Final Report: Energy Efficient and Affordable Commercial and Residential Buildings

CONSULTANT REPORT

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Prepared By:
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Vernon Smith, P.E. – Program Director

Architectural Energy Corporation

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Preface

This is the final report for the Energy Efficient and Affordable Small Commercial and Residential Buildings Program, contract number 400-99-011. It summarizes each technical project within the research program and serves as a preliminary information source for manufacturers, service providers, researchers, and the general public regarding the energy savings potential within California of each technology.

The report describes the objective of each project, background information, technical approach, technical and market outcomes, and an assessment of the energy saving potential of products or services using the technology. Major research reports from each project are referenced as attachments to this document, with an abstract on the content of each report and links to obtain them electronically.

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced this document as part of a multi-project programmatic contract (#400-99-011). The Buildings Program includes new and existing buildings in both the residential and the non-residential sectors. The program seeks to decrease building energy use through research that will develop or improve energy efficient technologies, strategies, tools, and building performance evaluation methods.

This document is part of report P500-03-096. For other reports produced within this contract or to obtain more information on the PIER Program, please visit http://www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

The Energy Efficient Small Residential and Commercial Buildings for California research program consisted of 17 innovative technical projects aimed at finding solutions to the electric energy challenges facing California. The projects were organized into six elements and were carried out from July of 2000 to July of 2003. Element 1 consisted of administrative tasks executed by Architectural Energy Corporation.

Element 2, Automated Commissioning and Diagnostics, had seven projects focused on finding ways to detect subtle, energy-wasting problems, or faults, within heating and cooling equipment and control systems. Finding a problem begs the question of what caused it, and much of the effort in these seven projects was devoted to isolating the causes of faults and estimating their impact on the energy and comfort performance of the heating, ventilating, and air-conditioning (HVAC) systems.

Project 2.1, ***Fault Detection and Diagnostics for Rooftop Air Conditioners***. Packaged air conditioners are the most poorly maintained type of HVAC system. In California, they use about 54% of the HVAC energy in the commercial sector. The Purdue research team developed thermo-fluids based fault detection methods that can pinpoint five common maintenance problems.

- This project was highly successful, resulting in a cost-effective method to detect simultaneous faults using only temperature sensors and models of normal operations.
- Controllers that embed these diagnostics methods will save energy and maintenance costs by providing alerts only when maintenance is needed and giving the mechanic better information.
- The historical data from the diagnostic system will also serve as a database for manufacturers to improve the reliability of components.

Project 2.2, ***Equipment Scheduling and Cycling***. Tracking electrical usage of HVAC system components, such as fans, pumps, chillers, and cooling towers, has traditionally required expensive submetering. This project used an innovative, single electrical monitor that can be installed at a motor control center or a building electrical service entrance to detect when multiple pieces of equipment turn on and off. The electrical monitor, called a Non-Intrusive Load Monitor (NILM), has been under development at MIT for over a decade. It is essentially an inexpensive computer that samples the electrical voltage and current at a very high frequency and uses software techniques to recognize the signature of each piece of electrical equipment.

- Motor loads such as reciprocating chillers, fans, and pumps can be identified and tracked using a single NILM.
- Loads turning on or off outside of the normal schedule can be detected, as well as abnormal cycling.
- The MIT research team achieved a major breakthrough by developing a method to detect certain loads driven by variable speed drives. In addition, they made considerable progress in automating the detection and tracking algorithms.

Project 2.3, ***AHU and VAV Box Diagnostics***. Maintenance problems with built-up air handlers and variable air volume boxes are often not detected by energy management systems because required data and analytical tools are not available. Because of the large volume of data requiring analysis it is most practical to conduct the analysis within the distributed unit controllers. The researchers at NIST continued their work on developing diagnostic rules for air-handling units (AHU) and variable air volume (VAV) boxes.

- Two rule sets (APAR and VPACC) were thoroughly tested in a NIST laboratory facility called the Virtual Cybernetic Building Testbed (VCBT) as well as using data from a half dozen field sites.
- NIST worked with three major building control manufacturers to embed these rules in their respective controller products using the native programming language of each. A fourth manufacturer recently expressed interest in the next phase of development, which will entail testing at dozens of facilities to prove the reliability of the algorithms in different HVAC systems and facility types.

Project 2.4, *Whole Building Diagnostician Demonstration*. Air handlers in commercial buildings often do not function properly due to sensor faults, control problems or scheduling errors. The objective of this project was to evaluate the usability of the Outdoor Air Economizer (OAE) module of the Whole Building Diagnostician (WBD) software, and to field test the software under three types maintenance management arrangements. Battelle, which developed the WBD under contract with US DOE, trained and supported use of the OAE by the operations staff of a large commercial office building, the energy manager of a government building campus, and the controls manager for a mechanical contractor providing services to a large commercial office building owner.

- The OAE was successful in detecting sensor and hardware problems as well as control setting problems at all of the demonstration sites.
- Fully automated data collection from some building automation systems was a challenge for the WBD. This can be overcome by working with BAS vendors and will, over time, likely disappear as better communications standards come into use.
- Once problems were identified by the OAE, too often no action was taken to make repairs. This suggests that a mechanism is needed for delivering the results to users in a way that better encourages them to correct the problems found, which may require changing incentives and rewards to inspire action by building staff.

Project 2.5, *Pattern Recognition Diagnostics*, led by Battelle with participation by Architectural Energy Corporation, pursued the automation of proven diagnostic methods that were manually exercised by an expert engineer using short-term data collection. The manual methods were embodied in Architectural Energy Corporation's ENFORMA® diagnostic software.

- The research team selected several diagnostic problems associated with chillers, boilers, cooling towers, and pumps, since other projects within the program were focused on air handlers, economizers, and VAV boxes,
- Review of the visual diagnostic process for these components indicated that the best automation method would be to use rule-based methods.
- A complete specification for the automation process was produced and a limited demonstration in prototype software was completed illustrating the efficacy of this approach. Field testing was not possible because of a lapse in co-funding in the second year of the project.

Project 2.6, ***Enhancement of the Whole Building Diagnostician***, provided a significant improvement to the WBD. Increases or decreases in whole building, or building systems, electrical or gas energy use may be caused by system faults or changes in occupant activity. For example, energy use will increase with increased sales in a restaurant, but it will decrease if an HVAC unit went off line due to compressor failure. The Whole Building Energy (WBE) module of the Whole Building Diagnostician, which is designed to flag anomalies in energy use patterns, was improved with changes to allow it to be used on a wide spectrum of building types.

- The added feature allows the user to specify any BAS variable or other accessible variable (such as sales volume) as one of up to five independent variables in the WBE module. The previous versions allowed only outside air temperature, outside humidity, and building schedule as independent variables. This will allow operators of similar buildings, such as chain retail stores and restaurants, to compare energy performance and spot positive and negative trends over time. The value to California chain managers could be a significant motivating factor to use or install energy management control systems.
- Methods and user interfaces for a second planned improvement, a module for energy use comparisons among peer buildings that could be used in near real time, were developed and partially implemented, but full implementation was not possible because of a second year lapse of co-funding.

Project 2.7, ***Enabling Tools*****.** As more FDD methods and products become available, selecting the most effective ones will be difficult because of the complexity of products and the lack of repeatability in faults. NIST previously addressed this problem by developing a laboratory, called the Virtual Cybernetic Building Testbed (VCBT), in which controllers and faults could be tested using building simulations. The FDD Test Shell was developed in this project to test FDD methods. These tools were then used to test the Whole Building Diagnostician.

- The project proved that VCBT/FDD Test Shell can independently and objectively assess the capability of new FDD tools quickly in a controlled environment. This tool will allow manufacturers and their prospective customers to test variations of FDD tools required for specific installations.
- The tool will accelerate the acceptance of FDD methods in the marketplace by giving building owners confidence that spending limited budgets on FDD features for their building automation systems will be a good investment.
- Testing of the Whole Building Diagnostician showed that it was successful in detecting eleven of fifteen faults without false alarms under normal sensitivity settings. Two of the undetected faults were due to "climate screening" (for example, a drift in the calibration of a return-air temperature sensor when the outdoor-air temperature and return-air temperature are nearly equal).

Element 3, Advanced Load Management and Control, had five projects covering a wide range of strategies to reduce peak loads and reduce energy use.

Project 3.1, ***Demand-Controlled Ventilation Assessment***, a joint project between Purdue and NIST, investigated energy and cost savings associated with demand-controlled ventilation (DCV). In addition to energy and economic simulation and analysis supported by field experiments, the project provided a general study of indoor air quality implications of demand controlled ventilation.

- In most cases, the payback period associated with demand controlled ventilation with economizer override was less than two years.
- The greatest cost savings and lowest payback periods occur for buildings that have variable and unpredictable occupancy levels, such as auditoriums, gyms and retail stores.
- The greatest savings and lowest payback periods occur in the more extreme inland climates. Mild coastal climates have smaller savings and longer payback periods.

Project 3.2, ***Night Ventilation with Building Thermal Mass*** As an alternative to leaving HVAC equipment off during unoccupied hours, this project examined ventilating with cool air during night and early morning hours to lower the temperature of the building mass. Taking advantage of the thermal storage capabilities of the building structure, this technique can shift a significant portion of a building's on-peak cooling requirements to off-peak periods, reducing both energy and demand costs. The goal of the project was to develop a simple, low-cost algorithm that could be integrated within a controller for packaged air conditioners with economizers, such as rooftop units.

- The algorithm was tested in simulations and a retail building located in southern California. The simulated building types included small office buildings, sit-down restaurants, retail stores, and schools (spaces including classroom wing, auditorium, gymnasium, and library).
- The greatest savings were predicted for buildings in coastal climates. Significant savings were also predicted for hot inland climates.
- The electrical energy savings varied between zero and about 8%. The electrical demand cost savings associated with night ventilation varied between zero and about 28%, whereas the total electrical cost savings ranged from zero to about 17%.

Project 3.3, ***Smart Load Control and Grid-Friendly Appliances*** had the objective of developing smart load controls for residential and commercial appliances such as air-conditioners, refrigerators, electric hot water heaters and other electric appliances, which would, enhance the dynamic stability of the power system, to prevent far-reaching blackouts and support the restoration of the power system after power outages. A key to the smart controller was to develop methods to detect the onset of a high stress event on the electric grid and then turn off the appliance or cycle it into a low power consumption mode.

- Two load controller prototypes were developed, built, and tested.
    - The first load controller prototype responded to under-frequency events and rapid decay in the grid frequency. This controller is reactive in its response to major electric grid events. It responds within a fraction of a second to an imbalance of generation and load and turn off electric appliance. The advantage of this controller is its simplicity and that it operates autonomously with requiring communications from the utility or grid operator.
    - The second load controller prototype was developed for the real-time statistical and spectral analyses of the grid-frequency. The objective of this

controller was to detect high grid stress conditions as a pre-cursor for impending problems in the California power grid.

- Significant insights into the complexity of detecting grid stress conditions were gained through dynamic simulations of the western US interconnected power system (WECC) and analysis of real data from two major outages in California.

Project 3.4*, Extending BACnet for Lighting and Utility Interfacing*, focused on developing software objects for the BACnet HVAC standard to include lighting controls and utility meters. The concept was to use the BACnet communications protocol to promote an open (as contrasted with proprietary) control scheme that would include lighting and energy meters as well as HVAC. NIST worked closely with the ASHRAE standards committee responsible for the BACnet standard and a number of international organizations to create consensus for the scope and functionality of the proposed objects. Progress was made in both areas.

- Two lighting control features, one to allow grouping of lighting control commands and one to interface to the DALI lighting protocol, should be part of the BACnet standard before the end of 2003.
- Two utility interface features related to remote meter reading were recently published for public comment.
- Integration of lighting controls and utility meters into the BACnet standard will promote energy conservation by giving building operators the opportunity to work on a single controls platform.

Project 3.5, *Aggregated Load Shedding* MIT researchers worked closely with the Los Angeles County Government to devise methods to reduce electrical demand in groups of buildings under a common utility meter. The County's original interest was to find manual control sequences that could be used to meet the local utility's call for load reduction under an interruptible power rate. The goals were to understand what actions to take and what load reduction to expect, to measure the load to assure that the reduction actually occurred, and to estimate what the comfort or productivity impact might be. MIT undertook simulation studies as well as short-term experiments to answer these questions.

- Non-Intrusive Load Monitors (described more fully under Project 2.1) as well as environmental sensors were installed to provide feedback to the County staff as well as the researchers.
- The control method explored was to simultaneously raise the zone thermostat setpoints or shut off the chillers for a period of time. Based on the specific building models, load patterns, weather conditions and rate structure used in this research, a peak load reduction of 2 – 14% and a cost-based peak load reduction of 2 – 12% for aggregation cases of two or three buildings with thermostats as control variable was achieved.
- Using night cooling (both fan-based and chiller-based), a 27% peak load reduction and around a 20% cost reduction in a two-building case was observed.

Element 4, Alternative Cooling Technologies and Strategies, had four projects. Two were designed to field test innovative HVAC equipment, another compared hydronic radiant distribution with forced air distribution in residential heating and cooling, and the fourth was an assessment of natural ventilation design options in California.

Project 4.1, ***Modular High-Efficiency Gas Absorption Heat Pumps,*** was a development effort headed by Oak Ridge National Laboratory in conjunction with Robur Corporation. The first phase of the research plan included field demonstration of Robur's small (5-ton) gas absorption chillers linked to a common water distribution loop to provide cooling to larger commercial loads, up to 30 tons. The second phase was to include a field demonstration of the gas absorption (GAX) heat pump. During the first project year, recruiting demonstration partners was not successful because the cost of natural gas had increased dramatically. There was considerable uncertainty at the time due to the volatility of natural gas and electricity prices. At the end of the first project year, these economic issues as well as delays in starting development work on the GAX heat pump led to a decision to reduce the scope of the project to just a GAX chiller link demonstration. During the second year, a facility with three GAX chillers was recruited, but preliminary data showed that the internal loads were not large enough to exercise all three of the chillers in sequence over the course of a typical day. The project was cancelled after consultation with the Program Advisory Committee. Development of the GAX heat pump concept continues at Oak Ridge National Laboratory. Based on recent research at ORNL, GAX heat pumps will be very efficient at heating and only moderately efficient at cooling, leading to suggested application in cold climates. Since most California climates are relatively mild, it is doubtful that GAX heat pumps should be applied in California.

Project 4.2, ***Ventilation Energy Recovery Heat Pump Assessment***, Purdue investigated application of a new heat pump application, called a "heat pump heat recovery" (HPHR) system. The heat pump in this case extracts heating or cooling energy from the exhaust air stream of an air handler or packaged air-conditioning unit and transfers it to pre-condition the incoming outside fresh air stream. In cooling season, it pre-cools the incoming air and in heating season it pre-heats it. The heat pump heat recovery (HPHR) system functioned properly during the field and laboratory testing. However, heating requirements are relatively low for California climates and therefore overall savings are dictated by cooling season performance.

- The HPHR system did not provide positive cost savings for most building type/climate combinations investigated using simulations.
- The HPHR system is an alternative to an economizer and so economizer savings are also lost when using this system. There are not sufficient hours of ambient temperatures above the breakeven point to yield overall positive savings with the HPHR system compared to a base case system with an economizer for the prototypical buildings in California climates.
- The HPHR system should not be considered for use in California, except in perhaps certain mountain areas with larger heating loads.

Project 4.3, ***Residential Hydronic Radiant Cooling and Heating Assessment***, led by Oak Ridge National Laboratory, compared the performance of different modes of heating and cooling in a single house. The house is equipped with an innovative HVAC system which includes a conventional forced air ductwork system, a variable speed air handler with a hydronic coil and an outside air economizer, and a slab-embedded hydronic radiant system. Mechanical cooling is supplied by a small DX chiller, a condensing water heater is used in heating mode. Three cooling modes were tested: (1) conventional air distribution, (2) conventional air distribution augmented by hydronic pre-cooling of the slab at night, and (3) conventional air distribution augmented by pre-cooling the building mass using outside air at night and hydronic slab pre-cooling if necessary.

- The radiant hydronic cooling was very effective in shifting the cooling load into off-peak hours and greatly reduced energy use.
- Using night ventilation in conjunction with hydronic radiant pre-cooling was even more effective at shifting load into off-peak hours.

Project 4.4, ***Design Methods and Guidelines for Natural Ventilation*** This NIST project objectives included developing natural ventilation design strategies and design methods for small commercial buildings, addressing the impact of outdoor air quality on natural ventilation, and developing natural ventilation software tools.

- A new ventilation cooling metric was described and used to demonstrate that the coastal climates of California are potentially very well suited to natural ventilation.
- The hotter, inland locations are less suited to a simple natural ventilation strategy but may be able to benefit from night cooling or hybrid system strategies.
- An eight-step design guide for natural ventilation applications was developed.
- A review of ambient air quality data indicated that much of California fails to meet the national standards for one or more contaminant. However, since ambient air quality problems may vary by season, time-of-day, and locality, natural ventilation strategies may still be considered acceptable at all times in some areas and part of the time in other areas through innovative hybrid systems.
- Natural ventilation design and analysis software, called LoopDA (for Loop Design and Analysis), was developed to aid in sizing and placement of natural ventilation devices. LoopDA is based on CONTAMW 2.0, a multi-zone airflow model.

Element 5, Alternative Construction Techniques and Technology, had one project, ***Project 5.1, Building Integrated Photovoltaics***. The project was conducted by NIST using laboratory and field tests at its headquarters in Gaithersburg, MD, to develop a validated design algorithm to predict the energy production of building-integrated photovoltaic panels.

- Performance and environmental data were collected for one year on four different BIPV technologies (single-crystalline, poly-crystalline, silicon film, and triple junction amorphous silicon panels), mounted in insulated and un-insulated configurations.
- The results of validated models were used to predict the energy savings possible by using curtain-wall photovoltaic products that are integrated for buildings in high growth areas of California.
- Insulation behind PV panels degrades power production slightly in three out of the four cell technologies tested. The fourth technology showed a very slight improvement in power output due to the insulation.
- The simulations demonstrated that shading will result in a significant reduction in power production from curtain wall BIPV products. In addition, the vertical orientation will adversely affect power production compared to roof-mounted PV systems, particularly during the summer.

Element 6, Assessment, had one project,

Project 6.6, ***Impact Assessment Framework***, which was performed by Battelle with significant support from Nexant, and with consultation from Xenergy. The project objective was to develop and demonstrate an impact assessment framework that explicitly identifies the assumptions and inputs to the assessment process and evaluates technologies for energy savings potential. The assessment framework developed for the commercial building sector is composed of four components 1) Product Characterization, 2) Market Segmentation, 3) Market Penetration, and 4) Analysis of Impacts. A graphical user interface was developed to demonstrate the use of the framework based on data from the PG&E CEUS database. A more comprehensive database is under development through another Commission project. When that database is complete, the framework will provide a starting point for the Commission to assess all projects within Buildings Area of the PIER Program.

Abstract

The Research Program had 17 technical projects organized into five elements as well as a management element. The Program was scheduled to finish within three years with a budget of $5,422,000. It finished on time and slightly under budget.

Element 2, *Automated Commissioning and Diagnostics*, had seven projects focused on finding ways to detect subtle, energy-wasting problems, or faults, within heating and cooling equipment and control systems. Finding a problem begs the question of what caused it, and much of the effort in these seven projects was devoted to isolating the causes of faults and estimating their impact on the energy and comfort performance of the heating, ventilating, and air-conditioning (HVAC) systems.

Element 3, *Advanced Load Management and Control*, had five projects covering a wide range of strategies to reduce peak loads. Two projects focused on optimizing strategies that would reduce energy consumption as well as peak demand (demand controlled ventilation, optimizing night cooling controls that used outside air or mechanical cooling to remove heat from the building's thermal mass). Two others investigated ways to reduce peak demand at periods of very high grid use (smart load controls built into appliances, and aggregated load shedding for buildings under a common utility meter). Finally one project explored options for extending the HVAC BACnet controls standard to include lighting controls and interfacing with the utility.

Element 4, *Alternative Cooling Technologies and Strategies*, had four projects. Two were designed to field test innovative HVAC equipment, specifically modular high-efficiency gas absorption heat pumps and a heat pump designed to recovery energy from the ventilation exhaust air stream. Another project compared the performance of residential cooling using hydronic radiant distribution and forced air distribution. The fourth project was an assessment of natural ventilation design options in California.

Element 5, *Alternative Construction Techniques and Technology*, had one project on building integrated photovoltaics. Its focus was to develop a validated design algorithm to predict the energy production of building-integrated photovoltaic modules and to assess the energy savings potential from using BIPV in California.

Element 6, *Impact Assessment Framework*, had one project focused on developing and demonstrating an impact assessment framework that explicitly identifies the assumptions and inputs to the assessment process and evaluates technologies for energy savings potential.

1.0 Introduction

The goal of the Energy Efficient and Affordable Small Commercial and Residential Buildings Program was to develop, demonstrate and deploy technological solutions for building energy end-uses that provide direct and tangible benefits to the California ratepayers. Key to achieving high impacts and direct benefits for every research dollar was a set of projects that were synergetic, market-oriented, and supported by industry. An important related goal was to provide significant economic benefits to building owners and health and performance benefits to occupants. The research results from this program will strengthen the growing energy efficiency industry in California by providing new jobs and growth opportunities for companies providing the technology, systems, software, design, and building services to the commercial sector.

TEAM

The Research Program team consisted of Architectural Energy Corporation, Battelle Memorial Institute, Northwest Divsion[1], Massachusetts Institute of Technology, National Institute of Standards and Technology, Oak Ridge National Laboratory, and Purdue University. The team worked with major manufacturers and California utilities to evaluate these technologies. The Research Program team members were:

Architectural Energy Corporation (AEC)	Donald Frey, P.E. Vernon Smith, P.E. Erin Coats Stuart Waterbury, P.E.
Battelle, Pacific Northwest Division (Battelle)	Michael Brambley, PhD Michael Kintner-Meyer, PhD Srinivas Katipamula, PhD David Chassin Krishnan Gowri, PhD Robert Pratt Robert Briggs Nathan Bauman
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[1] Battelle, Pacific Northwest Division, operates the Pacific Northwest National Laboratory for the U.S. Department of Energy and conducts research and development using these facilities as Battelle under a special-use agreement.

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Massachusetts Institute of Technology (MIT)	Les Norford, PhD Steven Leeb, PhD Doug Lee, PhD Peter Armstrong Helen Xing

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Xenergy	Michael Rufo Fred Coito

ELEMENTS

The Research Program was divided into a management element, four research elements, and an assessment element. Each element consisted of a number of projects. The elements are listed below. Additional background information on each project is presented as well as details regarding the research outcomes of the individual projects are presented in this report.

Element 1: Program Management. This element provided coordination with the Commission, the Program Advisory Committee, and program participants.

Element 2: Automated Commissioning and Diagnostics. This research element had seven projects focused on improving building operation and the quality of indoor environments through equipment and system fault detection and diagnostics.

Element 3: Advanced Load Management and Controls. Element 3's five projects investigated technology to save energy and to reduce peak electrical loads in buildings.

Element 4: Alternative Cooling Technologies. This research element had four projects which explored technologies to reduce or eliminate electricity consumption for cooling.

Element 5: Alternative Construction Techniques and Technologies. This element had one project, which focused on evaluating building integrated photovoltaic technologies.

Element 6: Technology Assessment. An impact assessment framework was developed under this element to provide a consistent methodology to evaluate the impact of new building-related energy efficiency technologies.

ORGANIZATION CHART

The Research Program Management Team had lead researchers from each organization. A Program Advisory Committee (PAC) provided strategic direction to AEC and the Commission. The relationships among these organizations are shown on the Management Plan Diagram (Figure 1.)

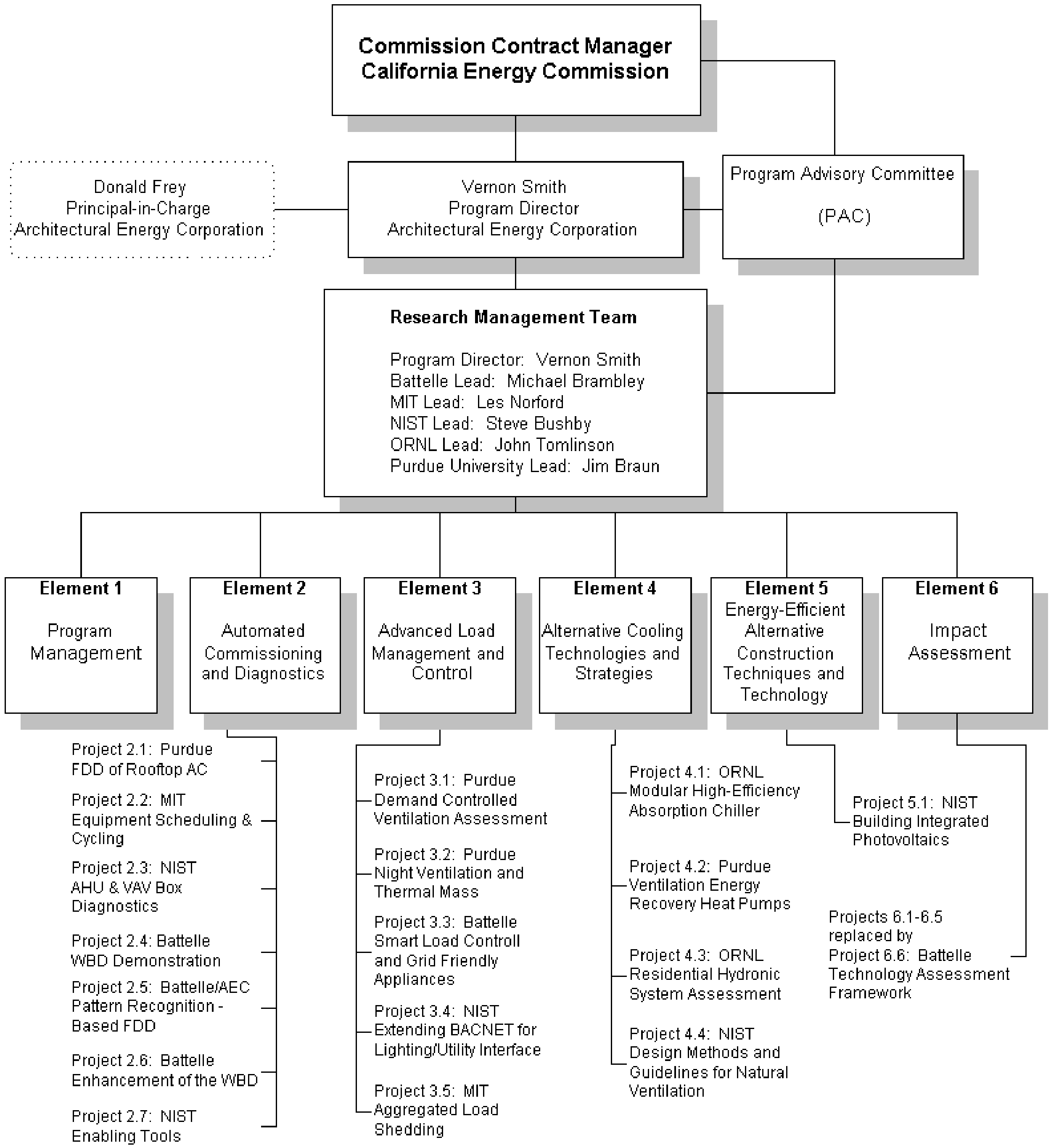

Figure 1. Management Plan Diagram

REPORT ORGANIZATION

The report is organized by element and by projects with each element. Major research reports from each project, which are referenced as attachments to this report, are available electronically as separate reports.

