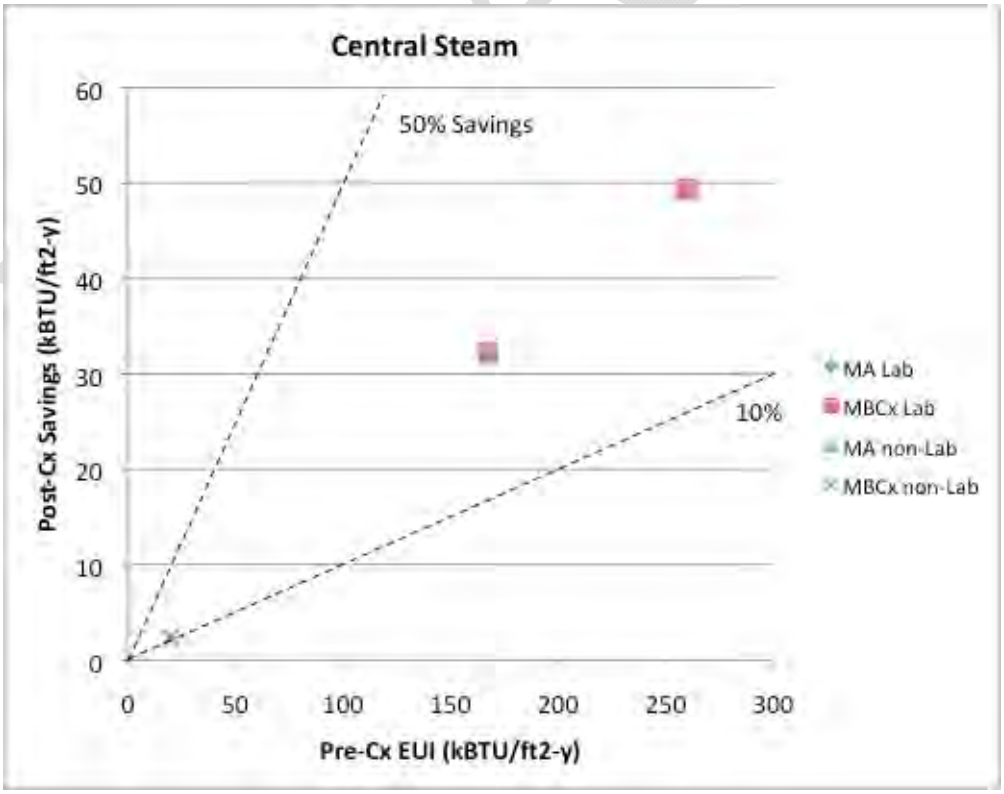


*Figure 13. Central plant steam pre-Cx energy use intensity vs. post-Cx savings*

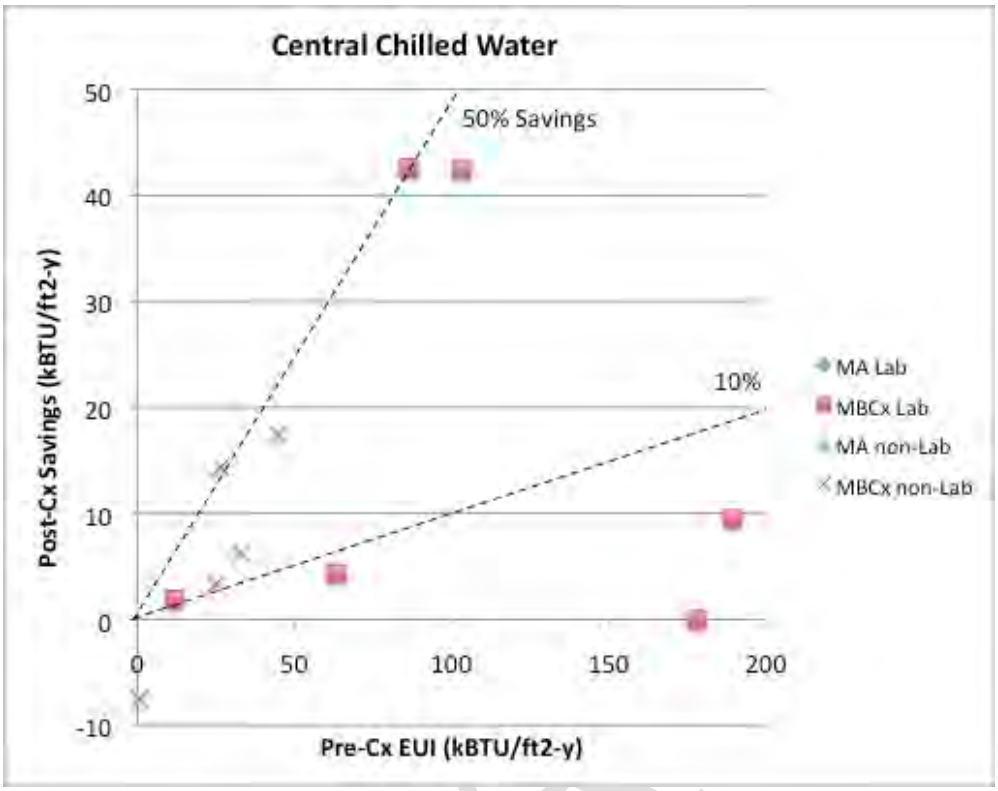


*Figure 14. Central plant chilled water pre-Cx energy use intensity vs. post-Cx savings*

## QA and other Diagnostics

In addition to the analysis of the key performance metrics shown above, additional analyses were used as part of the data QA process.

Figure 15compares savings using reported plant efficiencies vs. savings using standard (i.e. uniform) central plant efficiencies. With one exception, there were little or no differences, suggesting that the reported plant efficiencies were likely based on assumptions of typical efficiency that have been used for standard plant efficiencies.

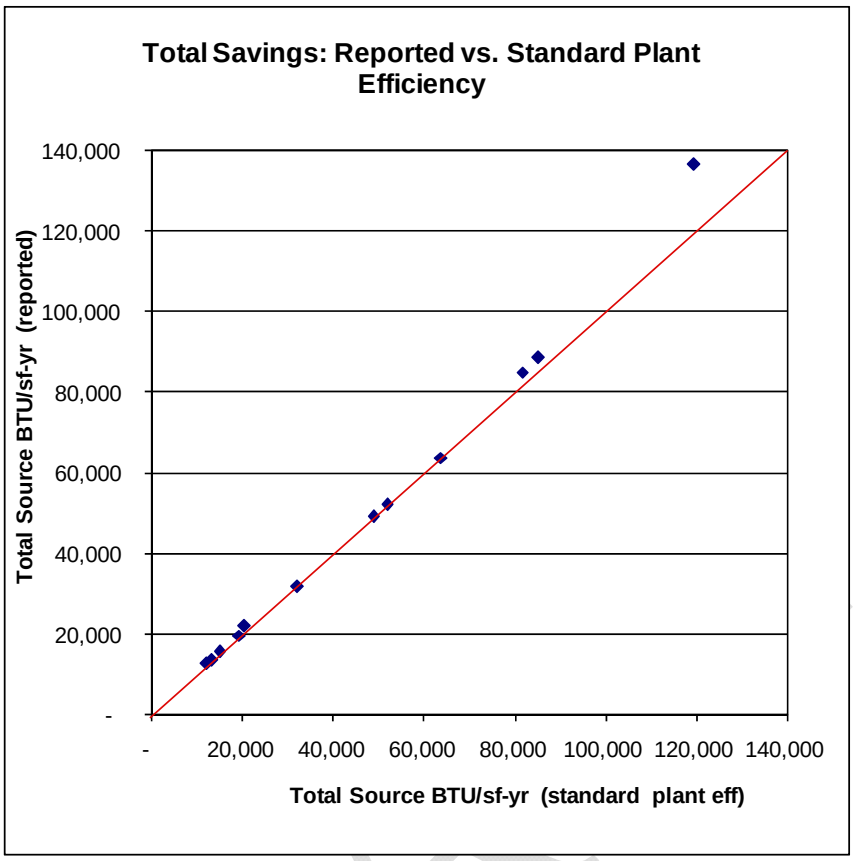


*Figure 15. Total source energy savings using reported plant efficiencies vs. standard (i.e. uniform) central plant efficiencies for MBCx projects that had central plant savings.*

Figure 16 and Figure 17 compare the historical baseline (prior to installation of metering equipment) vs. the revised baseline (after installation of metering equipment) for building electricity and gas respectively. The data show that in most cases, the historical baseline was revised based on metered data, thereby affirming one of the initial benefits of metering i.e. better baseline data.

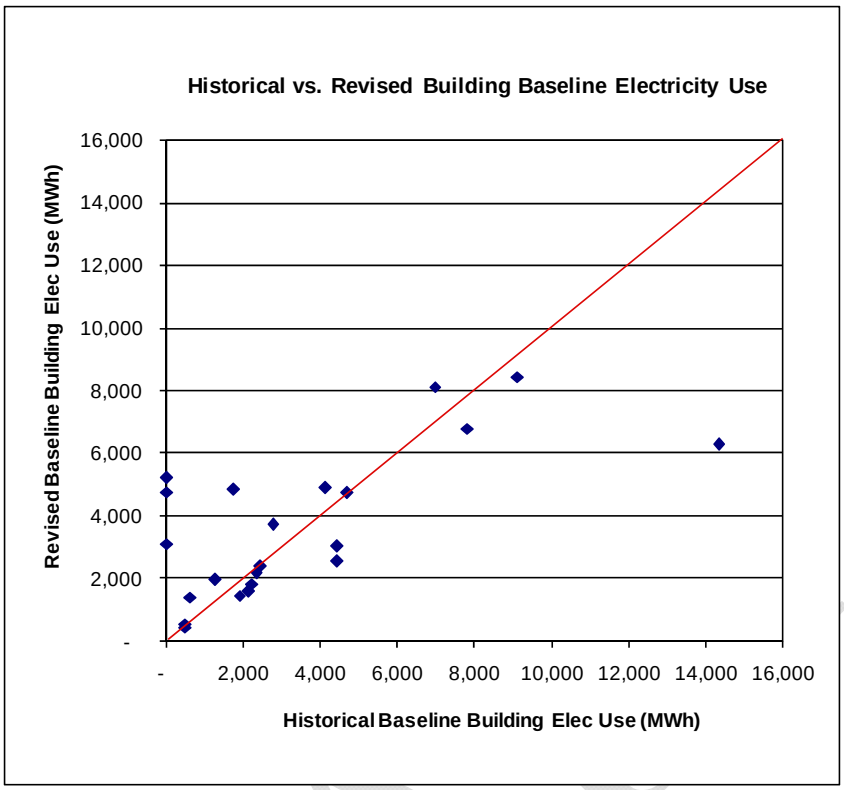


*Figure 16. Historical vs. revised baseline building electricity use*

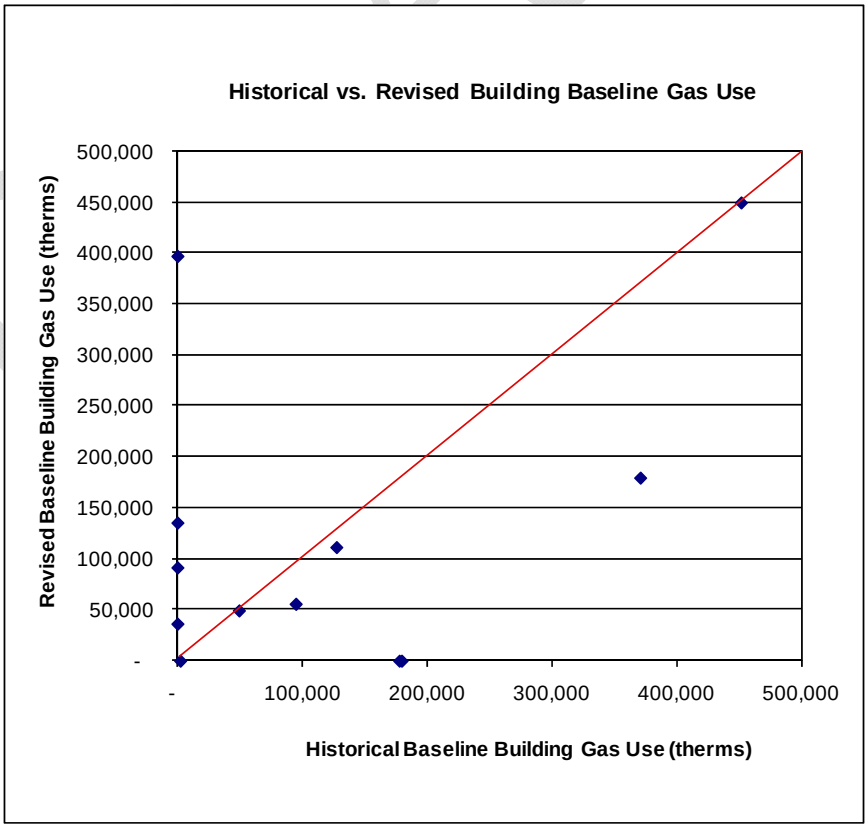

*Figure 17. Historical vs. revised baseline building gas use*

Figure 18 through Figure 20 compare the target vs. reported savings for total electricity, gas, and peak demand respectively. The data show that a majority of projects exceeded their targets.

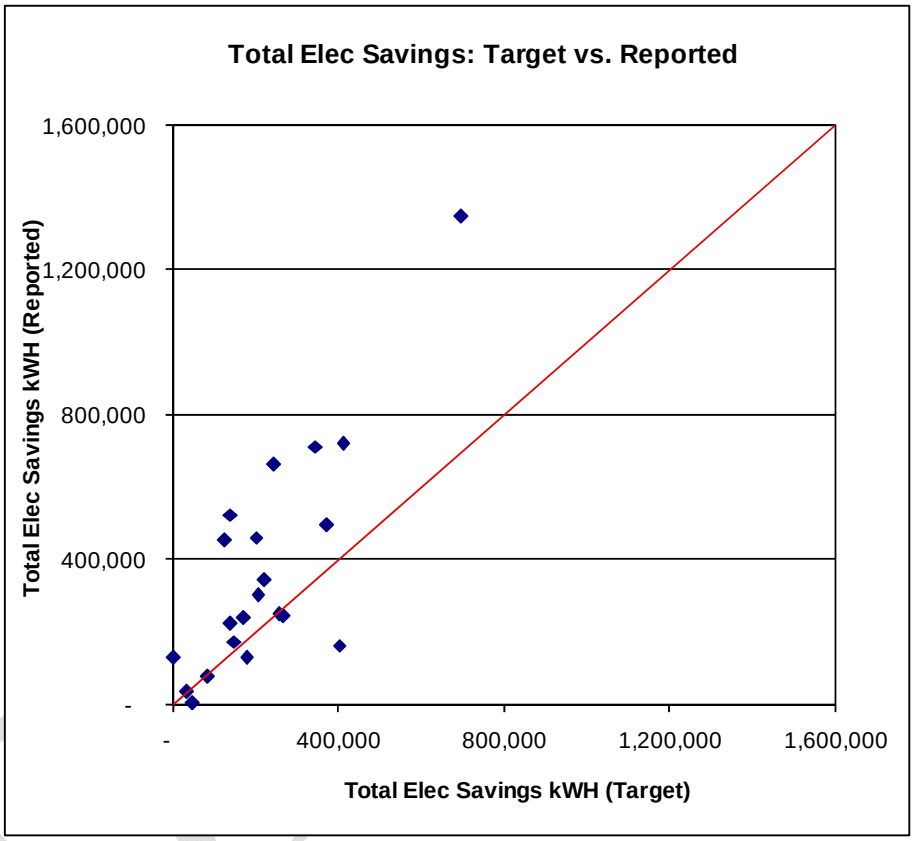


*Figure 18. Target vs. reported total electricity savings*

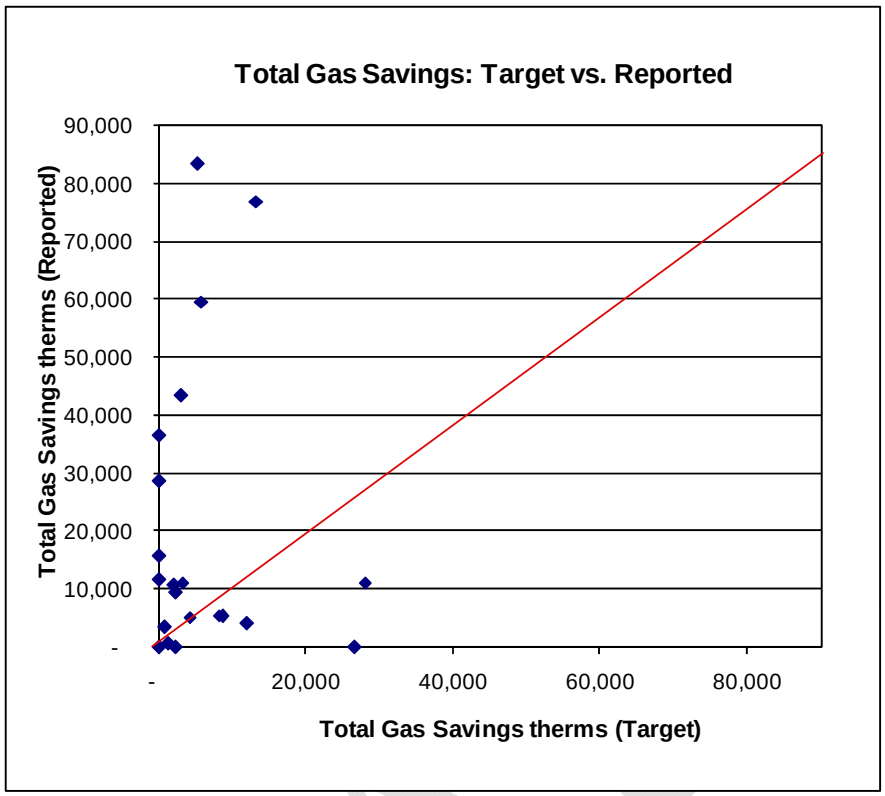


*Figure 19. Target vs. reported total gas savings*

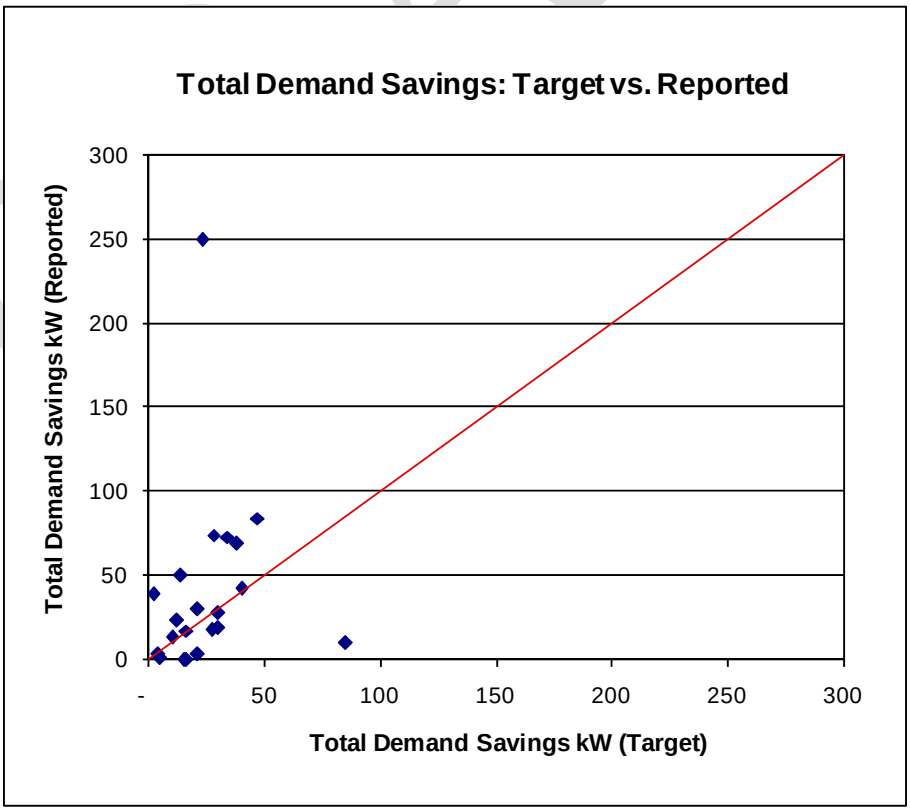

*Figure 20. Target vs. reported total demand savings*

# Conclusions and Areas for Further Study

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# Appendices

**Appendix A: Project Data**

**Appendix B: Key for Deficiencies-Measures Matrix**

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# APPENDIX J:
# Contract Task 2.4 Demonstrations

**DC Power Connectors for use in Data Center Applications**

DRAFT
John Halliwell, EPRI
November 13, 2008

**Introduction**
In previous work conducted by LBNL and other partners[1] in mid 2006, it was recognized that there was a need for a standard DC power appliance connector and a DC plug and socket-outlet system (hereafter call the connector systems) for server applications. There currently is no equivalent commercial market that can provide DC power connector systems that meet data center application needs while matching the required form factor while meeting safety agency certification. Server and power supply manufacturers are wary of committing to the use of DC power without readily available standard connector systems and connector system manufacturers want a viable market before committing resources to connector development. Facility managers don't want to install equipment that lacks Nationally Recognized Testing Laboratory (NRTL) approvals, such as UL or ETL.

Through the DC Power Partners (DCPP), it was hoped that the connector system issue could be moved forward such that a viable DC connector systems would be developed for data center use. In order for this to happen, it was recognized that the issue of standards and requirements would need to be addressed. Given the specialized nature of this discussion, the DCPP formed an ad hoc subcommittee to address the DC connector system issue.

**DCPP - DC Connector Subcommittee**
In March of 2008, a subcommittee of the DCPP was formed to investigate the connector system issue for DC power applications in data centers. This ad hoc committee consisted of members from connector systems, server and power supply manufacturers and other interested parties. Brian Davies of Anderson Power Products accepted the role of de facto chairman for the committee. Through a series of phone conferences held monthly, the group has sought to address a number of issues related to DC power connector systems.

