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FINAL PROJECT REPORT

ASSESSMENT OF WORST-CASE WEATHER CONDITIONS FOR PHOTOVOLTAICS IN SACRAMENTO AREA

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Transportation

Assessment of Worst-Case Weather Conditions for Photovoltaics in Sacramento Area is the final report for the Sacramento Municipal Utility District's ReGen Program (Contract Number 500-00-034), conducted by RLW Analytics Incorporated. The information from this report contributes to PIER's Renewable Energy Technologies program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Note: All figures and table within this report were created for this report, unless otherwise noted.

Abstract

This study analyzed historical weather data to assess the worst-case scenarios in the Sacramento, California, region for stand-alone photovoltaic systems in the winter, and air-conditioning systems in the summer.

The winter analysis used historical weather data including solar radiation data from 1961 to 1990 to determine:

- Maximum number of consecutive "cloudy days."
- Worst-case cloudy month.
- Worst-case cloudy two-month period.
- Worst-case cloudy winter (November through February).

Additionally, the study compared the simulated performance of photovoltaic module technologies using weather data from the "worst-case" month.

The summer analysis used historical weather data from 1951 to 2000 to determine:

- Maximum historical summer dry-bulb temperature. (dry-bulb temperature is the temperature measured of air that is been shielded from radiation and moisture)
- Maximum historical average peak temperatures for July and August.
- Historical occurrences of a high dry-bulb temperature with high humidity.
- Probable worst-case combinations of high temperature and humidity.
- Probable worst-case conditions for cooling.

The summer analysis also quantified the annual excess energy produced by a grid-tied PV array that had been sized to power a three-ton residential conventional air-conditioner under worst-case conditions.

The annual excess energy produced by a photovoltaic system sized to power a conventional standard three-ton air-conditioner cooling at the worst-case scenario of 46.1 degrees Celsius (115 degrees Fahrenheit) is approximately 9,285 Kilowatt-hour per year. A photovoltaic array sized to meet the peak demand of the cooling system generates more than six times the energy required over a typical year to cool a 2,000-square-foot-home built to current energy code standards.

Keywords: Photovoltaic, solar radiation, PV, weather data, summer, winter, humidity, dry-bulb temperature

Executive Summary

Introduction

This project analyzed Sacramento weather data to determine the worst-case weather scenarios for an off-grid photovoltaic system with battery backup in the winter and a grid-connected photovoltaic system to supply cooling needs in the summer. The study is divided into two parts: winter worst-case scenarios and summer worst-case scenarios. Winter scenarios focused primarily on consecutive cloudy days and energy input into photovoltaic systems. The information collected was then used to determine the general effectiveness of different PV systems. The summer scenarios focused chiefly on heat and humidity and their effect on the power draw of cooling systems. They explored the photovoltaic capacity necessary to power cooling systems during high heat and humid conditions while also measuring excess energy production in summer conditions. The information was also used to assess the viability of evaporative cooling systems in the Sacramento area.

Many applications can be economically served by stand-alone photovoltaic systems with battery back-up, rather than connected to the utility grid. The cost of photovoltaic systems is justified by eliminating the cost of connecting the applications to the utility grid. However, traffic lights, outdoor lighting, and other “mission critical” applications have safety and liability consequences upon failure. Decision makers may be reluctant to use stand-alone photovoltaic systems since the effect of multiple consecutive cloudy days could drain the system battery charge to the point of failure. This project quantified the worst-case, long-term cloudiness that is likely to occur in the Sacramento area.

Average summer climatic data for Sacramento are well-known, and American Society of Heating, Refrigeration, and Air-Conditioning design conditions exist for the area. However, if the worst-case heat and humidity in the Sacramento region exceeds the design conditions for dry-bulb temperature and humidity, cooling systems lose effectiveness. This project quantified the frequency and severity of historical worst-case cooling conditions and the effect of these conditions upon cooling system performance.

Objectives

This project had the following objectives from the analysis of Sacramento area historical weather data:

Winter Worst-Case Cloudiness Analysis Objectives

- Determine historical maximum number of consecutive “cloudy days.”
- Determine historical worst-case month.
- Determine historical worst-case two-month period.
- Determine historical worst-case winter (November through February).

- Determine the approximate electricity generation for a prototypical PV array for worst-case cloudiness conditions.

Summer Worst-Case Heat and Humidity Analysis Objectives

- Determine maximum historical summer dry-bulb temperature.
- Determine maximum historical average peak temperatures for July and August.
- Quantify historical occurrences of high dry-bulb temperatures with high humidity.
- Quantify probable worst-case combinations of high temperature and humidity.
- Quantify probable worst-case conditions for cooling.
- Quantify annual excess energy produced by a grid-tied PV array sized to power a three-ton residential conventional air conditioner under worst-case conditions.
- Evaluate practicality of evaporative cooling systems in Sacramento summer conditions.