2.0 ELEMENT 2—Automated Commissioning and Diagnostics

INTRODUCTION

Evidence of extensive performance problems in buildings shows that an efficient California building stock will not result solely from designing efficient buildings and installing efficient equipment in them. Comprehensive, top-down analyses by utility planning agencies of billing data for the population of new commercial buildings have shown consumption 10% higher than levels projected. This is determined by construction characteristics, even when based on metered end-use loads. These analyses support the conclusion that even newly constructed buildings are consuming more energy than they should.

These performance problems are not inherent in efficiency technologies themselves, but instead result from errors in installation and operation of complex building heating, ventilation, and air conditioning (HVAC) and control systems. These systems are becoming increasingly more sophisticated to obtain higher levels of energy efficiency, but this adds to the complexity and subtlety of problems. Problems are even more common in existing buildings, arising over time from operational changes and lack of maintenance. They often result in comfort control and indoor air quality problems that affect occupant health and productivity.

The traditional means of assuring efficient performance, commissioning of new buildings followed by regularly scheduled preventative maintenance, are clearly insufficient to address this issue. Manually commissioning buildings is valuable in terms of finding problems and developing techniques but does not yield persistent results.

Automated fault detection and diagnostics (FDD) methods are powerful tools that can extend the benefits of manual commissioning and regular maintenance. Element 2 had seven projects focused on finding ways to detect subtle, energy-wasting problems, or faults, within heating and cooling equipment and control systems. Finding a problem begs the question of what caused it, and much of the effort in these seven projects was devoted to isolating the causes of faults and estimating their impact on the energy and comfort performance of the heating, ventilating, and air-conditioning (HVAC) systems.

Project 2.1, Fault Detection and Diagnostics for Rooftop Air Conditioning, focused on FDD for packaged HVAC units, which use about 54% of heating, cooling, and ventilation energy use in California. Project 2.2, Equipment Scheduling and Cycling, used a novel electrical meter to look for scheduling and cycling faults in medium to large HVAC systems. Project 2.3, Air Handling Unit and VAV Box Diagnostics, continued development of automated rules to find faults in built-up air handlers and variable air volume boxes. Project 2.4, Demonstration of the Whole Building Diagnostician, gathered information about user interaction with an outdoor economizer diagnostic software module. Project 2.5, Pattern Recognition Based Fault Detection and Diagnostics, developed the software specifications to fully automate a set of diagnostic methods that had been successfully applied manually in the past. Project 2.6, Enhancement of the Whole Building Diagnostician, added new capability to the whole building energy diagnostic module making it more flexible and useful for most buildings with building automation systems. Project 2.7, Enabling Tools, integrated a new capability to accelerate developing and testing FDD software in a laboratory and field environment.

2.1. Project 2.1 Fault Detection and Diagnostics for Rooftop Air Conditioners

INTRODUCTION

Background and Overview

Rooftop air conditioners are used extensively throughout small commercial and institutional buildings, but compared to larger systems, they tend to be poorly maintained. Application of automated fault detection and diagnosis (FDD), which has been used widely in critical systems, will significantly reduce energy use & peak electrical demand, down time and maintenance costs.

There are three important barriers. FDD for HVAC systems, especially for rooftop air conditioners, is subject to economic constraints, which bring special difficulties and issues not encountered in critical systems. First, since a rooftop AC is itself relatively inexpensive, the cost to realize FDD for HVAC systems must be low. Different faults may have similar symptoms, and a variety of sensors can be helpful in identification, but some useful measurements such as flow rate, pressure or even humidity are simply too expensive. Limited available measurements must be used to extract as much information as possible. Computation requirements must be within the capabilities of a limited microprocessor-based system.

Second, since rooftop units are used in diverse weather conditions and climates, the behavior of the HVAC plant will vary drastically from site to site. In addition, since single-point sensor placement is generally used, measurements tend to be biased and noisy. The FDD must be able to cope with these difficult circumstances. This requires FDD for HVAC systems to have analytical redundancy, meaning the information from system measurements should be preprocessed extensively before it is used to detect and diagnose faults.

Third, unlike critical systems in which no fault can be tolerated, rooftop HVAC requires analysis of the economic impact of the fault: is it important enough to justify service? This requires a fault evaluation and decision step to be added to the software. Finally, unlike a critical FDD system that is engineered for a specific large system, FDD for packaged HVAC systems must be adaptive and generic enough to function on the same type of system, or at least on similar models from the same product family in order to reduce the per-unit costs.

In previous research, Purdue University developed a method that correctly detected and diagnosed single faults before there was about a 5% reduction in cooling capacity and efficiency. During evaluations of the method, faults were introduced in a single unit in the Purdue laboratory at various levels, and the sensitivity of the technique in diagnosing each fault was determined. Five faults were chosen for development and testing of an FDD method. Analyzing the service records from a service company that focuses on small commercial equipment identified the important faults.

- ✓ refrigerant leakage,
- ✓ condenser fouling,
- ✓ evaporator filter fouling,
- ✓ a liquid-line restriction, and
- ✓ compressor valve leakage.

OBJECTIVES

- Demonstrate the extension of a fault detection and diagnosis (FDD) system for rooftop air conditioners to families of manufacturer's rooftop units.
- Develop methods to detect simultaneous faults.
- Assess the economic benefits of applying the FDD system in California.

Research Team

Jim Braun and Haorong Li with Purdue University conducted the research with support from Todd Rossi and Doug Dietrich with Field Diagnostic Services, Inc., David Jump with Nexant and Lanny Ross of Newport Design Consultants.

APPROACH

- Extend test results from a single rooftop unit to all units within a model family. In addition to measured data, manufacturers' performance ratings at design conditions were used to develop models of expected performance for each unit within the family.
- Develop methods to model changes in normal behavior based online measurements from field installations. This is necessary for FDD systems that are added to existing equipment and for situations where maintenance service has changed the fundamental performance of the system under "normal" operating conditions (e.g., installing a new compressor or cleaning the coils). Four quick service restaurants, four K-12 classrooms, and two retail drugstores were field test sites for the project.
- FDD methods for handling multiple simultaneously faults were developed. In previous simulation testing, it was shown that the FDD method generally identifies the "worst" fault when two faults occur. After the identified fault is repaired, then the method identifies the second fault. Laboratory testing was performed to verify and further generalize the multi-fault method.

OUTCOMES

Technical Outcomes

- The project successfully demonstrated a fault detection and diagnosis (FDD) system for rooftop air conditioners that can be the extended to families of manufacturer's rooftop units. FDD for a single unit can be generalized to fault detection in families of equipment using temperature measurements and parametric values based on published information. A hybrid model of polynomial and GRNN was found to work best. Several modeling approaches were evaluated, including polynomial functions, general regression neural networks (GRNN), back propagation, and radial basis functions in their ability to detect anomalies.
- Significant improvements were made in methods for detecting single faults. A new steady-state detector was incorporated, which has better robustness for filtering transient data and thus improves overall FDD performance. A new modeling approach was used for predicting normal operation variables. A novel fault detection classifier, called the normalized distance method, was developed that eliminates probability calculations and requires very little computer memory. Overall performance models were created, which act as virtual sensors to estimate some system performance variables that cannot be economically measured.

- Multiple-fault FDD is also technically feasible and the methods are applicable to packaged rooftop air-conditioners with fixed orifice and thermal expansion valves. A new method capable of detecting at least three simultaneous faults was developed. The new model was tested using laboratory and field data and can be used on units with thermal expansion devices as well as fixed-orifice metering devices. Figure 2 is a screen capture of the multi-fault demonstration movie.

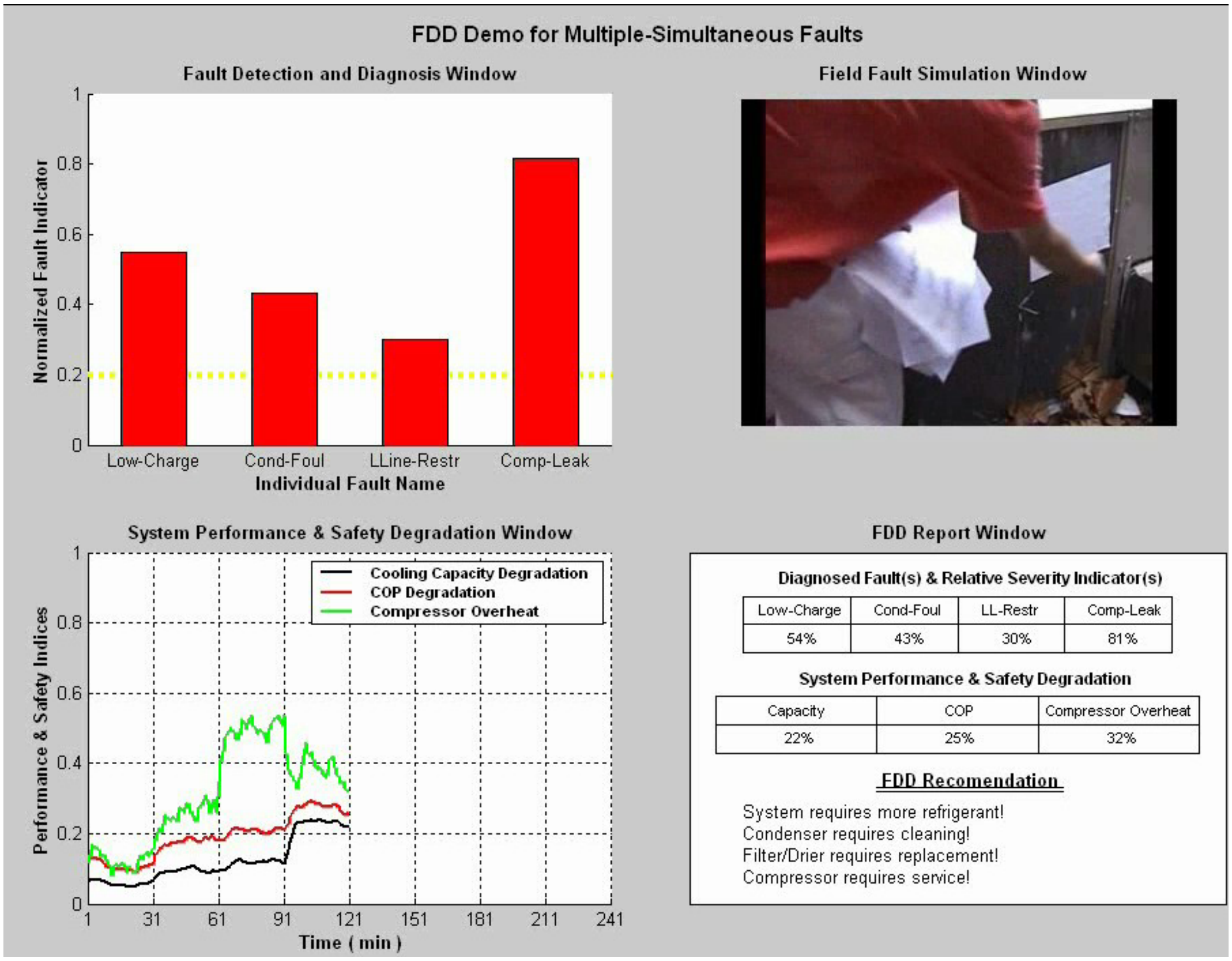

Figure 2. Snapshot of Multi-fault FDD Demonstration Movie

Market Outcomes

- The economics of using FDD technology shows promise**.** The range of net savings (total savings minus FDD system cost) over the ten year life of the unit is estimated to be between \$4000 to \$10,000 per RTU. Operational cost savings includes two parts, utility cost and equipment life savings, and could be significant for building owners. The utility cost savings are associated with the equipment operating more efficiently due to better maintenance. Equipment life savings are from better maintenance and less adverse operating conditions. Fault detection and diagnosis savings are possible, which includes unnecessary service and fault diagnosis savings. Unnecessary service includes regular service, such as coil cleaning, that is not justified and unnecessary repairs that are based upon incorrect fault diagnoses. Fault diagnosis savings are due to reduced technician time associated with diagnosing a problem. Greater savings are possible in hotter climates due to larger cooling requirements. The savings would be also greater for heat pumps because they operate throughout the whole year.

- The results will produce better indoor environments in California buildings. Usually equipment malfunctions are only detected when someone complains about a lack of cooling, heating, fresh air, or other comfort issues. Other problems simply continue unreported. Automatic FDD for rooftop equipment will call attention to problems before they lead to discomfort or health problems in a building's occupants.
- FDD can lead to more effective utilization of technician's labor. Having diagnostic results available before arriving at the site would allow technician's to plan their work time and have the right parts on the truck. Multiple trips to the site to work on the same problem could be avoided.
- FDD will prevent premature equipment failure. Compressor failure is the most expense repair on packaged rooftop units, and FDD technology can detect the faults that cause it as well as other problems.
- FDD technology will reduce unplanned outages. Using FDD to track repair histories as well as fault occurrences can assist building owners and mechanical contractors to make better "repair or replace" decisions.
- The results will provide energy benefits. Using FDD may improve rooftop air conditioner performance, providing better indoor conditions for less energy input. FDD may also allow a technician to rule out problems with a unit and look for problems elsewhere in the building. For example low flow across the cooling coil may be due to clogging of the evaporator coil caused by filter bypass, but it may also result for duct kinks and stuck dampers.
- Market penetration of FDD technology for packaged air-conditioning units will require adoption by air-conditioning manufacturers, air-conditioning component manufacturers, and building automation vendors. Market awareness of the value of built-in diagnostics will be needed before the manufacturers will offer FDD as part of the built-in controls of each unit, or as part of the fault reporting for a building automation system. In many cases, buildings using packaged air-conditioners do not have a building automation system. To provide a means of reporting the faults, software will be required that will provide an appropriate alarm or report to a person responsible for HVAC maintenance.

Major Deliverables

The major deliverables for the project may be downloaded from either of these web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Description of Field Test Sites.* (Feb 2003, rev.)
- *Description Of FDD Modeling Approach For Normal Performance Expectation* (Dec 2001)
- *Description And Evaluation Of An Improved FDD Method For Rooftop Air Conditioners* (Aug 2002)
- *Decoupling-Based FDD Approach For Multiple Simultaneous Faults* (June 2003)

- *Automated Fault Detection and Diagnostics of Rooftop Air Conditioners For California, Final Report and Economic Assessment*. (August 2003)

Two software demonstrations are also available at a third web address: http://web.ics.purdue.edu/~lihaoron/

- Demonstration of the De-coupling FDD Software.
- Service Economics Automated FDD for RTUs.
- Project 2.1 Conclusions and Recommendations

CONCLUSIONS

- Applying automated FDD to packaged air conditioning units will significantly decrease energy use, improve indoor comfort conditions, and reduce maintenance costs. The FDD methods investigated in this project could be applied to cooling equipment that supplies about 60% of building mechanical cooling in California. Over 500,000 tons of air-conditioning are supplied using packaged units.
- The new FDD method developed for simultaneous faults is applicable to packaged rooftop air-conditioners with fixed orifice and thermal expansion valves. Developing a technique applicable to thermal expansion valves increases the number of packaged units that can be served, as well as opening the possibility for application to walk-in refrigerated boxes.
- Adoption of FDD for packaged air-conditioners should be promoted to end users, service contractors, and HVAC manufacturers. The economic benefits of applying this FDD system in California ranges between $4000 and $10,000 per packaged unit over a 10-year life span, which should provide the economic incentive to use FDD.

Commercialization Potential

It is envisioned that the FDD methods would reside in the unit controller and use temperature measurements to continuously monitor performance to detect and diagnose faults. Field Diagnostic Services, Inc., a support contractor on the research project, is involved in developing FDD products, and Honeywell, Inc., a match fund provider on other projects within the program, participated in the field activities of this project. Both have expressed interest in further development of the automated FDD technology. FDSI is in discussions with other major controls manufacturers regarding development of diagnostic services and products from Project 2.1 research results.

Recommendations

- Additional research is needed in the areas of applying the de-coupling FDD technique online in field testing, improving the modeling approach based on manufacturer's data, continuing to improve the performance model, expanding the service cost database, and consider other control diagnostics.
- Recruit commercialization partners to expand the market. Primarily HVAC unit manufacturers and control component manufacturers need to understand the benefits of the FDD technology and why they should sell it to their customers.
- Establish incentive programs for mechanical contractors and building owners to promote acceptance and use of on-board diagnostics for rooftop units. This will assist in accelerating availability of units with FDD on- board.

- Provide awareness training for building owners, mechanical contractors, and HVAC trade unions. Testing with field data revealed that many units have multiple concurrent faults, confirming evidence from other PIER studies that maintenance of rooftop units is generally lacking.
- Develop automated follow up methods to ensure equipment functions as intended. The FDD methodology, along with increasingly sophisticated communications networks within buildings, should allow continuous or periodic reviews for equipment faults without visits to the site.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

The original baseline conditions and projected outcome were based on national estimates because there was no reliable data for California as a whole. During the course of the Program, the Commission has established a data set for California from which the original estimates can be improved. See Appendix I.

The new California data set established 10 end-use areas, including three of which may apply to packaged rooftop units: cooling, ventilation, and heating. The Commission used a national study [1] to estimate the types of cooling equipment used in California, which found that rooftop units provide 54% of the cooling end-use for buildings in the United States. Most rooftop units in California use natural gas for heating, although there are some climate zones in which heat pumps are used (estimated at about 7%, using data from [1]). Thus, the FDD methods investigated in this project could be applied to cooling equipment that supplies about 60% of building mechanical cooling in California. Heat pumps, in heating mode, account for 5% of energy used for heating.

Updated Baseline:

The GWh savings estimated in the original projected outcome was based on a baseline load of 74,677 GWh/yr for the entire State; the Commission's figure for Year 2000 is 91,771 GWh/yr. The California Commercial Electricity Consumption by Building Type in Year 2000 estimates that the cooling end-use consumed 15.5% of all electricity used in that year, or 14,255 GWh. Fifty-four percent of this figure, or 7698 GWh, may be attributed to DX rooftop units.

The cooling end-use is the primary target for the Project 2.1's technology. Proper functioning of the economizer, which affects the cooling end-use and the ventilation end-use, is a secondary target. The state-wide electric consumption for the ventilation end-use is 10% of the total, or 9,328 GWh/yr. Assuming that packaged AC units account for 54% of the ventilation energy used in the state, packaged air-conditioners account for additional 5,037 GWh/yr.

The installed cooling capacity of packaged air-conditioning units in California in Year 2000 is estimated to be 513,000 tons (refrigeration). Survey work sponsored under another PIER Program showed that packaged air conditioners in the range of 5 to 10 tons (refrigeration capacity) constitute about 70% of the installed units.

Updated Outcomes:

By 2015 the savings per year would be about 100 GWh for retrofit and new construction.

2.2. Project 2.2 Equipment Scheduling and Cycling

INTRODUCTION

Background and Overview

Detailed electrical-load information, at the component or system level, is not routinely measured because of the cost of obtaining and analyzing the data. Much has been learned from utility-sponsored building surveys where submeters were installed. But due to the expense of installing submeters, the benefits of such programs have been limited to building-class level information rather than insights into the operation of many individual buildings. For load information to be cost-effective for load management and diagnostics, less expensive and more capable instrumentation is needed.

Electrical-power data are useful for both whole-building performance assessments and component-specific Fault Detection and Diagnostics (FDD). Over a period of 16 years, MIT has developed a series of electrical load monitors that are capable, to varying degrees of accuracy, of identifying which pieces of equipment in the connected load are operating, and providing specific information about their power use and electrical characteristics. These meters are known as Non-intrusive Load Monitors (NILMs). The NILM is sensitive to the change in total power at the time equipment turns on or off. If power can be accurately estimated at this time and if there are reasonable models for equipment energy use between the time of startup and shutdown, it is possible to accurately estimate equipment energy consumption. In addition, the measurement and analysis of power at startup and shutdown provides a powerful tool for detecting a large class of faults in motor-driven equipment. This project focused on fully automated analysis of electrical data for detecting equipment scheduling and cycling faults.

At the beginning of this project, the on-line NILM was capable of detecting loads via analysis of the electrical-power transients observed during start-up of equipment. All other analysis, notably detection of loads via changes in steady-state power and detection of faults, was done off-line, via a combination of algorithms and intervention of an analyst.

OBJECTIVES

The overall goal was to develop and demonstrate fully automated diagnostic methods for HVAC equipment using the NILM technology, with emphasis on equipment scheduling and cycling faults and component faults that could be revealed via analysis of electrical startup transients. Three objectives were targeted.

- ✓ Detect loads automatically from step changes and distinguish among electrical loads at the motor control center level.
- ✓ Developing algorithms for fully automated detection of equipment operation (on/off events) for constant power/constant speed loads and for variable speed/variable power loads.
- ✓ Investigate fault detection methods, identify which faults can be detected with the NILM, and automate detection of those faults.

Research Team

- Les Norford, Steve Leeb, K. Douglas Lee, Peter Armstrong, and Chris Laughman with MIT conducted the research. Lanny Ross with Newport Design Consultants provided field support.

APPROACH

- Algorithm development was based on laboratory and field testing. Results from the NILM were compared to conventional submetering that was installed.

OUTCOMES

Technical Outcomes

- Detection of devices with step changes in power consumption was more fully automated and a better understanding of the limitations of this method was achieved. Testing in the first phase showed that there may be limits to detectable equipment of/off events based on the magnitude of the change in power relative to the total power measured by the NILM. A number of turn-on and turn-off events for fans and a chiller at the Iowa Energy Center's test building could be detected with two centrally located power meters. As a general rule, for equipment to be monitored from the integrated power profile, it was found that the relative magnitude of the component's power consumption to the system's total power input should not be less than 5% of the total power. Detection limits should determine the number and location of NILM meters required to obtain useful information about a building and its equipment. It may also be difficult for the NILM to discriminate between substantially identical equipment on the same connected load circuit.
- Automation of load tracking algorithms for constant power devices, such as fans, pumps, and reciprocal chillers was successfully demonstrated, as well as detection of a number of faults that are difficult to detect with non-electrical measurements. Major improvements included a state estimator and automation of steady state and transient detection filters that can detect device events in real time. Detection of variable power, constant-speed loads was started but not complete by the end of the project.
- A frequency-analysis FDD technique was developed to track variable-speed drives. Developing this technique was a major accomplishment, since variable speed driven motors change power levels very slowly. The same technique was used to detect power oscillations associated with faults such as a chiller vacuum leak, a mis-aligned fan shaft, and under-damped feedback-control loops. These faults would be very difficult to detect with more traditional thermo-fluid fault-detection methods. Figure 3 shows how the frequency characteristics change over the startup of a VSD system and the relationship between frequency and power.
- The project was successful in extending the ability of the NILM technology to automatically detect scheduling and cycling events for constant power equipment. Major improvements included a state estimator and automation of steady state and transient detection filters that can detect device events in real time. The technology was successful in detecting and identifying devices that turn on or off if the device load is more than five percent of the total load at the time the device cycles.

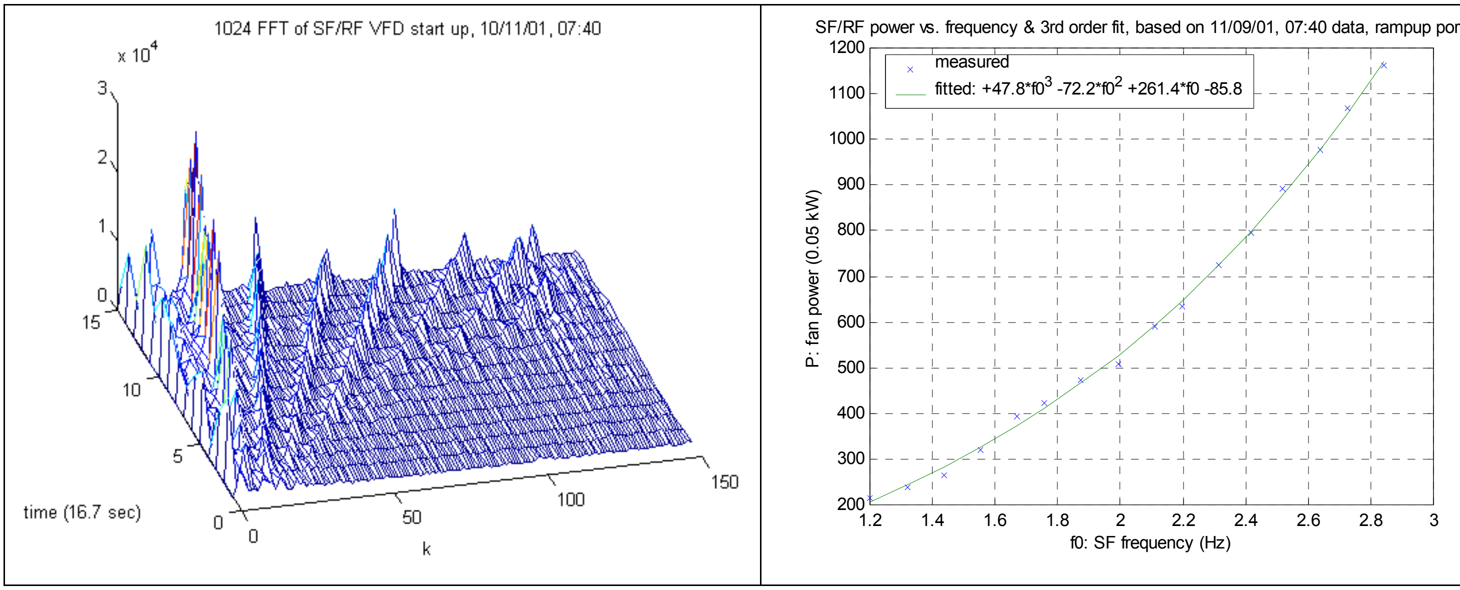

Figure 3. Illustration of Evolution of Frequency Components over 6-min Motor Startup and Power vs. Frequency

Market Outcomes

- NILM technology can provide end-use electricity consumption and demand data to building automation systems less expensively than traditional sub-metering. Building automation systems usually do not offer detailed electric load information because sub-metering at the equipment level is expensive. A NILM integrated into a utility meter, or included in a building automation system, could provide trend data to building operators, disaggregated by equipment type. By using statistical analysis of historical data, subtle changes in energy use patterns of individual pieces of equipment could be detected, allowing a more prompt investigation.
- NILM technology can enable real time pricing for small commercial buildings and allow automated load control when integrated into an energy management system. A barrier to using real time pricing is the lack of information about how electric energy is used at the end-use or individual appliance level. As a less expensive alternative to sub-metering, NILM technology could provide information to decide which loads to curtail.
- FDD based on NILM offers further insight into equipment operation, similar to vibration analysis, which can provide early clues about equipment malfunctions. A skilled and observant technician can discern details through the high-speed sampling data unobtainable any other way.