Some of the key goals of the sub-committee have been to:

[1] DC Power For Improved Data Center Efficiency, Ton, Fortenbery, Tschudi, January 2007, Lawrence Berkeley National Laboratory's (LBNL) "High-Performance High-Tech Buildings" Project/California PIER Program

- Harmonize the US effort for DC appliance connectors and plugs and socket-outlets with the EU and Japan/Asia (avoid the situation seen in AC power connectors today)
- Assess existing efforts to develop DC connector system standards worldwide and support them wherever possible (including safety standards)
- Review connector systems currently available in the marketplace
- Define a connector form factor (based on server needs, safety and electrical specifications)
- Define connector system current and voltage ratings
- Specify durability (wear during connect/disconnect)
- Define the overvoltage category
- Draft connector system specifications

Lack of accepted world standards has hindered DC power connector systems development for high voltage DC applications. While there are connector systems capable of handling high voltage DC in a number of current ranges, they lack both the proper form factor needed at the server level and NRTL safety certification. Not only are standards for the form factor lacking, but safety standards may also need to be developed or adapted from existing AC connector system standards to address the unique properties of DC power applications.

The sub-committee has considered the work of several standards bodies that are addressing DC power connector systems for high voltage (nominally 400Vdc) for appliances. These include:

- The DC Power Partners DC Connector Subcommittee
- CENELEC TC 23Bx working group 7 - initiated work to define a 400 VDC plug and socket-outlet system based on IEC 60884-1 "Plugs and Socket-Outlets for Household and Similar Purposes" (Wim de Kesel – convenor).
- CENELEC TC 23 Working Group 8 - evaluate electrical accessories within the scope of the TC for direct current applications (Wim de Kesel – convenor)
- ETSI EE 2. (Didier Marquet, chairman) – working to make a world standard for DC power connectors (basis of work is the EN 300 132 standard.
- NEMA – establishing a Technical Advisory Group (TAG) in the US to coordinate efforts of the IEC Technical Committee 23 Working Group 8 (Dennis Oddsen – Technical Advisor)
- Japan – no specific effort was identified; dialogue was started with DCPP members from Japan

**Form Factor**

Early in the discussion of DC power appliance connectors for application in data centers, it was decided that the connector form factor be compatible mechanically with the IEC320 plug and socket products currently used by server and server power supply manufacturers. This allows for retrofit of existing server case designs with DC power without the need to redesign server enclosures. The subcommittee felt that this was critical to speeding the adoption of DC power. In addition, it opened the possibility of field retrofitting of existing servers with DC power.

The form factor for the plug and socket outlet system was based on a frequently used dimension in industrial installations. It was also taken into account that the dimensions should be such that the socket-outlet can be used with the existing flush-mounting boxes all aver the world. In addition, the plug and socket-outlet should be as small as possible.

Another topic that arose in early discussions was the inclusion of an interlock, or safety in the basic DC power connector design. It was felt that this might be needed, both as a safety issue, and to help in addressing hot mating of power connectors. Testing conducted by several group members led to the decision that an interlock would not be needed for a 400Vdc connector with a maximum 5 amp rating. Connectors that seek to deliver higher currents were not addressed by the sub-committee as it was felt that they would not be needed in a typical data center application.

**Current and Voltage Rating**

Much discussion within the sub-committee centered on setting the desired current and voltage capabilities for the connector systems. The group set a goal of harmonizing US efforts to develop DC connector systems with ongoing efforts in the EU. Key concerns with such a linking were the expected slow pace of standards development for the connector systems at the international level and the fear that attempting to cover too many application needs with one set of connector systems would overcomplicate the connector system design process. The group settled on a set of connector systems rated for nominal 400Vdc and 5A maximum current. It was also decided to rate the appliance connectors as Category II for overvoltage (requiring a 2500V standoff capability) and to rate the plug and socket-outlet system overvoltage category III. See Appendix D for an in-depth consideration of overvoltage categorization. It was felt that this would not be an issue at the 5A level in an IE60C320 mechanical form factor. The 400Vdc rating is compatible with current power supply front end designs and with battery power sources.

**Durability**

Testing conducted in Europe by Netpower Labs and Legrand and in the US by Anderson Power Products (see also Appendix B and C) has shown that the key factor for connector wear is the inrush of current that occurs when the power connector is mated in a hot condition (see Figure 1 for photos of testing results). Due to the capacitive nature of the server appliance input, little or no arcing occurs at disconnect, but a large surge current occurs at mating. The peak value of this inrush current was found to be primarily related to the input capacitance of the power supply and not related to the current rating of a power supply. IEC standards for inrush (found in EN 300132 ) were focused on preventing nuisance tripping of overcurrent protection devices and are therefore specified as a multiple of the current rating of a load. This connection of current rating and the overcurrent inrush has been shown not to apply in the DC connector case for capacitive power supply inputs.

There is little agreement between the various international standards regarding the number of cycles a plug/socket combination or an appliance coupler system must be able to endure under worst case voltage and current conditions. While IEC60320 requires

1000 cycles, EN60884 requires 5000 cycles and UL requires 200 cycles. The testing conditions (load circuit, circuit impedances and the like) also vary from standard to standard. Based on the limited number of connect and disconnect cycles expected in data center applications and the capacitive nature of the server power supply's input, the DC connector sub committee agreed to a standard that allowed for 50 connect/disconnect cycles into a capacitive load with a limiting resistance adjusted to achieve a peak inrush current of 200A. The connector is tested under a steady state load current of 6.25A and at a voltage of 440Vdc which are designed to represent worst case conditions. The peak inrush current of 200A is based on the worst case input capacitance of server power supplies and the test results described in the previous paragraph.

The sub-committee has proposed that a standard test circuit and protocol be defined. A draft of the proposed standard for the DC connector is included in Appendix A of this document.

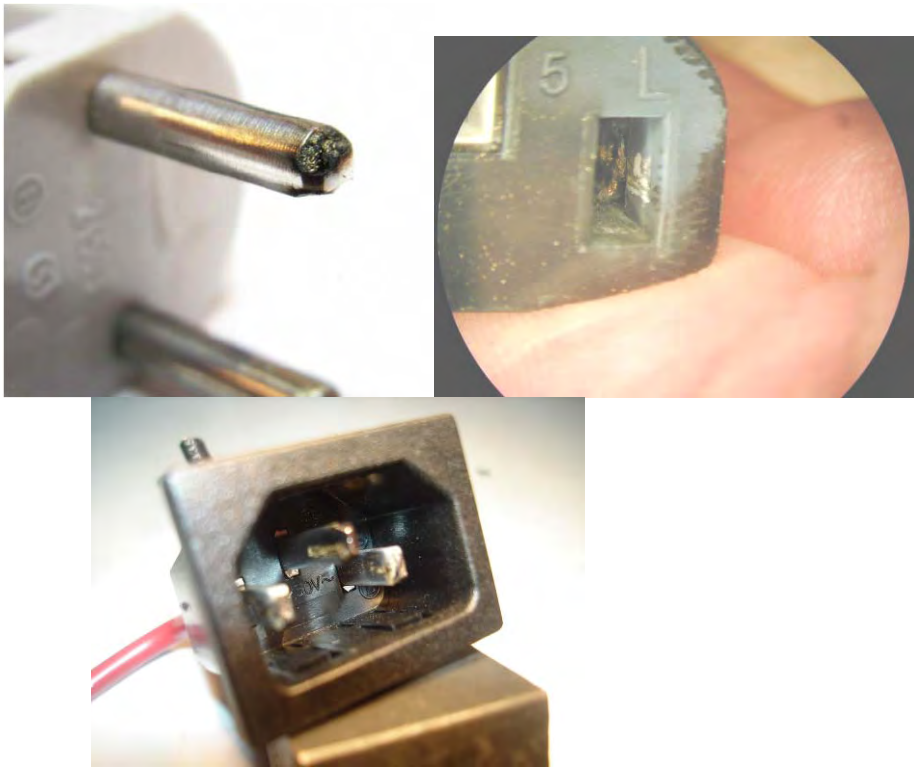


Figure 1- Photos of connector wear due to high voltage DC inrush current (upper left: testing conducted by Netpower Labs; upper right and lower left: testing conducted by Anderson Power Products)

**Prototypes**

At least one US manufacturer (Anderson Power Products) is pursuing manufacture of limited quantities of connectors from this specification. Submission to a Nationally Recognized Testing Laboratory (NRTL) is being contemplated, but may require progress toward commitments from power supply and/or servers manufacturers to use a sufficient quantity of connectors to justify the certification.

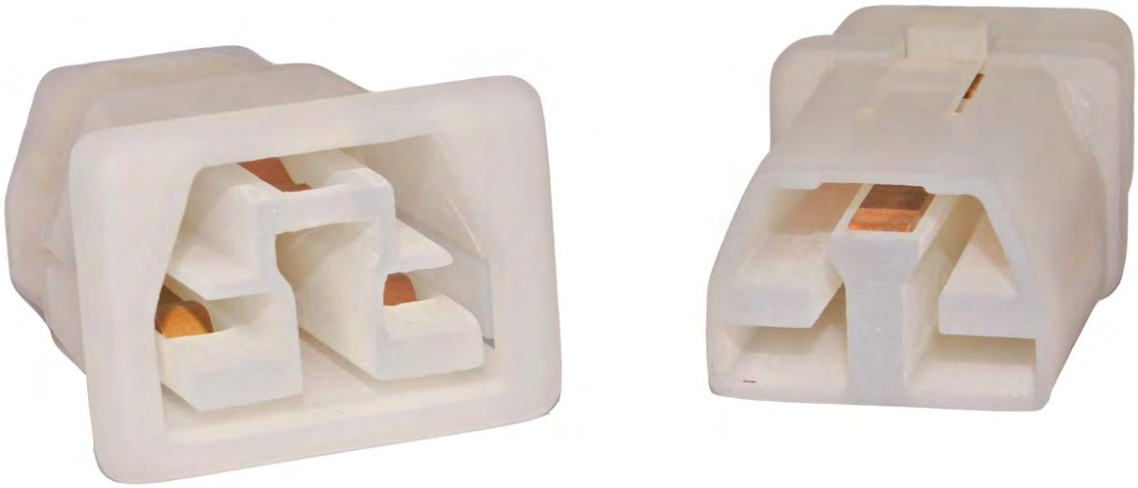


Figure 2- Prototype Connector Design (Anderson Power Products)

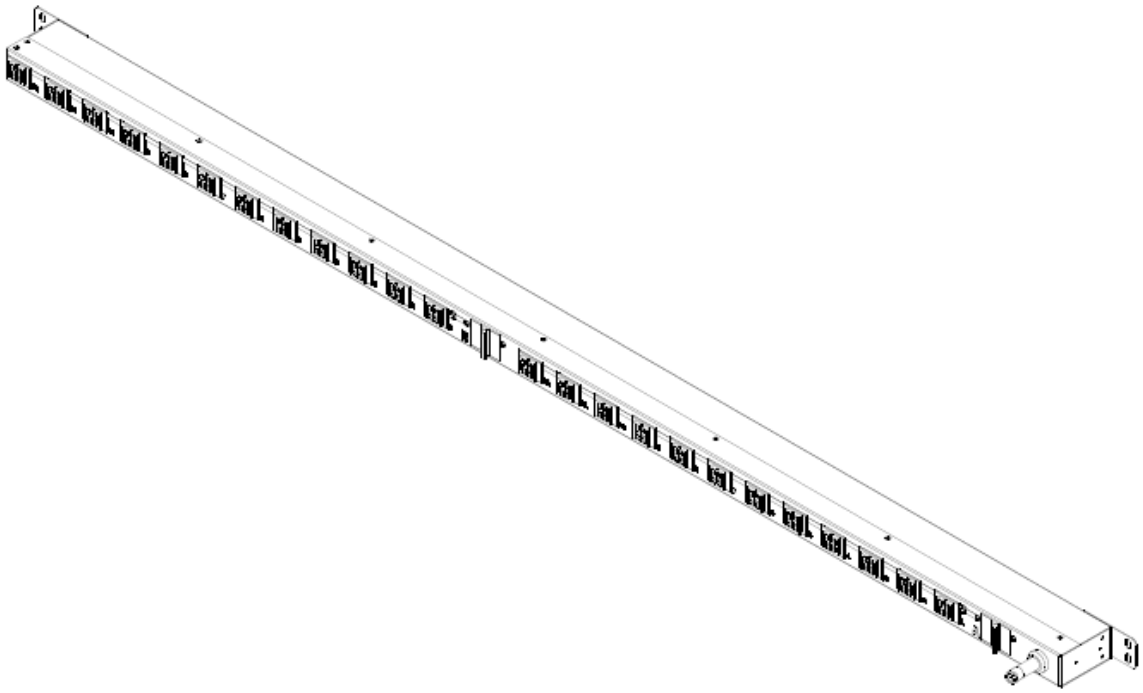


Figure 3 – Proposed Plug Strip.

**Connector Specification**

The DC connector sub-committee of the DCPP group has laid out a framework and foundation for future DC power connector progress. A draft specification defining many of the key parameters for a connector suitable for use in data centers has been completed (see Appendix A for the full document).

The connector specification document was drafted by Brian Davies of Anderson Power Products. His efforts included review of the CENELEC TC23BX WG7 draft for the 400Vdc version of IEC60884-1 (electrical plug and outlet). Based on this review and sub-committee member participation the following key 400VDC Appliance Connector specifications were developed:

- Nominal Operating Voltage 350 to 400 VDC
- Current rating 5A
- Ambient Temperature Range -5C to +55C (NEBS specification)
- Creepage and Clearance distances from IEC 60664, 4.0mm basic insulation, 8.0mm reinforced insulation
- Dielectric Strength, adopt CLC TC23BX proposal 3000VDC
- Temperature Test, adopt CLC TC23BX proposal 7.5A for 1 hour, maximum 45C rise
- Making & Breaking test, adopt CLC TC23BX proposal (influenced by findings of our committee members) 440VDC, 6.25A With an inrush current of 200A for 20 microseconds, 50 cycles
- Normal Operation Test, adopt IEC60320 standard, CLC TC23BX proposal considered overkill for appliance connector, consensus is that 400 VDC connector should meet same normal operation requirements of 220V connector standard except for operating voltage. 400VDC, 5.0A make and break 1000 cycles, 3000 cycles without current

The complete draft connector specification is included in Appendix A.

# APPENDIX A

Draft DC Connector (with emphasis on data center applications) Specification
Authored by Brian Davies – Anderson Power Products

DC Appliance Connector for Telecommunications Equipment

1. Scope

This specification applies to DC power inlet connectors for telecommunications equipment with rated nominal voltages from 350V to 400V

2. References

The following documents contain provisions which, through references in this text, constitute provisions of this specification.

IEC 60950, UL 60950
IEC 61302
IEC 60227
IEC 60245
IEC 60320
IEC 60512
IEC 60529
IEC 60664
IEC 61984

3. Definitions

4. Construction Requirements and Performance

4.1. General

Connectors shall be designed and constructed so that their performance is suitable for use in equipment designed and manufactured to IEC 60950 and UL 60950 standards. Connectors shall be reliable and without danger to the user or surroundings in normal use. Compliance shall be determined by carrying out all the tests as specified.

4.2. Construction

4.2.1. Connectors shall have terminals of the following type and quantity

- 2 line contacts of opposite polarity
- 1 protective earthing contact

4.2.2. Connectors shall be designed so that there is no risk of accidental contact between the current carrying contacts and the earthing contact. Compliance is checked by inspection

4.3. Standard Ratings

4.3.1. Standard rated current is 5 amp

4.3.2. Nominal rated voltage is 350 to 400 VDC

4.4. Marking and Identification

4.5. Clearance and creepage distances

Clearance and creepage distances shall not be less than the values shown in table 1. Compliance shall be checked by measurement

Table 1

| Minimum clearance and creepage distance | mm |
|---|---|
| between live parts and accessible metal parts<br>between live parts and the mating surface | 8.0 |
| between live parts of different polarity<br>between live parts and the earthing circuit | 4.0 |

4.6. Terminals, termination and cords

4.6.1. Connector terminals shall be so designed to terminate conductors of a cross-sectional area as specified in table 2.

Table 2

| | | | | |
|---|---|---|---|---|
| 16 awg | 1.5 $mm^2$ | 14 awg | 2.5 $mm^2$ | 12 awg |

4.6.2. Connector terminals shall be so designed to not dislocate when a pull is subjected to the attached conductor. Compliance shall be determined by test using a 20 lbs., 89 N force The force shall be applied to each conductor, in the direction of the axis of the terminal, for 1 minute without jerks. During the test, the conductor shall not move noticeably.

4.7. Cords (non re-wire able connectors)

Non re-wire able connectors shall be provided with a cord complying with either IEC60227 or IEC 60245

4.8. Re-wire able connectors

4.9. Provisions against incorrect mating

4.9.1. Connectors shall be designed so that electrical contact with IEC 60320 connectors is not possible by engagement. Compliance shall be determined by IEC 60512 test 13e, test force 20N.

4.9.2. Connector shall be designed so that contact between live contacts and protective earthling contacts is not possible by engagement. Compliance shall be determined by IEC 60512 test 13e, test force 20N.

4.10. Protection against electric shock

4.10.1. Connector shall be so designed that, when mounted and mated, its live parts are not accessible. Compliance shall be determined by test using the test pin per Figure 2B of IEC 60950

4.10.2. Plug or cord connector shall be designed so that, when terminated, its live parts are not accessible. Compliance shall be determined by test using the finger probe per Figure 2, test probe B of IEC 61302

4.10.3. Appliance inlet connector shall be design so that, after mounting, its live parts are not accessible. Compliance shall be

determined by test using the finger probe per Figure 2, test probe B of IEC 61302

4.11. Provision for earthing

The connector shall have a “first mate, last break” protective earthing contact. Compliance shall be determined by test per IEC 61984 section 7.3.3

4.12. Protection against accidental disconnect

The plug and inlet connectors shall so designed so as to not disconnect when a pull is subjected to the attached conductor. Construction of connectors shall allow the easy release of the plug from the inlet connector without provision for a tool.

Compliance shall be determined by test using a 20 lbs., 89 N force The force shall be applied to the conductor, in the direction of the axis of disconnection, for 1 minute without jerks. During the test, the plug connector shall not release from the inlet connector. Ease of release of the plug connector shall be determined by observation.

4.13. Temperature rise

The temperature rise of the contacts measured at the hottest point shall not exceed 45$^{o}$C. Compliance shall be determined by test at 7.5 amps according to IEC 60512 test 5a.The sum of the ambient temperature and the temperature rise of the connector shall not exceed 100$^{o}$C

4.14. Making and Breaking capacity

The connector shall have a breaking capacity greater than 5.0 amp. Compliance shall be determined by the following test.

The appliance inlet connector and plug connector shall be mounted horizontal to the axis of the test apparatus. The connector shall be connected and disconnected 50 times (100 strokes) at a rate of 30 strokes per minute. The length of the stroke shall be between 50mm and 60mm. The test voltage shall be 440VDC. The test load shall be 6.25 amps and the connector shall be connected in series with a capacitor and variable resistor such that a 200 amp in-rush current is maintained for 20 microseconds.

No current shall pass to the earthing circuit or the metal mounting of the appliance inlet connector. There shall be no flashover between live parts of different polarity nor shall there be sustained arcing. After the test, the contact plating shall not be breached in the area of electrical engagement at full mechanical engagement of the connector and the insulation around the contacts shall not show serious damage impairing its further use. The specimens shall withstand a dielectric strength test of 3000VDC

4.15. Normal Operation

Appliance connectors shall withstand without excessive wear or other harmful effects the mechanical, electrical and thermal stress of normal operation. Compliance shall be checked by testing connectors in the apparatus described in section 4.14

The appliance inlet and plug connector shall be connected and disconnected 1000 times (2000 strokes) at 400VDC with a non-capacitive 5 amp load and 3000 times (6000 strokes) without current flowing.

After the test, the contact plating shall not be breached in the area of electrical engagement at full mechanical engagement of the connector and the insulation around the contacts shall not show serious damage impairing its further use. The specimens shall withstand a dielectric strength test of 3000VDC

4.16. Arc flash

The connector shall be constructed such that the arc flash from current making and breaking is contained within the body of the connector. Compliance shall be determined by observation and test; section 4.15

4.17. Dielectric strength

The connector shall withstand the voltage proof test according to IEC 60512 test 4a using an impulse voltage of 3 kV for 1 min

4.18. Resistance to tracking

Insulating materials shall have a comparative tracking index of material group IIIa or better.