Approach

Worst-Case Winter Approach

The winter analysis for worst-case cloudiness simulated the performance of a stand-alone photovoltaic system with the following characteristics:

- 55° module slope (approximates latitude +15°)
- 0° module azimuth (faces due south)
- 20 percent ground reflection (standard assumption)
- Perez et al. computation model of solar radiation on a sloped array

The project team generated an hourly annual simulation of photovoltaic performance for each year of available data and exported the results to a database. The hourly "Radiation on Array" simulation output in watt-hours per square meter was collected for each day, and the results were based on daily totals.

Worst-Case Summer Approach

To determine the worst-case scenario for an air-conditioning unit, the authors collected dry-bulb temperature and humidity data from Sacramento Airport for the period of 1951 through 2000.

To measure annual excess energy generated from a photovoltaic array sized to power a conventional three-ton air conditioner during historical worst conditions, results of two simulation models were compared. A baseline residence simulation model provided the annual cooling system demand and a photovoltaic simulation model provided the annual generation. The excess energy was simply the difference of the two.

An evaporative cooling system's climatic range of effectiveness was compared with the weather data found above to assess the viability of the systems in a worst-case scenario.

Outcomes

Worst-Case Winter Analysis Outcomes

- Greatest number consecutive "cloudy" days: 16 (December 15 through December 30, 1985) (Daily irradiance of less than 1500 Wh per square meter (Wh/m^2) on fixed slope array).
- Worst-case Month: November 24 through December 23, 1970. (An irradiance total during the period of 49,674 Wh/m^2, a daily average of 1656 Wh/m^2).
- Worst-case two month period: November 23, 1985, through January 22, 1986 (An irradiance total of 119,809 Wh/m^2, or 1,997 per day).
- Worst-case November through February: November 1982 through February 1983 (An irradiance total of 316,563 Wh/m^2, a daily average of 2683 Wh/m^2).

The energy output of four different photovoltaic technologies was simulated for an array rated at 1 Kilwatt $_{STC}$. For the worst consecutive 30 days of weather, the average energy output for all the photovoltaic technologies was a total 47,769 Wh for this simulated array.

Worst-case Summer Analysis Outcomes

- Highest dry-bulb Temperature: 46.1°C (115°F) recorded June 15, 1961, at 4 p.m.
- Highest July average daily peak dry-bulb: 36.9°C (98.4°F) in 1988.
- Highest August average daily peak dry-bulb: 36.9°C (98.5°F) in 1996.
- Worst-case humidity and heat: August 4, 1986, at 3 p.m., 38.3°C (101°F) dry-bulb, 28°C (82.4°F) wet-bulb, 46 percent relative humidity.

Between 1951 and 2000 there were 84 days where the wet-bulb temperature reached 24.4°C (76°F) or higher. This equates to 1.84 occurrences per year. The probability that the wet-bulb will reach 24.4°C (76°F) in any given year at least once is 0.56. Between 1951 and 2000 there were 103 days where the dry-bulb temperature reached 40.6°C (105°F) or higher. This equates to 2.06 occurrences per year. The probability that the dry-bulb will reach 40.6°C (105°F) in any given year at least once is 0.74.

The annual excess energy produced by a photovoltaic system sized to power a conventional standard three-ton air conditioner cooling at the worst-case scenario of 46.1°C (115°F) is approximately 9,285 kWh per year. A PV array sized to meet the peak demand of the cooling system generates more than six times the energy required over a typical year to cool a 2,000-square-foot home built to current energy code standards.

Conclusions & Recommendations

Worst-Case Winter Conclusions

This study has identified the worst-case scenarios for stand-alone photovoltaic applications in the Sacramento area. By using the information identified in this study, a photovoltaic system with battery storage can be designed to operate through periods of protracted cloudiness.

Worst-Case Summer Conclusions

The intent of the summer analysis was to quantify the occurrence and severity of high dry-bulb and humidity events above and beyond American Society of Heating, Refrigeration, and Air-Conditioning design conditions and its effect on cooling system capacity, power draw, and residence cooling load.

The simulation of a residence cooled with a baseline conventional air-conditioning system demonstrated that the size and cost of a photovoltaic system to power the air-conditioning system under worst-case conditions would be impractical.

Also, with the results of this study, the viability of evaporative cooling systems in the Sacramento area can be better assessed. The results show that even during the historical maximum heat and humidity events there is some degree of evaporative cooling available. Relative humidity does not approach the 90 percent and above range during these events. Similarly, high wet-bulb events that reduce the effectiveness of evaporative cooling are infrequent.