Major Deliverables

The major deliverables for the project may be downloaded from either of these web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Detection of HVAC Equipment Turn On-Turn Off Events with Non-Intrusive Electrical Load Monitoring* (Aug 2001)
- *Fully Automated Analysis of Equipment Scheduling and Cycling* (Oct 2001)

- *Development of a Functioning Centrally Located Electrical-Load Monitor* (May 2003)
- A demonstration of the NILM software for automated analysis of equipment scheduling and cycling may be viewed at:
  http://66.120.20.99/~nilm/index.html

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- The NILM technology can make a significant contribution to improving control of energy use in building systems. The information generated by application of NILM technology will be less expensive than that created using traditional power submetering and acoustic/vibration monitoring. Electric power use information will be more widely available, allowing enhanced control and diagnostics features to be incorporated into energy management systems.
- More work will be required to fully automate the technology, as described in the Recommendations **section below.**

Commercialization potential

- The lead researchers investigated several alternatives for developing NILM based products or services. They had discussions with a major utility meter manufacturer as well as several energy management service providers. Although there is interest in the potential to provide additional information to end-users at a lower cost than power sub-metering, there are issues regarding identification of multiple units of devices that are of the same make and model within a facility or on a branch circuit. Additional field-testing will be required to address the accuracy of device identification and power estimation.
- Testing of the NILM to determine its commercial value has not been started. This work requires that NILM load-tracking output be compared with submeters and that a potential commercializer determine whether NILM output, either load tracking or power signatures associated with faults, has value to its customers.

Recommendations

- Development efforts should be geared toward a product for the small and medium sized commercial building market**.** Most small to medium size commercial buildings do not have a building automation system with energy management capability. Automating energy management is needed because the building owners and managers do not have the time or expertise to manually control energy use. The NILM technology could be an important contribution to reduce monitoring costs and to provide key electrical load information that is currently missing from most building automation systems.
- Several important additional research steps need to be taken**.**
- Ability to track variable-power, constant-speed loads. This last remaining load class includes most chillers and those fans still using inlet vanes. Relations between real and reactive power for these loads should be explored.
- Integration of the disaggregator for constant-power loads and the VSD tracker. The code was designed to be integrated. However, most constant-power loads are for pumps and tower fans associated with operation of a chiller. Until the chiller can be detected or is assigned remaining HVAC power, the integration has reduced practical value.

- Automated training of the NILM to the extent possible. The state estimator is a good start, because it makes a best guess of the loads in operation at the time the NILM is turned on. However, the state estimator and the load disaggregator rely on knowledge of the characteristics of individual loads. To date, this information has been gathered manually.
- Automated detection of faults. As a starting point, detection of faults associated with oscillatory power signals should be automated, based on frequency analysis. Automatic fault detection will aid those potential users who have limited time or ability to analyze NILM data.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

The NILM technology could, in theory, apply to all commercial building electrical loads. The current technology can successfully detect on/off transitions if the device loads are 5% or more of the total load at the time of the on/off event. Equipment classes that have qualifying loads (relatively large loads per device or system) are reciprocating chillers for space conditioning and refrigeration, fans and pumps associated with HVAC systems and lighting circuits. Buildings that have building automation systems (BAS) could use NILM technology to provide load information that is not available on the installed system. Buildings without BAS capability could use a web interface.

There appear to be two hardware configurations for NILM technology that could be used to provide information to a building owner, operator, or service provider. One package is a circuit board that would be installed in advanced electrical meters that have recently become available in the market. The second is a stand-alone device that is installed in electrical subpanels and feeds information to a building automation supervisory computer. The plug-in board and the stand-alone device would not have a user interface. Third-party computer applications or a website would use the data streams from the NILM devices.

The installed cost of a plug-in circuit board would likely be less than $200, if manufactured in the tens of thousands and installed at the factory. The installed costs for the stand-alone device would be about $500. In comparison, the installed cost for a load monitor (current transducer and signal conditioner) that could provide basic on/off information would be about $200 per device plus an estimated additional $100 per device for a supervisory product. The NILM system could handle circuits with five to ten major devices in most cases.

Updated Baseline:

The GWh savings estimated in the original projected outcome was based on a baseline load of 74,677 GWh/yr for the entire State. The Commission's figure for Year 2000 is 91,771 GWh/yr. Assuming the NILM technology can be applied in buildings that constitute 50% of the State load, the baseline load would be about 45,900 GWh per year.

Updated Outcome:

Savings per year at the end of the 10-year period after NILM units are commercially available would be about 219 GWh/yr.

2.3. Project 2.3 Air Handling Unit and Variable Air Volume Box Diagnostics

INTRODUCTION

Background and Overview

Building HVAC equipment routinely fails to satisfy performance expectations envisioned at design. Equipment and control failures often go unnoticed for extended periods of time. Additionally, higher expectations are being placed on a combination of different and often conflicting performance measures, such as energy efficiency, indoor air quality, comfort, reliability, limiting peak demand on utilities, etc. To meet these expectations, the processes, systems, and equipment used in both commercial and residential buildings are becoming increasingly sophisticated. At the same time, operations staff is stretched thin and are often untrained in trouble-shooting techniques. These conditions necessitate the use of automated diagnostics to ensure fault-free operation. The amount of data that must be analyzed to automate fault detection and diagnostics could overwhelm the communication network of an HVAC system. This argues for conducting as much analysis as possible within local unit controllers. Modern controllers provide a platform that is powerful and flexible enough to perform distributed fault detection and diagnostics (FDD) for the various building systems.

Researchers at the National Institute for Standards and Technology (NIST) focused on developing FDD methods for air handling units (AHU) and variable air volume (VAV) control boxes. The FDD tools for AHUs and VAV boxes were developed with distinct approaches because of the nature of the systems. VAV boxes are simple devices with a limited number of operation modes and possible faults. The VAV boxes typically have little instrumentation and controllers with limited capability. However, VAV boxes are very numerous in a typical HVAC system, resulting in a large amount of data to be monitored for faults. AHUs are more complex and thus susceptible to more kinds of faults. They also tend to have more instrumentation and more capable controllers. The FDD tools for both systems are designed to be robust so that they can adapt to the variety of applications typical of their use.

NIST developed two rule sets:

- The AHU Performance Assessment Rules (APAR) diagnostic tool is a set of expert rules derived from mass and energy balances that can be used to detect common faults in air-handling units. Control signals are used to determine the mode of operation for the AHU. A subset of the expert rules corresponding to that mode of operation is then evaluated to determine if there is a mechanical fault or a control problem. The rules apply to single-duct, variable-volume or constant-volume air handlers, with hydronic heating and cooling coils and economizers. Seven faults can be detected:
    - ✓ stuck or leaking mixing box dampers
    - ✓ stuck or leaking heating coil and cooling coil valves
    - ✓ temperature sensor faults
    - ✓ design faults such as undersized coils
    - ✓ sequencing logic errors
    - ✓ central plant faults that affect supply conditions at the AHU coils
    - ✓ inappropriate operator intervention

- The VAV box Performance Assessment Control Charts (VPACC) is a diagnostic tool that uses statistical quality control measures to detect faults or control problems in VAV boxes. VPACC can be applied to most VAV box control strategies. Fault thresholds are determined by statistical analysis of a database of "normal operation" data. The rules require three commonly available sensor measurements: (1) zone air temperature, (2) discharge air temperature, and (3) air flow rate. Faults due sensor drift or control problems can be detected (see Figure 4).

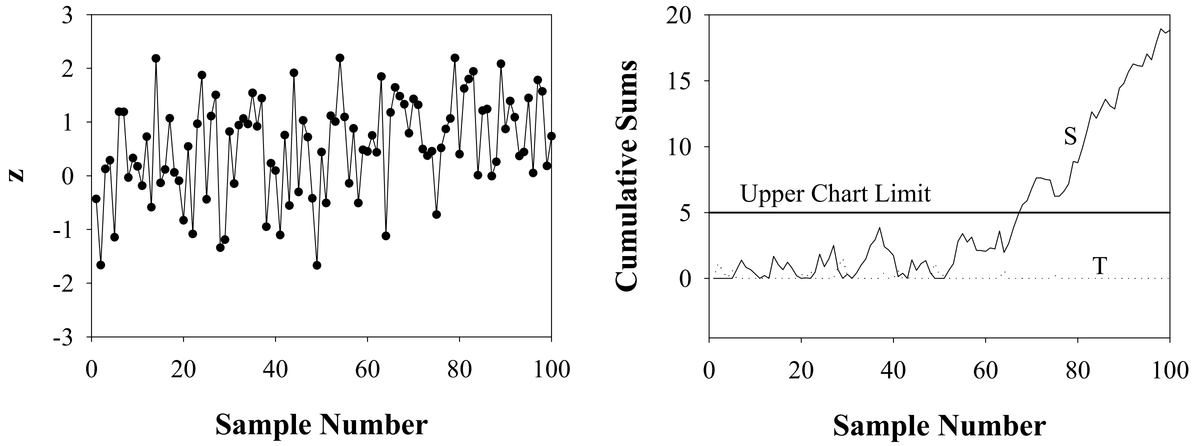

Figure 4. VPACC Example Showing How Signal Noise is Filtered to Show Gradual Fault Over Time

OBJECTIVES

The objectives of this project were to develop, test, and demonstrate FDD methods that:

1. Detect common mechanical faults and control errors in air-handling units (AHUs) and variable-air-volume (VAV) boxes,
2. Rely only upon sensor data and control signals commonly available in commercial building automation and control systems, and
3. Are sufficiently simple that they could be embedded in commercial building unit controllers.

Research Team

Steven Bushby, Natascha Castro, Jeffrey Schein, Cheol Park, and Michael Galler with NIST conducted the research, along with John House with the Iowa Energy Center.

APPROACH

- Test the APAR and VPACC rules using data generated by simulation, emulation, and laboratory testing**.** The laboratory study examined the breadth of faults that can be detected and the conditions under which they can be detected. The research involved a complementary set laboratory of experiments using commercial AHU and VAV box controllers under both normal operating conditions and operation with known faults, emulations using the NIST Virtual Cybernetic Building Testbed (VCBT), and computer simulations using HVACSIM+. The VCBT is an emulator that combines simulations of a building and its HVAC system with actual commercial controllers. It provides a way to conduct tests under a wide variety of carefully controlled conditions and to compare the results of several different commercial products. Emulation provides a test environment that is closer to a real building because it uses real building controllers but, like simulation, it also provides carefully controlled and reproducible conditions.

- Test the APAR and VPACC rules using AHU and VAV box data from several field sites, including an office building, a restaurant, as well as community college and university campuses, featuring constant- and variable-air-volume systems. The effectiveness of these tools in detecting commonly found mechanical faults and control problems, the reliability of the tools across several seasons, and the robustness of the tools in handling data from a variety of system types and configurations were investigated.

OUTCOMES

Technical Outcomes

- In laboratory testing, the APAR and VPACC tools were both found to be successful at finding a wide variety of faults. Faults correctly detected included stuck or leaking dampers and control valves, sensor drift, and improper control sequencing. It was also found that some faults could not be detected under certain operating conditions because the control system was able to mask the problem or because sensor data needed to detect the fault is not commonly available in commercial systems.
- In field-testing, APAR and VPACC successfully detected faults using data from several different sources. Data sources included an office building, a restaurant, and community college and university campuses, featuring constant- and variable-air-volume systems. Any evaluation using field data must contend with some inherent difficulties: reliance on sensor data to discern the true state of the system, the inability to report a “false negative” (an undetected fault), and ambiguity regarding what constitutes a fault. However, in this case consistent results across diverse testing environments give a high level of confidence that the FDD tools will perform in an even greater variety of applications. Faults have been successfully detected and confirmed by building operations staff. Every site has been found to have at least one fault. Even though the sample size is small, these results appear to confirm the hypothesis that faults of the type that can be detected by these tools are common.
- The APAR and VPACC rule sets were successfully embedded in controllers from three manufacturers using their respective native programming languages.

Market Outcomes

- The results will produce better indoor environments in California buildings. Usually equipment malfunctions are only detected when someone complains about a lack of cooling, heating, fresh air, or other comfort issues. Other problems simply continue unreported. Automatic FDD for AHUs and VAV boxes will call attention to problems before they lead to discomfort or health problems in a building's occupants.
- FDD can lead to more effective utilization of technician's labor. Having diagnostic results available before arriving at the site would allow technician’s to plan their work time and have the right parts on the truck. Multiple trips to the site to work on the same problem could be avoided.

- FDD will prevent premature equipment failure. Compressor failure is the most expense repair on packaged rooftop units, and FDD technology can detect the faults that cause it as well as other problems.
- FDD technology will reduce unplanned outages. Using FDD to track repair histories as well as fault occurrences can assist building owners and mechanical contractors to make better "repair or replace" decisions.
- The results will provide energy benefits. Using FDD may improve AHU and VAV box performance, providing better indoor conditions for less energy input. FDD may also allow a technician to rule out problems with a unit and look for problems elsewhere in the building. For example low flow across the cooling coil may be due to clogging of the coil caused by filter bypass, but it may also result from blockages or closed dampers.

Major Deliverables

The major deliverables for the project may be downloaded from either of these web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

Two reports document the laboratory-testing phase using the Virtual Cybernetic Building Testbed, and one report documents the field-testing phase.

- *Testing AHU Rule-Based Diagnostic Tool & VAV Diagnostic Tool Using the VCBT.* (Oct 2001)
- *Results from Simulation and Laboratory Testing of Air Handling Unit and Variable Air Volume Box Diagnostics Tools.* NISTIR 6964 (Jan 2002)
- *Results from Field-Testing of Air Handling Unit and Variable Air Volume Box Fault Detection Tools*, NISTIR 6994. (April 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- Both APAR and VPACC are suitable for embedding in commercial control products at little or no added direct cost**.** Many existing control products already have the computational horsepower needed to use the embedded rules. The initial cost to manufacturers will be in engineering and field evaluation to assure reliability. The APAR and VPACC rules, or variations on them, are highly likely to available commercially within the next five years.

Commercialization potential or commercialization initiated

Several commercial partners provided control products for use in the Virtual Cybernetic Building Testbed. The FDD rules were successfully embedded in the controls products by programming the APAR and VPACC algorithms in the native language of each product. There are four major buildings controls manufacturers that have expressed interest in working with NIST to embed the diagnostics in their respective products. These features may become the basis for optional features that increase revenue, or standard features that are used to distinguish a product from the competition.

Recommendations

Full commercialization of automated fault detection and diagnostics is one in which APAR and VPACC, along with appropriate parameters and thresholds, are packaged within HVAC control products. To become reality, more work is needed in three main areas.

Built-in APAR and VPACC functions would greatly simplify the task of embedding FDD in a control program. It is impractical to expect trend data to be evaluated to determine the necessary parameters and thresholds for each site, as was done in this study. Ideally, sets of robust parameters and thresholds that are effective across specified ranges of applications would be available. Additional field data from a wide variety of systems must be collected in order to determine these robust parameters and thresholds. Also, the current embedded FDD tools are written using generic mathematical functions available in the languages in which the controllers are programmed.

More work is needed to develop alternative ways to interpret FDD results and deliver this information to the building operator**.** For example, rather than automatically sending the alarm to the operator, the building control system could highlight, on demand, those devices having experienced the greatest number of alarms in a given period of time. Or, if an automated maintenance management system is used, an alarm could automatically generate an appropriate work order. However, many faults are the result of design or commissioning issues that are beyond the scope of the building maintenance staff.

A mechanism is needed to resolve multiple conflicting fault reports before reporting them to the operator. A fault in another piece of equipment, such as an air handling unit, boiler, or chiller, could result in a large number of alarms, perhaps overwhelming the operator.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline

The original baseline conditions and projected outcome were based on national estimates because there was no reliable data for California as a whole. During the course of the Program, the Commission has established a data set for California from which the original estimates can be improved. See Appendix I.

The diagnostics developed in Project 2.3 and the prior work at NIST are intended for air handling units and variable air volume units in larger commercial buildings with central plant systems. The estimated energy consumption for these components is 9328 GWh/yr for Year 2000. The electrical energy used by central plant chillers to provide cooling water to these devices is estimated to be 4872 GWh/yr. The total annual electric use is 14,759 GWh/yr.

Updated Outcome

Colleges, hospitals, and large office buildings are likely to have a large percentage of built-up air handlers and VAV boxes. The total floor area of these facility types was 1573 million SF. Assume that AHUs and VAV boxes that are controlled by controllers capable of having embedded diagnostics serve 50% of the total floor area. Further, assume that if faults are not corrected, they account for 1 kWh per square foot of floor area of energy use by these facilities. The total average annual consumption for heating, cooling, and ventilation for these facilities was about 7.9 kWh/SF in Year 2000. Thus, faults account for about 13% of electric energy used by these end uses for these types of facilities. If Project 2.3 diagnostics were used for 50% of the floor area for colleges, hospitals, and operators were 100% effective in timely correction of faults, the total energy savings would be 786 GWh/yr. Assuming the operators are 50% effective in responding and correcting faults, the savings would be 393 GWh/yr.

2.4. Project 2.4 Whole Building Diagnostician Demonstration

INTRODUCTION

Background and Overview

Developed by the DOE's Pacific Northwest Laboratory (operated by Battelle), with Honeywell, Inc. and the University of Colorado, the WBD is a production-prototype software package with two modules providing automated diagnostics for buildings based on data collected by direct-digital control (DDC) systems. These tools are incorporated within the WBD's user interface and data and process management infrastructure.

The WBD is a pre-commercial, production-prototype software package that connects to digital control systems (e.g. energy management systems), utilizing data from the control system's sensors to analyze overall building and system performance. It currently consists of two diagnostic tools, or modules, with a user interface designed to readily identify problems and provide potential solutions to building operators. The Outdoor-Air/Economizer module (OAE), the subject of this project, diagnoses whether each air handler in a building is supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outside air when appropriate and not wasting energy by supplying excess outside air. In addition to the two diagnostic modules, the WBD also has a data collection module to automatically retrieve data from some building automation systems.

Early experience with the WBD tool in new and existing buildings in Washington and California has confirmed the broadly held suspicion that problems with outside air economizers are endemic: The tool discovered problems in 29 of 30 air handlers examined in both existing and newly commissioned buildings. Over half of the 29 air handling units contributed a significant energy waste costing over $500/yr.

The WBD also contains a Whole Building Energy (WBE) module that monitors whole building or subsystem (end-use) performance at high levels. It does this by tracking expected and actual consumption as a function of time of day, day of week, and weather conditions. Using these data, it automatically constructs a model based on *actual* past system performance in a baseline period and then alerts the user when performance is no longer as good as past performance. The WBE module was not part of the Project 2.4 demonstration, but enhancements to it were the focus of Project 2.6.

OBJECTIVES

Test and demonstrate automated commissioning and diagnostics using the Whole-Building Diagnostician (WBD) in actual buildings with actual operators and energy service providers to:

- Prove WBD efficacy in automatically detecting energy efficiency and outside-air supply problems in buildings
- Test and demonstrate the ability of users to interpret and act upon the information provided by the tools to correct building operational problems
- Develop case studies of the impacts of using the tools in terms of the type and number of problems found, the energy savings, and fresh air-supply impacts of correcting the problems
- Provide feedback from users, based on their experience with the OAE/WBD, to guide development and implementation of the other tools in the future, including those in the program plan.

Research Team

Michael Brambley, Srinivas Katipamula, Rob Pratt, and Nathan Bauman with Battelle conducted the research. David Jump with Nexant and Lanny Ross of Newport Design Consultants provided field support to the participants.

APPROACH

Using demonstration sites, this project demonstrated the WBD's current automated diagnostic tools in three contexts:

- Single Building, Dedicated Operator: The single-building operator demonstration took place at the Symphony Towers building in San Diego, California, a 34-story 601,000 sq. ft., "Class-A", mixed-use development located at the hub of downtown San Diego's financial corridor. Symphony Towers was selected for the demonstration because of its visibility and energy conscious management. The management team had aggressively pursued optimal equipment performance and has accomplished numerous lighting, mechanical, plumbing, and controls enhancements.

  The building's HVAC (heating, ventilating and air-conditioning) system consists of two three-stage centrifugal chillers of 550 tons each, and two natural gas hydronic boilers of 3,000 MBtu/hr each. Four variable-air-volume air handlers with variable speed drives, equipped with enthalpy-controlled economizers, serve the occupied space. The air handlers only supply cooling; no heating coil is present. The system is controlled by a Johnson Controls Metasys building automation system, and provides convenient on-demand access to data by the WBD via a DDE (dynamic data exchange) server.

- Multi-Building, Dedicated Operator: The County of Alameda currently owns or leases approximately 120 buildings consisting of 6.2 million square feet of owned office space and 1.1 million square feet of leased office space. Among those buildings are a jail, a number of courthouses, clinics, office buildings and juvenile halls. The demonstration sites consist of two courthouses and two emergency buildings.

  The building's HVAC system consists of hydronic systems with centrifugal chillers, and natural gas hydronic boilers. Four large variable-air-volume (VAV) air handlers with heating and cooling coils, differential dry-bulb controlled economizers and variable speed drives serve the occupied space. A direct digital control (DDC) system from CSI controls the HVAC systems, which also provides a mechanism for trend logs.

- Mechanical Services Provider: Marina Mechanical, a mechanical services company headquartered in Oakland, was the demonstration partner. The firm provides HVAC construction and maintenance services to office and industrial building owners in northern California. The demonstration site selected by Marina Mechanical was the Capitol Mall office building, located in Sacramento. The Capitol Mall building is an 18-story 385,000 square foot premier "Class A" office building with integral covered parking structure. In addition to office space, the building houses a Café and a rooftop terrace. The building was built in 1984 and is located at 300 Capitol Mall, approximately six blocks west of the State Capitol. The building is an Environmental Protection Agency "Energy Star" qualified building. The demonstration included six air handlers ranging in capacity from 40,000 to 100,000 cfm, with a total capacity of 380,000 cfm.

Data collected during each demonstration included (1) raw metered data, (2) operator usage, (3) problems found by operators, (4) problems they fixed or tried to fix, and (5) user opinions of the WBD tools and problems with them. Collected Data was analyzed to measure the success of the WBD tools and provide feedback for future automated commissioning and diagnostic tools, including (1) user satisfaction, (2) user success in finding problems using the tools, (3) the number of problems found and fixed, and (4) cost savings, cost to fix problems, and fresh air supply improvements.

OUTCOMES

Technical Outcomes

The technical outcomes for each phase of the demonstration are organized by the project's objectives.

1. Prove WBD efficacy in automatically detecting energy efficiency and outside-air supply problems in buildings.

   Table 1 summarizes the faults detected at the three demonstration sites. Faults related to defective sensors could not be evaluated with respect to energy wasted until sensors were repaired. Faults that were evaluated during the demonstration had cost impacts ranging between $500 and $15,000 per year.

Table 1. Faults Detected by OAE

Faults Detected	Single Building Operator	Multi-Building Operator	Mechanical Services Provider
Excess outside air (greater than required by ASHRAE Std 62)	✓ (1 AHU)		
Sensor out of calibration or failure	✓ (3 AHUs)		
Excessive minimum outside air flow setpoint	✓ (4 AHUs)		
Damper not opening fully for economizer operation		✓ (4 AHUs)	✓ (6 AHUs)
Excess outside air during heating mode			✓ (6 AHUs)

2. Test and demonstrate the ability of users to interpret and act upon the information provided by the tools to correct building operational problems.

   In all cases the users indicated that they could interpret the information presented. For a number of reasons, only one user acted upon information during the demonstration period.

3. Develop case studies of the impacts of using the tools in terms of the type and number of problems found, the energy savings, and fresh air-supply impacts of correcting the problems.

   Case studies were not developed from the project because in almost all instances the building operators did not make changes or correct faults based on the information available from the WBD.

4. Provide feedback from users, based on their experience with the OAE/WBD, to guide development and implementation of the other tools in the future, including those in the program plan.

   Table 2 presents feedback from the users at the end of the demonstration period.

Table 2. User Feedback Regarding Usability of the OAE/WBD

	Single Building Operator	Multi-Building Operator	Mechanical Services Provider
Ease of Use, Scale 1 to 5 (1 = very easy, 5 = very difficult)	2	1	5
Ease of Configuration	No difficulties	Somewhat difficult, requires a lot of information about the building AHUs	Not too difficult, but requires a lot of information about the building AHUs
Suggested changes to OAE	None	Data collection process needs to be improved	Interface needs to be simplified; tool should be less modular; modified data collection process needed to be automated
Additional features for WBD	None	Would like FDD for boilers, chillers, and cooling towers	Tool should be less modular
Suggested Audience	Building operators, but not managers or owners	Building operators and managers	Building operators, but not managers or owners
Add sensors building systems to enhance information from OAE?	Yes	Yes	No, budget not within his control
Made repairs based on OAE results	Yes, but only once; control system upgrade underway	No, too busy with network upgrade	No, too many management layers
Continue using OAE after demonstration period?	Yes	Yes	Maybe

The project clearly showed that diagnostic software design is very important for delivering information, but energy savings will not be achieved with information alone. The participants in this demonstration did not take corrective action on major problems during the monitoring period. The reasons were varied: (1) the OAE information was being reviewed by a person who did not have financial authority to make timely decisions about repairs, (2) other operational challenges, including major HVAC renovations and network upgrades, required the full attention of the building operators, and (3) following up on multiple diagnoses for a problem was viewed as too time consuming in light of other operational tasks.

Figure 5 shows before and after screen shots of the OAE/WBD for a fault at Symphony Towers.