4.19. Ambient temperature limits

4.20. Connector shall comply with a lower temperature limit of -5$^{o}$C and an upper temperature limit of 55$^{o}$C

4.21. Resistance of insulating materials to heat and fire.

Insulating materials shall be rated UL94V0 or better

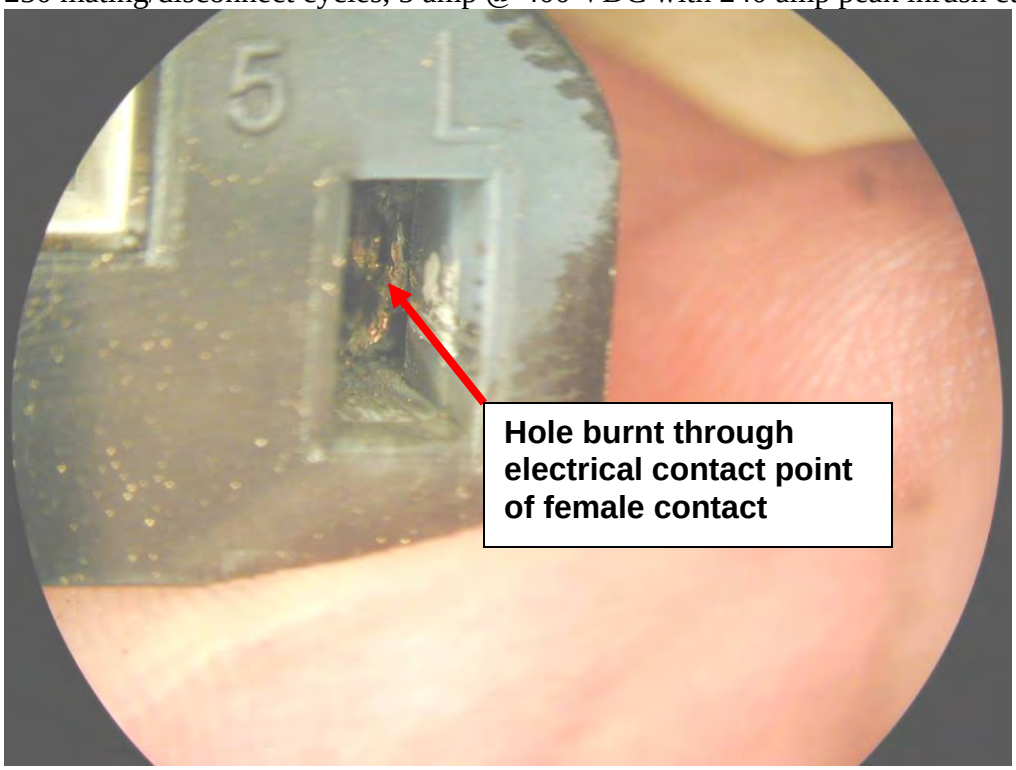
4.22. Forces necessary to insert and to withdraw connector

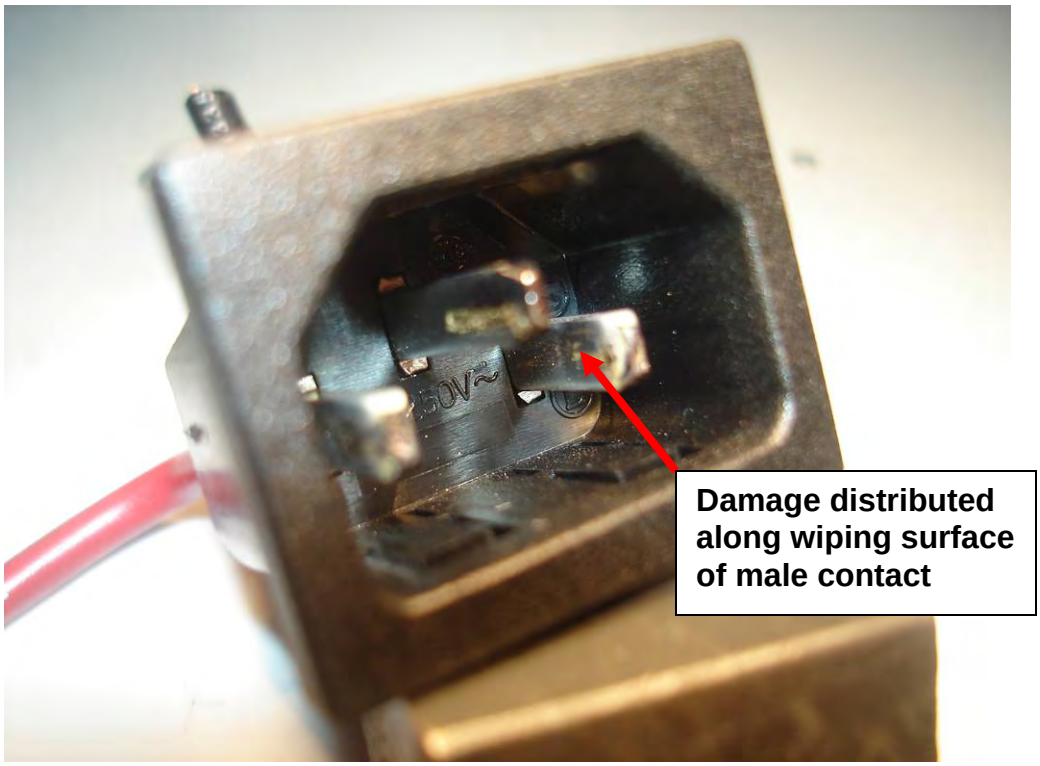
Construction of connectors shall allow the easy insertion and withdrawal of the connector.

# Appendix B

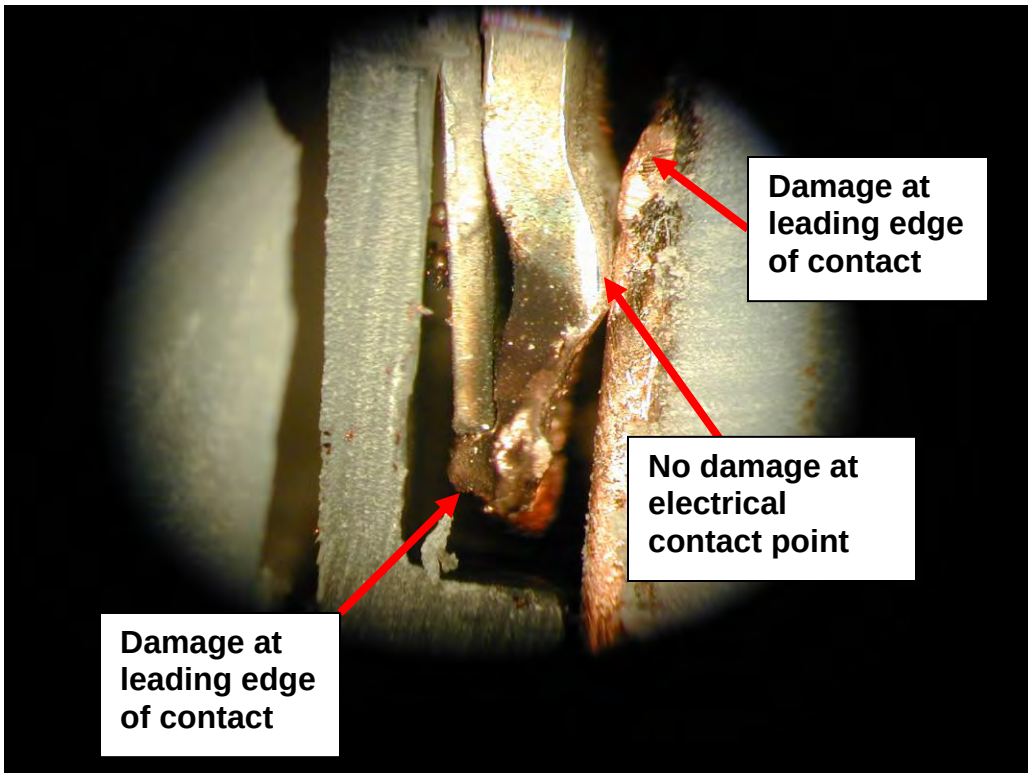
Testing Conducted by Anderson Power Products
Authored by Brian Davies – Anderson Power Products

Anderson Power Products Hot Mating Test
IEC 320 Plug and Receptacle –
250 mating/disconnect cycles, 5 amp @ 400 VDC with 240 amp peak inrush current



Anderson Power Products Hot Mating Test
APP 400VDC appliance connector prototype
250 mating/disconnect cycles, 5 amp @ 400 VDC with 240 amp peak inrush current




The Anderson Power Products, Power Pole® contact system is designed such that arcing damage is limited to "sacrificial" leading areas of the contact. The arcing damage does not compromise the integrity of the point of electrical contact once full connector mating is achieved.

With IEC 320 female contact, the point of arcing damage is one and the same as the final point of electrical contact. Damage from arcing will degrade IEC 320 connector performance, increasing resistance, with the prospect of cascading thermal failure.

The Anderson Power Products, Power Pole® contact system, although fully functional after 250 hot mating cycles of 240 amp in-rush current, would not appear capable of meeting a 1000 cycle specification. APP is re-designing the contacts to increase the mass of the "sacrificial" leading areas which will extend the life. Even with this enhancement, it is unlikely this or any IEC320 size product will pass a 200 amp in-rush for 1000 cycles.

Anderson Power Products recommends that the specification for mating life of a 400 VDC appliance connector be specified as follows:
250 cycles, 200 amp in-rush current for 10 milliseconds
1000 cycles, 5 amp resistive load
3000 cycles, no load

**Appendix B**

Draft test sprecification for DC plugs and socket-outlets (with emphasis on data center applications) Specification
Authored by Wim De Kesel – Legrand – based on the work done by CLC TC23BX WG7
The details first draft standard will be available beginning 2009

# 1 Discussion on the conclusions of the ad hoc group 2 on the architecture of the distribution system – TC23BX/WG07/Conv0039/INF

## *1.1 Ratings*

The convenor went through the document explaining the different issues. The following conclusions are made:

- the working voltage of the plug and socket-outlet will be normally between 350 and 380V. The rated voltage of the system is 400V.
- 95% of the servers used in data centres have a consumption less than 1000W.
- This means that with a plug and socket-outlet system rated 5A, more tan 95% of the cases are covered.

## *1.2 Insulation resistance and electric strength*

It was agreed to use the values as propose in document TC23BX/WG07/Conv0033A/CC for both subclauses:

### 1.2.1 Insulation resistance :

DC voltage 1000V 1min

Insulation resistance ≥ 5MΩ

### 1.2.2 Electric strength

3000V DC for 400V accessories

## *1.3 Temperature rise test*

In TC64, the maximum current flowing under normal conditions is 1.45 times the rated current.

The WG agreed on:

- a temperature rise test at 7.5A for 1 hour with
- limit being 45K

## 1.4 Making and breaking test

The loads relevant to dc installations are capacitive. Thus, it is the inrush current which is important.

Tests have shown that the inrush current of a typical load is not dependent on the rated current of the load. The inrush current is normally between 140A and 180A. These figures have been confirmed by US experts.

In addition, the ad hoc 2 based his conclusions on the EN300132-2. But this standard is more relevant to the 48V systems used in telecommunication but not to the newly designed 400V dc systems. ETSI agreed to review this standard in view of the 400V dc distribution.

After a long discussion the WG agreed on the following characteristics for the making and breaking:

- 440V dc
- 6.25A dc
- With an inrush current of 200A with a profile close to figure 2 of the EN300132-2
- 50 cycles at a speed as defined in the IEC60884-1 for a 250V system.

440V is 1,1 times the rated voltage and 6.25A is 1.25 times the rated current (equivalent to the requirements of IEC60884-1).

A question was raised if the profile as given in the EN300132-2 is relevant for a 400V dc system. This will be further analysed by the ETSI experts.

## 1.5 Normal operation

Following the requirements for an ac system, the WG agreed on the following specifications

- 400V dc
- 5A dc
- Inrush current 50A with a profile close to figure 2 of the EN300132-2
- 5000 cycles

Evaluation after the normal operation tests

- temperature rise test done at rated current
- limit being 45K
- Electric strength: reduced to 2000V DC for 400V accessories

# Distribution TOC High Level

## Executive Summary

A comparative analysis was conducted for two data center power distribution schemes. One was based on a conventional data center design where power is distributed to rack mounted servers at 208Vac. A second system was analyzed where power was delivered to the servers at 380Vdc. This study concludes that the DC power data center has a number of advantages including: a reduced footprint; lower power consumption for a given server load; reduced cooling due to lowered energy consumption; and reduced cable plant cost.

## Introduction

Through the DC Power Partners organization, the Electric Power Research Institute in cooperation with Lawrence Berkley National Laboratory has been working with a group of data center industry stakeholders to investigate the potential benefits of the use of 380VDC power distribution in data centers. When compared on strictly an efficiency basis, the DC powered data center shows promise for improved system efficiency. Such an isolated comparison of the two power schemes, ignoring equipment cost impact, does not reveal which system may be more practical from a cost standpoint in a real world application. This study has attempted to use real data for all efficiency values and has sought guidance and input from data center stakeholders in obtaining cost, physical layout and structural data for the designs that are analyzed.

Comparison of data center structures, especially when different power distribution schemes are considered is a difficult task. Building a meaningful comparison of data center systems that have both physical and electrical differences requires consideration of how to “build” equivalent systems. For this analysis, power consumption at the server level was considered as the basis for comparison. Each data center considered is assumed to have the same number of servers consuming the same amount of power at the server motherboard level. Independent of their physical or electrical layout, these data centers would offer the same amount of “computing” power as a system. Since computing power is the product of a data center, an analysis based on comparison of data centers with equivalent compute power, independent of the power scheme, should provide an unbiased evaluation of the systems.

## Analysis Philosophy

Consideration has been given to a full, end to end, Total Cost of Ownership (TCO) analysis for the competing data center power schemes. In planning and developing our analysis scheme during the course of this effort, it became obvious that such a full TCO analysis will require a full data center design to be developed, complete with all components specified and with actual cost data collected for each component. Within the constraints of time and budget, a more preliminary study has been undertaken and is reported on in this document. It is

hoped that this study will act as a basis and springboard for a future, more detailed TCO analysis effort.

Limiting the scope of an analysis has both advantages and disadvantages:

Pros:

- Focuses on areas of interest
- Yields results with a less complicated model
- Is not as influenced by design nuances
- Can be limited to readily available data

Cons:

- May miss factors that impact the cost or performance of a system
- The simple model does not reveal the impact of system layout on cost and performance
- Is not a truly, real world, assessment

Understanding these limitations, there is still value in a simplified analysis approach. For this analysis, three key areas have been identified for inclusion in the study:

- Material cost for large capital items unique to each system structure
- An estimate of the copper plant needed to provide power to the system based on an assumed layout geometry, power consumption, delivery voltage and wire ampacity
- Calculation of the data center input power based on a fixed server motherboard load, reflecting the operational efficiencies of the full power chain (from motherboard to medium voltage input)

It is assumed that the servers themselves would be identical for each system, varying only in the power supplies installed in the server and the voltage feeding these power supplies. Many other system components, which are common independent of the power scheme, are not considered since they will not result in a cost differential between the designs. The greatest limitation of the analysis is the failure to capture cost impacts at the sever power supply level. For the example analyzed there were 7680 servers. For a 2N system, this implies the use of 15,360 power supplies. Due to these large numbers, variation in power supply cost between the AC input and DC input versions could have a significant impact on capital costs. If AC input power supplies were $100 each and the DC version was 30% more expensive (due to smaller production volumes), this would result in a cost impact of over $460k.

A Tier 4 data center design, with 2N redundancy is used, since this is a common data center form and represents a worst case scenario for system efficiencies (due mainly to the very light loading of system components under normal operating conditions).

## System Architectures

Two system architectures are considered for comparison. The 480Vac-208Vac design represents a common current form of data center power distribution design. The proposed 380Vdc system seeks to optimize system efficiency by elimination of the several system component layers.

### *480Vac-208Vac Data Center*

This represents a basis design and is a common design used in the data center industry. Components for this system are well matured with many vendors working to improve efficiency for each system component. Figure 1 shows a simplified one-line diagram of the system layout. The key components used in this analysis are highlighted in the red box on the figure.

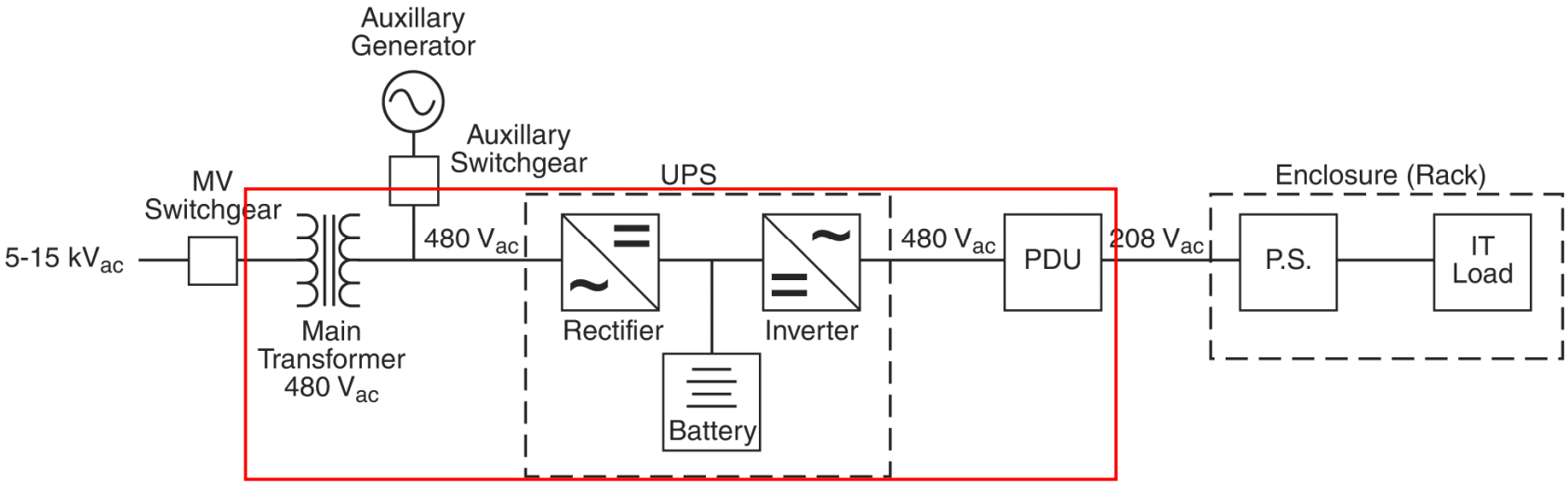



**Figure 1**
**480Vac-208Vac Reference Design; Red box highlights key elements addressed in the cost comparison**

Source: Uptime Institute

### *480Vac-380Vdc Data Center*

This is a proposed architecture that has been used in a limited number of applications. Figure 2 shows a simplified one-line diagram of the system layout. Some of the components (mainly the server power supplies) are not readily available in the commercial market. As can be seen in comparing Figures 1 and 2, the 380Vdc system has fewer layers of lossy components between the medium voltage power source and the server motherboard. Losses at the motherboard cascade up the power chain. Simply reducing the number of lossy components in the chain has the potential to improve overall system efficiency. The components that are the focus of this study are contained in the red box shown in the one-line figure.

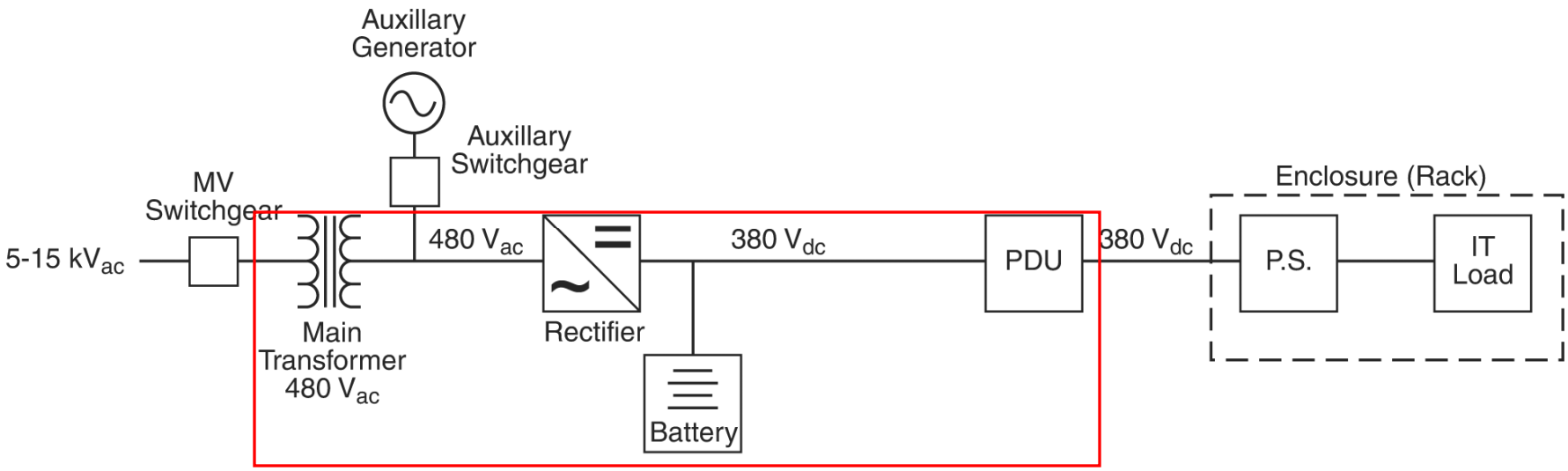



**Figure 2**
**380 Vdc, facility-level and rack-level distribution; Red box highlights elements considered in cost comparison**

Source: Turner P, Seader H, Brill K, Tier Classifications define site infrastructure performance, Uptime Institute.

## Power Calculations

Power calculations are based on system component loading that would be found in a Tier 4, 2N system. The worst case efficiencies occur at the server power supply due to the fact that these supplies are often loaded at less than 20% of their rated capacity. The efficiency numbers used in this study come from single output server power supply testing conducted by EPRI in 2007-08. These represent lab measurements of power supplies at light loading levels. Due to the previously mentioned cascade effect, power loss at the server is multiplied by all the losses in the power chain, making the server power supply efficiency a critical element in overall system performance.

Power at the sever motherboard is assumed to be a fixed value of 180W for each data center design. The fixed power represents equivalent “compute” capacity for each system. Since the efficiencies of the two power schemes do not match, the power required at the system inputs is not matched, even though they produce the same compute power.

Table 1 shows how the cascade of system layers impacts efficiency for the two systems.

**Table 1 - Power Flow in Data Center System**

| *Power in MW* | Server Load | PDU Load | UPS/Rect Load | XFMR Load | Total Load |
|---|---|---|---|---|---|
| 208Vac | | | | | |
| Best Case | 1.382 | 1.589 | 1.655 | 1.881 | 1.939 |
| Worst Case | 1.382 | 1.975 | 2.057 | 2.338 | 2.410 |
| 380Vdc | | | | | |
| Best Case | 1.382 | 1.503 | 1.503 | 1.582 | 1.631 |
| Worst Case | 1.382 | 1.686 | 1.686 | 1.775 | 1.829 |

## Cable Plant

Data center power wiring represents a significant system capital cost and installation cost. Comparing two data center designs that are not fully developed (down to the nuts and bolts level) requires that some simplifying assumptions be made. For this analysis, it was assumed that the two data centers would have the same physical layout and thus equivalent cable lengths. Wire sizes reflect both the power level at a given point in the system and the current required in delivering that power. A section of wiring operating at higher voltage will deliver the same amount of power as a lower voltage at a lower current level. This allows wire sizes to shrink as voltage is increased. For the designs considered, 480Vac will result in the lowest system currents and smallest wire gauge needed to deliver a given power level, then 380Vdc and finally 208Vac. The calculations used to assess the cable plant reflect the estimated lengths cable runs at each system voltage. There is an advantage in delivering power at the highest possible voltage over the longest distance possible.