Benefits to California

This study identifies worst-case historical weather conditions for stand-alone photovoltaic applications in the Sacramento region. By using this data, the designer of a mission critical stand-alone application can confidently size a battery backup system that will continue to supply power during protracted periods of cloudiness. This additional data may promote the implementation of stand-alone photovoltaic applications, thereby reducing load on the grid and increasing the use of renewable energy in California. Californians will benefit from a reliable, economical option to power critical loads and from the renewable energy used for those applications.

The air-conditioning load associated from development of the Central Valley contributes to the state’s peak system demand on hot days. The data from this study will aid designers and decision-makers in selecting the most efficient and effective cooling technologies. Evaporative systems use a fraction of the electricity that a conventional air-conditioning system draws on a hot day. Therefore, an increase in implementation of evaporative systems, where feasible, will reduce load on the grid during peak demand periods. Widespread use of evaporative cooling systems may reduce the need for additional generation.

1.0 Introduction

1.1 Background

This study had two goals—to identify the worst-case weather for off-grid photovoltaic systems in the Sacramento region, and identify the worst-case weather conditions for cooling systems. RLW Analytics relied on historical weather data from the Sacramento Airport for the study.

Because of the ample sunlight available in the Sacramento region, photovoltaic (PV) systems are one option for supplying energy to local loads while reducing demand on the utility grid. Stand-alone photovoltaic systems are an alternative solution for applications that can be isolated from the electrical grid, such as street lighting. The cost of a stand-alone PV system can be justified, in part, by eliminating the cost of connecting the application to the electricity grid. However, the battery storage for stand-alone PV systems that power mission-critical applications, which have safety and liability consequences upon failure, must be sized to provide power for the maximum potential consecutive cloudy days. To aid SMUD in sizing PV systems for off-grid applications, RLW Analytics analyzed weather data for the Sacramento region to project the worst-case, long-term cloudiness and examined the performance of several PV module technologies under cloudy conditions.

The air-conditioning load from development of the Central Valley is a significant contributor to the state's peak electricity demand during the summer. Energy efficient air-conditioning technologies, such as evaporative cooling, can be used to reduce the electricity demand during the peak summer periods, but the systems must be able to perform during the worst-case conditions for cooling—hot and humid days. Evaporative systems draw a fraction of the load that a conventional air-conditioning system draws on a hot day. Therefore, any increase in implementation of evaporative systems would reduce the load on the grid at the most critical times. Widespread use of evaporative cooling systems has the potential to reduce the need for additional power plants. RLW Analytics quantified the historical worst-case cooling conditions for the Sacramento region to increase the confidence of designers and decision-makers in selecting evaporative cooling technologies for use in the Sacramento area.

The utility peak demand could be further reduced if electricity generated by PV was utilized to completely offset the air-conditioning load. The study also designed a PV system required to power a traditional 3 ton air-conditioning unit during the worst-case scenario.

1.2 Project Objectives

The objective of the analysis was to provide SMUD with data on PV usefulness for mission critical off-grid applications and use of more efficient cooling technologies to reduce the summer electricity demand.

The specific objective of the winter analysis was to determine the worst-case weather scenario for the operation of a stand-alone PV system with the identification of:

- Maximum number of consecutive "cloudy days."

- Worst-case month.
- Worst-case two-month period.
- Worst-case Winter (November through February).
- Develop approximate sizing for a prototypical PV array for worst-case Sacramento winter weather conditions.

The specific objective of the summer analysis was to determine the worst-case weather scenario for operating air-conditioning with the identification of:

- Maximum historical summer dry-bulb temperature.
- Maximum historical peak temperatures for July and August.
- Historical occurrences of a high dry-bulb temperature, high humidity.
- Probable worst-case combinations of high temperature and humidity.
- Probable worst-case conditions for cooling.
- The excess energy produced by a grid-tied PV array sized to power a 3 ton conventional air-conditioner under worst-case conditions.

2.0 Project Approach

The project had two components: the analysis of worst-case conditions for PV in the winter and the analysis of worst-case conditions for air-conditioning systems in the summer. The winter analysis examined weather data from 1961 through 1990 to determine the maximum number of consecutive cloudy days that are likely to occur from November through February. The summer analysis reviewed data from 1951 through 2000 to determine the maximum wet and dry-bulb temperatures that occur in the Sacramento region during the summer.

2.1 Worst-case Winter Analysis

RLW Analytics analyzed weather data from the Solar and Meteorological Surface Observation Network (SAMSON) for the Sacramento Airport to determine:

- Maximum number of consecutive cloudy days.
- Worst-case month.
- Worst-case two-month period.
- Worst-case winter (November through February).