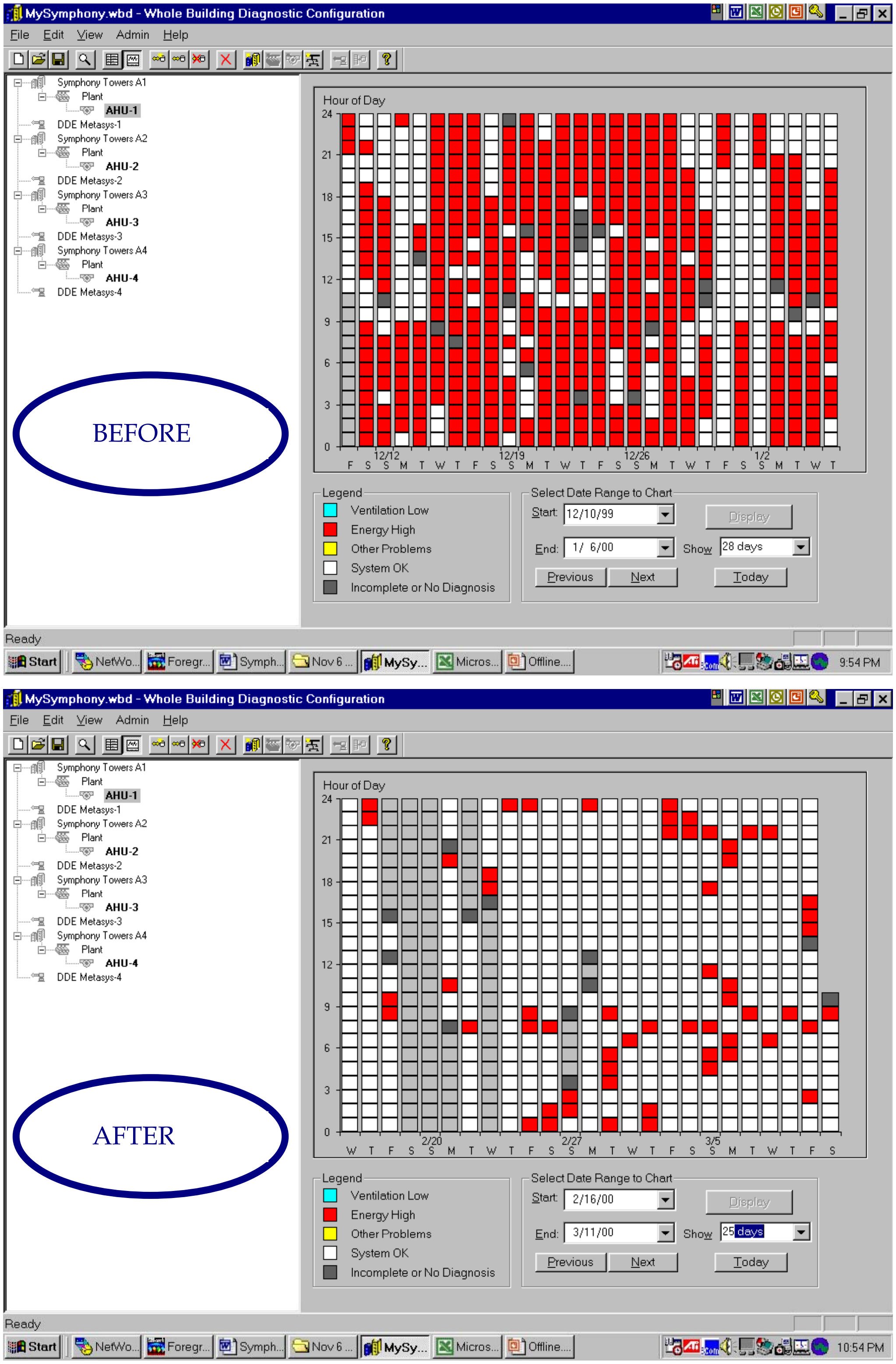

Figure 5. Screenshot Showing "Before" And "After" Graphics For A Fault Detected And Corrected

Market Outcomes

- The results will produce better indoor environments in California buildings. Usually equipment malfunctions are only detected when someone complains about a lack of cooling, heating, fresh air, or other comfort issues. Other problems simply continue unreported. Automatic FDD for air handlers, especially outdoor air related issues, will minimize problems before they lead to discomfort or health problems in a building's occupants.
- FDD can lead to more effective utilization of technician's labor. Having diagnostic results available before arriving to start a repair or troubleshooting would allow technician's to plan their work time and have the right parts available. Multiple trips to a unit location to work on the same problem could be avoided.
- FDD will prevent premature equipment failure. Component failure, especially sensor failure or calibration drift, are problems that can be avoided with proper use of the OAE/WBD.
- FDD technology will reduce unplanned outages. Using FDD to track repair histories as well as fault occurrences can assist building owners and mechanical contractors to make better "repair or replace" decisions. The OAE/WBD software can provide information to help track repair history.
- The results will provide energy benefits. Using FDD for outdoor air and economizer operation will improve HVAC energy performance, providing better indoor conditions for less energy input. FDD may also allow a technician to rule out problems with a unit and look for problems elsewhere in the building. For example low flow across the cooling coil may be due to clogging of the coil caused by filter bypass, but it may also result from blockages or closed dampers.
- Market penetration of FDD technology for packaged air-conditioning units will require adoption by air-conditioning manufacturers, air-conditioning component manufacturers, and building automation vendors. Market awareness of the value of built-in diagnostics will be needed before the manufacturers will offer FDD as part of the built-in controls of each unit, or as part of the fault reporting for a building automation system. In many cases, buildings using packaged air-conditioners do not have a building automation system. To provide a means of reporting the faults, software will be required that will provide an appropriate alarm or report to a person responsible for HVAC maintenance.

Major Deliverables

The deliverables from this project may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Final Report – Single Building Operator Demonstration – On-line Testing* (Mar 2003)
- *Final Report – Multi-Building Operator Demonstration – On-line Testing* (Aug 2003)
- *Final Report – Mechanical Services Provider Demonstration – On-line Testing* (Jul 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Fault detection and diagnostics for air handlers can save significant amounts of energy in medium and large office buildings. The Outdoor Air Economizer module of the Whole Building Diagnostician successfully detected significant energy wasting faults in the three demonstration projects. The annualized cost of single faults detected ranged from $500 to $15,000.

The demonstration reinforced the notion that diagnostic tools produce savings only when the identified problems are fixed. Merely identifying operation problems and their impacts is not sufficient by itself; building staff must fix them. If building operators are not able to use their control systems to correct problems, are too busy with other duties, or lack resources to obtain help from contractors, savings will not be realized. A delivery mechanism is needed that helps ensure that building staff take action when alerted to problems with significant impacts.

The time and cost of diagnostic-tool installation is a significant component to implementing diagnostic technologies. Labor costs to set up tools like the WBD (~1 week) will likely exceed the purchase cost of commercialized software. Sites with larger air handlers (10,000 cfm or larger air flow rates) have greater savings per problem fixed, while installation costs do not vary with air handler size (i.e., savings are greater relative to costs). Installation costs per air-handler also go down as the number of air handlers at a site increases, provided the units use similar operating control strategies and are part of the same underlying control system.

Commercialization potential

- Battelle is interested in licensing the WBD software to a commercialization partner. Contact Carl Imhoff, Product Line Manager, Energy Products & Operations, Battelle Memorial Institute, Northwest Division, carl.imhoff@pnl.gov, voice 509/375-4328.

  An applications service provider, Northwrite, Inc., expressed interest in cooperatively developing a web-based version of the WBD. Its particular interest was the WBE module, which was enhanced under Project 2.6. The OAE module could be added after the WBE module is available.

Recommendations

- Additional investigation is required into approaches for delivering the diagnostics in forms that can be readily used in existing and future generations of BAS. The project experienced considerable difficulty in getting data automatically in near-real time from the CSI BAS at the Alameda County facilities as well as the BACnet compatible BAS at the Capitol Mall building. Data acquisition from BAS trend logs, however, was not a problem. Motivating building owners and operators to act on the information from the WBD or other FDD tool is clearly a major hurdle to actually achieving savings.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline

The original baseline conditions and projected outcome were based on national estimates because there was no reliable data for California as a whole. During the course of the Program, the Commission has established a data set for California from which the original estimates can be improved. See Appendix I.

The diagnostics tool demonstrated in Project 2.4 is intended for application to package HVAC units as well as air handling units in larger commercial buildings with central plant systems, such as colleges, hospitals, and large office buildings. The estimated energy consumption for these components (listed as supply, return, and exhaust fans in Commission's data) is 9328 GWh/yr for Year 2000. The electrical energy used by central plant chillers to provide cooling water to these devices is estimated to be 4872 GWh/yr. The total annual electric use is 14,200 GWh/yr.

Updated Outcome

Colleges, hospitals, and large office buildings are likely to have a large percentage of built-up air handlers. The total floor area of these facility types was 1,573 million sf in Year 2000. Assume that AHUs that are controlled by controllers capable of having embedded diagnostics serve 50% of the total floor area. Further, assume that if faults are not corrected, they account for 1 kWh per square foot of floor area of energy use by these facilities. The total average annual consumption for heating, cooling, and ventilation for these facilities was about 7.9 kWh/SF in Year 2000. Thus, faults account for about 13% of electric energy used by these end uses for these types of facilities. If Project 2.4 diagnostics were used for 50% of the floor area for colleges, hospitals, and the OAE diagnostics were 100% effective in timely detection of faults, the total energy savings would be 786 GWh/yr. To date, the OAE has found 29 of 30 air handlers on which it has been tested to have faults, supporting the contention that faults are endemic to outdoor-air control and economizing. Furthermore, Project 2.7 test results for the OAE showed that it detected 11 out of 15 faults and that two of the undetected faults were masked by ambient conditions used for the tests. These two additional faults would be detected during normal monitoring year round, indicating that the OAE would likely detect and alert building and service staff to a large percentage of the faults in air handling equipment.

New and retrofit construction is adding about 380 million sf of commercial space per year. Packaged HVAC units used about 54% of ventilating, cooling, and heating in Year 2000. Assuming this percentage applies to new and retrofit construction, 205 million sf of new conditioned space would be available each year. Assuming that OAE diagnostics are built into control systems for new packaged units, and that the OAE is available on 25% of new units installed, and that the OAE diagnostics were 100% effective in timely detection of faults, the total additional energy savings would be 95 GWh/yr.

2.5. Project 2.5 Pattern Recognition Based Fault Detection and Diagnostics

INTRODUCTION

Background and Overview

Architecture Energy Corporation developed the ENFORMA® diagnostic system, the first software tool that supports the user in commissioning and diagnosing a broad range of problems in building heating, ventilation, and air conditioning (HVAC) systems. This tool supports the user in designing and configuring short-term metering systems to monitor the performance of a range of building systems, including economizers, variable-air volume air handlers, chiller plants, and cooling towers. It also supports manual import of data from other sources, such as control systems. Once the data are collected, the tool supports the user with a variety of flexible quality assurance, aggregation, manipulation, and plotting tools for data. It contains a library of over 150 plots of good and bad performance for these systems that can be used for side-by-side comparisons with the short-term data collected. This helps the user draw conclusions about whether the systems are operating correctly, and, if not, what the problem might be.

The diagnostic capabilities embodied by ENFORMA are of particular use to engineers and others with expertise to interpret the plots and draw conclusions about them. While commissioning agents and energy consultants have such expertise, typical building operators do not. These users require more substantive *conclusions* about what is wrong and what to fix. This project will automate the comparisons involved and present this information to the user in the form of simple conclusions recognizable at a glance.

Research Team

Rob Briggs and Michael Brambley with Battelle, and Stuart Waterbury with Architectural Energy Corporation, conducted the research. Teresa Carlon, S. Gaines and R. Lucas with Battelle provided project support.

OBJECTIVES

Develop pattern-recognition techniques that automate the detection and diagnosis of faults based on comparison of plots of good and bad system performance, obtained from both simulation and actual field measurements and stored in a library for a broad number of faults. A commercially available diagnostic tool often used in building commissioning that makes use of this approach, but with expert interpretation applied manually, is Architectural Energy Corporation's ENFORMA. This project will extend this technique by taking the additional step of automating the interpretation step and presenting conclusions to the user.

APPROACH

The steps taken to perform this project were the following:

- Examine, categorize, select, and document initial set of diagnostics to be automated.
- Review, select and document pattern recognition techniques to be applied.
- Implement and test initial pattern recognition algorithms in software.
- Develop a user interface within the framework of the Whole Building Diagnostician Developer's Toolkit or a stand-alone interface to demonstrate the initial pattern recognition algorithms.
- Perform field test and document results.
- Develop a software module compatible with the Whole Building Diagnostician, or generic code suitable for adaptation in other stand-alone software programs. Expand the user interface to accommodate improvements based on the field test under Task 2.5.5.Project 2.5 Outcomes.

Technical Outcomes

- Chillers, boilers, and pumps (circulation and cooling towers) were selected for development of FDD methods. At the beginning of the project, the research team decided to limit the systems and components investigated to those not covered in other PIER FDD projects.

- Analysis of how an expert analyzes the plots of data for chillers and boilers led to adoption of rule-based methods for detecting faults associated with chillers and boilers. Research on general pattern recognition techniques was documented in an excellent summary report on methods that could be applied to building energy fault detection and diagnostics.
- A spreadsheet with a VBA graphical user interface was developed to implement a small set of FDD algorithms to test and illustrate the concept of automation.
- A prototype diagnostic software tool was developed for chiller diagnostics. The full set of diagnostic algorithms was not implemented to the level originally anticipated because of an unexpected match-funding shortfall in the second year of the project and greater than expected level of effort required to capture and document the underlying diagnostics.
- Testing was performed using real data collected from buildings in pre-program projects. The match-funding shortfall also resulted in eliminating the field testing of the FDD tool.
- A fully documented software specification was produced that documented the diagnostic algorithms for all selected building components (chillers, boilers, pumps, and cooling towers) as well as the software actually implemented. This report, along with an economic impact letter report, will guide future efforts to more completely develop an FDD tool. The match-funding shortfall also curtailed full development of the software.

Market Outcomes

Automation of diagnostic techniques that are currently applied manually will increase the number of facilities that use diagnostics as part of routine maintenance. Large office buildings, which tend to have building automation controls in place, represent over 1,000,000 SF of floor area in California's commercial building stock and are a primary target for diagnostic software. Development of automated diagnostic tools for a spectrum of systems and equipment would respond to one of the needs expressed by building managers and operators participating in Project 2.4.

Incorporating Project 2.5 diagnostic methods into a web based diagnostic module is the goal of a follow-on project. Trial testing of this module should be started by the fall of 2004.

Major Deliverables

The reports may be downloaded from either of these web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Task Report: Select Diagnostics for Automation* (Feb 2001)
- *Task Report: Select Pattern-Recognition Techniques* (Feb 2001)
- *Task Report: Implement and Test Techniques* (Dec 2001)
- *Automated Diagnostics: Software Requirements Specification* (Jul 2003)
- *Evaluation of Energy Impact of Faults* (May 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- The diagnostic approach is suitable for periodic or continuous monitoring. The rule-based algorithms could be implemented in existing building control systems or component controllers or used for processing at a central service center.
- Diagnostic rules are now available from this project for automating FDD for a much broader set of HVAC equipment and systems than previously. These could be used to create a software tool suite that would provide automated continuous monitoring and diagnostics for most building systems, helping to alleviate the many undetected problems that persist in commercial buildings.

Commercialization Potential

Architectural Energy Corporation is exploring adding these diagnostics, as well as others from its ENFORMA HVAC Analyzer software, into a web-based diagnostic service. The web-based service will be available for licensing by third-party application service providers or as a service directly from AEC.

Recommendations

Additional research on the effect of sensor calibration and sensor placement is needed to understand the impact of these factors on false alarms and missed faults.

Additional research is needed to develop a method to detect short-term anomalous chiller behavior.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline

The original baseline conditions and projected outcome were based on national estimates because there was no reliable data for California as a whole. During the course of the Program, the Commission has established a data set for California from which the original estimates can be improved. See Appendix I.

The original estimate was based on applying diagnostic methods to all types of HVAC equipment and components. The diagnostics selected during work on Project 2.5 apply only to central plant equipment components including chillers, boilers, condenser water pumps, chilled water pumps, and cooling tower pumps and fans. The statewide electric energy consumption of these components (except boilers) was estimated to be 6,030 GWh and 3592 MW peak demand in Year 2000.

Updated Outcomes

Large buildings with central plants are typically controlled with building automation systems. These systems have supervisory computers that can host diagnostic methods documented in Project 2.5. Central systems are installed in larger facilities, such as large office buildings. Applying the diagnostic methods to 50% of the large office, college, and hospital buildings in

California within the next 10 years, should result in savings of at least 123 GWh/yr. There are other building types that have central plants, and the methods are likely to be applied to those facilities as well.

2.6. Project 2.6 Enhancement of the Whole Building Diagnostician

INTRODUCTION

Background and Overview

Developed by the DOE's Pacific Northwest National Laboratory (operated by Battelle), with Honeywell, Inc. and the University of Colorado, the WBD is a production-prototype software package with two modules providing automated diagnostics for buildings based on data collected by DDC systems. See Project 2.4 for a detailed description of Outdoor Air Economizer (OAE) module.

The WBE monitors whole-building and major subsystem (end-use) performance by tracking expected and actual daily consumption as a function of schedules time of day, day of week (and schedules that are correlated with time), and weather conditions. Examples of subsystems that could be monitored, using on-line data from the BAS, include total building energy, electric energy, thermal energy, HVAC energy, and chiller energy. The WBE automatically constructs a empirical model derived from *actual* past building or system performance and then alerts the user when performance is no longer as good as (or, for retrofits and O&M programs, is better than) past performance. It presents its analysis results as an Energy Consumption Index (ECI) for each day. The ECI is the ratio of actual energy consumption to expected energy consumption. The values of expected energy consumption are generated by a model that performs a statistical analysis of a baseline set of historical data collected from the building or systems. Statistical properties of the expected value are compared to the actual value to determine whether the actual measurement is significantly different.

The existing WBE model used time of day, day of the week, outdoor-air dry-bulb temperature, and relative humidity as independent variables. These variables were found to be good predictors for office buildings, but not for buildings with significant process loads, such as sales volume, refrigeration, cooking, and many manufacturing operations. Energy managers for companies with many similar facilities, such as retail outlets, can benefit from using additional variables, as well as the ability to compare the energy use patterns of similar sites. This project was developed to address these issues.

Research Team

Michael Brambley, Krishnan Gowri, and David Chassin with Battelle Memorial Institute, Northwest Division led the research team.

OBJECTIVES

The Objectives of this Project are to develop two enhancements to the Whole Building Energy (WBE) tool of the Whole-Building Diagnostician (WBD) with the following enhanced capabilities:

- Modify the WBE to allow the performance baseline to be established on any two non-schedule variables the user selects from those available (currently the only two supported are outdoor temperature and humidity), and to optionally display hourly results as well as the daily results for users concerned about peak loads.

- Add a peer-group comparison to the tool that, via the internet or a utility interface, compares current building consumption in quasi-real time against that of a set of similar participating buildings in the same vicinity or climate zone.

These enhancements will provide California with a flexible tool for monitoring and diagnosing system-level energy consumption in new and existing commercial buildings of all sizes

APPROACH

The planned activities were:

- Modify the existing computer code and interface to accommodate analysis based on additional independent variables
- Field test the modified software at the Project 2.4 demonstration sites.
- Develop concepts for presenting peer-to-peer energy use comparisons and present these to the Program Advisory Committee for comment
- Develop new code and interface screens to implement the peer-to-peer feature
- Field test the modified software at the Project 2.4 demonstration sites or other sites that may become available.

OUTCOMES

Technical Outcomes

The first objective was fully completed by adding the capability to use any five independent variables selected by the user instead of two. The original plan envisioned allowing substitution of any two other variables. The actual implementation allows up to five independent variables, which provides significantly more flexibility for users in customizing the WBD to their own operations. In addition, the new version also enables the user to select any dependent energy use to track, not only the five originally specified in the tool.

Due to an unexpected shortfall in match funding, most of the work on the second objective was cancelled under this project and remaining funds were allocated to finishing other projects. User interface concepts were presented to the Project Advisory Committee along with analytic approaches for peer comparisons. After a long hiatus caused by the funding shortfall, the peer comparison methodology was implemented in the current version of the WBD along with a user interface for viewing results. This prototype was then tested with a hand-crafted data set for 12 office buildings. .

No field testing was performed due the match funding shortfall. The match funding loss occurred during the second year, delaying work on both objectives, such that field testing could not be supported under the project.

Market Outcomes

The WBD software, or derivatives based on its concepts, holds significant promise to save energy and improve indoor environmental conditions in California.

The Program Advisory Committee suggested that the focus of the peer-to-peer comparison module be shifted from independent building operators who pooled data within certain climate and geographical bounds, to chain operators who have multiple buildings with similar floor plans but with large diversity in climate and location.

Major Deliverables

The reports may be downloaded from either of these web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Instructions for Installation of the Whole-Building Diagnostician Software Release 2.10-162* (Aug 2003)
- *Instructions for Configuration of the Whole-Building Diagnostician Software Release 2.10-162* (Aug 2003)
- *Whole Building Energy Enhancement Report* PNWD 3317 (Aug 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The enhanced features of the WBD will promote wider use by building operators.

Data collection, as reported in Project 2.4, is a significant barrier to effective use of the WBD on line. The WBD documentation provides instructions for creating files for batch processing by the WBD, which removes most of the difficulties associated with data collection.

Commercialization potential

- The WBD software may be licensed from Battelle. Contact Carl Imhoff, Product Line Manager, Energy Products & Operations, Battelle Memorial Institute, Northwest Division, carl.imhoff@pnl.gov, voice 509/375-4328.
- An Internet applications service provider, Northwrite, Inc., expressed interest in cooperatively developing a web-based version of the WBD. Its particular interest was the WBE module, which was enhanced under this project. Significant additional funding will be required to accomplish this goal. FEMP expressed interest in co-funding the development of the web-based version for deployment in federal government buildings.

Recommendations

Standardization of data collection and access to data from building automation systems should be pursued at the national level through organizations such as ASTM, ASHRAE or a government agency.

Full commercialization of the WBD or derivatives will require field testing and should be supported through a future Energy Commission project, or a CPUC program.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline

The GWh savings estimated in the original projected outcome was based on a baseline load of 74,677 GWh/yr for the entire State. The Commission's figure for Year 2000 is 91,771 GWh/yr. The WBD technology can be applied in buildings that have energy management and control systems, which constitute about 29% of the State commercial and institutional building floor area and 29% of the statewide electric load. This is based on the prevalence of EMCSs in Pacific Gas and Electric Company's territory. The baseline load for the WBD's WBE module would be about 23,700 GWh per year.

Updated Outcome

Assuming that the WBD's Whole Building Energy diagnostic module could be applied to 20% of the baseline building load, and that 5% savings could be achieved, the total savings would be about 237 GWh/yr.

2.7. Project 2.7 Enabling Tools

INTRODUCTION

Background and Overview

Building automation and control systems are a special niche in the broad spectrum of distributed computing and control technology. The features and capabilities of building control systems change rapidly, driven to a significant extent by new computing technology developed for other applications with larger commercial markets. The advances in building automation technology have taken place for a variety of building services including heating, ventilating, and air conditioning (HVAC) control systems, lighting control systems, access control systems, and fire detection systems. Adoption of the BACnet standard communication protocol has made it practical to integrate building control products and systems made by different manufacturers.

In spite of these advances in technology, many building control systems do not work as intended. In some cases they never did because the design, installation, or commissioning were not done well. In other cases, inadequate maintenance has resulted in a deterioration of system performance over time. Computer hardware and software problems sometimes contribute to the difficulties. Because the ability to interconnect traditionally independent systems in a building is a recent development, there is much that the industry needs to learn about how to best take advantage of this kind of integration. Commissioning, automated fault detection and new approaches to applying system integration are all areas of active research. However, it can be difficult to conduct this research in actual buildings because of the need to maintain comfortable and safe conditions for the building occupants.

To overcome the difficulty of conducting this kind of research using real buildings and outdoor weather conditions, NIST has developed tools that emulate an entire building. This enables building systems research to be conducted under controlled, reproducible conditions. This project involves two enabling tools that have been developed to advance these research efforts. It focuses on the use of these tools to develop and test automated fault detection and diagnostic (FDD) technology for HVAC systems.

The two enabling tools are the Virtual Cybernetic Building Testbed (VCBT) and the FDD Test Shell. The VCBT consists of a variety of simulation models that together emulate the characteristics and performance of a cybernetic building system. The simulation models are interfaced to real state-of-the-art BACnet speaking control systems to provide a hybrid software/hardware testbed that can be used to develop and evaluate control strategies and control products that use the BACnet communication protocol. The FDD Test Shell is a data-sharing tool that was developed as part of IEA Annex 34 to enable side-by-side testing and comparison of two or more FDD tools and to support the integration of information from multiple FDD tools. The objective of the work presented here was to evaluate the effectiveness of the FDD tools for a variety of fault conditions and a variety of weather conditions.

Research Team

Steve Bushby, Natascha Castro, Michael Galler, and Cheol Park with NIST created the enhancements to the VCBT and the FDD Test Shell, along with John House of the Iowa Energy

Center. Srinivas Katapamula and Michael Brambley of Battelle participated in the joint research task of blind testing the WBD, along with Jeffrey Schein of NIST.

OBJECTIVES

- Enhance the VCBT and FDD Test Shell tools by embedding typical faults in the VCBT and developing communication tools needed for demonstrating diagnostic tools in real buildings.
- Conduct blind tests of the Whole Building Diagnostician to test its effectiveness, and to test the communication tools within the VCBT/FDD Test Shell framework.

APPROACH

The first phase of work included modifications to the VCBT and the FDD Test Shell to accomplish the following:

- VCBT AHU simulation modified to include embedded faults.
- FDD Test Shell modified to include interfaces to BACnet controllers and database.
- FDD Test Shell interfaced to VCBT controllers.
- Begin online laboratory testing of diagnostic tools interfaced to VCBT via the FDD Test Shell.

The plan for the second phase of work focused on interfacing the FDD Test Shell to real building controllers to allow real-time testing of FDD tools:

- FDD Test Shell interfaced to real building controllers.
- Complete online laboratory testing of diagnostic tools and begin real building testing of FDD tools.

A third phase of work was added at the end of the first Project Year. Battelle and NIST collaborated in blind testing the Whole Building Diagnostician using the FDD Test Shell and data sets generated by the VCBT.