In order to avoid the need to design around specific wire, cable or bus-way types, the calculations used in this comparison focused on calculating the volume and mass of copper required to deliver power at a given voltage. Since cable cost is directly related to the amount of copper used, it was felt that this would provide a good metric of relative cable costs across different system architectures without the need to address specific cable types or the impact of the detailed system physical layout. The comparison is based on the assumption that the power cables would be laid out in identical fashion independent of the delivery voltage. This metric does not take into account the impact of possible non-linear variations in cable or bus-way cost as a function of gauge or size.

### System Cost

The system cost comparison is based on consideration of large capital cost items that are unique to each system type. This was done to avoid the need for a fully detailed bill of materials for the complete data center. Thus, the system cost reported reflects more the cost differential between system power architectures and not the total cost of a data center's hardware. A more accurate assessment of TCO would be obtained by capturing more of the system components. This issue is discussed in the future work section of this report.

### Results of Analysis

Table 2 provides a summary of the result of the study. The key metrics tabulated are Selective Capital Cost, Energy Usage, cable plant Copper Usage by Weight, and the Energy Cost per Year (based on 8 cents per kWh). The System Input Power shows a range of values based on the best and worst case efficiencies for server power supplies.

**Table 2 - Summary of Data Center Comparison**

| | 480Vac-208Vac | 480Vac-380Vdc |
|---|---|---|
| Selective Capital Cost | $2,720,000 | $3,000,000 |
| Energy Usage | 1.94 - 2.41 MW | 1.63 - 1.83 MW |
| Copper by Weight (kg) | 5556 | 5909 |
| Energy Cost per year | $1.4 - 1.7M | $1.1 - 1.3M |

*Selective Capital Cost*

The selective capital cost is based on pricing of the major system elements based on the energy usage computed. Items considered in this cost comparison are those contained in the red boxes found in Figure's 1 and 2.

*Energy Usage*

The energy usage comparison looks at power consumption as influenced by the system efficiencies. The 380Vdc case benefits from having fewer lossy stages in the power chain and slightly improved efficiency at the server power supply level.

*Copper by Weight*
The copper weight is based on the delivering a fixed amount of power (2.4MW) at the system voltages over estimate copper run lengths. The assumption was made that the copper runs would be the same length for both data center cases. Two factors should be considered in assessing the results: power was assumed to be fixed, whereas, it will be lower in the 380Vdc case do to the efficiency advantages; power delivery below the PDU level was not considered – 380Vdc will have an advantage here due to the higher delivery voltage.

*Energy Cost per Year*
The best and worst case power consumption numbers were used to calculate annual energy cost assuming an 8 cent per kilowatt hour rate.

**Summary**

While based on simplifying assumptions, this study has shown the potential for cost and energy benefits that would result from the use of 380Vdc power distribution in the data center environment. The 380Vdc powered data center has a cost premium of about $280K. This cost adder is about the same as the energy cost savings for approximately a year and half of operation. Copper usage may be less for the 380Vdc system when cabling after the PDU is considered.

The 380Vdc system has a slightly higher capital cost for the large system components considered. This cost adder is compensated for by the cost differential in one year of energy usage.

While not fully conclusive due to simple models used, the study should provide a springboard to a more complete analysis in the future.

**Future Work**

This study lays the groundwork for a more in-depth data center comparison. By expanding the component list used in the comparison and estimating installation cost for the components, a more accurate assessment of the TCO can be made. It is felt that such a study will require that full data center designs be completed for each voltage distribution scheme. These designs would need to specify both physical and electrical layout and include full bill of material lists for all components used in the design. Such an exhaustive study, while yielding a more accurate cost for a given design is still subject to the difficult task of establishing equivalence of the designs and being sure that each design is fully optimized.

# A Demonstration Study on Liquid-based Spray Cooling Technology for Effectively Cooling IT Racks in Data Center

**Final Report**

**To**

**California Energy Commission**

**2008**

**Tengfang Xu**

**Lawrence Berkeley National Laboratory (LBNL)**

**Berkeley CA 94720**

**And**

**Rich Thomas**

**SprayCool, Inc.**

**And**

**Tahir Cader**

**HP Inc.**

## Overview

This  paper documents a study to demonstrate an alternative cooling technology, namely, liquid spray to provide cooling of servers in data centers, as part of research projects sponsored by California Energy Commission PIER program.

In this demonstration study,  the actual operating conditions are achieved by controlling servers at various loads, server inlet air temperatures (e.g., 68-80F), and supply cooling water temperatures (e.g., 65-85F)  considering cooling requirements for the selected servers installed in the data center.

This paper includes specific characteristics of the spray cooling module, characteristics of server loads, and measurements for use of evaluating operation performance under various operating conditions.  This paper includes the following sections:

- Technical objectives
- Technical information on the characteristics of the individual spray cooling system and servers
- Measured parameters
- Test procedures and sequence
- Data acquisition and compiling process
- Performance metrics for spray cooling
- Before- and after-integration tests

In combination with the evaluation of energy performance of spray and a modular cooling systems and that of the facility systems, estimates of potential energy savings will be discussed and may be drawn from the data analyses in the report.

# Demonstration Study on Spray Cooling System

### *Technical objectives*

The project intends to evaluate a modular localized cooling solution provided by vendor 2 for a data center located in Sun Microsystems, Inc. The evaluation included monitoring and measurement of selected parameters, and establishing and calculating efficiency metrics for the selected product, which is a modular, scalable pair of parallel cooling modules with hot aisle containment in this study.  The scope is to quantify energy performance of the modular cooling unit corresponding to various server loads and inlet air temperatures.

The information generated from this study may be used to estimate potential energy savings from implementing modular cooling compared to conventional cooling in data centers.

The spray cooling module provides a means of spot cooling heat generation sources inside servers with high-heat density in typical data centers.  Different from the majority

of modular, scalable cooling technologies that are increasingly applied in data centers, a spray cooling system captures a portion of the heat from typical CPU before the heat transfers to the ambient air using liquid spray cooling. Normally up to 40% of a typical server's heat can be removed directly by a spray cooling module [to insert a reference from spraycool], thereby reducing the net heat output to the ambient environment which in turn will reduce the cooling demand for air conditioning systems inside a data center. The demonstration study intends to evaluate and demonstrate the effectiveness of such an emerging cooling alternative for data centers, through performing on-site measurements and evaluation of a spray cooling system. The evaluation included monitoring and measurement of selected parameters, and establishing and calculating efficiency metrics for the spray cooling system. In this study, a spay cooling module works in combination with a modular cooling module with hot aisle containment [4]. The scope is to quantify energy performance of the spray cooling as it corresponds to server loads, inlet air temperatures, and water temperatures supplied to the spray cooling module.

## *Technical information on the characteristics of cooling systems and servers*

The study was performed in a data center space located in Santa Clara, California. The datacenter area was approximately 12,800 square feet, with a ceiling height of 13 ft 6 inches and no raised floor. All server racks and support equipment was installed directly on the slab floor. There were various types of servers, rack sizes, shapes, from various vendors. The data center was specifically designed to support racks with any type of IT equipment.

Power, chilled water, and communication cables to the server racks were provided through overhead pathways. 700 tons of cooling is provided to the space from the central chilled water plant for cooling the IT equipment. The chilled water is supplied by a 2,000 ton central chilled water plant.

Power for thirty six 150kW PDUs was provided through a 480v AC bus way system.. The 150kW power distribution units (PDUs) were located throughout the space. The PDUs transformed the power from 480v AC to 208v AC for distribution to the server racks. The data center currently can support 190 watts/ft$^2$ of floor area. The design load per rack footprint was 5kW/rack with growth to 9kW/rack.

### Server

There were 37 servers, each with a size of 28"x17"x1.75", in each of the server cabinets tested. . For this study, the thermal management unit was placed in the bottom of the rack, the manifold mounted to the side of the rack. The spray cooling equipment is designed to handle server load up to 15kW per rack, in this study however, the maximum load per server cabinet available for this demonstration was up to 12 kW. Details of the servers provided in this study are publicly available [1].

## Server power management

Using a commercially available software program, the load within each rack was to the was effectively controlled at desired levels by dynamically turning on and off servers and running a power management program [2] at various CPU loads to produce the necessary heat and power consumption. Prior to the test, reference measurements on each type of server that was in the racks were performed to measure idle and loaded power consumption. Depending on the load level (kW/rack) to achieve, the number of servers needed at 100% load was calculated to get power consumption to the levels needed and turned them on - and turned the rest off. For example, the number of servers used at each load level are 12kW - 37 servers; 5kW - 17 servers. Depending on the servers used (various models that were in the rack) and real time measurements of server power, adjustment of turn on/off additional servers were made to effectively achieve desired loads.

To manage the overall server power, we also manually arranged the servers in front of the air temperature probes at three heights to be on. In cases when we could not get enough servers to run at 100%, we added some idle ones to increase power consumption to the desired levels, or even just turned them on. In any case, power consumption was verified against the readings of the power strip and adjusted as needed until the power consumption was stable.

During the initial reference measures, the team recognized a difference in power consumption from various Sun V20 servers. Although the servers looked alike from the outside, they had different add-on boards significantly changing their power consumption.

## Cooling modules

One important aspect of this demonstration is to evaluate and verify the ability of spray cooling module to cool with non-chilled water. In order to vary the temperatures of water entering the spray cooling module, an additional coolant distribution unit (CDU) was installed and connected to the spray cooling system. The CDU was a separate skid was used to raise the chilled water temperature to simulate cooling tower water (Figure 1). The CDU consists of a water-to-water heat exchanger that provided isolation between the primary chilled water loop and secondary cool water loop that is connected to the modular system. The CDU contains its own pump and monitor equipment to measure primary and secondary chilled water pressure, temperatures, and flow rates.

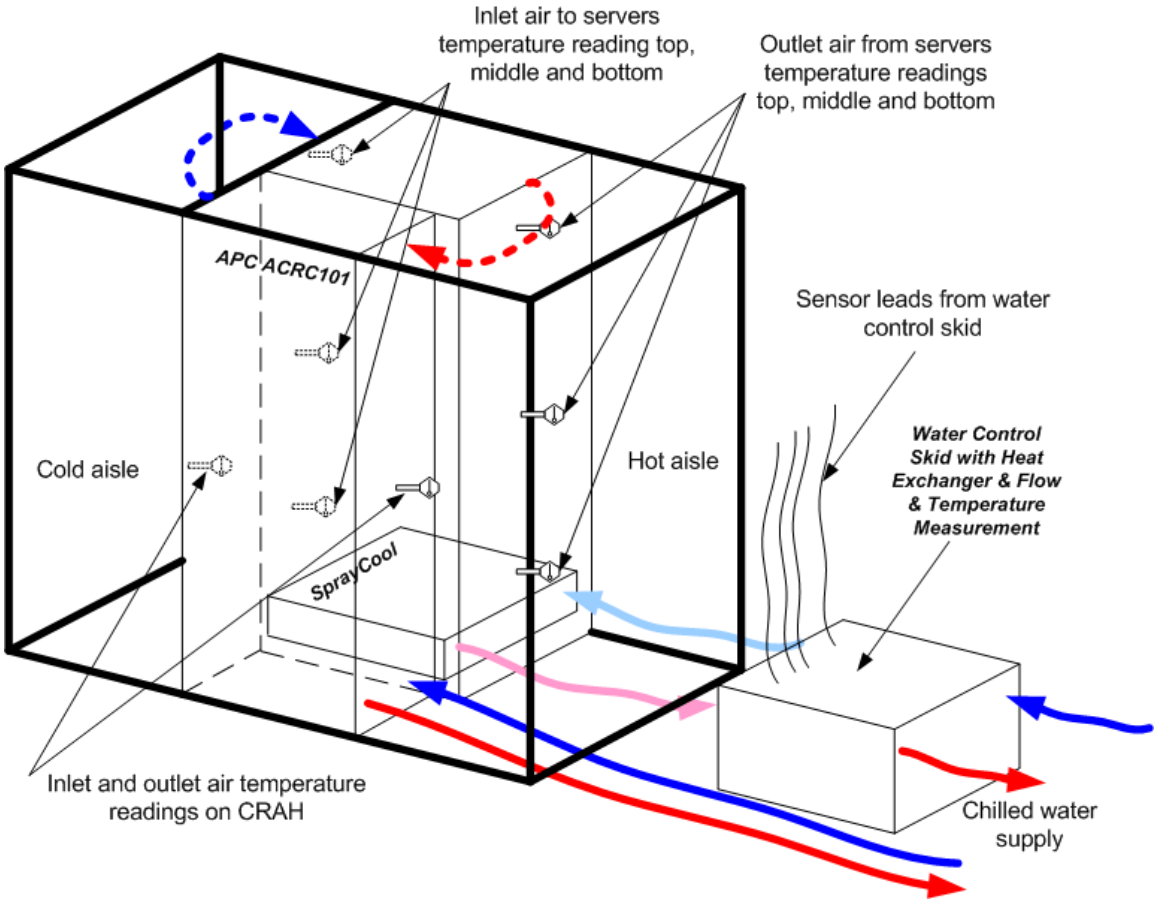



**Figure 3 CDU with spray cooling module**

The spray cooling module was used to removed partial heat directly from the CPU on a single rack, with the auxiliary cooling module to deal with remaining heat output to the rack. These cooling modules (spray cooling and auxiliary modular cooling) were physically separated in the test. The heat rejection unit of the spray cooling module is called the "thermal management unit" (TMU), which includes the coolant, pumps, controller, heat exchanger, and reservoir. , In TMU, the coolant is supplied to the servers via the rack manifold, which collects the coolant fluid and returns it to the TMU. The CPU cooling units can be called spray-cooled cold plates. The waste heat not removed via spray cooling was removed via the auxiliary modular cooling, which is a chilled-water-based cooling solution combined with a hot aisle containment system.

The liquid-rack cooling system studied consisted of a single modular system with the size of 78"x12"x48" attached to two equipment cabinets that measured 78"x24"x48". The modular system was powered via a single 208V single-phase 20A circuit, or by two such circuits when redundancy was available and required. Water connections were made at the rear of the unit via two externally threaded 1" connections.

The auxiliary cooling module (42"x23"x78") was used to air-cool the IT Rack (each sizing 42"x29x78") that shared a hot aisle (with a width of 36") with other racks in the data center. The hot aisle was contained with modular clear ceiling panel along with access doors at the end of the aisle. The chilled-water modular cooling unit contains a chilled water coil, chilled water flow control valve, multiple variable speed fans, DC power supply, instrumentation and controls needed to assure continuous automatic operation. The fans in the auxiliary cooling module pull hot air from the hot aisle through the chilled water coil and transport the cooler supply air into the cold aisle.

## Equipment location

One server rack was positioned at the southwest corner of the data center in this study. the server, together with the modular system and CDU was separated from the rest of the data center by an array of curtains surrounding them.
Two rows of server racks were positioned at the southwest corner of the data center in this study. They were separated from the rest of the data center by an array of curtains surrounding the six server racks and the two cooling modules. The space within the curtain has a floor area of 110" x 178" and a height of 86".
The spray cooling equipment was integrated with a rack with 37 servers and was installed at the bottom of the server rack. The test was set up to thermally isolate the rack with other cooling units from the inside the data center.

## Measured parameters

The following parameters were monitored or measured during the evaluation

- Power demand of servers and cooling modules
    - Actual power demand for the server rack used in this study.
    - Actual power demand for the APC In-Row cooler.
    - Actual power demand for the TMU

- Air temperatures
    - Cold inlet air temperature to the server rack - There were three temperature sensors (RTDs) installed at the top, middle, and bottom positions (0.65”, 37.5”, and 69”, respectively)..
    - Hot outlet air temperature from the server rack - There were three temperature sensors (RTDs) installed at the top, middle, and bottom positions (0.65.”, 37.5”, and 69”, respectively).
    - Air temperature entering the APC In-Row cooler
    - Air temperature leaving the APC In-Row cooler
    - Rich, weren’t there several servers with numerous thermocouples installed? - 3 servers had about 10 thermocouples in them (location/specs??)

- Spray cooling water (secondary loop from CDU)
    - Cooling-side entering and leaving water temperatures - water temperatures in the supply and return pipes were measured by installing two temperature sensors within the water pipes.
    - Cooling-side of CDU water flow rate
    - Cooling-side CDU entering and leaving water pressure differential.
- Water to auxiliary cooling module-apc
    - Entering and leaving water temperature entering the auxiliary row cooler
    - Pressure drop across the auxiliary row cooler
    - Water flow rate
- Outdoor air temperatures (dry-bulb & relative humidity).
- Data center air temperatures (outside the enclosed test area): from building energy system

The following parameters were recorded manually to quantify the magnitude of power demand in the data center and chilled water plant.

- Total power demand kW going into all IT equipment in the data center
- Total power demand to chiller plant (manual kW measurement and recording of total power supplied to the chiller plant)
- Total cooling tonnage provided by chiller plant (trend log of building system to record the following parameters:
    - Chilled water flow rates
    - Chilled water temperatures (supply and return)
    - Pressure differential between supply and return chilled water

### *Test procedures and sequence*

- Perform baseline tests on the APC In-Row cooler (pre-integration of spray cooling):
  - Temperature of supply water to the APC In-Row cooler was the same as chilled water around 45°F .
  - Control and adjust the cold aisle air temperature (i.e., server inlet air temperature) at discrete set points of from 80°F down to 68°F, with a step of 4°F.
  - For each desired inlet air temperature level, allow sufficient operating time, and perform steady-state test and monitoring.
  - Decrease the server load from full (100%, 12 kW available from the rack) to 50% (6 kW/rack). Perform steady-state test and monitoring for each load level.

The matrix of various inlet air temperatures (from 68°F to 80°F ) with 45°F supply water before spray cooling (baseline) under both full load and half load in this study is presented in the following table.

| Supply water temperature (F) | Inlet air temperature set point (F) | Targeted total server load (kW) for one server rack | Various server loads (kW) per rack | |
|---|---|---|---|---|
| | | | 100% | 50% |
| 45 | 68 | 12 | 12 | 5.4 |
| 45 | 72 | 12 | 12 | 5.4 |
| 45 | 76 | 12 | 12 | 5.4 |
| 45 | 80 | 12 | 12 | 5.4 |

- Perform tests for post-integration of spray cooling:
  - Temperatures of supply water to spray cooling was controlled at 65°F, 75°F, and 85°F , while the temperature of supply water to the auxiliary cooling module was the same as chilled water around 45°F .
  - Control and adjust the cold aisle air temperature (i.e., server inlet air temperature) at discrete set points of from 80°F down to 68°F, with a step of 4°F.
  - For each desired inlet air temperature level, allow sufficient operating time, and perform steady-state test and monitoring.

- Decrease the server load from full (100%, 12 kW available from the rack) to 50% (6 kW/rack). Perform steady-state test and monitoring for each load level.

The matrix of various inlet air temperatures (from 68°F to 80°F ) with various temperatures (from 65°F to 85°F) of supply water to spray cooling under both full load and half load in this study is presented in the following table.

| Supply water temperature (F) | Inlet air temperature set point (F) | Targeted total server load (kW) for one server rack | Various server loads (kW) per rack | |
|---|---|---|---|---|
| | | | 100% | 50% |
| 65 | 68 | 12 | 12 | 6 |
| 65 | 72 | 12 | 12 | 6 |
| 65 | 76 | 12 | 12 | 6 |
| 65 | 80 | 12 | 12 | 6 |
| 75 | 68 | 12 | 12 | 6 |
| 75 | 72 | 12 | 12 | 6 |
| 75 | 76 | 12 | 12 | 6 |
| 75 | 80 | 12 | 12 | 6 |
| 85 | 68 | 12 | 12 | 6 |
| 85 | 72 | 12 | 12 | 6 |
| 85 | 76 | 12 | 12 | 6 |
| 85 | 80 | 12 | 12 | 6 |

## *Performance metrics for auxiliary cooling*

In order to evaluate overall thermal performance of the spray cooling module in combination APC In-Row cooler, pre-integration evaluations were performed on the APC In-Row cooler. “Coefficient of performance (COP)” is defiend as the ratio of cooling produced by the auxiliary cooling module to the total power demand for the operation of the module (water pump and fan). Normally COP of a cooling module is the ratio of the heat removed by the module to the work supplied to the module. The COP is unitless, with a higher value representing higher efficiency for the cooling module. The COP can be calculated under applicable operating conditions (a range determined by inlet air temperature and server load **Tim, was there also a limit placed on volumetric flow rate of the water? In other words, there should be a spec for the water flow rate and pressure drop that is allowed by the facility).

In this evaluation, the work supplied is the pump and fan power required to produce the required water and air flows from the cooling module, while the heat removed is equivalent to the cooling provided by the module.

$$COP_{pre} = \frac{Cooling_{aux}}{P_{auxiliary}}$$

Where $Cooling_{aux}$ is the cooling provided by the cooling module, and $P_{auxiliary}$ is generally defined as the total power demand for all components (e.g., fan, pump) in the auxiliary cooling module. Because there were fans and water pumps in the cooling module, the total power demand was for pumping and air-circulating requirement in this pre-spray-cooling test.

The actual cooling provided by the auxiliary cooling module can be calculated from the chilled water temperature rise and chilled water flow rate, using the following formula:

Where

$$Cooling_{aux} = \frac{60\rho Q_{aux} C_p \Delta T_{w,aux}}{3412.1}$$

$Cooling_{aux}$ = cooling produced from the auxiliary cooling module, in kW.