OUTCOMES

Technical Outcomes

- Phase 1: Typical HVAC system and component faults were embedded in the VCBT simulation engine and the FDD Test Shell was interfaced to the VCBT**.** Adding the virtual faults allowed testing of FDD tools. Development of the communication tools between the VCBT and FDD Test Shell was successful. This allowed BACnet compatible building control systems to provide data to the Test Shell, which in turn will decrease development time and reliability testing of FDD tools.
- Phase 2: Data acquisition capability was added to the FDD Test Shell and off-line testing with data from real buildings was completed, but on-line testing was not completed. The BACnet Data Source (BDS) was developed to extend the FDD Test Shell capabilities by adding a component that can exchange messages with BACnet controllers as a way to collect the data needed by the FDD tool. The data can be made available in real time or stored in a file for later retrieval and analysis. Off-line testing was completed with data sets from over a half dozen buildings. On-line testing was not completed due to difficulty in obtaining a demonstration partner able and willing to allow real time access.

- Phase 3: The performance of the WBD/OAE diagnostician in the blind tests was analyzed for low, normal, and high sensitivity. Using the OAE at its low sensitivity setting, 8 of the 15 faults were correctly identified, no false positives were obtained, and 7 faults were not detected (false negatives). For the normal sensitivity setting, 11 of the 15 faults were correctly detected, no false positives were reported, and 4 faults were not detected. With the high sensitivity setting, 10 of the 15 faults were correctly identified, 2 false positives were reported, and 3 faults were not detected (false negatives). In each of the three sensitivity test sets, two of the false negatives were due to the conditions masking the faults so that even though the fault existed in the model, conditions (e.g., temperatures) were not appropriate for system performance to be affected by the presence of the faults.
- Phase 3: In three of the four blind trials on the WBD/WBE diagnostician, it correctly identified anomalous energy use caused by a fault. The single false negative (undetected problem) was due to the small magnitude of the fault (this fault had an energy impact below the WBE reporting threshold of $1/day).

Market Outcomes

The VCBT and FDD Test Shell, as enhanced during this project, will cut development time and improve the robustness of FDD methods deployed in building control systems.

Major Deliverables

The reports may be downloaded from either of these web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Using the Virtual Cybernetic Building Testbed and FDD Test Shell for FDD Tool Development.* NISTIR 6818. (Oct 2001)
- *Use of the BACnet Data Source in the FDD Test Shell for Testing of FDD Tools in Real Buildings*. (Aug 2002)
- *Development of a BACnet Interface for the Whole-Building Diagnostician (WBD).* (Aug 2002)
- *Results of Testing WBD Features under Controlled Conditions.* (Apr 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The improvements made under this project to the VCBT and FDD Test Shell enabled testing of WBD and demonstrated the feasibility of laboratory testing of FDD tools.

Commercialization potential

Several HVAC controls manufacturers provided hardware and software for the project. They were briefed periodically by the research team and are interested in being involved with continued FDD tool research.

The VCBT and FDD Test Shell is available to manufacturers and other interested parties as a platform for product development and testing. Since it promotes rapid development and testing in a controlled environment, it should allow faster product development and allow users to bring products to market sooner.

Recommendations

Doing the following could enhance market penetration of FDD Tools:

- Inform the building controls manufacturing market about the VCBT and its capabilities.
- Develop standard test data suites, such ASHRAE's Standard 140, BestTest, for FDD tools to provide an objective basis for improving performance and give end users a means of ranking different FDD Tools relative to particular HVAC system configurations.
- Additional research is needed in the following areas:
  - Develop analytical techniques to improve isolation of the causes of faults without additional sensors.
  - Study impact of sensitivity settings further.
  - Develop guidance for operators for selecting sensitivity settings.

BENEFITS TO CALIFORNIA

The VCBT and FDD Test Shell will be used to test diagnostic tools and communications in the controlled environment of the laboratory. Simulation/laboratory testing of this type contributed greatly to the success of the BACnet demonstration performed for GSA at the Philip Burton Federal Office Building and has proven to be equally beneficial in testing the Whole Building Diagnostician.

The availability of the tools at the national level will benefit California because the makers of building controls sell their products into the national and international market. Given the current utility cost structure in California, the national level manufacturers are more likely to adopt FDD tools if California customers request them.

3.0 ELEMENT 3—Advanced Load Management and Control

INTRODUCTION

Electric curtailment options have been offered by the electric utilities to residential, commercial, and industrial customers as a means to manage their load in cases of low spinning reserves. The utility provides economic incentives in the form of interruptible rates, and the customer is called upon to shed loads, or the utility remotely interrupts main electric feeds to a customer or air-conditioner equipment for residential customers. The service curtailments or interruptions generally negatively impact the customer's production process or compromises thermal comfort of occupants if service interruptions persist over several hours. Very little research and product development has been done to investigate strategies to perform load-management with acceptable and controlled impacts to the customers.

This Program Element had five research projects that explored strategies and communication protocols to reduce peak electrical loads in buildings, individually and in groups. Projects 3.1 and 3.2 address load reduction in individual buildings using demand controlled ventilation and night ventilation to pre-cool the building mass. Project 3.3 investigated methods to allow appliances to turn themselves off in response to sensed conditions on the electrical grid (without a command from a utility controller) as well as methods to detect high stress in the grid. Project 3.4 promoted the continued development of communications protocols to integrate lighting controls into the HVAC BACnet control standard and to allow two-way communication through the utility meter between the building control system and the electric utility grid managers. Project 3.5 explored practical ways to coordinate load reduction among buildings on a common utility meter while minimizing comfort impacts on occupants.

3.1. Project 3.1 Demand-Controlled Ventilation Assessment

INTRODUCTION

Background and Overview

Products have recently appeared on the market that incorporate CO_2 sensors for controlling ventilation air flow according to the occupancy levels. This technology has the potential for reducing energy usage, costs, and peak electrical demand while ensuring adequate ventilation for acceptable indoor air quality. However, the savings are very dependent upon the situation and whether an economizer is incorporated or not. Recently, a simulation study was performed by researchers from Purdue University and the University of Colorado to evaluate typical energy requirements associated with alternative ventilation control strategies for systems used in small commercial buildings. The energy savings associated with economizer and DCV strategies were found to be very significant for both heating and cooling. As much as 20% savings in electrical energy for cooling are possible with DCV. The savings in heating energy associated with DCV are generally much larger, but are strongly dependent upon the building type and occupancy schedule. Also, a recent literature review performed at NIST on CO_2-based DCV identified two key needs: well-documented demonstration projects and system-specific design guidance.

The manner in which relevant ventilation codes address DCV will impact the application of this technology. Currently, ASHRAE Standard 62 '*Ventilation for Acceptable Indoor Air Quality*' allows the use of DCV but provides no specific design requirements or guidance. California's energy code, Title 24, speaks to demand controlled ventilation but does not contain specific design guidance. Very few designers will attempt to implement this technology without this specific information.

PROJECT OBJECTIVES

- Assess the potential for energy and cost savings associated with the application of CO_2-based demand controlled ventilation (DCV) strategies in California for small commercial and institutional buildings
- Identify key drivers determining the cost-effectiveness of DCV, such as micro-climates and utility rates.
- Provide design requirements and guidance to deploy DCV strategies.

Research Team

This project was a joint effort between Purdue University (Jim Braun, Kevin Mercer, and Tom Lawrence) and NIST (Andy Persily and Steven Emmerich). Amy Musser with the University of Nebraska collaborated with the NIST research team. Todd Rossi and Doug Dietrich provided data collection services and field support, and Lanny Ross with Newport Design Consultants and David Jump with Nexant provided field support as well. Honeywell Corporation was a match fund partner, providing DCV controllers and other hardware for the Project.

APPROACH

The project plan included:

- Review the state-of-art for DCV technology and applications.
- Collect DCV data from twelve demonstration sites. Similar buildings were to be used for side-by-side comparisons of demand-controlled and fixed minimum ventilation strategies. Each site would have one or two packaged HVAC units.
- Perform DCV energy simulations. These included a number of occupancy types and climate zones to evaluate energy costs for alternative ventilation strategies.
- Perform detailed simulations of indoor air-contaminant concentrations for specific test sites.
- Verify the simulation results with the field data.
- Estimate cooling and heating energy impacts of DCV in occupancy types and climate zones that did not have demonstration sites.
- Prepare design requirements and guidance for DCV applications with the results of the simulations and field studies. The best combinations for indoor air quality and economizer strategies were to be identified, and changes to incorporate DCV design requirements and guidance in ASHRAE Standard 62 were to be suggested.

OUTCOMES

Technical Outcomes

- The literature review revealed that there is a fairly wide consensus on the best applications for CO_2 control. Most discussions of CO_2-based DCV mention the following building types as good candidates: public buildings such as cinemas, theaters and auditoria, educational facilities such as classrooms and lecture halls, meeting rooms, and retail and restaurant establishments. However, it is interesting to note that most of the case studies have investigated office buildings and that most reported studies did not include enough information about CO_2 readings, sensor locations, and other important data to resolve a number of important questions.

- Ten demonstration sites were recruited. The initial plan was to recruit 12 sites to serve Projects 2.1 (FDD for Rooftop AC), Project 3.2 (Night Ventilation and Building Thermal Mass), and Project 4.2 (Ventilation Recovery Heat Pumps). Pairs of McDonald's restaurants were recruited in Oakland and Sacramento (with DCV applied only to the play rooms since these are isolated from the interactions of the dining and kitchen HVAC systems). Oakland Unified School District and Woodland Joint Unified School District (near Sacramento) each provided two modular school rooms. Walgreen's agreed to provide two stores in southern California but since each store had 5 HVAC units, the number of sites was limited to 10.
- A stand-alone ventilation strategy assessment tool was developed to perform the DCV energy simulations. The research team elected to develop a stand-alone assessment software tool, Ventilation Strategy Assessment Tool (VSAT)[2], to evaluate DCV, heat pump energy recovery (HPHR) (Project 4.2), and enthalpy exchanger heat recovery (HXHR). The primary evaluation approach involved the use of detailed simulations to estimate operating costs and economic payback periods.
- The cooling and heating season performance of DCV at the quick service restaurants and the modular schools was evaluated for two alternative control strategies. DCV with economizer control (DCV On) and economizer cooling only (DCV Off) yielded the following results:
    - The quick service play rooms had greater savings due to larger changes in occupancy compared to the modular school rooms.
    - In general, inland climates had greater savings compared to coastal climates.
    - For cooling, greater energy savings were achieved at the restaurant play rooms than for the modular schoolrooms. Primarily, this is because the play rooms have more variability in their occupancy than the schoolrooms.
    - The largest energy savings were achieved at one of the inland restaurants, which appears to have the lowest average occupancy level compared to the others. The savings in condensing unit energy were 35% and 16% for one of the inland sites and one of the coastal sites, respectively.

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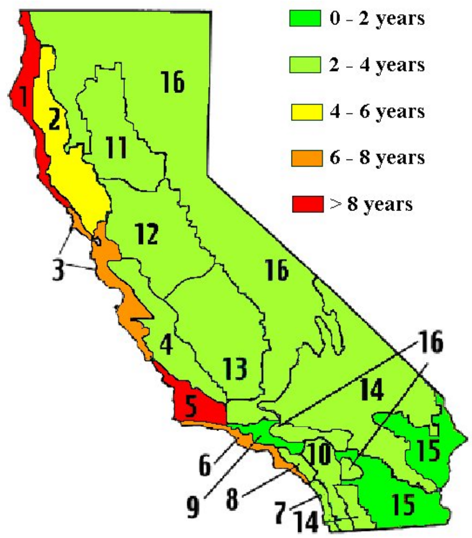
2 VSAT is derived from a simulation tool that was developed by Braun and Brandemuehl (2002) called the Savings Estimator. It performs calculations for each hour of the year using fairly detailed models and TMY2 or California Climate Zone weather data. The goal in developing VSAT was to have a fast, robust simulation tool for comparison of ventilation options that could consider large parametric studies involving different systems and locations. Existing commercial simulation tools do not consider all of the ventilation options of interest for this project. VSAT results were validated against TRNSYS and Energy-10 simulations for the same building models included in VSAT.

- The total annual air conditioning cost savings were smaller (23% and 6%, respectively) because the supply fans operates continuously during occupied times for both strategies and fan energy is a significant fraction of the total energy usage.
- There were no substantial cooling season savings for the modular school rooms, although the calibrated VSAT model for the Oakland school site does indicate small (about 4%) savings. The occupancy for the schools is relatively high with relatively small variability and the sites are also on timers or controllable thermostats that mean the HVAC units only operate during the normal school day. The schools are also generally unoccupied during the heaviest load portion of the cooling season.
- The amount of heating required for the California sites is relatively small and therefore absolute savings are relatively small for application of DCV. However, very large relative savings were estimated using calibrated VSAT predictions. Overall, the total costs for providing heating at these sites is smaller than for cooling, so percentage savings are more important for the cooling cases.

- The indoor air contaminant simulations had the following results:
  - The CO_2 control cases had moderately higher concentrations than the reference cases based on Standard 62-2001 and proposed addendum 62n. CO_2 and VOC concentrations in six space types were simulated for seven ventilation control strategies in four California climate zones. Indoor VOC concentrations were calculated as a means of assessing the impact of CO_2 control on non-occupant generated contaminants, for example those emitted by building materials and furnishings. Based on the assumed emission rates, which were not particularly low relative to the limited data from field studies, the average indoor VOC levels during occupancy were always less than 0.4 mg/m3 and less than 0.1 mg/m3 in most cases.
  - The average VOC concentrations, and more so the maximum concentrations, were heavily influenced by the build-up in concentration during unoccupied hours. The buildup during unoccupied hours, in turn, depends on the values assumed for the fan-off infiltration rate and VOC emission rate. As discussed earlier, these elevated concentrations early in the day can be tempered by a nonzero minimum ventilation rate under CO_2 control or with an early morning flush-out.
  - The spaces with more variable occupancy resulted in significant energy savings in all the climates studied. These results indicate that CO_2 DCV is not likely to provide much energy benefit in offices in the milder California climates for the relatively stable occupancy patterns used in this study. However in more "severe" climates, the savings in the office space were more significant. The energy savings in the classroom spaces are strongly dependent on the system operating schedule versus the occupancy schedule, and while significant load reductions were seen in this study, application of CO_2 DCV in classrooms may require more careful consideration.
- The annual energy load reductions due to the use of CO_2 control were significant in most of the cases, ranging from 10 % to 80 % depending on the space type, climate and ventilation strategy. For the office space studied, the reductions are generally around 20 % given the relatively stable occupancy pattern in that space relative to some of the others. Spaces with more variability in occupancy, such as the Conference Room and

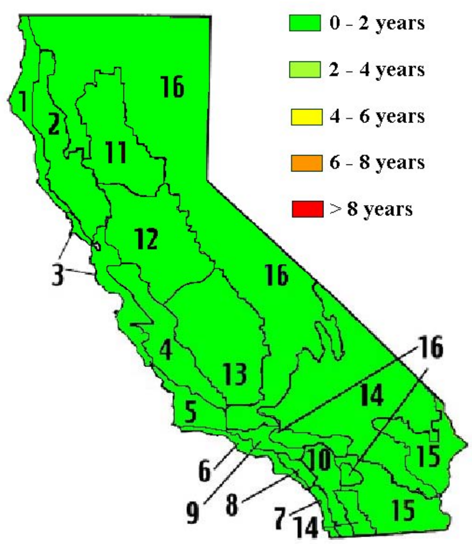
Lecture Hall, exhibit larger reductions in energy loads. The energy load reductions associated with the use of proposed addendum 62n relative to the ventilation requirements in Standard 62-2001 are as large as 30 % to 50 % in the spaces where the 62n rates are indeed lower.

- The VSAT simulation study considered both retrofit and new building designs. In both cases, demand-controlled ventilation coupled with an economizer was found to give the largest cost savings and best economics relative to an economizer only system for the different prototypical buildings and systems evaluated in the California climate zones. Figure 6 shows that most inland climate zones had relatively short simple payback periods.

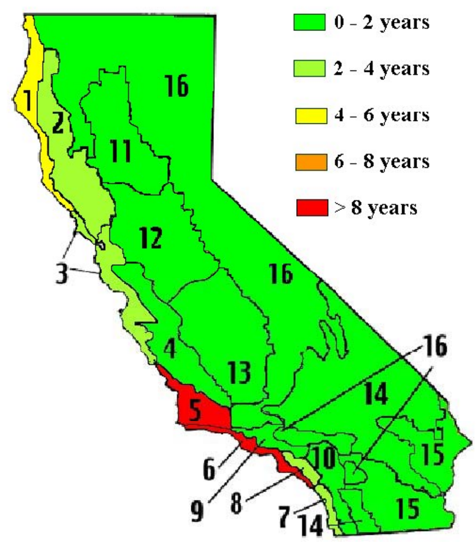


Office

Restaurant



Retail Store



School Classroom

Figure 6. Sample Payback Periods for DCV + EC in a Retrofit Application

Market Outcomes

DCV technology is available in the marketplace. The results from this project can be used to promote the following:

- make better decisions regarding DCV applications,
- fine-tune existing installations, and

- make early screening available during the design concept phase of new construction and retrofit projects.

Major Deliverables

The deliverables from this project may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Modeling and Testing Strategies for Evaluating Ventilation Load Reductions Technologies* (April 2001)
- *Description of Field Test Sites*. (Feb 2003, rev.)
- *State-of-the-Art Review of CO_2 Demand Controlled Ventilation Technology and Application*. NISTIR 6729 (Mar 2001)
- *VSAT – Ventilation Strategy Assessment Tool*. (Aug 2003)
- *Initial Cooling and Heating Season Field Evaluations for Demand-Controlled Ventilation*. (Feb 2003)
- *Simulations of Indoor Air Quality and Ventilation Impacts of Demand Controlled Ventilation in Commercial and Institutional Buildings*. NISTIR 7042 (Aug 2003)
- *Recommendations for Application of CO_2-Based Demand Controlled Ventilation: Proposed Design Requirements and Design Guidance for ASHRAE Standard 62 and Title 24*. (Aug 2003)
- *Evaluation of Demand Controlled Ventilation, Heat Pump Technology, and Enthalpy Exchangers*. (Aug 2003, rev)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- The completed research shows that office, retail, and certain restaurant spaces are good targets for DCV in the inland climate zones. Certain institutional spaces with large changes in occupancy, such as theaters, lecture halls, auditoriums, and gyms, would also benefit from DCV.
- DCV was not beneficial for modular school rooms with adequate existing ventilation because the occupancy profile is fairly flat and does not change much during the school year. Investigators found that the typical ventilation rates for certain common HVAC units was less than required by buildings codes. This result was communicated to appropriate school officials.

Commercialization potential or commercialization initiated

DCV controllers are available from HVAC controls manufacturers. The results from this project will guide application of DCV and promote appropriate use of the technology.

Recommendations

Market Connection**:**

The results of this project will be cited in a brochure prepared as a deliverable under the Program Administration Element. It will be available on the Commission web site and Architectural Energy Corporation's web site.

The brochure should be sent to ASHRAE and AIA local chapter presidents for distribution to members and posting on local chapter web sites.

Articles for HVAC trade publications should be prepared. In addition to design professionals, contractors and suppliers read these publications.

Future Research**:**

The impact of DCV on comfort and productivity has not been studied. As interest in DCV increases due to high utility costs and building energy code changes, this topic should be investigated to provide designers and owners with new information.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline

The DCV technology evaluated in this project applies to packaged air-conditioning systems. These systems are prevalent in small office buildings, retail stores, and miscellaneous categories. The school, hotel, and restaurant categories have smaller fractions of space that are served by packaged air-conditioners. The total floor area for all of these categories is about 3,109 million square feet. The Commission data for Year 2000 shows that buildings with packaged air-conditioners used 8,226 GWh and accounted for 4,900 MW of peak demand.

Assuming that 25% of small office, retail, and miscellaneous floor area, 10% of school floor area, and 5% of hotel and restaurant floor area could be served with DCV technology, about 626 million square feet would be the target.

Updated Outcome

The research showed that application of DCV to building spaces with favorable occupancy characteristics could result in a two-year payback or less for a $900 per AC unit. Assuming that the average utility rate is $0.15/kWh, each unit would save about 3000 kWh/year. Assuming that total packaged AC tonnage, based on 400 sf/ton, is about 1,564,000, and that the average installed unit size is 7.5 tons, then there are 208,500 units available for application of the DCV technology. Electricity savings would be about 626 GWh and demand savings would be about 373 MW (assuming that demand savings are proportional to the usage savings).

3.2. Project 3.2 Night Ventilation & Building Thermal Mass

INTRODUCTION

Background and Overview

For certain building types, it is possible to take advantage of the storage capabilities of the building structure and shift a significant portion of a building's on-peak cooling requirements to off-peak periods, thereby reducing both energy and demand costs. This can be a significant demand management tool that does not require a major capital retrofit in a building. One of the more effective methods for pre-cooling a building involves the use of "free" cool night air to reduce cooling requirements for the next day. In reality, the use of outside air is not free, since energy is required to operate the air-handling fans. As a result, the best strategy involves a tradeoff between fan power and cooling provided. Currently, control products for employing nighttime ventilation do not exist.

Maximum potential savings associated with optimal control of building thermal mass as compared with conventional night setback control through the use of optimization routines applied to computer simulations of buildings and their associated cooling systems has been demonstrated in prior research at Purdue. Results of this study showed there is a significant potential for reducing operating costs. The most dramatic relative savings over conventional control occur during times when nighttime ventilation cools the building zones and yet cooling is required during the day. Depending upon the building and HVAC system, the estimated daily savings in costs for cooling associated with nighttime ventilation were between about 10% and 50% when compared to conventional night setup control. The greatest savings occur in climates with large diurnal temperature swings, such as occur in dry regions of California.

Initial work in developing a control strategy for nighttime ventilation pre-cooling in conjunction with building thermal mass has been done in prior research. The strategy utilizes utility rate information along with simple estimates of building and HVAC system design characteristics. The method was tested in simulation and showed seasonal cost savings of up to 30% for dry climates, such as San Diego.

OBJECTIVES

Develop, implement, and demonstrate a control strategy for using night-time ventilation and building mass to reduce cooling requirements and peak cooling demand while ensuring adequate thermal comfort.

Research Team

Jim Braun and Zhipeng Zhong of Purdue University conducted this research project. Todd Rossi and Doug Dietrich of Field Diagnostic Services, Inc., provided data collection services and field support. Lanny Ross with Newport Design Consultants provided field support as well.

APPROACH

The planned tasks were:

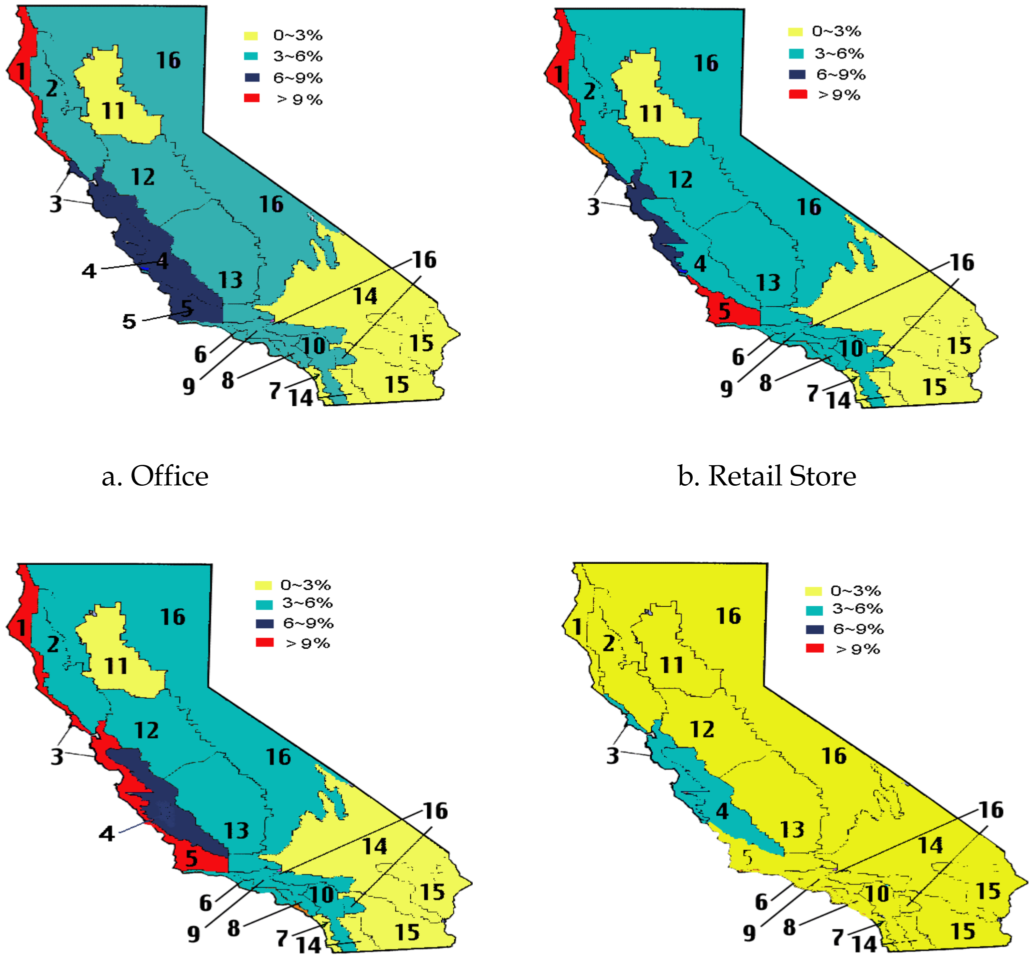
- Develop a simulation tool to evaluate a proposed night ventilation control algorithm for packaged air-conditioners. The simulation tool would be developed to accommodate simulation requirements for this project as well as Projects 3.1 and 4.2. It would serve as a screening tool using representative buildings and systems and allowing evaluations in different climate zones.
- Evaluate the control algorithm with field tests. One of the 12 demonstration sites selected for research on Projects 2.1, 3.1, and 4.2 would be selected to test the algorithm.
- Compare the field monitoring data and the simulation data and improve the algorithm based on the comparisons.
- Summarize the results and present recommendations regarding the overall potential for cost savings using night ventilation with building mass in California applications.

OUTCOMES

Technical Outcomes

- A simple night ventilation control algorithm was developed and evaluated using the VSAT simulation tool. The evaluation was performed for a small office building, a sit-down restaurant, a retail store, a school class wing, a school auditorium, a school gymnasium, and a school library. The night ventilation precooling algorithm uses a set of rules to enable precooling. Whenever the ambient temperature drops below the zone temperature, the ambient air can be used to precool the zone and reduce cooling loads during the next day. However, the next day savings associated with operating the ventilation system at night should be sufficient to offset the cost of operating the fan. In addition, the ambient humidity should be low enough to avoid increased latent loads during the next day and the ambient temperature should be high enough so as to avoid additional heating requirements after occupancy.
- A simplified version of the control algorithm operated correctly within two field sites. The first field site, located at the Field Diagnostic Services, Inc. (FDSI) headquarters near Philadelphia, PA, was used primarily for initial debugging of the implementation. The second field site is a Walgreens located in Rialto, CA. The Walgreens site employs five rooftop units (RTUs) each with a controller that provides ventilation precooling under the appropriate conditions.
- The electrical energy savings varied between 0 and 8%. The electrical demand cost savings associated with night ventilation varied between about 0 and 28%, whereas the total electrical cost savings ranged from about 0 to 17%. For the default building and system parameters, the savings in compressor energy ranged from about 0 to 53% depending on the location and building type. However, the savings in total air conditioning electrical energy usage are much smaller than the compressor savings due to an increase in fan energy.

Figure 7 shows relative savings by climate zone for offices, retail stores, classrooms, and restaurants.



a. Office

b. Retail Store

c. School Class Wing

d. Restaurant

Figure 7. Mechanical Night Ventilation Cost Savings in California for Different Buildings

Market Outcomes

- Generally, the greatest percentage compressor and total cost savings occur in coastal climates with relatively mild ambient temperatures. However, the savings are also significant in hot inland climates having larger total loads.
- The savings are considerably smaller for the restaurant than for the other buildings. Compared to the other buildings, the restaurant has less thermal mass, a longer occupancy schedule, and greater ventilation requirements.
- Even greater savings would be possible if efficient, variable-speed fan motors were employed.
- For areas with high utility rates or demand charges, the energy savings would be higher.

Major Deliverables

The deliverables from this project may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *VSAT – Ventilation Strategy Assessment Tool*. (Aug 2003)
- *Development and Evaluation of a Night Ventilation Precooling Algorithm* (Aug 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The night ventilation precooling strategy can be implemented using the same sensors and control hardware employed within an economizer controller. Therefore, it should be cost effective to integrate night ventilation control with economizers for packaged equipment used in small commercial buildings. Even greater savings should be possible for packaged units that use variable speed fan control.

If night precooling is being considered for a new design, a return air damper should be specified and controlled so that it closes during night ventilation precooling.

Applying night ventilation precooling to existing construction will probably require retrofitting controller hardware.

Commercialization potential

Technical integration of the precooling algorithm in new packaged units will depend on the sophistication of the controllers offered by the manufacturers. It is close to a no-cost addition since no additional sensors are required. However, the addition of a return air damper and controls will probably add as much as $300 to $500 to the price of a unit.

Recommendations

- Conduct a market survey of available packaged units to determine the range of fan and motor efficiencies, as well as whether variable speed indoor fans are available. Building code changes should be considered to promote two-speed, or fully variable speed, fan motors.
- Publish the results of the market survey to architects, engineers, and building managers.
- Promote designs with greater mass integrated into the interior in climate zones where night ventilation precooling is effective.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline:

This project focused on assessing the potential for night ventilation in conjunction with use of building thermal mass for buildings with packaged air-conditioning. The Commission data for Year 2000 shows that buildings with packaged air-conditioners used 8,226 GWh and accounted for 4,900 MW of peak demand.

Updated Outcome:

Assuming that nighttime ventilation may be applicable to 25% of the commercial building stock with packaged air-conditioning, this fraction would account for estimated electricity use of

2,056 GWh and 1,225 MW of peak demand. Assuming that 5% savings could be achieved, the estimated electricity savings would be 103 GWh and demand savings would be 61 MW.

3.3. Project 3.3 Smart Load Control and Grid-Friendly Appliances

INTRODUCTION

Background and Overview

With the deregulation of the electric utility industry in California, operation of the grid will be increasingly pushed to the full margin of its capability. This leaves the system vulnerable to events outside its control such as loss of interstate transmission lines or voltage support. By safely operating the grid closer to its limits, ratepayers need not pay for large capital investments in capacity of the T&D infrastructure and large operating costs for reserve generation capacity needed to ensure grid stability.

Concepts for simple, inexpensive control strategies for residential and small commercial appliances (e.g., air-conditioners, hot water heaters, refrigerators, cloths washer/dryer, etc.) should be researched that the risk of power outages and enhance the grid reliability in California.

Techniques should be developed to drop specific end-use loads for short periods, both during grid crises and upon restoration of power, to reduce the stress placed on the grid during these transient operations. Dropping loads during crises can reduce the overall load momentarily, helping stabilize the grid and prevent an outage. Similar benefits can be obtained during recovery from an outage.

OBJECTIVES

Develop smart load controls for residential and commercial appliances (e.g., refrigerators, electric hot water heaters, and other appliances) that enhance the reliability of the power system in California, and support Cold Load Pickup after power outages.

Research Team

Michael Kintner-Meyer, R. Guttromson, D. Oedingen, and S. Lang with Battelle conducted this research project.

APPROACH

- Develop, implement, and test new methods for detecting pre-cursors of impending problems in the California electric power grid. The approach pursued used information that is measurable at the wall outlet anywhere in California. It deliberately focused on methods that do not require communication from an outside source. Relying on a local sensor that measures the frequency of the alternating current (AC) power at the wall outlet would allow the device to function autonomously. Adding control intelligence to the device would allow automated power-down and power-up for individual appliances. With large volume manufacturing, the device can ultimately be implemented at low cost in commonly used appliances for homes and businesses.
- Develop and test a microprocessor controller under laboratory conditions to perform autonomous load reduction services. An algorithm decides if and over what period of time load shedding will be performed. This algorithm will utilize a simplified load

prediction approach that will use month of the year, day of the week, and hour of the day. It will also utilize current outdoor air temperature.

- Prepare written hardware and software specifications for the control device. One controller will be built and tested under laboratory conditions with appliances including a refrigerator, compressor unit of an air-conditioning system, and an electric water heater.

OUTCOMES

Technical Outcomes

- Two load controller prototypes, based on detecting under-frequency events and based on spectral analysis, were developed, built, and tested. The first load controller prototype responded to under-frequency events and rapid decay in the grid frequency. The controller was based on a personal computer (PC) platform with a Microsoft DOS operating system. The second load controller prototype was used for the statistical and spectral analysis of historic frequency data of known grid events. It was based on a PC with a Linux operating system that provided real-time controller capability as well as processing historic data read from a data file.
- Using dynamic simulations of the western US interconnected power system (WECC) that includes the power grid in California, a set of hypotheses were postulated that proposed distinct differences in the dynamic behavior of the grid frequency as the power system transitions from a low-stress to a high-stress condition. The analysis was focused on the dynamic stability problem that is specific for California. It was hoped that distinct differences in the dynamic behavior between low- and high-stress conditions may be used to design a detection algorithm that would identify pre-cursors of impending stability problems in the grid and upon recognition would turn an appliance off. The hypotheses were tested on historic data. The historic data represented two distinct and recent grid events. The first data set represented the WECC breakup of August 10, 1996 that caused wide-spread outages in the western region. The other data set (dated October 8, 2002) represented a transmission line trip followed by some remedial action and scattered load loss.
- The results of the data analysis did not support the hypotheses. The randomness and magnitude of constantly changing loads, adjustments by generators to meet the demand, and the randomness of the unplanned outages, cause changes in the topology of the network making it very difficult, if not impossible, to definitively declare a state of the power system as low stress. Even during periods at night, when the load tends to be lower than during the day, it is not obvious that the system attains a low or lower-stress state. Transmission outages, planned or unplanned, may pose a difficult burden on transmission engineers to keep the system in stable and safe condition. Because of the inherent inability to establish a state of low stress as a reference case, it became difficult during this analysis of historic data to detect the transition from a safe condition to that of an impending problem.

Market Outcomes

As a result of this data analysis, it appears questionable whether the chosen approach will be successful in the long-run. The major obstacle for this approach is the necessity to establish a reference scenario that would represent safe grid operating conditions. To establish this, a large series of the conditions needs to be analyzed to become familiar with the spectrum of variability for each indicator to establish signatures or patterns for impending problems.

An alternative approach to detecting grid instability focuses on determining the transfer function that describes the dynamic behavior of the entire power system, from which the standard stability analysis methods can be applied. So far, no one has successfully established a power system transfer function of sufficient accuracy with which to perform a meaningful stability analysis.

Deliverables

The deliverables from this project may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Final Report: Smart Load Control and Grid Friendly Appliances* (Jul 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The control approaches investigated were not successful in detecting high stress conditions in the power grid.

Commercialization potential

The approaches investigated should not be commercialized**.** Other approaches discussed under the *Recommendations* section may have better promise.

Recommendations

With the insights gained from the simulation and data analysis, the following recommendations for additional research are made:

- Under-frequency load control could provide an important grid reliability enhancement. Although reactive in its response, an under-frequency load control strategy with frequency responsive appliances and devices could provide reserves that are currently furnished by generators that are either already spinning or that can be ramped up in their output.
- To enhance fundamental understanding of the stability characteristics of the power system, it is recommended that system identification techniques be used to approximate a real-time transfer function of the entire power system. If a real-time system transfer function of sufficient accuracy can be established, it would enable the use of standard stability analysis tools for determining distance to the stability edge.
- For dealing with voltage stability problems, we recommend the use of under-voltage relays of induction motors, as found in compressor motors for air-conditioning systems and other appliances. The under-voltage protection prevents motor stalling caused by decreasing voltage as a result of a line fault or high system loading. The stalling of induction motors perpetuates the decreasing voltage to a point, where the voltage may drop sharply and quickly and propagate through the distribution systems as other electric motors reach the same conditions.

BENEFITS TO CALIFORNIA

Unlike others in this Program, the objective of this project was not to save electric energy or to reduce electric peak demand, but rather to enhance the grid reliability in the California power system and to prevent power outages. Because of this difference in the objective, baseline and outcome comparisons are not stated:

3.4. Project 3.4 Extending BACnet for Lighting and Utility Interfaces

INTRODUCTION

Background and Overview

Past work at the National Institute of Standards and Technology (NIST) in the area communication protocols for building automation and control systems has resulted in the adoption of the BACnet protocol as ANSI/ASHRAE Standard 135. BACnet has also been adopted as a pre-standard by the European Community (ENV 1805-1, ENV 13321-1) and as a Korean national standard (KS X 6909). Japan is progressing towards adopting BACnet as a national standard. BACnet has been proposed as an ISO standard and is currently being processed by ISO TC 205 Building Environment Design. Today there are over 40 manufacturers of commercial BACnet products and approximately 10,000 installed systems worldwide.

NIST facilitated a cooperative arrangement between NEMA, NFPA, and ASHRAE to specifically address the use of BACnet to integrate fire systems with HVAC and other building control systems. The results have been the endorsement of BACnet by NEMA as the preferred way to integrate fire systems with other building systems, additions to the BACnet standard for fire systems that are currently in public review, and a project to revise NFPA 72, the national fire alarm code.

NIST formed a BACnet Interoperability Testing Consortium that has 22 member companies. The work of this consortium has led to the development of proposed companion standard to BACnet that defines conformance tests. This proposed standard has been approved for public review and comment. As part of this work NIST developed software tools for testing BACnet implementations. In February 2000 a BACnet Manufacturer's Association was formed with a charter to establish an industry certification program based on the proposed standard and the work of the NIST consortium.

OBJECTIVES

- To develop enhancements to ASHRAE Standard 135 (BACnet) to support lighting control services.
- To develop enhancements to the BACnet standard to support communications between a building and the utility.

Research Team

Steven Bushby, David Holmberg, and Stephen Treado with NIST conducted this research project.

APPROACH

- Establish a liaison relationship between ASHRAE SSPC 135[3] and key representatives of the lighting control industry, as well as utility industry. Working groups would be created to explore how the BACnet standard should be amended to accommodate lighting controls and utility/building control interactions. The target was to identify data exchanges that would most likely be commercially viable in by 2005.
- The goals for the working groups were:
- Prepare one or more BACnet addenda proposals for lighting control.
- Propose a mechanism to integrate BACnet systems with utility meters conforming to ANSI C12. Prepare a written proposed BACnet addendum addressing utility/building control interactions.

OUTCOMES

Technical Outcomes

- Two working groups within ASHRAE SSPC 135 were created: a Lighting Applications Work Group (LA-WG) and a Utilities Interface Working Group (UI-WG). LA-WG established formal liaisons with National Electrical Manufacturers Association (NEMA) and Illuminating Engineering Society of North America (IESNA). UI-WG developed liaisons with Electric Power Research Institute (now known as EPRI) and the Institute of Electrical Installation Engineers of Japan (IEIEJ). Meetings of these working groups over the past three years resulted several proposed amendments.
    - Two lighting control objects are expected to be approved as amendments to the BACnet standard before the end of 2003.

      Multiplexer Object Type. This object allows grouping of a set of outputs to control lighting in areas such as hallways or rooms. It makes setting up a control system easier and reduces network traffic.

      Lighting Control (DALI) Object. This object allows dimming, switching and ramping, and will be compatible with the emerging DALI standard for digital electronic ballasts.
    - Two new objects recently went through a public review. Accumulator Object and Pulse Converter Object. Together these two objects meet most of the needs of both US and international participants in providing a simple functionality to allow building control systems to read the pulse from an electric utility meter. This in turn provides billing and power management capabilities to the building control system.
- Work is progressing on three additional topics that have not been submitted for approval by SSPC 135.
    - *Load Control Object*. The object allows for a command to be sent by a utility (or building master controller) to direct a building controller or equipment controller to reduce load.

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[3] ASHRAE Standing Standards Project Committee 135 - *BACnet - A Data Communication Protocol for Building Automation and Control Networks*.

LCO objects can be nested to provide management flexibility and also a way to scale up to large complex systems.

- *Real Time Pricing (RTP)*. This is a complex topic that EPRI has been working on. NIST is working with EPRI on a demonstration of BACnet features needed to accomplish RTP.
- *Interfacing with Advance Utility Meter Features*. The utility meter industry has an existing meter standard, ANSI C12.19, which has enhanced information features. The work in progress is addressing how best to interface to the meter—via what protocol and network transport.

Market Outcomes

- Integrating lighting control and utility meter interfacing into the BACnet Standard will provide a common, non-proprietary, standard communication framework for building automation systems.
- It will reduce the costs of supporting multiple standards within controls products, making it less expensive to provide controls in all commercial buildings.
- Controls in more buildings will reduce energy use and improve indoor environments.

Major Deliverables

The deliverables from this project have been summarized in a single final report that may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Proposed Amendments for Extending the BACnet Standard to Include Lighting Control and Interfacing Building Systems with Utilities*. (May 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Although the standards making process takes a long time because it is a consensus process, the integration of lighting controls and utility meters into the BACnet standard will promote energy conservation by giving building operators the opportunity to work on a single controls platform.

Commercialization potential or commercialization initiated

The international involvement in the committee's activity makes it likely that the end products will become an international standard. The involvement of building automation system manufacturers and utility representatives makes it likely that the changes will be implemented in commercial products.

Recommendations

The Commission should support continued work on expanding the scope of BACnet to include lighting controls and utility meter interfacing. As an open standard, BACnet can be used by specifying engineers, lighting vendors, controls manufacturers and utility meter manufacturers. to promote integration of building automation controls.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline

Indoor and outdoor lighting was 39% (35,886 of 91,771 GWh) of annual electricity use in California in Year 2000.

Updated Outcome

Assuming that improved lighting controls will reduce consumption by 10%, and that improved controls can be made available to 25% of the building stock, annual savings would be 896 GWh. Average demand savings would be 102 MW.

3.5. Project 3.5 Aggregated Load Shedding

INTRODUCTION

Background and Overview

While much effort has been devoted to load management, including load shedding, in individual buildings, little reported work has focused on aggregates of buildings. Building aggregation is increasingly of interest due to the role of load aggregators in electricity-purchase contracts and the efforts at multi-building campuses to reduce electricity bills for aggregates of buildings. MIT, working with Drexel University, conducted exploratory research into opportunities for load management in aggregates of buildings, with emphasis on college campuses and multi-building medical facilities.

OBJECTIVES

- Identify opportunities to better control electrical loads in groups of buildings by aggregating load shapes and by coordinating control actions,
- Evaluate the potential impact of aggregated load control,
- Identify needed developments in control and communication systems.

Research Team

Les Norford, Peter Armstrong, and Helen Xing with MIT conducted this research project. Lanny Ross with Newport Design Consultants provided field support.

APPROACH

- Aggregated building load management issues were investigated that included the engineering aspects, implementation issues, customer motivation and legal issues.
- Simulations and field monitored data were used to assess the theoretical limits to aggregated load shedding as well the practical aspects of actual implementing a load shedding strategy. To accomplish the research objectives, the research team focused on:
    - Emphasizing short-term manual or semi-automatic set point adjustments;
    - Using centralized load monitors for operator feedback; and
    - Considering small-scale aggregates of buildings under a single revenue meter.

- Simulations were used to define the limits of load shedding, and optimum combinations of strategies. The research team considered the following:
  - Define hypothetical cases to quantify load aggregation benefits (building function, building load shapes, building equipment, climate)
  - Select control strategies (internal loads, thermal mass, secondary equipment, primary equipment)
- The demonstration partner selected for the research was the County Government of Los Angeles. The County was participating in Southern California Edison's load curtailment program. It was interested in learning what curtailment measures to implement to accomplish demand reduction without seriously affecting comfort levels in its facilities. The County operates a 200 acre building complex, including social services, courts, prisons, and administrative buildings. Two buildings were selected for monitoring and load control experiments, including the Edmund Edelman Children's Court (ECC) and the Internal Services Division (ISD) building.
- Data were collected for analysis to support building a thermal response model of each building to predict electric demand due to cooling loads**.** MIT installed power and environmental (zone and HVAC system temperatures) instrumentation in the monitored buildings. Weather data were collected from an on-site weather logging station (ambient temperature, humidity, solar radiation, wind speed and direct, etc).
- Load curtailment (shutting off the chillers and upward adjustment of setpoints) and night pre-cooling experiments were conducted for several days, including a winter period and a summer period. Models were calibrated with the measured data and then run with a number of different pre-cooling schemes to predict annual changes in energy costs.

OUTCOMES

Technical Outcomes

- Load shedding potential is a function of many variables, which may be summarized in three building/occupancy characteristics and one control parameter.
  - aggregate magnitude of operating loads (primarily lighting and plug loads) that can be shut off *at the time that load curtailment is called for*;
  - cooling plant efficiency (that is, what is the reduction in HVAC plant power that can be realized per kW reduction in lighting and plug loads); and
  - potential for thermal storage within the conditioned space (determines what additional reduction in cooling capacity can be achieved).
- Aggregated-load shedding for groups of two or three buildings is effective in reducing peak demand and overall power consumption. Based on the specific building models, load patterns, weather conditions and rate structure used in this research, a peak load reduction of 2 – 14% and a cost-based peak load reduction of 2 – 12% for two or three building aggregation cases with thermostats as control variable was achieved. A 27% peak load reduction and around 20% cost reduction in a two-building case with both fan-based and chiller-based night cooling enabled was observed. Exact numbers depend on the correlation and interdependence of the individual participants.

- Short duration (one hour) load curtailment experiments showed that about 330 kVA could be saved in the ECC building and about 250 kVA in the ISD building.
- Night pre-cooling experiments demonstrated that chiller and pump power could be reduced by 20% for an entire day by pre-cooling the building the night before. The researchers noted that extended periods of night pre-cooling, including over weekends would be needed to establish the full potential of the strategy.
- Numerous faults were discovered through analysis of the monitored data and through visual observation during site visits.

Market Outcomes

Although the results show that aggregated load shedding is feasible, the complexity of simulating and optimizing load shedding on an aggregated basis for only two or three buildings is very high. Defining a set of California guidelines to cover a large range of building types, occupancies, HVAC systems, and climate zones will require a significant amount of additional research.

Independent of the research project, the County decided not to continue participating in the utility load curtailment program after some experience with the costs and benefits. Utilities may need to restructure the incentives to attract a stable pool of participants.

Major Deliverables

The deliverables from this project have been summarized in a single final report that may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Issues Affecting Load Control in Aggregates of Commercial Buildings* (Mar 2001)
- *Analysis and Field Test of Semi-Automated Load Shedding in LA County Test Buildings* (Jun 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- Night pre-cooling may be viable long-term option for many commercial buildings to consistently reduce electric energy use and demand.
- Short-term load curtailment by shutting down chillers can provide an hour of load reduction without adverse comfort impact and without exceptional demand increases upon release from curtailment. Some commercial buildings may be able to curtail longer without comfort impacts, but there is a greater risk of increased demand upon return to normal operations.
- Aggregated load curtailment by an operator of multiple buildings on a common meter is feasible. A load shedding plan and sufficient power sub-metering and environmental monitoring capability from a single location are required prior to an event.

Commercialization potential or commercialization initiated

Comprehensive optimal control strategies are not in common usage because controls manufacturers have yet to implement, on a widespread basis, algorithms now in the literature.

Customer demand for these features is likely to increase as the installed cost of sensors and fault diagnostic systems decrease.

Utilities should be encouraged to provide monitoring tools to customers on interruptible service. This will also allow the building operator as well as the utility to confirm that actions taken resulted in verifiable load reductions.

Recommendations

- Building automation system manufacturers should be encouraged to expand the capabilities of their products to include programmable optimization of control sequences.
- Aggregated load shedding strategies should be investigated for other building types. The strategies investigated with the simulated three-zone VAV building model may be more or less successful with other building systems.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline

The updated energy use data for Year 2000 is 91,771 GWh/yr and 20,741 MW for all commercial buildings. Aggregation of loads would be more likely for buildings on campuses, such as college and hospital complexes. The total load for these building types was estimated to be 13,505 GWh/yr and 3,339 MW.

Updated Outcome

The portion of all college and hospital buildings that are on single campus-wide meters is not known. A load aggregation program applied to 50% of college and hospital load, using either thermostat set-up, night pre-cooling with ventilation, or night pre-cooling with chillers, could save 338 GWh/yr and 167 MW demand, assuming aggregate load reductions of 5% for consumption and 10% for demand.

4.0 ELEMENT 4—Alternative Cooling Technologies and Strategies

INTRODUCTION

Conventional cooling technologies used about 14,255 GWh in Year 2000, according to Energy Commission estimates. This represents 16% of the 91,771 GWh consumed by the commercial sector in Year 2000. Element 4 research projects investigated four concepts that could potentially reduce electric use and demand in the future.

The first project extended research and development that has proceeded for more than a decade on natural gas absorption technologies and natural gas engine-driven vapor compression cycles. The goal was to develop a gas absorption heat pump based on a small, modular, high-efficiency gas absorption chiller that had been developed in a research partnership between Oak Ridge National Laboratory and Robur Corporation.

The second project assessed the application of a heat pump applied to the outside air and exhaust air streams of a conventional packaged HVAC unit. Energy recovery from the exhaust air stream could be an important source to reduce the cost and energy for conditioning outside air.

The third project initially planned to assess the energy savings potential of a relatively new residential hydronic distribution system using fan coils. Early consideration of market barriers for this system by the Program Advisory Committee led to the decision to shift the project to an assessment of a residential hydronic distribution system to store cooling and heating in a floor slab. The assessment included a field test of three cooling modes, including conventional forced air and combinations of night force-air cooling with radiant slab pre-cooling.

The fourth project focused on the role that natural ventilation could play in California. The project's objectives included developing natural ventilation design strategies and design methods for small commercial buildings, addressing the impact of outdoor air quality on natural ventilation, and developing natural ventilation software tools.

The key barriers to introducing alternative cooling technologies are unfamiliarity on the part of designers, lack of credible evidence of efficacy and criteria for their selection, lack of equipment in smaller sizes, and unknown or uncertain maintenance requirements.

4.1. Project 4.1 Modular High Efficiency Gas Absorption Heat Pumps

INTRODUCTION

Background and Overview

U.S. Department of Energy (DOE) has invested $4M per year in the development of double-effect gas-fired absorption-cycle (GAX) cooling equipment. The double-effect cycle provides increased cooling efficiency to a coefficient of performance (COP) of 0.68 (when considering the conversion of fuel into electricity this is equivalent to a 10-SEER electric air conditioner) over conventional absorption cycles whose COPs are around 0.48. More importantly, it eliminates the need for an electric-powered compressor while utilizing inexpensive natural gas during low-demand summer periods.

With technical support from Oak Ridge National Laboratory, Robur, Inc. has developed a high-efficiency 3- to 5-ton absorption cooling module that is currently being field tested in a large-scale residential demonstration project by Southern California Gas Company. The cooling module supplies chilled-water to fan coil units. While their first cost is about 20% higher than conventional equipment, this cost is mostly recovered by reducing the size of the building's electric service.

The absorption cooling cycle is currently being adapted with DOE funding so it can be reversed to create a heat pump, providing an integrated heating/cooling device. In heating applications, the GAX heat pump (COP=1.25-1.4) will heat the building with significantly reduced energy consumption and reduced emissions compared to the most efficient existing gas furnaces and boilers (maximum efficiency 96%; typical efficiency 80%). As an option, the GAX heat pump link can also be developed to provide simultaneous domestic hot water for the building, further increasing efficiency by recycling waste heat during cooling operations.

This technology reduces the peak impacts of cooling loads on electric-generation resources and the T&D grid by shifting cooling loads from electricity to natural gas (when the natural-gas distribution system is underutilized). It also increases the efficiency of natural gas utilization for heating compared to traditional gas furnaces.

Objectives

Test the hypothesis that small modular gas-fired absorption chillers, when staged to serve 15 to 25 ton loads, will have a net energy efficiency equal to, or greater than, conventional electric motor-driven chillers by doing the following:

- Demonstrate a control system linking modular 5-ton gas-fired absorption chillers to create typical 15- to 25-ton packages suitable for small and medium commercial and institutional buildings, such as schools, retail strip malls, and office buildings.
- Develop a modular 5-ton absorption heat pump system and demonstrate it using a control system linking units to serve 15- to 25-ton loads.

Research Team

Bob DeVault and Richard Murphy with Oak Ridge National Laboratory were the lead researchers on this project. Vernon Smith with Architectural Energy Corporation and Scott Byington with Conditioned Air Technicians provided field support. Robur Corporation was the supplier of the GAX chillers. Southern California Gas assisted with locating a demonstration site.

APPROACH

The original plan for this project called for parallel laboratory and field demonstration work.

- Develop a packaged hydronic distribution and control system that would allow multiple 5-ton GAX chillers to serve small to medium commercial loads.
- Demonstrate the chiller link control system in a small commercial site.
- Develop a heat pump version of the GAX module.
- Demonstrate multiple GAX heat pumps with the linked controls in a small commercial site.