P = Water density in lb/gal, assuming water density ρ of 8.34 lbm/gal (or 62.4 lbm/ft$^3$)

$Q_{aux}$ = Averaged water flow rate measured in the auxiliary cooling module, in gallon per minute

Cp = Specific thermal conductivity of water, 1 BTU/F-lbm

$\Delta T_{w,\,aux}$ = Measured water temperatures rise in the auxiliary cooling module, in °F

Therefore,

$$Cooling_{\text{aux}} = 0.1467 Q_{\text{aux}} \Delta T_{w,\text{aux}}$$

**Rich, I get 1.0972 for the constant immediately above…what do you get?

$$COP_{pre} = \frac{Cooling_{\text{aux}}}{P_{auxiliary}} = \frac{0.1467 Q_{\text{aux}} \Delta T_{w,\text{aux}}}{P_{auxiliary}}$$

The portion of chiller pumping power required to deliver the chilled water volume in the primary-loop was ignored for this evaluation.

An alternative metric, defined as the module's power usage index, is the ratio of power demand for the cooling module to computer load under selected operating conditions. A higher value of the power usage index indicates higher cooling energy demand for the cooling module at a given server load under an operation condition.

$$PUI_{pre} = \frac{P_{auxiliary}}{P_{server}}$$

## *Performance metrics for Spray cooling*

Based upon the measurement of the heat load removed by the combination of the SprayCool solution and the APC In-Row cooler, and the power required to remove that heat from the server rack, we quantify the overall "coefficient of performance (COP)" of the spray cooling in combination with the APC In-Row cooler by performing post-spray-cooling-integration evaluations. COP is the ratio of total heat removed by spray cooling and auxiliary cooling modules to the total power demand for the operation of both cooling modules. The COP can be calculated under applicable operating conditions (a range determined by inlet air temperature and server load).

$$COP = \frac{Cooling}{P_{total}}$$

**Tim, it would also be good to have a separate COP calc for SprayCool alone. This can be defined as:

COP = Cooling/$P_{sc}$

Where:

Cooling = cooling provided by the SprayCool system, i.e., all the CPU heat (can be determined from the energy balance across the TMU)

$P_{sc}$ = power consumed by the TMU (measured directly)

This will highlight the efficiency of the spray cooling system on its own – this type of performance can be achieved if all the heat is removed via spray cooling. I am concerned that we were not operating the APC In-Row cooler at its optimum efficiency, i.e., we

were using a unit designed to remove 18 - 20 kW for only 6 kW worth of waste heat. I am sure the other solutions were operating close to peak performance.

Where Cooling is the cooling provided by the cooling modules, and $P_{total}$ is defined as the total power demand for all components (e.g., fan, pump) in the two cooling modules, $P_{total} = P_{auxilary} + P_{spray}$.

The actual cooling provided by the cooling modules can be calculated from the secondary-loop chilled water temperature rise and chilled water flow rate measured from each of the cooling modules, respectively, using the following formula:

Where

$$Cooling = \frac{60\rho C_p (Q_{aux}\Delta T_{w,aux} + Q_{spray}\Delta T_{w,spray})}{3412.1}$$

Cooling = cooling produced from the cooling module, in kW.

P = Water density in lb/gal, assuming water density ρ of 8.34 lbm/gal (or 62.4 lbm/$ft^3$)

Q = Averaged water flow rate measured (in spray cooling and auxiliary cooling modules, respectively), in gallon per minute

Cp = Specific thermal conductivity of water, 1 BTU/F-lbm

$\Delta T_w$ = Measured water temperatures rise (in spray cooling and auxiliary cooling modules, respectively), in °F

Therefore,

$$Cooling = 0.1467(Q_{aux}\Delta T_{w,aux} + Q_{spray}\Delta T_{w,spray})$$

$$COP = \frac{Cooling}{P_{total}} = \frac{0.1467(Q_{aux}\Delta T_{w,aux} + Q_{spray}\Delta T_{w,spray})}{P_{auxilary} + P_{spray}}$$

The portion of chiller pumping power required to deliver the chilled water volume in the primary-loop was ignored for this evaluation.

## Conclusions

Effectiveness of spray cooling - effective cooling with the use of warmer water (65F-85F) – what parameter to quantify the effectiveness (temperature range of CPU?) under server load at 12kW

## References

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# ENERGY EFFICIENT & SUSTAINABLE HPC AT PNNL

# Spray Cooling Demonstration


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**September 17, 2008**

Pacific Northwest NATIONAL LABORATORY

# OVERVIEW

**The presentation will cover…**

- Description of PNNL’s Energy Smart Data Center Test Bed Facility (ESDC - TBF)
- Description of the NW-ICE Liquid-Cooled Cluster
- Overview of SprayCool Technology
- Results from The ESDC - TBF
- Fluid Coolants – Sustainable Chemistries

# PNNL’S ENERGY SMART DATA CENTER TEST BED FACILITY (ESDC – TBF)

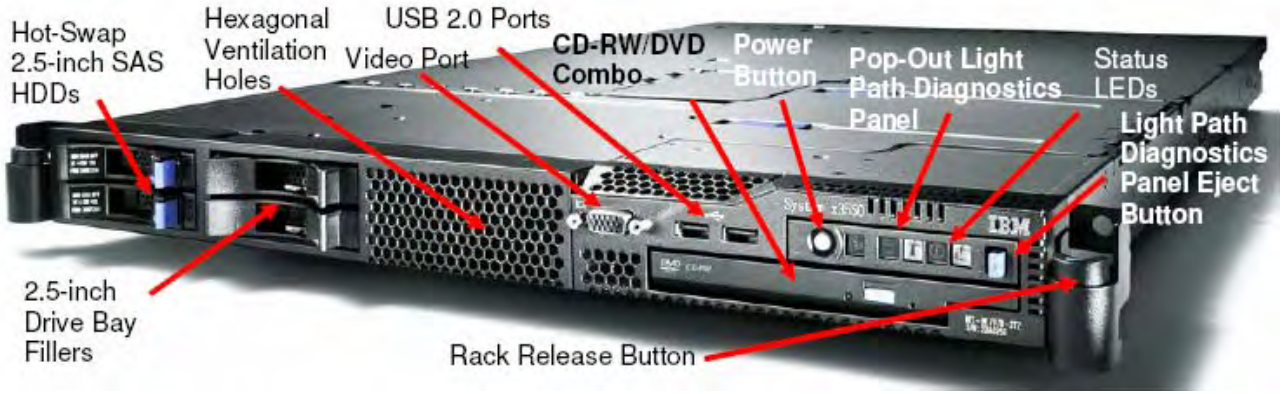
# Energy Smart Data Center – Test Bed Facility

- 800 $ft^2$ data center housed in a mixed-use facility
- Houses a 9.58 Tflops (sustained) IBM x3550 cluster
  - 196 IBM x3550 servers
  - 7 total compute racks (5 spray cooled)
  - 12 kW power dissipation per rack
- CPUs are liquid-cooled, with waste heat rejection to 30C, non-refrigerated condenser water
- 3 highly instrumented servers per compute rack
- All rack, data center, and facility instrumentation tied in to a single software solution (FRED)
  - Enables quasi real-time quantification of ESDC – TBF's energy efficiency (DCiE)

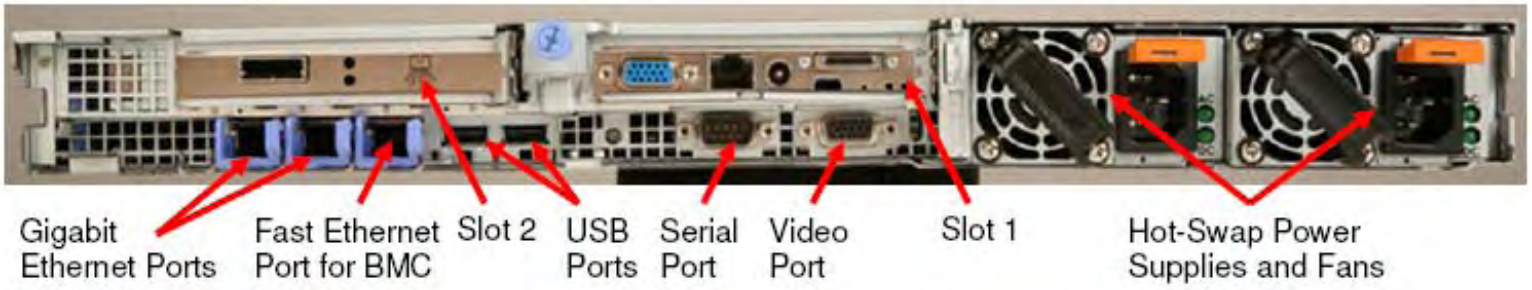
# NW – ICE CLUSTER

## Spray Cooled IBM x3550 Cluster

# IBM System x3550

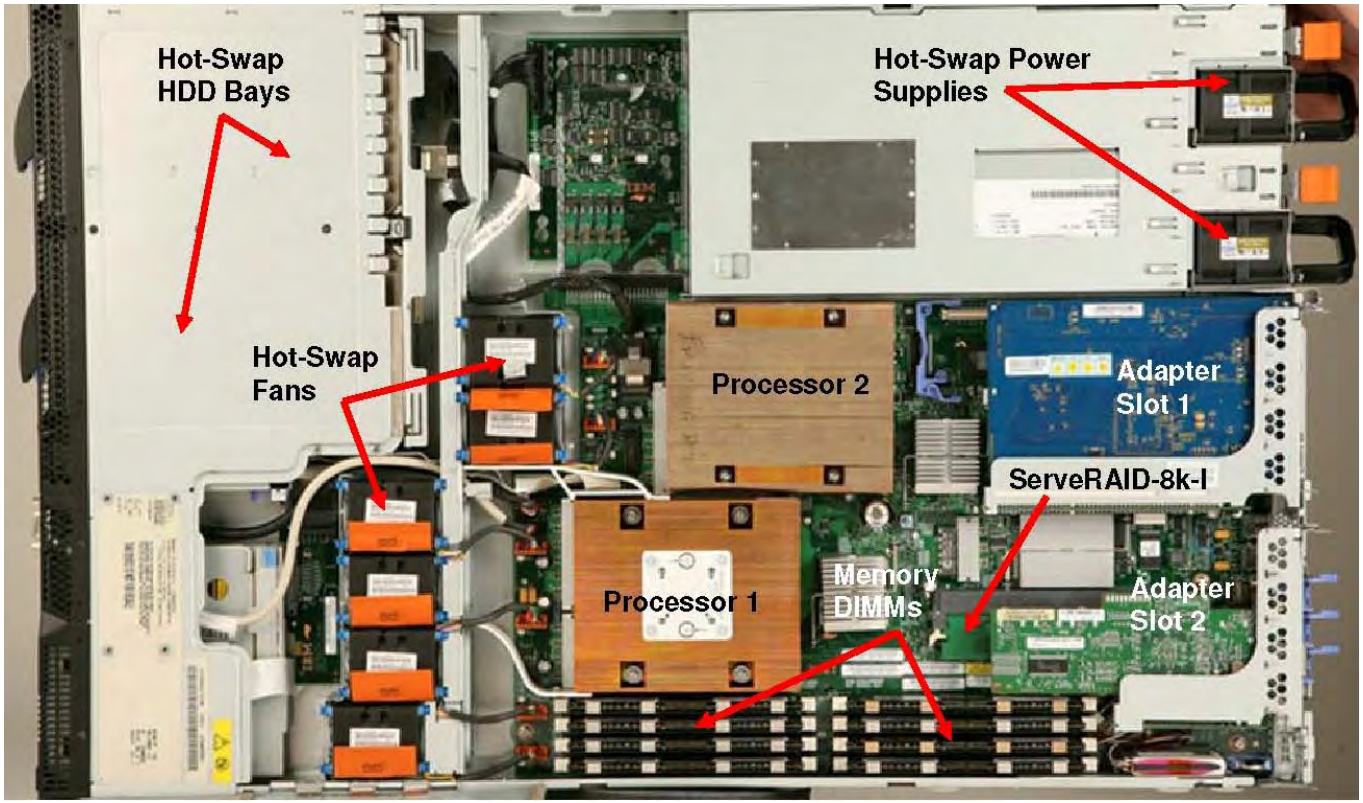



Front View




Rear View

# IBM System x3550 Platform

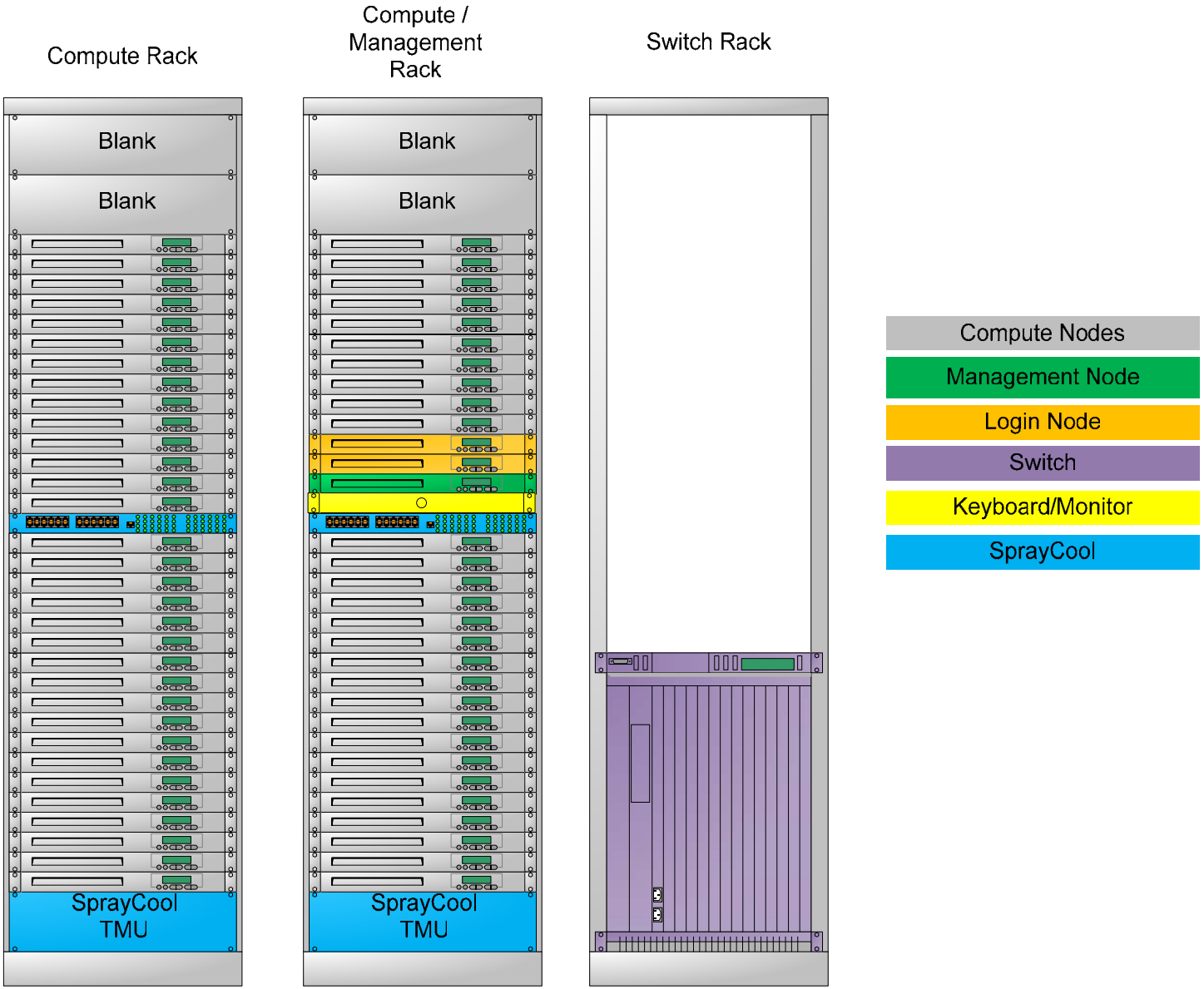



***Compute Nodes:***

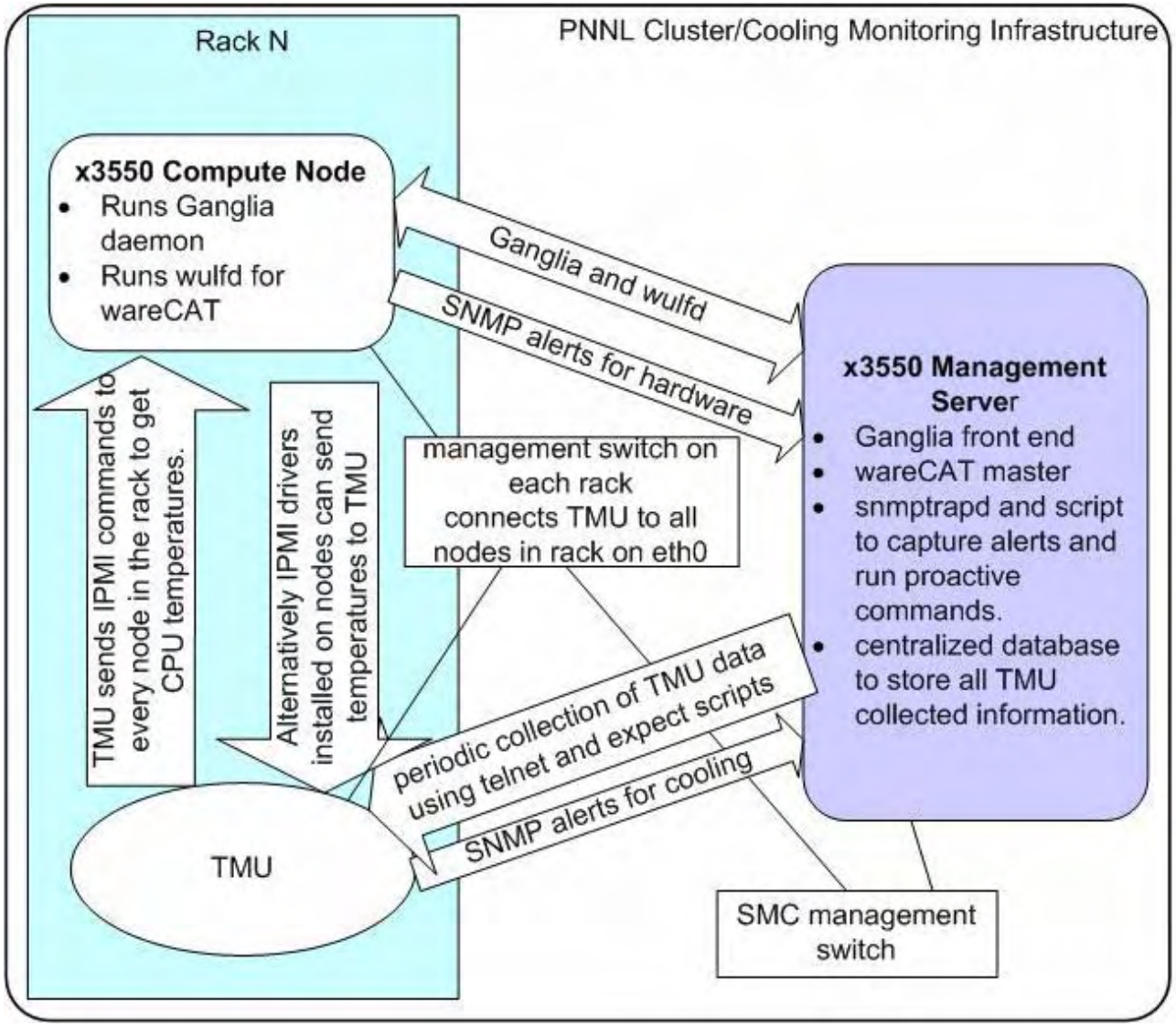
There are 192 compute nodes that are based on the IBM System x 3550 drawer configured as follows:

(2) Intel Xeon 5345 2.33GHz quad-core processors (Clovertown);
(4) 1GB PC2-5300 CL5 ECC DDR2 Chipkill FB-DIMMs 667MHz;
(1) Onboard Broadcom 5708S Gigabit Ethernet adapters connected to the management VLAN;
(1) Onboard Broadcom 5708S Gigabit Ethernet adapters connected to the cluster VLAN;
(1) 80GB Internal SATA disk drive – used for data storage; and redundant fans.