OUTCOMES

Technical Outcomes

- Development of the GAX heat pump was cancelled at the end of the first year due to changed market conditions. During the first project year, Southern California Gas had difficulty recruiting a demonstration partner because the cost of natural gas had increased dramatically. There was considerable uncertainty at the time due to the volatility of natural gas and electricity prices. At the end of the first project year, these economic issues as well as delays in starting development work on the GAX heat pump led to a decision to reduce the scope of the project to just a GAX chiller link demonstration.
- A demonstration site for the linked chiller concept was identified. During the second year Southern California Gas Company had difficulty recruiting a demonstration partner due to continuing uncertainty in the energy markets. A demonstration site was finally located, a small medical facility with a whole body scanner, that had three of the GAX chillers installed within the last year to serve only the scanner unit. The chillers were not installed with Robur's linked design, but instead were piped and controlled according to a design provided by the facility's mechanical contractor. Based on a 12-ton design load for the whole body scanner and its peripheral equipment, it appeared that this site would provide demonstrate the use of the 5-ton GAX chillers to provide staged cooling that could be controlled as climate and internal loads required.
- The linked GAX chiller demonstration was cancelled after determining that the monitored loads did not meet the experimental design requirements. Shortly after data acquisition equipment was installed, it appeared that the loads were not as high as designed and that the control system needed to be commissioned to stop undesired unit cycling. Efforts to commission the system over two months yielded some reduction in the cycling, but further data analysis showed that even on the warmer days with a heavy patient load, the output of two chillers should have met the load. During the commissioning period, it was learned that the facility owner had changed some of the equipment shortly after the GAX chillers were installed, resulting in reduced loads. The project was terminated after concluding that even if all of the controls issues could be resolved that the facility and climate loads would not require all three units to stage on and off.

Market Outcomes

Small gas absorption chillers, whether using a manufacturer's distribution and control design, or a engineered system designed by others, should be a viable design alternative for commercial sites. This is particularly true for sites with large thermal process loads, where combined heat and power systems can attain a high level of efficiency and reduce the demand on electric grid.

Major Deliverables

No deliverables were produced except project progress reports.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- Although the project did not result in a successful demonstration of GAX heat pump or GAX chiller link technologies, gas absorption chillers still have a role to play in controlling the level of electrical demand in California.
- The challenge for gas absorption technology is maintaining high levels of efficiency and operational convenience in the face of uncertain natural gas and electric power costs.

Commercialization potential

Development of the GAX heat pump was not pursued under this project, but DOE and Oak Ridge National Laboratory continued work on GAX heat pumps. ORNL's web page http://www.ornl.gov/ORNLReview/rev28_2/text/gas.htm states these heat pumps should be available in the next several years. It also states that they are expected to be installed in cold climates because the GAX technology has very high efficiency for heating and has average efficiency (compared to DX cooling units) for cooling.

The uncertainty in future prices for natural gas and electric power may hinder growth of the gas absorption chiller technologies.

Recommendations

Although residential heating and cooling applications in southern California were the original target for this technology, further investigation of applications in California may not be warranted based on the information at ORNL's web site.

BENEFITS TO CALIFORNIA

The projected benefits of this project may be substantially less than those originally estimated because the gas heat pump technology appears to be better suited for cold climates. Small, modular gas chillers are available and may play a role in the California market as a fuel-switching alternative.

4.2. Project 4.2 Ventilation Recovery Heat Pump Assessment

INTRODUCTION

Background and Overview

The heating and cooling loads associated with providing ventilation can be a significant portion of the energy requirements in commercial buildings. There are several approaches to reducing these loads, including the use of demand-control ventilation and heat-recovery heat exchangers. Recently, a major equipment manufacturer has developed a heat-pump energy recovery unit specifically designed to operate between the ventilation makeup and exhaust flow streams. During the cooling season, the unit operates to cool and dehumidify the makeup air and rejects heat to the exhaust stream. However, during the heating season, the cycle is reversed, and the unit removes heat from the exhaust stream and rejects heat to the makeup air stream. It is believed that there is an overall efficiency advantage associated with the use of ventilation-recovery heat pumps as compared with heat-recovery heat exchangers. Under most circumstances, the heat pump cooling and heating rate would exceed the energy gains or losses associated with ventilation. As a result, the loads on the primary equipment would be less than those associated with heat recovery heat exchangers. For cooling, both the sensible and latent loads would be reduced. Furthermore, the heat pump would most likely have a higher efficiency than the primary equipment due to more favorable operating temperatures.

OBJECTIVES

- Identify the most promising applications of ventilation recovery heat pumps for small commercial buildings in California.
- Demonstrate the technology in a favorable application and document its performance.

Research Team

Jim Braun and Kevin Mercer of Purdue University conducted this research. Todd Rossi and Doug Dietrich of Field Diagnostic Services, Inc. provided data collection services and field support.

APPROACH

- Test a heat pump heat recovery (HPHR) unit in a laboratory to characterize its performance and to develop a model that would be suitable for use in a simulation tool.
- Demonstrate and monitor an HPHR installed in commercial or institutional facility in California.
- The field-monitored data would be used to verify the model results and make adjustments to the model if required.
- Use the simulation tool developed in Project 3.1 with the model developed during the laboratory testing to predict performance and make economic assessments for several building types in California's climate zones.
- Prepare a final report to document the results.

OUTCOMES

Technical Outcomes

- The HPHR system did not provide positive cost savings for most building type/climate combinations investigated. The heat pump heat recovery (HPHR) system functioned properly during the field and laboratory testing. However, heating requirements are relatively low for California climates and therefore overall savings are dictated by cooling season performance. The cooling COP of the HPHR system must be high enough to overcome:
    - additional cycling losses from the primary air conditioner compressor,
    - additional fan power associated with the exhaust and/or ventilation fan,
    - additional cooling requirements due to a higher latent removal and
    - a lower operating COP for the primary air conditioner compressor because of a colder mixed air temperature.
- The HPHR system is an alternative to an economizer and so economizer savings are also lost when using this system. There are not sufficient hours of ambient temperatures above the breakeven points to yield overall positive savings with the HPHR system

compared to a base case system with an economizer for the prototypical buildings in California climates.

Market Outcomes

Based on the technical outcome of this project, it is unlikely that heat pump heat recovery systems will be specified for California commercial buildings.

Major Deliverables

The deliverables from this project may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Modeling and Testing Strategies for Evaluating Ventilation Load Reductions Technologies* (April 2001)
- *VSAT – Ventilation Strategy Assessment Tool.* (Aug 2003)
- *Evaluation of Demand Controlled Ventilation, Heat Pump Technology, and Enthalpy Exchangers*. (Aug 2003, rev)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The HPHR system should not be considered for use in California, except in perhaps certain mountain areas with larger heating loads

Commercialization potential

Commercialization within California should not be pursued.

Recommendations

No further research regarding use of heat pump energy recovery should be pursued for California.

4.3. Project 4.3 Assessment of Residential Hydronic Radiant Cooling and Heating Systems

The scope for this project originally focused on a residential hydronic distribution system that uses highly efficient fan/coil units for distribution. Early review by the Program Advisory Committee indicated that market acceptance of this system in California was doubtful, primarily because the fan/coil units were designed for low wall mounting. The PAC's viewpoint was that this unit would take up too much wall space in low to medium priced homes.

The fan/coil scope was abandoned in favor of investigating a high velocity air distribution system that could be used in new construction and retrofit cases as a method to reduce duct leakage. A demonstration site that became available was evaluated from technical and economic perspectives. It was concluded that installation at this particular site would likely result in a research demonstration budget overrun. Shortly thereafter, an evaluation of an innovative hydronic radiant cooling and heating system was proposed and accepted as the scope of work that was ultimately completed.

INTRODUCTION

Background and Overview

Pre-cooling a residence using a hydronic distribution system has the potential to reduce cooling energy consumption and reduce peak demand by shifting cooling load into non-peak periods. There are few studies comparing the relative efficiencies of conventional air distribution and hydronic/radiant distribution for cooling.

The study was performed in a contemporary house near Sacramento, California that has unique Heating Ventilating and Air-conditioning (HVAC) features which includes radiant floor heating and cooling, forced-air hydronic heating and cooling, and ventilation at night to reduce air conditioning load by pre-cooling building mass.

OBJECTIVES

Compare the energy consumption and electrical power demand characteristics of a house during the heating and cooling seasons under a variety of heating and cooling modes to determine which mode might yield the best energy alternative under established comfort standards.

Research Team

Evelyn Baskin with Oak Ridge National Laboratory was the principal investigator. David Springer and Marc Hoeschle with Davis Energy Group provided instrumentation installation and monitoring services.

APPROACH

This study was performed in a contemporary house in Winters, California, located approximately 30 miles west of Sacramento to compare electrical power demand characteristics of a house during heating and cooling seasons under a variety of heating and cooling modes and ascertain the most energy efficient mode and comfort.

- Three cooling and two heating modes were tested:

  Cooling Modes:

- Mode1: Conventional forced-air to meet cooling loads in response to a thermostat setting
- Mode 2: Conventional forced-air combined with hydronic slab precooling,
- Mode 3: Conventional forced-air combined with night ventilation precooling supplemented as needed with hydronic slab precooling.

  Heating Modes:

- Mode H1: Hydronic radiant slab heating
- Mode H2: Hydronic and forced-air heating

- Comfort testing was performed for Cooling Mode 2, according to standard techniques developed by the American Society for Heating Refrigeration and Air-conditioning Engineering (ASHRAE).

OUTCOMES

Technical Outcomes

- Mode 1 used about 11 kWh per day with an average peak demand of 1.4 kW occurring after 7 pm. In Mode 1, 14% of the average energy use occurred between mid-night and 11 am. The average outside temperature during Mode 1 was 77.7°F.
- Mode 2 used about 4.6 kWh per day with an average peak demand of 1.1 kW occurring just before 7 pm. Cooling performance results revealed that slab pre-cooling in Mode 2 caused about 13% the energy use to shift from on-peak to off-peak hours. The average outside air temperature during Mode 2 was 75.4°F, which accounts from some of the reduction in energy use and average peak demand.
- Mode 3, through 9/25/02, used about 9.7 kWh per day with an average peak demand of 1.1 kW occurring just after 4 am. In Mode 3, 72% of cooling energy was used from mid-night to 11 am. The average outside air temperature during Mode 3 was 75.8°F.
- During heating season, the energy consumption with hydronic forced-air heating (Mode H1) was similar compared against hydronic radiant slab (Mode H2) heating, with neither mode showing an advantage over the other.

Market Outcomes

- Residential radiant cooling using exposed floor slabs is an attractive additional feature for marketing radiant heating systems that will also shift energy use to off-peak hours.
- Residential night ventilation, used with or without radiant cooling, is also an attractive technology for shifting energy use and demand from on-peak to off-peak periods.

Deliverables

The deliverables from this project may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Monitoring Plan, Springer Residence* (May 2002)
- *Final Report, Residential Hydronic Radiant Cooling and Heating Assessment* (May 2003)

CONCLUSIONS AND RECOMMENDATIONS

Commercialization potential

There are currently 54 member firms of the Radiant Panel Association in California and the market penetration for radiant heating with hydronic distribution is small, probably under 1%. Since it is difficult to retrofit hydronic distribution in slab-on-grade construction, this technology is likely to gain market penetration only in new construction.

Recommendations

Results of the project should be published in construction trade journals, energy-related engineering magazines and home improvement magazines.

Both the radiant cooling using hydronic distribution and the night ventilation technologies could be promoted by utilities as means of shifting loads from on-peak to off-peak periods.

Additional research should be focused on thermal comfort aspects of radiant floor slab cooling, since the limited testing performed under this project showed that it is possible to maintain comfort, but the range of settings and conditions should be investigated further.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline

Electrical energy used in California residences in Year 2000 was 77,633 GWh, of which HVAC accounted for 9,610 GWh. HVAC also accounted for 7475 MW of 17,221 MW total demand in 1999. The energy used in residences for cooling (including fans) is about 56% of the HVAC total, or 5382 GWh. The peak demand due to residential HVAC is 7475 MW. Assuming that compressors and fans account for 90% of this peak demand, the cooling end use accounts for an estimated 6727 MW.

Updated Outcome

Assuming new residential construction is adding 227,000 homes per year, or roughly 2% of 11.3 million homes existing in Year 2000 by 2015 radiant cooling could save about 0.6 GWh and 0.7 MW annually. This is based on assuming that radiant cooling is installed in 1% of these new units in the first 5 years and is installed in 2% of new homes after that, and that the technology will save 20% of cooling energy and demand.

Although the focus of the project was on radiant cooling and heating, night ventilation was tested in conjunction with radiant cooling and conventional forced air distribution. Night ventilation also showed promise as means of shifting peak demand, particularly in conjunction with radiant cooling. Night ventilation systems could also be retrofitted into existing units. The chief saving from night ventilation was shifting demand to off-peak hours. Assuming similar growth rates (1% for five years and 2% thereafter) for new and existing construction and assuming a 50% reduction in peak demand, demand reduction would be about 3.6 GW by 2015.

4.4. Project 4.4 Design Methods and Guidelines for Natural Ventilation

INTRODUCTION

Background and Overview

Natural ventilation is being increasingly proposed as a means of saving energy and improving indoor air quality in commercial buildings, particularly in the "green buildings" community. These proposals are generally made without any engineering analysis to support the claimed advantages. In addition, design approaches are not available in this country to incorporate natural ventilation into commercial building system designs.

While natural ventilation is becoming more common in Europe, significant questions exist concerning its application in U.S. commercial buildings. These questions include the reliability of the outdoor air ventilation rates, distribution of this outdoor air within the building, control of moisture in naturally ventilated buildings, building pressurization concerns, and the entry of polluted air from outdoors without an opportunity to filter or clean it. Some climates within California are probably well suited to natural ventilation, but many of these same questions must be addressed for these locales. The NIST multi-zone airflow and indoor air quality (IAQ) analysis model, CONTAM, is capable of addressing these and other issues related to natural ventilation in buildings. In addition, the airflow calculation capabilities of CONTAM can serve as the basis of a natural ventilation design tool, enabling wider use of natural ventilation in a technically sound manner.

NIST currently has projects to investigate the potential of natural ventilation in U.S. commercial buildings and to validate the ability of CONTAM to correctly predict air flows in naturally ventilated buildings, providing a solid basis for extending this work to California-specific issues and buildings.

Natural ventilation has the potential to significantly reduce the energy cost required for mechanical ventilation of buildings. These natural ventilation systems may reduce both first and operating costs compared to mechanical ventilation systems while maintaining acceptable indoor air quality. Also, some studies have indicated that occupants perceived better indoor air quality with natural ventilation than mechanical ventilation. Improving indoor environmental conditions can also potentially increase occupant productivity by reducing absenteeism, reducing health care costs, and improving worker productivity.

OBJECTIVES

- Develop natural ventilation strategies for cooling load reduction in small commercial buildings in California.
- Develop natural ventilation design methods, construction techniques, and strategies that address non-energy benefits, such as occupant comfort and indoor air quality.
- Develop natural ventilation software tools for design to improve building energy efficiency and lower the cost of building design, construction, and operation.

Research Team

Andrew Persily, Steven Emmerich, and Stuart Dols, with NIST conducted this research. James Axley, now at Yale University, also participated in the research.

APPROACH

- Review natural ventilation strategies used predominantly in Europe, identifying specific issues and opportunities that apply to California.
- Develop a natural ventilation design and analysis tool, based on the multi-zone model CONTAM.
- Develop a natural ventilation design screening method to evaluate the suitability of natural ventilation across California's climate zones.
- Document the results from these analyses in reports and publish the design methods and software.

OUTCOMES

Technical Outcomes

- A new ventilative cooling metric was described and used to demonstrate that the coastal climates of California are potentially very well suited to natural ventilation. The hotter, inland locations are less suited to a simple natural ventilation strategy but may be able to benefit from night cooling or hybrid system strategies.
- An eight-step design approach for natural ventilation applications was developed. The steps covered
  - (1) develop design requirements,

- (2) plan airflow paths,
- (3) identify building uses and features that require special attention,
- (4) determine ventilation requirements,
- (5) estimate external driving pressures,
- (6) select types of ventilation devices,
- (7) size ventilation devices, and
- (8) analyze design.

- A review of ambient air quality data indicates that much of California fails to meet the national standards for one or more contaminant. However, since ambient air quality problems may vary by season, time-of-day, and locality, natural ventilation strategies may still be considered acceptable at all times in some areas and part of the time in other areas through innovative hybrid systems.
- Natural ventilation design and analysis software, called LoopDA (for Loop Design and Analysis), was developed to aid in sizing and placement of natural ventilation devices. LoopDA is based on CONTAMW 2.0, a multi-zone airflow model.

Market Outcomes

The analyses from this project will allow architects and mechanical engineers to evaluate the potential application of natural ventilation, or hybrid ventilation, to proposed new buildings.

The LoopDA software will provide architects and engineers with a faster and more reliable way to design natural ventilation apertures.

Major Deliverables

The deliverables from this project may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Natural Ventilation Review and Plan for Design and Analysis Tools (NISTIR 6781)* (Aug 2001)
- *LoopDA – A Natural Ventilation System Design and Analysis Software Manual* (Aug 2003)
- *LoopDA – Natural Ventilation Loop Design Assistance Software* (Jun 2003) http://www.bfrl.nist.gov/IAQanalysis/LOOPDAdesc.htm
- *Impact of Natural Ventilation Strategies and Design Issues for California Applications, Including Input to ASHRAE Standard 62 and California Title 24* (Sep 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Five important considerations specific to the application of natural ventilation to commercial buildings in California are climate suitability, ambient air quality, internal loads, thermal mass, and relevant codes and standards.

The coastal climates in California are very well suited for natural ventilation. The inland climates are not, but night cooling and hybrid ventilation systems might work well provided design parameters are suitable.

Commercialization potential

Application of natural ventilation to new buildings requires careful assessment of climate, occupancy, ambient air conditions, and ambient noise conditions. Natural ventilation should be used in coastal areas, but is not recommended in hot inland areas unless used in conjunction with a mechanical system (a hybrid system).

Recommendations

Review codes and standards to identify issues that impede application of natural ventilation.

Research the impact of other issues, such as building security and fire safety, on natural ventilation applications.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline

Natural ventilation has the greatest potential in new construction located in coastal climates. Pacific Gas and Electric, Southern California Edison, Los Angeles Department of Water and Power, San Diego Gas and Electric, and several smaller utilities serve the California coastal climate zones (1, 2, 3, 4, 5, 6, and 7). Commercial floor area data by building type are not available by climate zone. However, using US census data and assuming that the location of commercial building space is directly proportional to population, the estimated total commercial floor area in climate zones 1 through 7 totals 1,943 million sf (based on 34% of the population in 2000 living in climate zones 1 through 7). New commercial construction for Year 2000 added about 156 million square feet. The annual growth rate in new construction is expected to range between 2.7% and 2.4% each year through 2015. Between 2001 and 2015, the total new commercial office space is estimated to be 2,444 million sf. Assuming that new construction is also proportional to population and that the coastal climate zones maintain 34% of the total population, the new construction will total 831 million sf.

Cooling and ventilation consumed 15.5% and 10.2% of 91,771 GWh used by commercial buildings in Year 2000 (1.62 kWh/sf-yr and 2.50 kWh/sf-yr, respectively). Although natural ventilation could replace both end-uses, the use of ventilation fans to also distribute heating energy means that ventilation fans are likely not to be displaced by natural ventilation design. More likely, using ventilation fans for heating distribution will encourage hybrid designs. For purposes of estimating energy savings from natural ventilation, only the cooling end use will be considered.

Updated Outcome

Early adoption of natural ventilation, or hybrid ventilation, as alternative cooling strategies is likely to be slow due to building owner and tenant perception that only mechanical ventilation is reliable and comfortable. Assuming that 1% of new construction in the coastal climate zones, or 8.3 million square feet, is designed with natural ventilation systems by 2015, the avoided cooling energy would be about 13.6 GWh/yr.

5.0 ELEMENT 5—Alternative Construction Techniques and Technology

INTRODUCTION

Element 5 had one project on building integrated photovoltaics. Its focus was to develop a validated design algorithm to predict the energy production of building-integrated photovoltaic modules and to assess the energy savings potential from using BIPV in California.

5.1. Project 5.1 Building Integrated Photovoltaics

INTRODUCTION

Background and Overview

The widespread use of building-integrated photovoltaics appears feasible as a result of the continuing decline in photovoltaic manufacturing costs, the relative ease in which photovoltaics can be incorporated within a building envelope, and the fact that buildings account for over 40 percent of the energy used within the United States.

Specific examples of building integrated photovoltaic products are curtain walls that incorporate crystalline, polycrystalline, and amorphous cell technologies. This research will address a significant barrier to the widespread adoption of photovoltaics--the lack of long term measured data to validate predictive performance models needed to quantify achievable energy savings. The resulting validated model will be used to quantify the energy performance of building-integrated photovoltaics for climatic regions having high growth rates within the State of California. The resulting tool and analytic results will provide a basis in follow-on market transformation work in California aimed at capturing this valuable energy resource to reduce grid-provided electricity consumption and peak loads.

OBJECTIVES

- To develop a validated design algorithm to predict the energy production of building-integrated photovoltaic modules.
- To use the resulting model to predict the energy savings possible by using curtain-wall photovoltaic products that are integrated for buildings in high growth areas of California.

Research Team

Hunter Fanney, Brian Dougherty, Mark Davis, Eric R. Weise, and Kenneth R. Henderson with NIST conducted this research project. Fred Porter and Vernon Smith with Architectural Energy Corporation provided simulation support for the economic assessment study.

APPROACH

- Monitor the performance of PV panels with four different PV technologies, installed with and without backing insulation, for one year**.** The research team designed, procured, and installed building-integrated photovoltaic (BIPV) panels in the south façade of NIST's Building and Fire Research Laboratory. Performance and environmental data were collected for one year on four different BIPV technologies (single-crystalline, poly-crystalline, silicon film, and triple junction amorphous silcon panels), mounted in insulated and un-insulated configurations.

- Characterize the cell technologies using a solar tracker facility. The short-term characterization data and measured meteorological data were used with existing algorithms to predict the performance of building-integrated PV panels. Based on the comparative results, improved algorithms were developed.
- Prepare an economic assessment of the four PV panel technologies using simulations in coastal and inland California climate zones. Coefficients from the improved algorithms were used in a DOE 2.2 model to predict the estimated impact of integrated PV building products on electrical demand, peak loads and energy consumption in commercial buildings in California. The modeled building was a three-story, "L"-shaped, with 10,000 sf per floor. Two orientations were investigated: one with no self-shading (convex side of the "L") and the other with self-shading (concave side of the "L"). It is known from previous research that arrays with more series voltage connections are more susceptible to power loss due to partial shading than arrays with more parallel voltage connections. The simulated array was assumed to be the best case, i.e., maximizing the parallel voltage connections. Two coastal climate zones (CZ-03 – Bay Area, and CZ-06 – South Coast) and two inland climate zones (CZ-10 – Riverside, and CZ-12 – Sacramento) were simulated.

OUTCOMES

Technical Outcomes

- The highest overall conversion efficiency (sunrise to sunset) was achieved using single-crystalline cells. The insulated single-crystalline panel efficiency was 3.8 % lower than the non-insulated panel, 9.9 % versus 10.3 %. The polycrystalline panels differed by 3.1 %: 9.4 % for the insulated panel compared to 9.7 % for the non-insulated panel. The non-insulated and insulated silicon film panels converted 6.0 % and 5.8 % of the incident solar energy into electrical energy, a 3.3 % difference. Finally, the addition of insulation to an amorphous silicon panel improved the panels' efficiency from 5.9 % to 6.0 %.
- The parameters that have resulted from this research were incorporated into the IV Curve Tracer and PHANTASM models.
- Table 3 shows that savings predicted by the DOE 2.2 simulation model ranged from about $450 to $1200 per year based on a south-facing, unshaded vertical array with a gross area of about 1050 sf.
- Self-shading, or shading from other buildings or vegetation will reduce the savings, in some cases substantially, due to BIPV circuitry. Power production from PV panels is sensitive to the way in which the panels are circuited. Panels wired in series tend to produce less power when partially shaded compared to panels wired in parallel. Series wiring allows higher voltage output, which is advantageous in matching loads, particularly in commercial applications.

Table 3. Predicted Electrical Energy Savings for 1050 sf PV Array Mounted on a Curtain Wall

		Module			Array		Annual Savings		Normalized Annual Savings		
Climate Zone	BIPV Type	Area (sf)	Rating (W)	Count	Area (sf)	Rating (kW)	Net Energy (kWh)	Value ($)	kWh/sf	kWh/kW	$/kWh
Ctz03 - Bay Area											
	MonoC	17.5	133.4	20	1051.1	8.0	7,290	1,052	6.9	911	0.144
	PolyC	17.5	125.8	20	1051.1	7.5	7,304	1,059	6.9	968	0.145
	SiFilm	17.5	104.0	20	1051.1	6.2	5,285	760	5.0	847	0.144
	TripleJ	21.8	57.0	16	1047.1	2.7	3,124	464	3.0	1,141	0.149
Ctz06 - South Coast											
	MonoC	17.5	133.4	20	1051.1	8.0	8,310	1,176	7.9	1,038	0.142
	PolyC	17.5	125.8	20	1051.1	7.5	8,356	1,188	7.9	1,107	0.142
	SiFilm	17.5	104.0	20	1051.1	6.2	6,213	876	5.9	996	0.141
	TripleJ	21.8	57.0	16	1047.1	2.7	3,786	556	3.6	1,383	0.147
Ctz10 - Riverside											
	MonoC	17.5	133.4	20	1051.1	8.0	8,607	1,174	8.2	1,075	0.136
	PolyC	17.5	125.8	20	1051.1	7.5	8,745	1,202	8.3	1,159	0.137
	SiFilm	17.5	104.0	20	1051.1	6.2	6,579	892	6.3	1,055	0.136
	TripleJ	21.8	57.0	16	1047.1	2.7	4,136	576	4.0	1,511	0.139
Ctz12 - Sacremento											
	MonoC	17.5	133.4	20	1051.1	8.0	7,189	1,023	6.8	898	0.142
	PolyC	17.5	125.8	20	1051.1	7.5	7,336	1,049	7.0	972	0.143
	SiFilm	17.5	104.0	20	1051.1	6.2	5,256	745	5.0	843	0.142
	TripleJ	21.8	57.0	16	1047.1	2.7	3,309	485	3.2	1,209	0.147

Market Outcomes

Past obstacles to the proliferation of BIPV include the lack of validated computer simulations to predict the electrical performance of BIPV and an insufficient database on how well these products perform. Economic decisions regarding the use of BIPV are dependent upon the availability of product performance data, especially under representative field installation conditions. The research results from this project should accelerate the deployment of BIPV by providing high quality experimental data for the development, validation, and improvement of computer simulation tools.