# Key Elements of PNNL's NW-ICE Cluster



# Cooling Monitoring Infrastructure for NW-ICE



# ESDC - TBF Requirements

## *PNNL Spraycool Facilities Requirements*

| | Rack types | | | | | |
|---|---|---|---|---|---|---|
| **Single Rack** | Compute 1 | Compute 2 | Mgmt 7TF | Mgmt 8TF | Mgmt 9TF | Switch |
| **Packaging** | | | | | | |
| Size (LxWxH) Inches | 43.3x25.4x79.3 | | | | | |
| Weight (lbs) | 1659 | 1493 | 1659 | 1435 | 1659 | 1057 |
| Service area, front | 35x23.5" | | | | | |
| Service area, rear | 30x23.5" | | | | | |
| Acoustic Noise Level (dBa) | 65 | | | | | |
| **Power** | | | | | | |
| Voltage | 208V | | | | | |
| Power Factor | 1 | | | | | |
| Hertz Tolerance | 47-63 | | | | | |
| Current | 59 | 54 | 56 | 40 | 52 | 32 |
| Maximum Power (KVA) | 12.9 | 11.8 | 12.1 | 8.6 | 11.4 | 6.7 |
| Maximum Power (KW) | 12.6 | 11.6 | 11.9 | 8.4 | 11.2 | 6.6 |
| # of circuits and connector type | (4)NEMA L6-30R | | | | | |
| # of wires | 3 | | | | | |
| # of Phases | 1 | | | | | |
| Circuit Breaker Size | 30A | | | | | |
| **Cooling** | | | | | | |
| ***Air:*** | **yes** | | | | | |
| **CFM required (w/o ISR)** | 1200 | 1100 | 1200 | 800 | 1200 | 700 |
| **CFM required (w/ ISR)** | 600 | 550 | 600 | 400 | 600 | 700 |
| Front to Back or Back to Front or Bottom to Top | Front to Rear | | | | | |
| ***Water:*** | **ISR** | | | | | |
| Type | SprayCool | | | | | |
| Water Temperature | 7 to 30 degC | | | | | |
| Gallons per minute | 9 GPM @ 30 degC | | | | | |
| **Power Dissipation (kBTU) (w/o ISR cooling)** | 43.1 | 39.5 | 40.5 | 28.8 | 38.1 | 22.4 |
| # of ISR coolable drawers | 30 | 27 | 29 | 20 | 26 | 0 |
| **Power Dissipation (kBTU) (with ISR cooling)** | 21.6 | 17.4 | 24.8 | 7.9 | 25.9 | 22.4 |

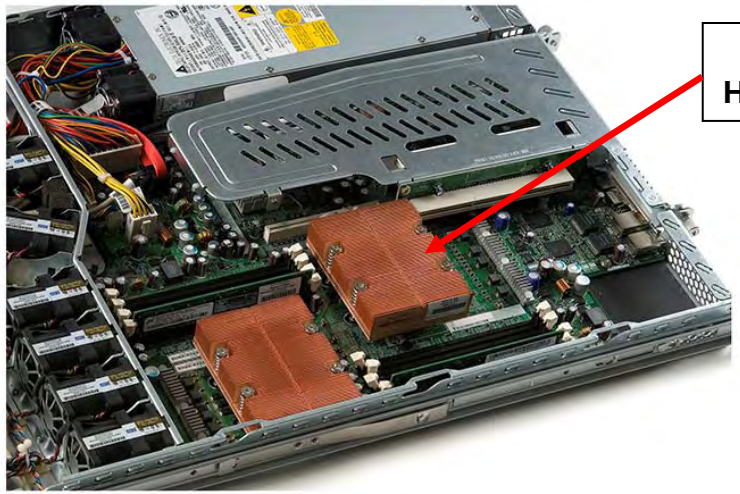
# Environmental Characteristics for IBM x3550 Cluster

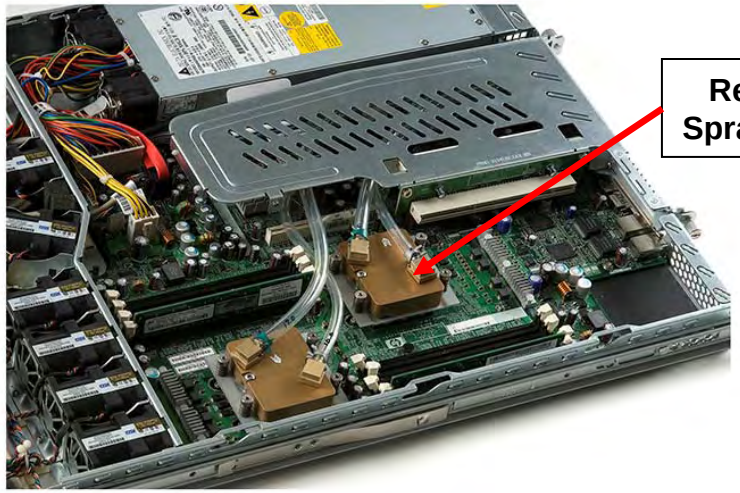
| 9TF System | Compute 1 | Compute 2 | Mgmt 7TF | Mgmt 8TF | Mgmt 9TF | Switch |
|---|---|---|---|---|---|---|
| **# of Racks by type** | 0 | 6 | 0 | 0 | 1 | 1 |
| Total area footprint including aisle space (Sq.Ft.) | *160* | | | | | |
| Maximum Power (KVA) | 89 | | | | | |
| Power Factor | 1 | | | | | |
| Maximum Power (kW) | *89* | | | | | |
| **Type of Cooling (Air and/or Water)** | | | | | | |
| Air: | yes | | | | | |
| CFM required (w/o ISR) | 1200 | | | | | |
| CFM required (with ISR) | 700 | | | | | |
| Power Dissipation (kBTU) (w/o ISR cooling) | 297 | | | | | |
| Power Dissipation (kBTU) (w ISR cooling) | 153 | | | | | |
| Power Dissipation (kW) (w ISR cooling) | 45 | | | | | |

# OVERVIEW OF SprayCool TECHNOLOGY

# SprayCool Server

- Air-cooled heatsinks are replaced with liquid-cooled SprayModules
- SprayModules consist of a base plate with attached fluid supply/return tubes
- Coolant is electrically non-conducting
- Processor heat is rejected to facility water (30C+)



# SprayCool Rack

- 3U high thermal management unit (TMU) is placed in bottom of rack
- TMU rejects processor heat to facility water
- TMU communicates directly with individual nodes (IPMI) and IBM x3550 Management node (SNMP)

Rear View

Rack Manifold

Server

Thermal Management Unit

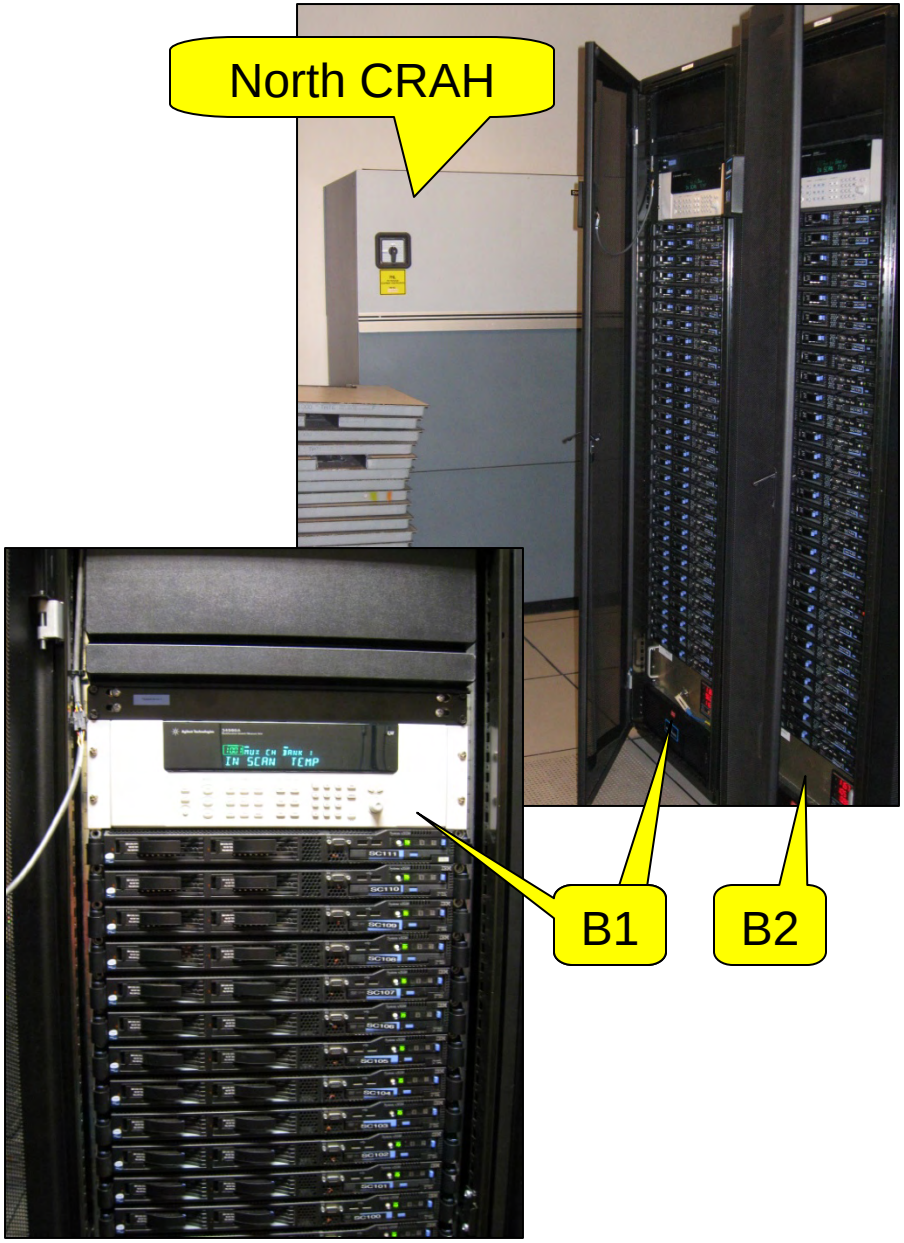
# RESULTS FROM THE ESDC - TBF

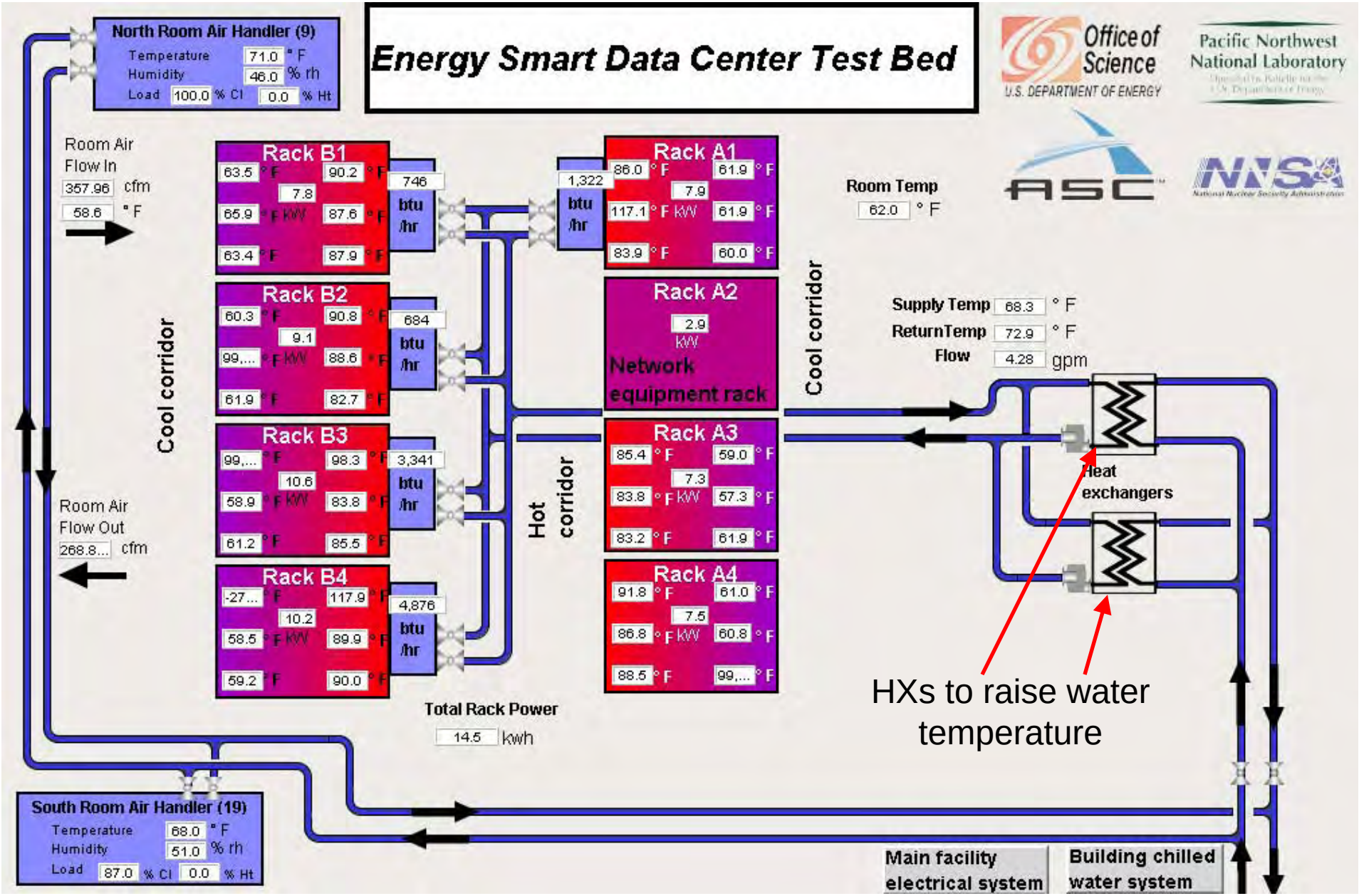
# Background of Experiments…

- **Purpose**
  - To conduct an experiment to examine the energy consumption of the spray cool technology
- **Configuration**
  - Two of the spray cooled racks (B1 & B2) running an application that stresses the functional units of the processors and generates a large heat load (CPU Burn)
- **Temperature Setpoints**
  - CRAHs set to 80°F (26.67°C)
  - Water Heat Exchanger set to:
    - 68°F (20°C)
    - 86°F (30° C)

# …Background of Experiments

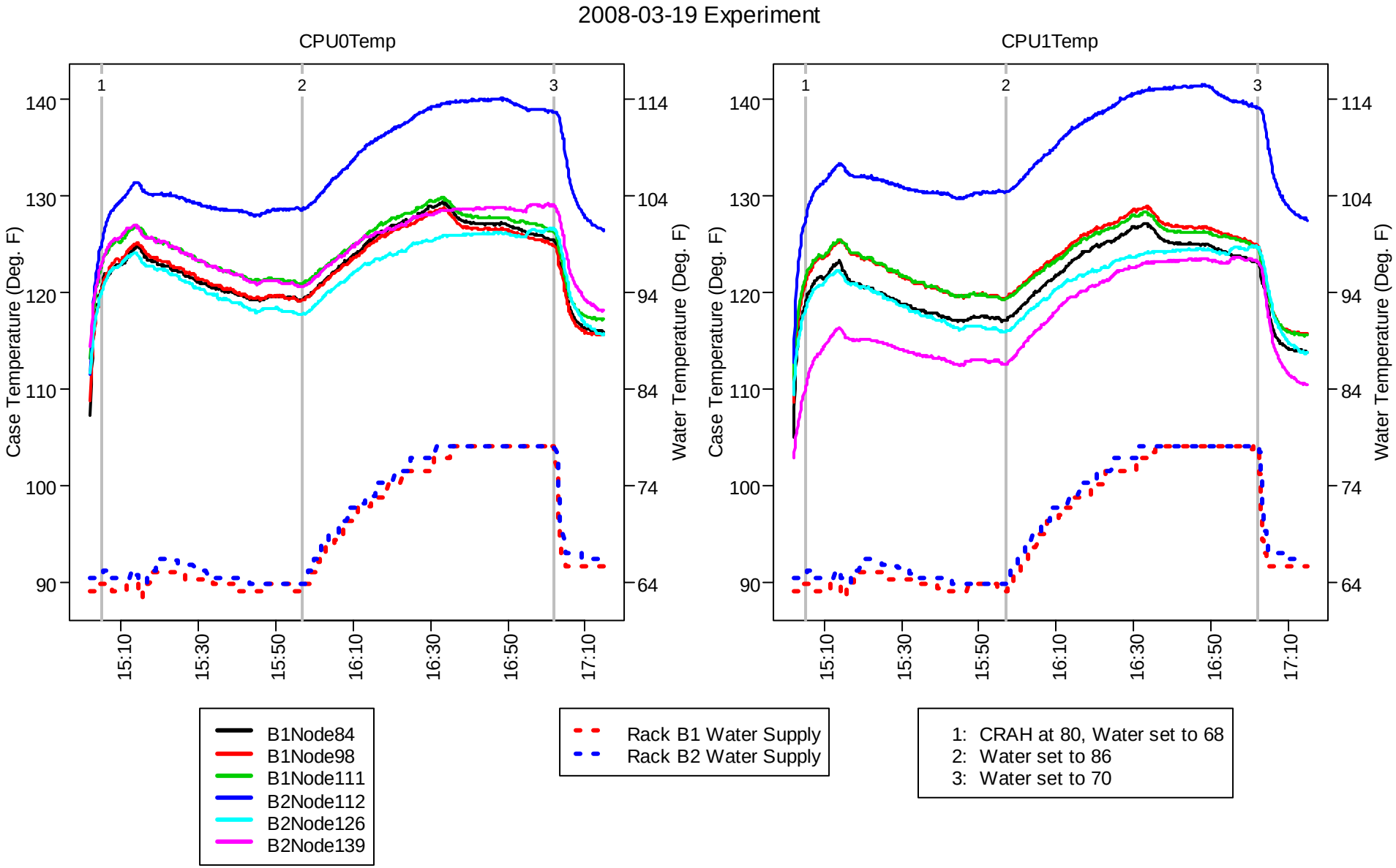
- Experiment conducted on March 19, 2008
- Sequence of experimentation
  - ~14:50, Bring up spray cooled system, CRAHs set to 80°F, water HX set to 68°F
  - ~15:05, CPU burn running on two spray cooled racks (B1 & B2)
  - ~16:00, Water HX set to 86°F
  - ~17:00, Conclude experiment and transition back to original configuration of data center



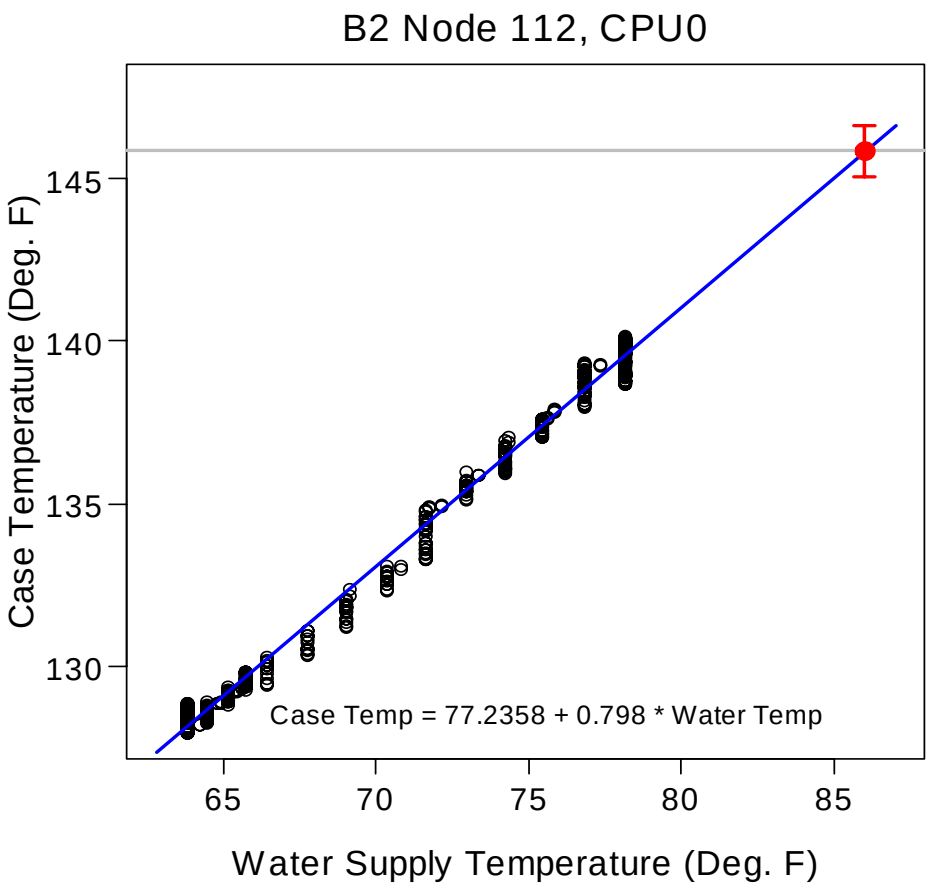

Energy Smart Data Center Test Bed
Office of Science
U.S. DEPARTMENT OF ENERGY
Pacific Northwest National Laboratory
ASC
NNSA
North Room Air Handler (9)
Temperature 71.0 °F
Humidity 46.0 % rh
Load 100.0 % Cl 0.0 % Ht
Room Air Flow In
357.96 cfm
58.6 °F
Room Air Flow Out
268.8... cfm
Cool corridor
Hot corridor
Rack B1
63.5 °F 90.2 °F
7.8
65.9 °F kW 87.6 °F
63.4 °F 87.9 °F
746 btu /hr
Rack B2
60.3 °F 90.8 °F
9.1
99,... °F kW 88.6 °F
61.9 °F 82.7 °F
684 btu /hr
Rack B3
99,... °F 98.3 °F
10.6
58.9 °F kW 83.8 °F
61.2 °F 85.5 °F
3,341 btu /hr
Rack B4
-27... °F 117.9 °F
10.2
58.5 °F kW 89.9 °F
59.2 °F 90.0 °F
4,876 btu /hr
1,322 btu /hr
Rack A1
86.0 °F 61.9 °F
7.9
117.1 °F kW 61.9 °F
83.9 °F 60.0 °F
Rack A2
2.9 kW
Network equipment rack
Rack A3
85.4 °F 59.0 °F
7.3
83.8 °F kW 57.3 °F
83.2 °F 61.9 °F
Rack A4
91.8 °F 61.0 °F
7.5
86.8 °F kW 60.8 °F
88.5 °F 99,... °F
Total Rack Power
14.5 kwh
Room Temp
62.0 °F
Supply Temp 68.3 °F
ReturnTemp 72.9 °F
Flow 4.28 gpm
Heat exchangers
HXs to raise water temperature
South Room Air Handler (19)
Temperature 68.0 °F
Humidity 51.0 % rh
Load 87.0 % Cl 0.0 % Ht
Main facility electrical system
Building chilled water system

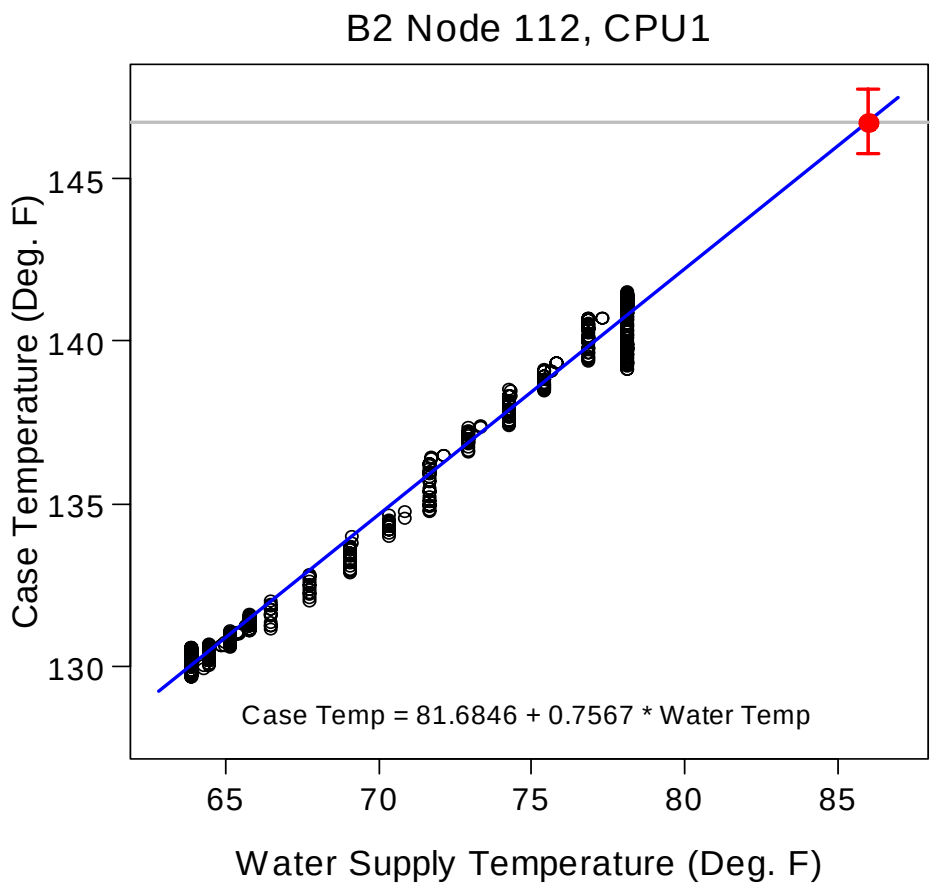
# CPU Temperatures

Max case temperature recommended by manufacturer: 150.8°F (66°C)



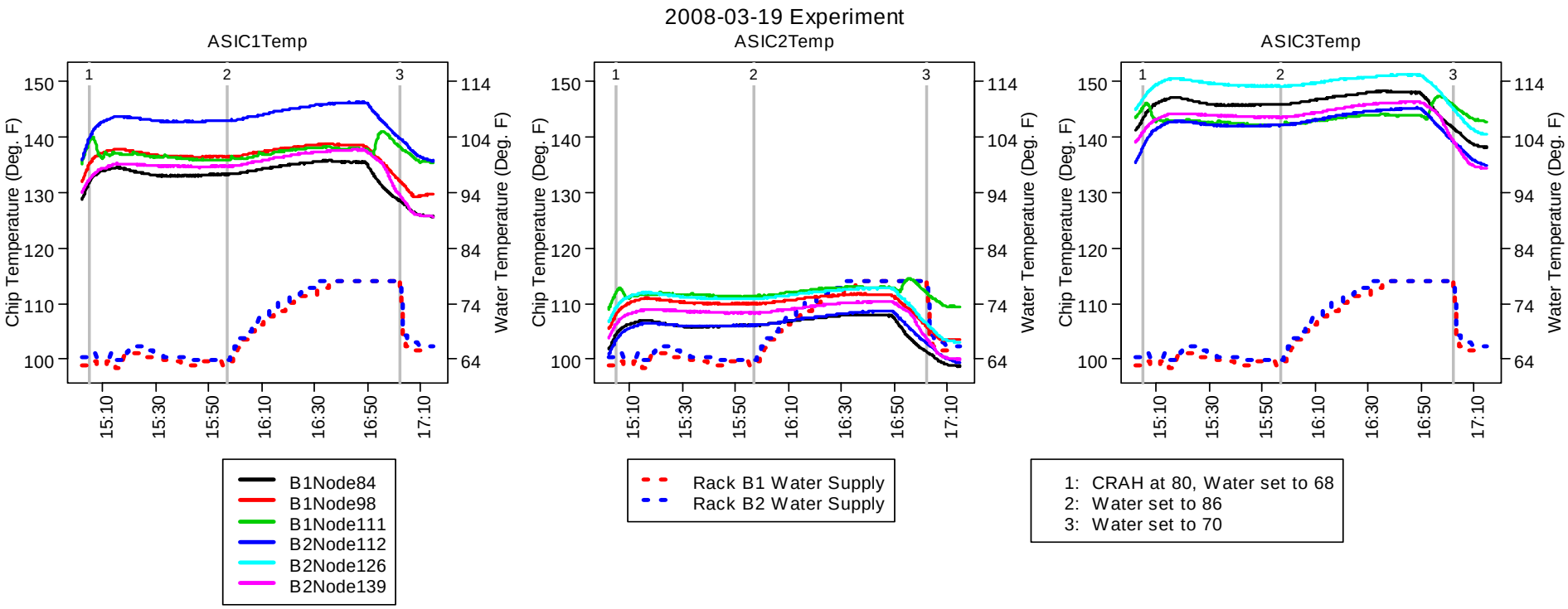
# Extrapolation of CPU Case Temperatures at 86°F (30°C)

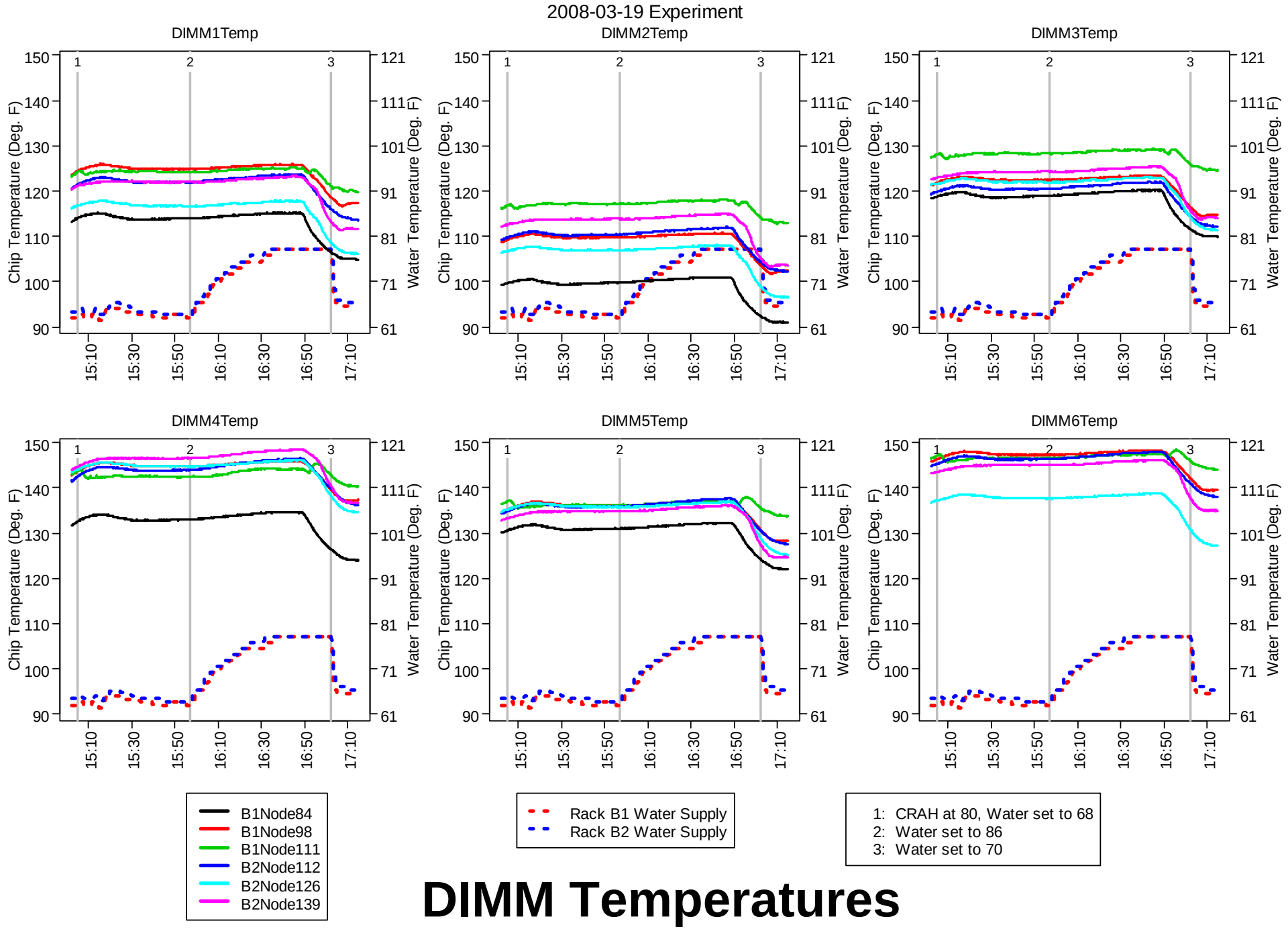


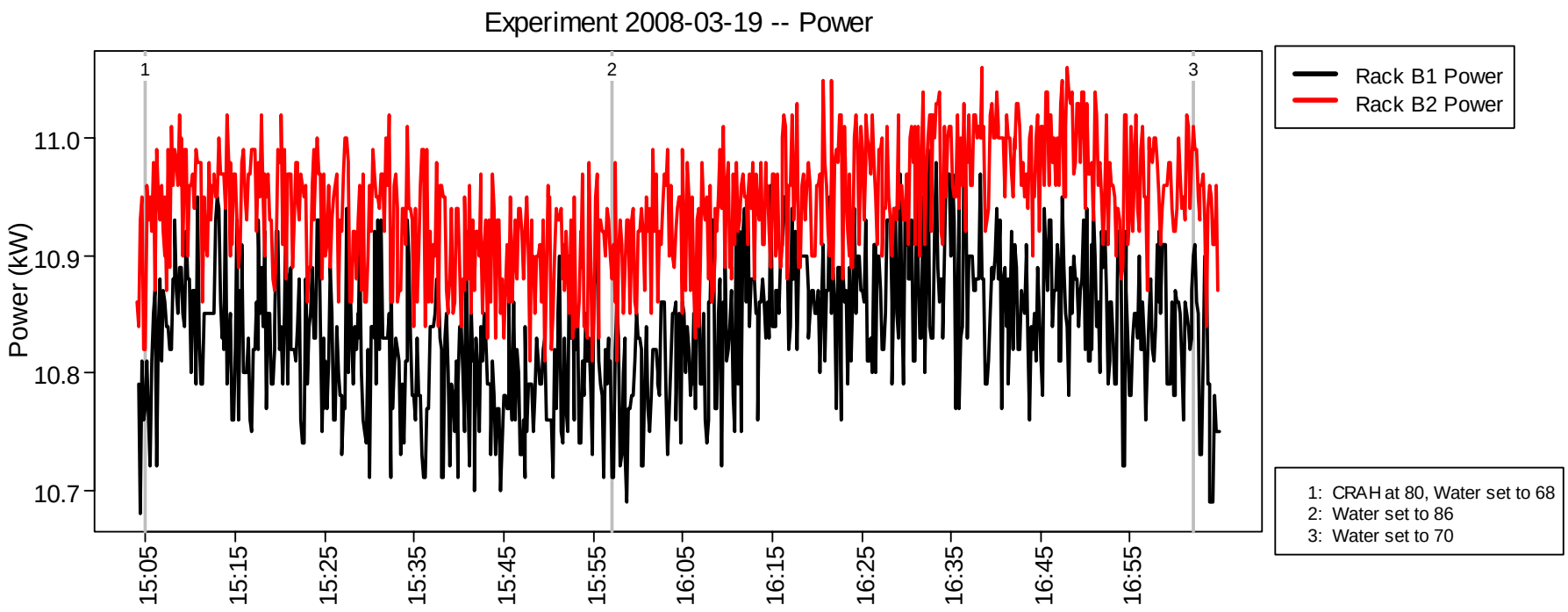

- Data selected from the ‘stable’ period between 15:25 and 17:02
- |--●--| indicates the 95% prediction interval
- Presumes that the physical properties of the cooling fluids don’t change over the range of the extrapolation

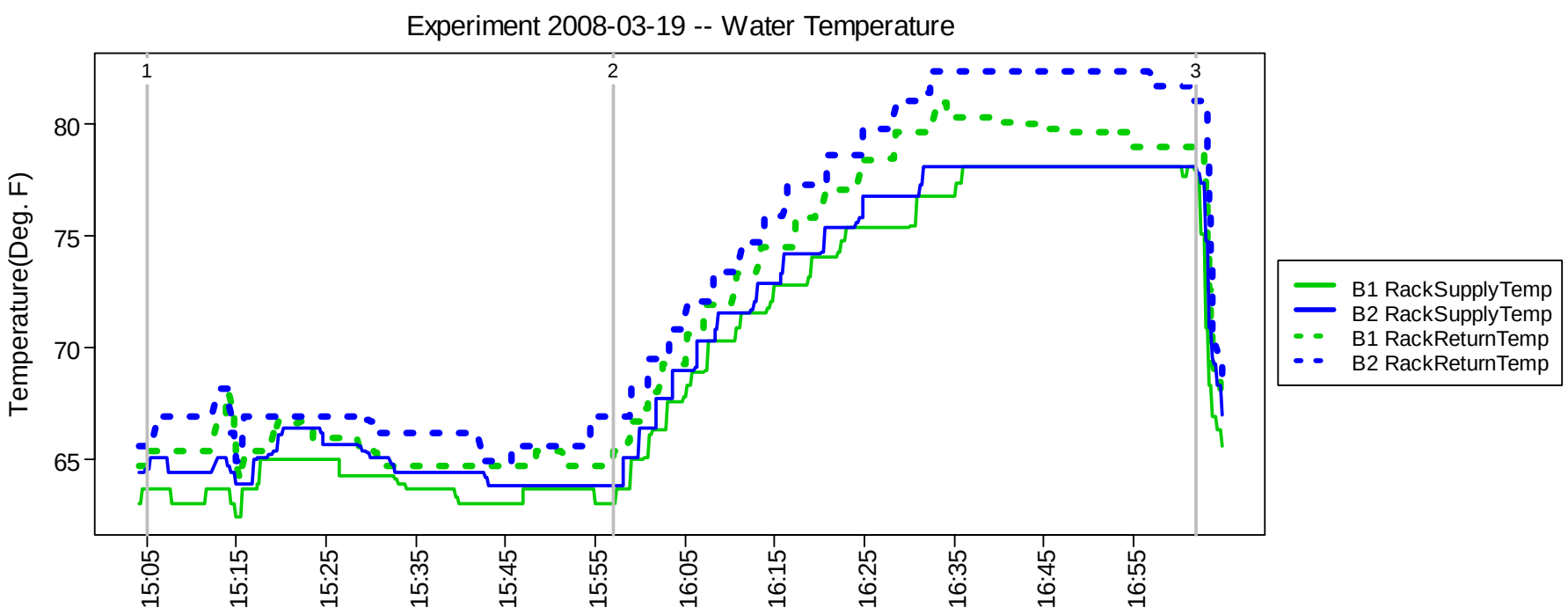
# ASIC Temperatures






# DIMM Temperatures


Experiment 2008-03-19 -- Power
Power (kW)
11.0
10.9
10.8
10.7
1
2
3
15:05
15:15
15:25
15:35
15:45
15:55
16:05
16:15
16:25
16:35
16:45
16:55
Rack B1 Power
Rack B2 Power
1: CRAH at 80, Water set to 68
2: Water set to 86
3: Water set to 70


Experiment 2008-03-19 -- Water Temperature
Temperature(Deg. F)
80
75
70
65
1
2
3
15:05
15:15
15:25
15:35
15:45
15:55
16:05
16:15
16:25
16:35
16:45
16:55
B1 RackSupplyTemp
B2 RackSupplyTemp
B1 RackReturnTemp
B2 RackReturnTemp

# Summary

- Can run with water at 78°F (25.6°C) and still keep CPU case temps at or below 142°F (61.1°C)
- Extrapolations *suggest* that water at 86°F (30°C) will result in worst case CPU case temps no higher than 147.8°F (64.3°C), below the manufacturer recommendation of 66°C
- Calculating DCiE
  - Where we are:
    - We currently calculate and record IT Equipment Power usage in real time
    - We partially measure the power of the cooling chain in real time and the remaining components are assumed to be constant under nominal operation
  - Where we want to go:
    - Total facility power will be calculated using real time measurement observations and by analytical calculation of the components that are not directly measured

# FLUID COOLANTS

## Sustainable Chemistries

# Perfluorocarbons

- Current Working Fluid is Perfluorohexane or $C_6F_{14}$
  - Boiling Point 56ºC
  - Typical Perfluorocarbon (PFC) properties
    - Clear, colorless, odorless, non-flamable
    - Electric resistivity ~1 million Giga Ohm-cm
    - Dielectric strength > 40kV for 2.5mm gap
    - Extreme inertness, “Liquid PTFE”
    - Thermally stable at 250ºC
    - Low solvency = Excellent Material Compatibility
    - Practically non-toxic
    - High Global Warming Potential (GWP)
      - Listed along with HFC refrigerants as greenhouse gases in Kyoto Protocol
      - Use inconsistent with growing global trend to use materials with lowest possible environmental impact.

# Hydrofluoroethers

- Segregated Hydrofluoroether (HFE) Alternatives
  - Example $C_4F_9OCH_3$, Boiling Point 61ºC
  - How they differ from PFCs
    - Much shorter Atmospheric Lifetimes = Lower GWP
    - Electric resistivity ~0.1 Giga Ohm-cm
    - Higher hydrocarbon solvency
    - Thermally stable to >150ºC
    - Very good toxicological properties but not as good as PFCs

# Fluoroketones

- Fluoroketone (FK) Alternatives
  - Example: $C_2F_5C(O)CF(CF_3)_2$, boiling point 48ºC
  - How they differ from PFCs
    - Very short-lived in the atmosphere = Lowest GWP
    - PFC-like material compatibility, dielectric and thermal stability properties
    - Very good toxicological properties but not as good as PFCs
    - Reactive with liquid water
  - Currently being studied for use in SprayCool applications

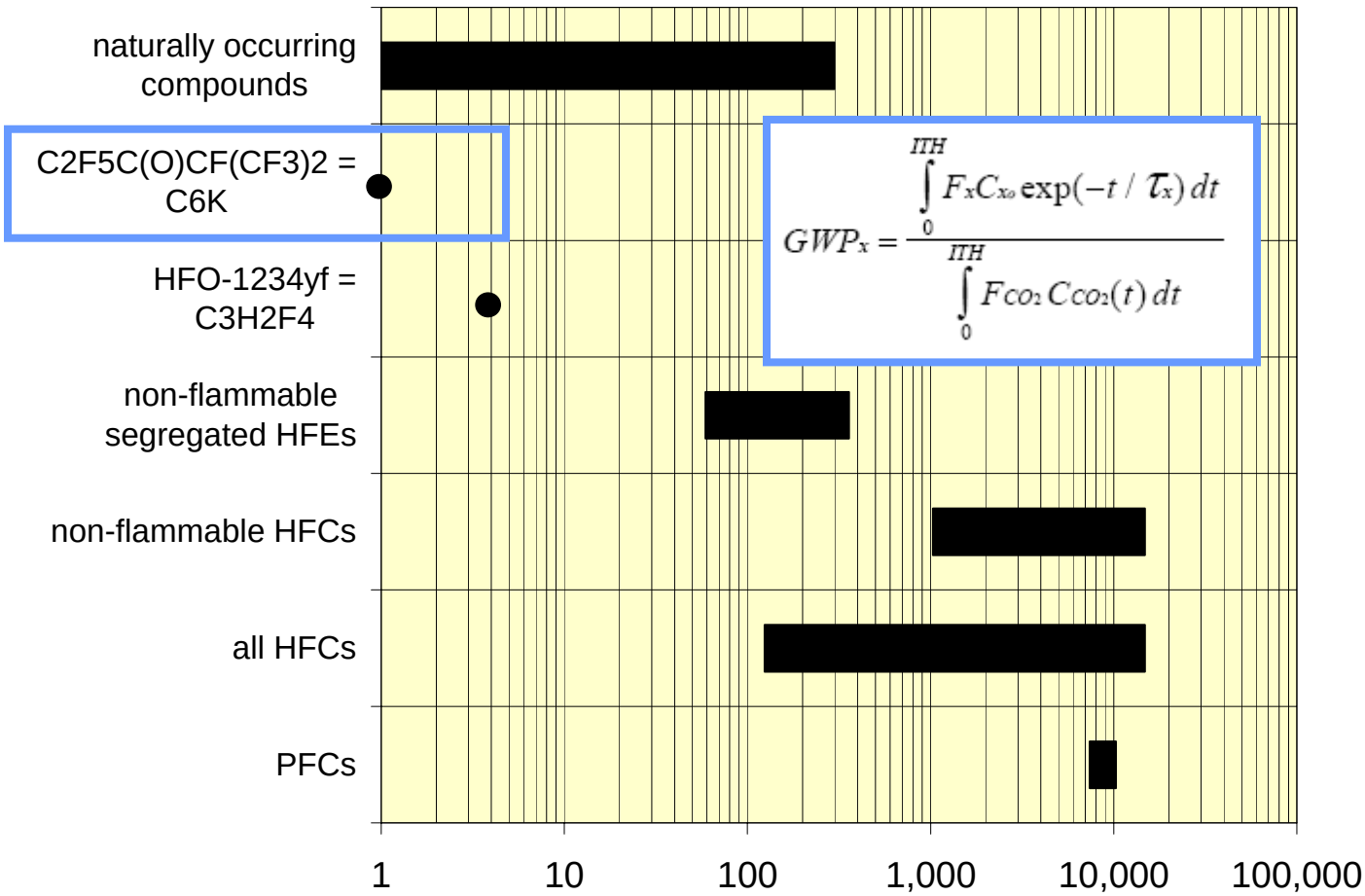
# Coolant Properties

| Molecular Formula | $C_2F_5C(O)CF(CF_3)_2$ | $C_6F_{14}$ | $C_2F_2H_2$ | $C_3F_7OCH_3$ |
|---|---|---|---|---|
| Fluid Type | fluoroketone | perfluorocarbon | hydrofluorocarbon | hydrofluoroether |
| Abbreviation | C6K | - | HFC-134a | HFE |
| Normal Boiling Point [°C] | 49 | 56 | -26 | 34 |
| Critical Temperature [°C] | 169 | 178 | 101 | 165 |
| Critical Pressure [MPa] | 1.87 | 1.83 | 4.06 | 2.48 |
| Freezing Point [°C] | <-100 | <-100 | <-100 | <-100 |
| Closed Cup Flashpoint [°C] | None | None | None | None |
| Open Cup Flashpoint [°C] | None | None | None | None |
| Surface Tension [dynes/cm] | 11.4 | 12.0 | 8.2 | 12.4 |
| Thermal Conductivity [W/m-K] | 0.059 | 0.057 | 0.081 | 0.075 |
| Liquid Specific Heat [J/kg-K] | 1103 | 1050 | 1424 | 1250 |
| Liquid Density [kg/m$^3$] | 1610 | 1680 | 1206 | 1401 |
| Kinematic Viscosity [cSt] | 0.42 | 0.40 | 0.18 | 0.32 |
| Latent Heat [kJ/kg] | 88 | 88 | 178 | 142 |
| Vapor Pressure at 25ºC [kPa] | 40.4 | 30.9 | 665 | 64.6 |
| Vapor Pressure at 100ºC [kPa] | 441 | 350 | 3972 | 706 |
| Resistivity [Gohm-cm] | 10,000 | 1,000,000 | NA | 0.1 |
| Dielectric Constant | 1.84 | 1.76 | NA | 7.4 |
| Dielectric Strength [kV@2.54mm] | ~40 | ~40 | ~40 | ~40 |
| Solub. $H_2O$ in Fluid [ppmw] | 21 | 10 | 1100 | 60 |
| Atmospheric Lifetime [year] | 0.014 | 3200 | 14 | 4.9 |
| Global Warming Potential[1] | 1 | 9300 | 1430 | 370 |
| Ozone Depletion Potential | 0 | 0 | 0 | 0 |