Deliverables

The deliverables from this project may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Building Integrated Photovoltaic Test Facility* (Mar 2001)
- *Measured Performance Of Building Integrated Photovoltaic Panels* (Feb 2002)
- *Short-Term Characterization Of Building Integrated Photovoltaic Panels* (Feb 2002)
- *Measured Versus Predicted Performance Of Building Integrated Photovoltaics* (Oct 2002)
- *Evaluating Building Integrated Photovoltaic Performance Models* (Oct 2002)

- *Measured Performance Of A 35 Kilowatt Roof Top Photovoltaic System* (May 2003)
- *Economic Assessment of Building Integrated Photovoltaics in California* (Aug 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- Insulation behind PV panels degrades power production slightly in three out of the four cell technologies tested. The fourth technology showed a very slight improvement in power output due to the insulation.
- BIPV energy production and demand reduction were insensitive to climate location**.** Maximum building peak demand reductions were in Riverside and were about 20% of the rated panel output. Other sites and systems were as low as 5%. Peak demand was set during the summer due to air conditioning loads.
- A vertical south-facing BIPV panel has a small effect on building or system peak demand. PV panels integrated into vertically mounted curtain wall products will not produce as much power as roof-mounted panels. This is primarily due to reduction of incident solar radiation on the panel due to its mounting angle. Shading from other buildings or objects, such as trees close to the building will also significantly reduce power output. Rooftop and/or parking lot shading structures provide a better match for reducing peak demand.
- Simple payback periods for all locations are from about 20 to 90 years. The cost of BIPV may be offset in California by utility or government rebate programs, but it is clear that vertically mounted curtain wall BIPV is expensive relative to other distributed power generation options. Rooftop and parking structure PV systems have better payback periods due to higher power production and coincidence in peak power production with peak cooling loads.

Commercialization potential

BIPV algorithms are now embedded in DOE 2.2, but the current version does not do shading analysis, which must be done manually. DOE 2.2 is a widely used hourly, whole-building energy simulation program.

Recommendations

- For new construction, vertical BIPV should be considered when the cost of the installed BIPV is less than the initially specified curtain wall material. This may be the situation for show case office buildings.
- For new construction and retrofit, BIPV in vertical curtain-walls may have public relations value. Although this may be an intangible benefit, it directly demonstrates the building owner’s commitment to sustainable design.
- Curtain-wall mounted BIPV should be considered when installing a rooftop or parking lot system to take advantage of its public visibility. A rooftop system is usually hidden from public view. Adding curtain-wall mounted BIPV to a rooftop system project would likely lower the marginal installed costs and provide a public relations benefit.

BENEFITS TO CALIFORNIA

Based on new data regarding the characteristics of California building stock and statewide energy use, the projected benefits of this project are updated as follows:

Updated Baseline

It is estimated that about 2.4 million square feet of new commercial construction will be added to the existing building stock between Years 2000 and 2015. Assuming that only 2% of this new construction adopts BIPV, about 48 million square feet of floor area would be included. Assuming a square footprint, about 7 million linear feet could be positioned toward the south. Further assume that only 25% is facing south or southwest and that of this 25%, that only 25% is truly unshaded all year. The net amount of suitable south facing linear feet is about 0.44 million feet. Assuming the an average building height of 21 feet, the total area suitable for BIPV is 9.2 million square feet. In a typical installation, about 20% of this area would be covered with BIPV.

Updated Outcome

Assuming average annual electrical production is 6 kWh per installed square-foot of BIPV and that there is no offsetting summer peak demand reduction from vertically mounted BIPV, the annual energy savings by 2015 would be 11 GWh.

6.0 ELEMENT 6—Impact Assessment Framework

INTRODUCTION

Predicting the influence of a new technology on market products and services is clearly more art than science. The seemingly endless number of variables and the lack of knowledge about the interactions among them underlie the difficulty in assessing the potential of new technology. Selecting research topics for funding is more challenging because the outcome is not certain.

The Program included this Element to assess the market potential for products or services that might be created from the research results. The Commission requested that a broad approach to assessment be taken by developing a comprehensive method for evaluating the potential energy savings from buildings related research under the PIER Program. This project was the result of many communication exchanges between the research team and the Commission project managers. The objective of project was to develop a comprehensive impact assessment framework with universal applicability of any PIER buildings-related project whose goal it is to reduce energy consumption and/or electric peak demand.

6.1. Project 6.6 Development of an Impact Assessment Framework

INTRODUCTION

Background and Overview

Technological advancements may be in the form of gains in knowledge, demonstration and validation of performance of hardware or software, development of new control strategies, and development of new hardware. The objectives that a comprehensive impact assessment framework should address include:

- Define and characterize the target market sectors and their market size, the market delivery mechanism, and the time to market for each technological-advancement.
- Provide a cost/performance characterization of each technology-advancement.
- Identify market barriers and analyze the potential impacts imposed by existing or likely future regulatory requirements.
- Assess impacts of each technological advancement relevant and related to:
- Rapid growth in energy consumption in hot inland areas
- Non-energy benefits
- Public health and safety
- Building and housing affordability, value, and the state’s economy.
- Characterize the benefits of each technology-advancement to the California ratepayer and to the state’s economy.
- Provide a method for technology ranking based on impact assessments and projections.

OBJECTIVES

Develop and demonstrate an impact assessment framework that explicitly identifies the assumptions and inputs to the assessment process and evaluates technologies for energy savings and electric peak demand reduction potential.

Research Team

M. Kintner-Meyer, D. Anderson, and D. Hostick, with Battelle Memorial Institute, Pacific Northwest Division, performed this research project. Mike Rufo and Fred Coito with Xenergy provided consultation regarding development of the market segmentation framework. Ken Barnes with Nexant, Inc. developed the database and database queries to support the examples used to exercise the framework.

APPROACH

The project methodology and framework was designed for assessing the energy-related benefits of products that may emerge from the Commission's PIER Program research for the commercial buildings sector. The methodology defines a process that starts with the initial product characterization and identification of the product's market segment, determines the market penetration trajectory as a function of time, and concludes with estimating the impacts on electricity use, electricity demand, and monetary expenditures on electricity.

The key features of the assessment framework are, in summary:

- General applicability to all energy efficiency products for commercial buildings. The framework has been developed specifically for analyzing impacts of energy efficiency products relevant for the commercial buildings sector in California. It provides a generic product characterization schema that allows the user to adjust the level of specificity of the product characterization based on the current level to which the characteristics of future energy efficiency products are known. It is sufficiently flexible to enable the user to analyze very specific products such as a 25-ton high energy efficient air-conditioner system on the one hand, as well as a less defined product such as, advanced controls software that will enable utilization of natural ventilation systems in buildings.
- Market penetration models. Two approaches were provided for estimating market penetration of new products. The first approach requires expert judgment applied to a generic "S"-shaped market penetration model to achieve a specific "S"-shaped market penetration trajectory. This approach is recommended for estimating impacts of single products or a set of aggregated products for which competing technologies either do not exist or are difficult to characterize. The second market penetration approach uses the Peterka multi-competitor market penetration model to explicitly model market competition. It requires estimates of specific capital cost and O&M costs for the new products competing in the same marketplace. It is often difficult to assign values of cost to future products that currently do not exist. The uncertainties associated with this may be high and, thus, the user should be aware of the inherent uncertainties of the input data to the penetration model and then judge the output of the model accordingly. The largest value of this market penetration model lies in its use as an instrument to gain insights into the market dynamics by conducting sensitivity analyses and evaluating relative competitiveness between competing products.
- Exposure of Assumptions. The guiding principal in designing the assessment framework was to provide transparency of all assumptions made during the assessment process. Several assumptions are generally employed for postulating future growth trajectories for prices, energy consumption, building stock, and other trends that impact the results of an assessment. To this end, the framework was designed such that it exposes key variables explicitly rather than aggregating and lumping them together to represent

many mechanisms. As a result, this method requires the user to explicitly assign values to variables and be prepared to substantiate them through defensible sources and logical arguments, so that peers can review them.

OUTCOMES

Technical Outcomes

- The assessment framework developed for the commercial building sector is composed of four components 1) Product Characterization, 2) Market Segmentation, 3) Market Penetration, and 4) Analysis of Impacts. Figure 8depicts the simplified view of the processes within the assessment framework.
- Product Characterization provides detailed information about cost and performance characteristics, as well as a set of requirements necessary for the product to be sold and applied. The product characteristics can be grouped into the following major categories:
  - Requirements for defining the applicability of the product and its market segment (niche)
  - Cost and performance characteristics that describe improvement over existing or standard technologies.

The set of requirements reduces the applicability of the product to a specific market segment.

- Market Segmentation involves identifying and characterizing the size of this market segment. It is defined as the theoretical bound on the size of the market that a product could capture.
- Market Penetration provides projected rates of adoption of a product in the applicable market segment.
- The Impact Analysis process uses the market penetration projection and the technical-improvement characteristics of a product to estimate the impacts in terms of electricity savings, reduction in peak electric power demand, and savings on energy expenditures.

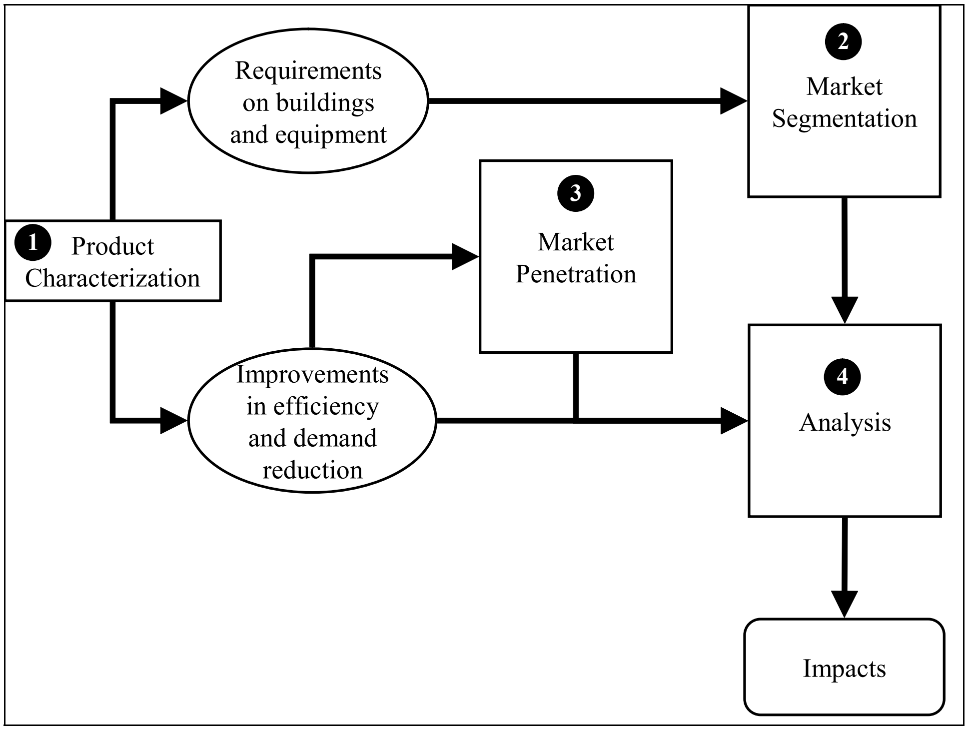

Figure 8. Overview of the Assessment Framework

- The framework was exercised in a pair of examples to illustrate some of its behavior and to demonstrate how Commission staff may use the framework in the future. The example products were chosen from two key research areas of the Program, automated diagnostics and advanced controls for commercial HVAC systems. A set of products that could be retrofitted to existing HVAC systems were chosen to illustrate the impact assessment process for this category of energy efficiency products. To contrast the use of the framework for retrofitable products, the assessment process was demonstrated for new products that can be used in new equipment that is installed in new construction or as replacements for existing equipment.

Market Outcomes

The Impact Assessment Framework will provide a platform on which research concepts and emerging technologies can be compared objectively. Using this process will allow the Energy Commission and its contractors to make better informed decisions regarding funding of project concepts. As with any modeling and analysis framework, careful application of the tools and approaches remains the responsibility of the analyst using the framework. Because most assumptions are made apparent in this process, the users of the assessment framework can check and validate projection assumptions, data, calculations, and impact estimates for agreement with citable sources, industry experience, and analytical intuition.

Deliverables

The deliverables from this project may be downloaded from the following web addresses:

http://www.energy.ca.gov/reports/reports_500.html
http://www.archenergy.com/cec-eeb/reports/

- *Final Report – Development of the Assessment Framework* (May 2003)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- Product description and market segmentation are very important for defining market potential.
- Market penetration estimates have a wide range of uncertainty, even with the benefit of a well-defined assessment methodology. The predicted outcomes using the market penetration models are highly sensitive to initial estimates of market share.

Commercialization potential

The product of this research project is a tool for evaluating commercialization potential. The assessment framework itself is probably not, in itself, likely to be commercialized, although other governmental and private sector organizations may benefit from the availability of the assessment framework.

Recommendations

Bidders on Commission RFPs and Commission contractors should use the assessment framework to help define the market potential for the their proposed or on-going research projects.

The value of this framework would be enhanced if extended to the residential and industrial sectors of the electricity market. Commission research is likely to lead to new products that will affect electricity demand for residential and industrial electricity customers (including agriculture), in addition to commercial buildings. Typically, these demands are just as significant as those posed by the commercial sector.

Automating all steps of the process and increasing the breadth of product characteristics to create a user-friendly tool for use by the Commission in evaluating proposals and the outcomes of completed research. This would enable Commission staff to perform impact assessments and scenario analyses of potential impacts of the entire Commission PIER buildings portfolio.

BENEFITS TO CALIFORNIA

The impact assessment framework allows objective evaluation of buildings-related energy research to improve the potential for market implementation. It should lead to selection of research that either has a quicker influence on the market or a greater savings impact in the longer term.

7.0 References

1. Westphalen, D. and Scott Koszalinski. *Energy Consumption Characteristics of Commercial Building HVAC Systems. Volume I: Chillers, Refrigerant Compressors, and Heating Systems*. U.S. Department of Energy. April 2001.
2. ASHRAE Standard 135 *BACnet - A Data Communication Protocol for Building Automation and Control Networks*. American Society of Heating Refrigeration and Air-conditioning Engineeers, Atlanta, GA. 2001.

8.0 Glossary

AHU	Air Handling Unit
APAR	AHU Performance Assessment Rules
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
BACnet	Building Automation and Control Network, a tradename denoting the HVAC communications protocol under ASHRAE Standard 135
BAS	Building Automation System
BIPV	Building Integrated Photovoltaics
CEUS	Commercial Energy End Use Survey
DALI	Digital Addressable Lighting Interface
DCV	Demand Controlled Ventilation
DX	Direct eXpansion refrigerant cycle
FDD	Fault Detection and Diagnostics
GAX	Generator-Absorber heat eXchanger
HPHR	Heat Pump Heat Recovery
HVAC	Heating Ventilating and Air Conditioning
HXHR	Enthalpy Exchanger Heat Recovery
MIT	Massachusetts Institute of Technology
NILM	Non-Intrusive Load Monitor
NIST	National Institute of Standards and Technology
OAE	Outdoor Air Economizer module of the Whole Building Diagnostician
ORNL	Oak Ridge National Laboratory
PV	PhotoVoltaic
VAV	Variable Air Volume
VCBT	Virtual Cybernetic Building Testbed
VPACC	Performance Assessment Control Charts
VOC	Volatile Organic Compound
VSAT	Ventilation Strategy Assessment Tool
WBD	Whole Building Diagnostician
WBE	Whole Building Energy module of the Whole Building Diagnostician

Appendix I

California Commercial Electricity Consumption by Building Type in Year 2000 (GWh)

End Use	Colleges	Food Stores	Hospitals & Health Care	Hotels/Motels	Large Offices	Misc.	Restau-rants	Retail Stores	Schools	Small Offices	Ware-houses	Total	kWh/sf by End Use	%
Ventilation	432.97	722.76	779.88	242.57	3052.88	1428.23	736.97	919.86	347.22	284.71	379.78	9327.83	1.64	10%
Cooling	635.01	585.14	2377.48	636.02	4273.98	2347.62	641.02	1235.86	338.20	910.64	274.36	14255.34	2.50	16%
Heating	213.52	76.32	203.03	532.57	464.88	309.18	65.92	92.01	111.37	60.20	102.52	2231.52	0.39	2%
Indoor Lighting	833.43	2689.36	2983.91	922.63	9302.53	2893.27	1055.39	4930.26	1350.72	1672.44	2104.86	30738.82	5.39	33%
Office Equipment	49.44	17.74	222.17	6.06	786.93	168.62	4.67	83.07	30.52	284.60	30.96	1684.78	0.30	2%
Outdoor Lighting	55.66	385.50	99.70	135.90	1193.26	774.31	471.37	919.67	371.22	488.69	231.49	5126.76	0.90	6%
Cooking	18.32	24.21	32.79	28.41	21.87	14.74	420.67	20.11	27.97	3.92	0.17	613.17	0.11	1%
Refrigeration	82.66	4025.62	90.60	239.79	20.06	99.75	1202.21	165.02	56.54	15.27	660.42	6657.93	1.17	7%
Water Heating	86.94	20.18	106.30	27.26	67.19	82.52	15.20	24.03	78.30	19.73	6.74	534.37	0.09	1%
Misc.	398.38	1921.52	3802.59	635.79	3957.32	3042.88	1346.50	1411.35	217.18	1221.77	2644.75	20600.03	3.61	22%
Total Gwh	2,806	10,468	10,698	3,407	23,141	11,161	5,960	9,801	2,929	4,962	6,436	91,771	16.10	100%
Floorspace (millions)	270.127	230.52	278.574	270.872	1024.28	992.522	145.17	882.35	457.468	361.027	787.43	5700.34		
kWh/square foot	10.4	45.4	38.4	12.6	22.6	11.2	41.1	11.1	6.4	13.7	8.2	16.1		

California Residential Electricity Consumption & Peak Demand by End Use

Residential Sector End Uses	MW	% of Total MW	Total Energy (GWh/Year)	% of Total Energy
Appliances	5,910	34.32%	39,378	50.70%
HVAC	7,475	43.41%	9,610	12.40%
Other	781	4.54%	6,909	8.90%
Total	17,221	100.00%	77,633	100.00%

Total Homes** **11,362,903**

Notes:
* Year 1999 Data
** Year 2000 Data
*** Lighting Demand Data Includes Miscellaneous

Refrigerator	18%
Laundry	8%
Cooling	7%
Heating	6%
Water Htg	6%
Pool/Spa	5%
Misc	5%
Cooking	5%
Color TV	4%
Freezer	3%
Water Bed	3%
Dishwashing	3%
	100%

List of Attachments

REPORT TITLE	PROJECT #	ATTACHMENT #
• Final Report Compilation for Project 2.1, Fault Detection and Diagnostics for Rooftop Air Conditioners	P-2.1	P500-03-096-A1
• *Description of Field Test Sites* (Feb 2003, rev.)		
• *Description of FDD Modeling Approach For Normal Performance Expectation* (Dec 2001)		
• *Description And Evaluation Of An Improved FDD Method For Rooftop Air Conditioners* (Aug 2002)		
• *Decoupling-Based FDD Approach For Multiple Simultaneous Faults* (June 2003)		
• *Automated Fault Detection and Diagnostics of Rooftop Air Conditioners For California, Final Report and Economic Assessment* (Aug 2003)		
▪ Final Report Compilation for Project 2.2, Equipment Scheduling and Cycling	P-2.2	P500-03-096-A2
• *Detection of HVAC Equipment Turn On-Turn Off Events with Non-Intrusive Electrical Load Monitoring* (Aug 2001)		
• *Fully Automated Analysis of Equipment Scheduling and Cycling* (Oct 2001)		
• *Development of a Functioning Centrally Located Electrical-Load Monitor* (May 2003)		
▪ Final Report Compilation for Project 2.3, AHU and VAV Box Diagnostics	P-2.3	P500-03-096-A3
• *Testing AHU Rule-Based Diagnostic Tool & VAV Diagnostic Tool Using the VCBT* (Oct 2001)		
• *Results from Simulation and Laboratory Testing of Air Handling Unit and Variable Air Volume Box Diagnostics Tools. NISTIR 6964* (Jan 2003)		
• *Results from Field-Testing of Air Handling Unit and Variable Air Volume Box Fault Detection Tools, NISTIR 6994* (April 2003)		
▪ Final Report Compilation for Project 2.4, Whole Building Diagnostician Demonstration	P-2.4	P500-03-096-A4
• *Final Report – Single Building Operator Demonstration – On-line Testing* (Mar 2003)		
• *Final Report – Multi-Building Operator Demonstration – On-line Testing* (Aug 2003)		
• *Final Report – Mechanical Services Provider Demonstration – On-line Testing* (Jul 2003)		

On-line Testing (Jul 2003)		
▪ Final Report Compilation for Project 2.5, Pattern Recognition Diagnostics	P-2.5	P500-03-096-A5
• *Task Report: Select Diagnostics for Automation* (Feb 2001)		
• *Task Report: Select Pattern-Recognition Techniques* (Feb 2001)		
• *Task Report: Implement and Test Techniques* (Dec 2001)		
• *Evaluation of Energy Impact of Faults* (May 2003)		
• *Automated Diagnostics: Software Requirements Specification* (Jul 2003)		
▪ Final Report Compilation for Project 2.6, Enhancement of the Whole Building Diagnostician	P-2.6	P500-03-096-A6
• *Instructions for Installation of the Whole-Building Diagnostician Software Release 2.10-162* (Aug 2003)		
• *Instructions for Configuration of the Whole-Building Diagnostician Software Release 2.10-162* (Aug 2003)		
• *Whole Building Energy Enhancement Report* PNWD 3317 (Aug 2003)		
▪ Final Report Compilation for Project 2.7, Enabling Tools	P-2.7	P500-03-096-A7
• *Using the Virtual Cybernetic Building Testbed and FDD Test Shell for FDD Tool Development. NISTIR 6818.* (Oct 2001)		
• *Use of the BACnet Data Source in the FDD Test Shell for Testing of FDD Tools in Real Buildings*. (Aug 2002)		
• *Development of a BACnet Interface for the Whole-Building Diagnostician (WBD)*. (Aug 2002)		
• *Results of Testing WBD Features under Controlled Conditions.* (Apr 2003)		
▪ Final Report Compilation for Project 3.1, Night Ventilation with Building Thermal Mass	P-3.1	P500-03-096-A8
• *Modeling and Testing Strategies for Evaluating Ventilation Load Reductions Technologies* (April 2001)		
• *Description of Field Test Sites.* (Feb 2003, rev.)		
• *State-of-the-Art Review of CO2 Demand Controlled Ventilation Technology and Application. NISTIR 6729* (Mar 2001)		
• *VSAT – Ventilation Strategy Assessment Tool.* (Aug 2003)		
• *Initial Cooling and Heating Season Field Evaluations for Demand-Controlled Ventilation.* (Feb 2003)		

• *Simulations of Indoor Air Quality and Ventilation Impacts of Demand Controlled Ventilation in Commercial and Institutional Buildings. NISTIR 7042* (Aug 2003)		
• *Recommendations for Application of CO2-Based Demand Controlled Ventilation: Proposed Design Requirements and Design Guidance for ASHRAE Standard 62 and Title 24.* (Aug 2003)		
• *Evaluation of Demand Controlled Ventilation, Heat Pump Technology, and Enthalpy Exchangers.* (Aug 2003, rev)		
▪ Final Report Compilation for Project 3.2, Night Ventilation with Building Thermal Mass	P-3.2	P500-03-096-A9
• *VSAT – Ventilation Strategy Assessment Tool.* (Aug 2003)		
• *Development and Evaluation of a Night Ventilation Precooling Algorithm* (Aug 2003)		
▪ Project 3.3, Smart Load Control and Grid-Friendly Appliances	P-3.3	P500-03-096-A10
• *Final Report: Smart Load Control and Grid Friendly Appliances* (Jul 2003)		
▪ Project 3.4, Extending BACnet for Lighting and Utility Interfacing	P-3.4	P500-03-096-A11
• *Proposed Amendments for Extending the BACnet Standard to Include Lighting Control and Interfacing Building Systems with Utilities.* (May 2003)		
▪ Final Report Compilation for Project 3.5, Aggregated Load Shedding	P-3.5	P500-03-096-A12
• *Issues Affecting Load Control in Aggregates of Commercial Buildings* (Mar 2001)		
• *Analysis and Field Test of Semi-Automated Load Shedding in LA County Test Buildings* (Jun 2003)		
▪ Final Report Compilation for Project 4.2, Ventilation Energy Recovery Heat Pump Assessment	P-4.2	P500-03-096-A13
• *Modeling and Testing Strategies for Evaluating Ventilation Load Reductions Technologies* (April 2001)		
• *VSAT – Ventilation Strategy Assessment Tool.* (Aug 2003)		
• *Evaluation of Demand Controlled Ventilation, Heat Pump Technology, and Enthalpy Exchangers.* (Aug 2003, rev)		
▪ Final Report Compilation for Project 4.3, Residential Hydronic Radiant Cooling and Heating Assessment	P-4.3	P500-03-096-A14
• *Monitoring Plan, Springer Residence* (May 2002)		

• *Final Report, Residential Hydronic Radiant Cooling and Heating Assessment* (May 2003)		
▪ Final Report Compilation for Project 4.4, Design Methods and Guidelines for Natural Ventilation	P-4.4	P500-03-096-A15
• *Natural Ventilation Review and Plan for Design and Analysis Tools (NISTIR 6781)* (Aug 2001)		
• *LoopDA – A Natural Ventilation System Design and Analysis Software Manual* (Aug 2003)		
• *LoopDA – Natural Ventilation Loop Design Assistance Software* (Jun 2003) *http://www.bfrl.nist.gov/IAQanalysis/LOOPDAdesc.htm*		
• *Impact of Natural Ventilation Strategies and Design Issues for California Applications, Including Input to ASHRAE Standards 62 and California Title 24* (Sep 2003)		
▪ Final Report Compilation for Project 5.1, Building Integrated Photovoltaics	P-5.1	P500-03-096-A16
• *Building Integrated Photovoltaic Test Facility* (Mar 2001)		
• *Measured Performance Of Building Integrated Photovoltaic Panels* (Feb 2002)		
• *Short-Term Characterization Of Building Integrated Photovoltaic Panels* (Feb 2002)		
• *Measured Versus Predicted Performance Of Building Integrated Photovoltaics* (Oct 2002)		
• *Evaluating Building Integrated Photovoltaic Performance Models* (Oct 2002)		
• *Measured Performance Of A 35 Kilowatt Roof Top Photovoltaic System* (May 2003)		
• *Economic Assessment of Building Integrated Photovoltaics in California* (Aug 2003)		
▪ Final Report Compilation for Project 6.6, Impact Assessment Framework	P-6.6	P500-03-096-A17
• *Final Report – Development of the Assessment Framework* (May 2003)		