[1] Based upon a 100 year Integration Time Horizon (ITH), 2007 IPCC Report

**Source:** Phil Tuma, 3M, Semi-Therm 2008 proceedings.

# Global Warming Potential




$$GWP_x = \frac{\int_0^{ITH} F_x C_{x_0} \exp(-t/\tau_x)\,dt}{\int_0^{ITH} F_{CO_2} C_{CO_2}(t)\,dt}$$

**Global Warming Potentials (GWPs) of new (●) and commercially significant compounds. Note use of logarithmic scale.**

# APPENDIX K:
# Contract Task 2.5.1 Technology Transfer Activities

## Outreach & Technology Transfer

**Prepared for the California Energy Commission**
High-Performance Buildings for High-Tech Industries

by

Lawrence Berkeley National Laboratory
Applications Team

UC Research Agreement, Contract #500-02-004
Task Work Plan: Task 6

Accomplishments for the Period August 2007 – December 2008
Task Lead: Evan Mills

For more information on this project, see:
http://hightech.lbl.gov

## OBJECTIVES

### The Opportunity

The California Energy Commission's PIER Industrial Program has recognized that energy consumed by buildings used in California's high-tech industries and institutions represents an attractive opportunity for energy savings and peak electricity demand reductions, often coupled with significant non-energy benefits. High-tech buildings are characterized by large base-loads operating 24 hours a day with energy intensities much larger than typical office buildings. High-tech buildings include laboratories, cleanrooms, and data centers that are essential to various industries (and to public-sector energy users such as schools and government facilities) important to the state's economy.

The overarching goal of this project is to improve the energy efficiency of high-tech buildings—cleanrooms, laboratories, and data centers—thereby reducing energy use in California, providing financial benefits to California companies, retaining high-tech companies in California, and improving the health and safety of California workers. A number of major technical have been conducted, as described elsewhere in the Final Report.

Communications with key constituencies have been central to the success of the project. This report outlines Outreach & Technology Transfer efforts to support the dissemination of results from the aforementioned technical tasks to the public and key stakeholders and decision-makers in the high-tech facilities arena. The Outreach & Technology Transfer activities within the project have been coordinated by Evan Mills, with active involvement of researchers in each research task.

**Measures of Success**

- Short term: Specific goals included communicating results (text, data, graphics) of individual tasks to key audiences and decision-makers likely to utilize the information. As a result, the "high-tech facilities" activities have increased visibility in the energy and facilities management communities.

- Long term: widespread (and actionable) awareness of the products of this project among key decision-makers, and actions taken on the basis of our results leading to significant energy savings in new and existing high-tech facilities.

While the project's reach is global (see map showing sources of project website traffic over the past year), the impacts center on California.

## APPROACH

## Strategy

We initiated this period of work by refining a detailed portrait of our diverse audiences, and mapped them against the relevant communications channels and techniques. This "map" improved on our prior versions by helping to more precisely define technology transfer objectives. We arrived at the following strategies to achieve technology and information transfer to these audiences:

- Establish "Basic Infrastructure"
- Interact with Project Advisory Committees (PACs)
- Produce Self-published Products
- Disseminate Information Through the Trade and Technical Media
- Seek Visibility Through The Popular Media
- Distribute Results Through The Internet: Web & E-mail
- Distribute Results Through Conferences, Meetings, and Workshops
- Transfer Technology Through Standards & Guidelines; Service on Technical Committees
- Distribute Results Through Curriculum & Training

## Target Audiences and Communications Channels

Communications planning appropriately began with an assessment of the intended audiences, and the channels available for reaching them. The resulting matrix, shown below, exemplifies productive intersections between target audiences and communications channels, and is being used as a roadmap for creating and targeting communications products and activities within this Project.

## High-Tech Communications and Outreach Matrix

| | | Communication Channel or Method | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Priority | Audience | Reports; Presentations | Newsletter | Best-Practices Briefs | Standards & Guidelines | Face-to-Face (conf's, mtgs) | Utility Workshops | Trade Journals | Tech. Journals | In-House Media | Popular Media | Exhibits | Curriculum & Training | Tools | Internet* | Intranet |
| ***** | End users (Facility owners, operators, designers, etc – public/private) | | x | x | x | x | x | x | | | | x | x | x | x | |
| ***** | PACs (one for Labs & Cleanrooms; one for Data Centers) | x | x | | | x | | | | | | | | | x | x |
| ***** | Clients; Policymakers | x | x | x | | x | | | | | x | x | | | x | x |
| **** | Benchmarking Sites | x | x | x | | x | | | | | | | | x | | |
| **** | Industry associations (Silicon Valley Mfr's. Group, etc.) | | x | x | x | x | x | x | | | | | x | x | x | |
| *** | Product manufacturers, designers, contractors, etc. | | x | x | x | x | | x | x | | | | | x | x | |
| *** | Utilities | | x | x | x | x | x | | x | x | | x | x | x | x | |
| *** | Educators | | x | x | | | | x | | x | | x | x | x | x | |
| ** | Other Researchers | x | x | x | | x | | | x | x | | | | x | x | |
| ** | General Public | | | | | x | | | | x | x | x | | | x | |
| * | Other spokespeople for efficiency in Hi-Tech facilities (e.g., Labs 21 & USGBC) | x | x | x | x | x | | x | x | x | | | | | x | |

Note: For first column, one star = least emphasis; five stars = greatest emphasis

* Internet tools: flat pages, wiki's, interactive maps, blogs, simulators/tools, link directories, RSS and other feeds

# OUTCOMES

## Description of Work

Many task-specific technology transfer efforts were covered in their respective Task Description documents. The following discussion pertains to the overall plan and complementary crosscutting activities involving particular audiences and/or communication channels. Special emphasis has been given to the results of the demonstration projects and associated "Best Practices" findings. A comprehensive list of downloadable publications is located here: http://hightech.lbl.gov/library.html

- Establish "Basic Infrastructure"

  Included preparation of business collateral: PowerPoint templates; project and public web sites, etc., as well as identification of key audiences and communications channels (see previous table). This task also involved maintaining a "Stakeholder" database (which currently stands at over 500 names) that has been used for regularly broadcasting outreach products to key sub-groups such as trade press editors, facility managers, etc.

- Interact with Industry Partners

  Industry advisors have first-hand insight into the sectors in question and ways of effectively targeting and communicating our results. The Advisors are also comprised of important constituents for the project results. Advisors are listed here: http://hightech.lbl.gov/advisors.html

- Produce Self-published Products

  Following are the generic types of products that we publish (specific examples will be given below).

  - CEC core deliverables & administrative reporting
  - Best-Practices Briefs (large audience)
  - Posters (for permanent or portable display)
  - LBNL technical reports (small audiences)
  - PowerPoint Presentations (mid-sized audience)
  - Web content (see below; large audience)

Brief articles (<500 words) are periodically published in LBNL's "EETD Newsletter", which reaches approximately 10,000 readers. These also serve a dual function of forming the basis for longer trade press articles. EETD articles are also automatically posted on the web.

- Disseminate Information Through the Trade and Technical Media

We periodically issued media advisories to trade journals (as distinct from full articles, which will also be done). Many trade journals do not publish articles from outside authors, but ran "news" stories on topics of interest to their readership.

We continually sought publication opportunities and other forms of collaborations with trade journals and trade media outlets, i.e.:

- E Source. 2008. "DC Power Distribution Cuts Data Center Energy Use." PIER Buildings Technical Brief, October, 2pp.
- Garris, L.B. 2008. "8 Energy Benchmarking Hurdles (and How to Get Over Them)." *Buildings*. July, pp 56-61.
- Mills, E., W. Tschudi, J. Shalf, H. Simon. 2008. "Supercomputers: Superpolluters?" *The Data Center Journal*, vol. 7, May, p. 16-18.
- *The Data Center Journal*. 2008. "Data Center Research and Lawrence Berkeley Lab." vol. 6, April, p. 18-19.
- The Berkeley Hood (Article in *From the Lab to the Marketplace - 10 years later*)

We published in various appropriate professional and technical journals or conferences.

- Shehabi, A., Ganguly, Traber, S.K., Price, H., Horvath, A., Nazaroff, W.M., and Gadgl, A.J. 2008. "Energy Implications of Economizer Use in California Data Centers." *Proceedings of the 2008 ACEEE Summer Study on Energy Efficiency in Buildings*, Asilomar, CA.
- Shehabi, A., A. Horvath, W. Tschudi, A.J. Gadgil, and W. W. Nazaroff. 2008. "Particle Concentrations in Data Centers." *Atmospheric Environment* 42:5978-5990.
- Mills, E., P. Mathew, N. Bourassa, M. Brook, and M.A. Piette. 2008. "Action-Oriented Benchmarking: Concepts and Tools." *Energy Engineering*, Volume 105, Number 4, pp. 21-40. LBNL-358E.
- Mathew, P., E. Mills, N. Bourassa, M. Brook. 2008. "Action-Oriented Benchmarking: Using the CEUS Database to Benchmark Commercial Buildings in California." *Energy Engineering*, Volume 105, Number 5, pp. 6-18. LBNL-502E.
- Faulkner, D., D. DiBartolomeo, and D. Wang. 2007. "Demand Controlled Filtration in an Industrial Cleanroom." Lawrence Berkeley National Laboratory Report No. 63420.

In the last cycle of work, based on a suggestion by Genentech, we prepared a White Paper for corporate decision-makers on the energy and non-energy benefits of increasing the energy performance of high-tech facilities. Target audiences included CFOs, Supply Managers, Purchasing Managers, and those issuing corporate energy policies. Authors: Gary Shamshoian (Genentech), Michelle Blazek (AT&T), Phil Naughton (SEMETECH), Bob Seese (Critical Facilities Associates), Evan Mills and Bill Tschudi (LBNL). An update of this work was subsequently published as the opening article in the premiere issue of a new international journal called *Energy Efficiency* (Springer).

A “sequel” article was prepared, this time targeting researchers themselves. It provides an estimate that research facilities are responsible for $10 billion in annual

energy expenditures across the US, and compels the research sponsors to conserve research funds by promoting more energy-efficient research facilities and equipment. The article is slated for publication in *ES&T*, which is very widely read throughout the research community.

- Mills, E., G. Shamshoian, M. Blazek, P. Naughton, R.S. Seese, W. Tschudi, and D. Sartor. 2007. "The Business Case for Energy Management in High-Tech Industries." *Energy Efficiency*, 1(1). DOI 10.1007/s12053-007-9000-8.
- Mills, E. 2008. "Sustainable Scientists." *Environmental Science and Technology* (in press).

- Seek Visibility Through The Popular Media

LBNL's news release service is used at selected points where we have particularly notable results. This serves as the means of reaching general audiences. We were very successful in having our work reported in the popular or wide-circulation media, including:

- *Environmental Leader*. 2008. "'Old' IT Doesn't Have to Mean 'Inefficient'." June 30.
- *New York Times*. 2008. "Demand for Data Puts Engineers in the Spotlight." June 17.
- *The Scientist.* 2007. "Can Labs Go Green?" Vol. 21, No. 6.
- *Forbes.* 2007. "Building a Greener Grid."
- *KGO TV* (Channel 7). 2007. "Tackling Data Center Energy Consumption."
- *Computerworld.* 2007. "Green Grid to Deliver More Studies by Year's End." August 8.

- Distribute Results Through The Internet: Web & E-mail

We built out a one-stop "umbrella web site" integrating our currently disparate communication products and results. All written products (reports, presentations, etc.) have been posted/linked there. http://hightech.lbl.gov

Additions to the website included new areas for demonstration projects (http://hightech.lbl.gov/demonstrations.html) and training, which focused initially on datacenters (http://hightech.lbl.gov/training/training.html).

We continued to publish an electronic newsletter entitled *High-tech News*, which is distributed to about 400 technical stakeholders plus 133 media reporters. Two issues were released during the period covered by this report

- Issue #3 - http://hightech.lbl.gov/htnews/htn-issue3.html
- Issue #4 - (in press)

- Distribute Results Through Conferences, Meetings, and Workshops

Project staff presented results from this project at 25 meetings (during this reporting period). We regularly partnered with industry groups to find experts to contribute to the discussions. A comprehensive list of presentation titles and venues (including downloadable versions of the talks) can be found here: http://hightech.lbl.gov/events.html

- Presentations during this reporting period
    - November 20, 2008: Best Practices Data Centers Workshop. Austin Energy and State Energy Conservation Office [Best Practices Training: Part 1 [D. Sartor] and Part 2 [W. Tschudi] - Austin, TX]
    - November 15-19, 2008: SC08 Scientific Computing Conference [Should utilities give away supercomputers with the purchase of a power agreement? - W. Tschudi, D. Sartor - Austin, TX]
    - October 26-28, 2008: CEC and Public Utilities - Emerging Technology Conference [San Diego, CA]
    - October 22, 2008: USDOE - Weatherization & Intergovernmental Programs [Opportunities for Energy Efficiency in Data Centers - W. Tschudi - Webcast]
    - September 16-18, 2008: Labs21 [San Jose, CA][*]
    - June 27, 2008: SVLG - Energy Summit held at Sun Microsystems [Santa Clara, CA]
    - June 26, 2008: Silicon Valley Leadership Group [Data Center Demonstration Project Results - W. Tschudi, D. Sartor, T. Xu, and R. Ghatikar - Santa Clara, CA] Hosted by Sun Microsystems. More information
    - June 21-25, 2008: ASHRAE Meeting [Data Center Energy Efficiency Metrics - W. Tschudi - Salt Lake City, UT]
    - June 17-19, 2008: Federal Environmental Symposium West (FES-West) [Data Center Energy Efficiency Opportunities - W. Tschudi - Big Sky, MT]*
    - June 11, 2008: Intel - Eco-Technology Great Debates Forum [AC versus DC Power - W. Tschudi - Santa Clara, CA]
    - June 10, 2008: IDC Green IT Forum West [D. Sartor - Santa Clara, CA]
    - June 10, 2008: PG&E - Data Center liquid cooling workshop held at Pacific Energy Center [T. Xu and W. Tschudi - San Francisco, CA]
    - June 2-4, 2008: Federal Environmental Symposium East [Bethesda, MD]*
    - May 21, 2008: [Saving Energy in Federal Data Centers - D. Sartor and M. Hydeman - Kansas City, MO]
    - May 21, 2008: Sematech workshop to review proposed Environmental Performance Criteria (LEED type criteria) for Cleanrooms [W. Tschudi - Austin, TX]

[*] Items denoted with an asterisk (*) were funded at least in part from non-CEC sponsors (e.g. DOE). These events leveraged PIER funding as a means of delivering the results of PIER research to important end-user audiences.

- February 27, 2008: Intel Chief Technology Officer Meeting [CTO Challenge - W. Tschudi - Santa Clara, CA]
- February 21, 2007: SMUD Data Center Training [W. Tschudi - Sacramento, CA]
- January 9-11, 2008: ASHRAE [Data Centers and Cleanrooms - W. Tschudi - New York, NY]
    - Energy Reduction Opportunities in Pharmaceutical Clean Rooms
    - Demonstrations to Illustrate Energy Efficiency Opportunities in Data Centers
- December 18, 2007: DOE Workshop on Assessment Tools*
    - DOE Data Center Energy Efficiency Program and Tool Strategy [Paul Scheihing - USDOE]
    - DOE Data Centers Tool Suite [William Tschudi and others]]
    - Overview
    - Data Center Energy Profiler - "DCPro" Tool
    - HVAC
    - Electrical
- December 4, 2007: Southern California Edison [Data Center Training - W. Tschudi [Part 1 | Part 2] - Irwindale, CA]
- November 29, 2007: Sonoma Mountain Village [Data Center Energy Efficiency - W. Tschudi - Sonoma, CA]
- November 11-16, 2007: SC07 High-Performance Computing Conference [W. Tschudi, Reno, NV]*
    - Data Center Energy Efficiency
    - LBNL and Government Data Center Programs
- November 8, 2007: UC/CSU Data Center Energy Efficiency Training [California State University, Dominguez Hills - Carson, CA]
    - Introduction
    - Overview - Bill Tschudi
    - Data Center Design Issues - Bill Tschudi
    - HVAC System Design - Mark Hydeman
    - Overview of Liquid Cooling Systems - Peter Rumsey
    - Data Center Controls - Mark Hydeman
    - Group Think - Mark Hydeman
    - Leading Energy Efficiency in High Tech: PG&E's Program & Service Portfolio - Mark Bramfitt
    - IT Equipment Efficiency - Peter Rumsey
    - Electrical Systems Efficiency - Bill Tschudi
    - Data Center Cx - Mark Hydeman
- October 29, 2007: Uptime Institute [Data Center Energy Use: Metrics and Rating Systems - S. Greenberg and J. Koomey - Santa Fe, NM]*
- October 28-31, 2007: 24 x 7 Exchange [Federal Data Center Programs - W. Tschudi, Grapevine, TX]*
- October 18, 2007: Data Centers Training at Dominguez Hills [W. Tschudi - Carson, CA]
- October 2-4, 2007: Labs21 Conference [G. Bell - North Charleston, SC]*

- September 26, 2007: E Source Forum [Data Centers: They're Back - W. Tschudi, Boulder, CO]
- September 25, 2007: Gene Acres [D. Sartor, P. Mathew, San Francisco, CA]

A variety of activities involved working directly with California Utilities. We also held two workshops on the Sun "chill-off" at the Pacific Energy Center. We began work with Southern California Edison and San Diego Gas and Electric on an HVAC DOE-2 front end to model data centers. We also gave a number of presentations and trainings at the request of utilities. Presented two "Chill-Off" events at PEC to present PIER-funded results on data centers and putting vendors in contact with PG&E customers. PG&E co-sponsored the Labs21 and Datacenters21 meetings (co-sponsored by CEC/PIER as well).

- Transfer Technology Through Standards & Guidelines; Service on Technical Committees

Various tasks in the project utilized this "channel" for technology transfer. Activities involved in these issues include, work related to contamination issues in IT equipment and work related to DOE's DC Pro Assessment tools.

Product Rating/Labeling: ENERGY STAR served as another natural form of guideline and several of the tasks that produced analyses and data (e.g. for power supplies) that could support eventual inclusion of high-tech products and/or facilities in the ENERGY STAR programs.

Voluntary Standards and Guidelines (examples for fume hoods and data centers):

- ASHRAE: Work with Technical Committee TC 9.9 which has issued seven books for data centers with several more in progress.

- Industry Technical Committee Work: Project participants serve on a number of industry technical committees, e.g., which provide a key channel for outreach:

  - ASHRAE Clean-spaces technical committee TC 9.11 [Tschudi]
  - ASHRAE TC 9.10 (laboratories) [Bell]
  - Critical Facilities Round Table (CFRT) Committee on data centers. [Tschudi, Greenberg, Xu]
  - IEEE 1621 [Chair]. Power Control User Interface Standard [Nordman]
  - IEST Working Group 12 on cleanroom design considerations. [Xu]
  - IEST Working Group 36 on fan-filter unit test procedure. [Xu]
  - IEST WG on Mini environment, which has close relevance with WG12. [Xu] - Pending
  - USGBC LEED™ for Labs committee [Mathew]
  - 7x24 Exchange National and Local meetings [Greenberg, Tschudi]
  - AFCOM local chapter [Tschudi]

- Distribute Results Through Curriculum & Training

- We continued to channel our datacenter research materials into an extensive special self-paced "training" website See http://hightech.lbl.gov/DCTraining/top.html
- Several California utilities invited us to lead or participate in training sessions for their constituents. These are cataloged at: http://hightech.lbl.gov/events.html

**Implementation Team and Responsibilities**

1. Task Leader: Evan Mills
2. Other Staff: Bill Tschudi, Dale Sartor, plus task-specific leaders
3. Other partners: Media Allies (e.g. trade magazine editors), utilities collaborating in trainings, etc.