For the purposes of this project a “cloudy day” is defined as a day with less than 1500 Watt-hours (Wh) of energy from sunlight per square meter hitting a solar array with the following characteristics:

- 55° Module Slope
- 0° Module Azimuth
- 20% Ground Reflection
- Perez et al. computational model of solar radiation on a sloped array surface

The weather data was then used to run a simulation model of a stand-alone photovoltaic system with the characteristics listed above. For the simulation, the data for 1961 through 1990[1] was formatted for use with Maui Software’s PV Design Studio v5.0a application.

RLW Analytics ran the simulation model using four photovoltaic arrays with different module technologies, identical operational characteristics, and similar peak output. The model performed an hourly annual simulation of photovoltaic performance for each year and the output in Wh per square meter was aggregated for each day.

1. RLW attempted to reproduce their work for 1951 to 1960 and 1991 to 2000, the years lacking SAMSON data. However, the modeling methodology was not available and “reverse engineering” the methodology proved difficult and well beyond the scope of the project.

2.2 Worst-case Summer Analysis

RLW Analytics reviewed weather data from the Sacramento Airport to determine the maximum wet and dry-bulb temperatures for the period of 1951 through 2000 and the historical occurrence of the worst heat and humidity.[2] Using the same data, RLW Analytics determined the probable worst-case for combined heat and humidity and the probable worst-case summer conditions for cooling.

High wet-bulb temperatures combined with high dry-bulb temperatures create the worst-case scenario for cooling. Although the dry-bulb temperature can vary with a given wet-bulb temperature, resulting in varying degrees of comfort, high wet-bulb temperatures are always uncomfortable. Additionally, wet-bulb temperature establishes the limit for evaporative cooling, and the effectiveness of evaporative cooling in a given climate can be gauged by the wet-bulb conditions of that climate. Evaporative cooling technologies can only operate under conditions of less than 90% humidity.

The weather data for this analysis was collected using a variety of instruments during the 1951 to 2000 time period. From May 1, 1985, through the present, readings at the Sacramento Airport have been taken with an HO-83 hygrothermometer.[3] A HO-60 hygrothermometer was in use May 1, 1960, through April 30, 1985. Prior to May 1, 1960, humidity readings at the airport were likely taken with a sling psychrometer. Readings were considered invalid if greater than those normally occurring in the northern hemisphere or if inconsistent with surrounding measurements.

RLW Analytics constructed a model of a standard 2000 square foot home to simulate cooling load and system performance based on the Sacramento weather data. The simulation results were compared for the historical peak conditions as well as the peak conditions that the air-conditioning unit was designed to operate in.

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2. Wet-bulb temperature is measured using a standard thermometer wrapped in wet muslin. The water in the muslin evaporates, creating a cooling effect, so the temperature indicated by the wet-bulb thermometer is less than the temperature indicated by a normal thermometer. The rate of evaporation is affected by the humidity in the air. High humidity will result in slower evaporation, therefore a higher wet-bulb temperature. For this reason, the difference in the temperatures indicated by the two thermometers gives a measure of atmospheric humidity. Dry-bulb temperature refers to the temperature taken by a normal thermometer.

3. After the hygrothermometer began service in May 1985, the peak recorded wet-bulb temperatures jumped several degrees higher than had been recorded in previous years. From 1951 through 1984 there was only one day with a recorded a wet-bulb temperature above 78°F. During the 1985 to 2000 time period, the wet-bulb temperature has been recorded above 78° on 20 different days. This variation calls into question the accuracy of the data collected. Because this is the only National Weather Service station that measures humidity in the area validation of the data is exceedingly difficult and outside the scope of this project. Therefore, this analysis utilized the data as recorded except for the obviously bad data points.

The final step in the summer analysis was to run a model of a rooftop photovoltaic array sized to meet cooling system demand during historical peak conditions. The annual energy output of the system was then compared with the annual cooling system energy requirement to determine the excess energy produced by the PV system.

3.0 Project Outcomes

3.1 Worst-case Winter Analysis Outcomes

The winter weather analysis yielded the following data:

- Maximum number of consecutive cloudy days.
- Worst-case month.
- Worst-case two-month period.
- Worst-case winter (November through February).
- Prototypical PV array sizing to determine average daily electricity generation for worst-case winter conditions.

Date	Radiation On Array
	(W-h/m^2)
12/15/1985	1,259
12/16/1985	1,087
12/17/1985	1,047
12/18/1985	1,157
12/19/1985	1,201
12/20/1985	1,118
12/21/1985	1,249
12/22/1985	1,290
12/23/1985	1,249
12/24/1985	1,248
12/25/1985	1,120
12/26/1985	1,209
12/27/1985	1,233
12/28/1985	1,293
12/29/1985	997
12/30/1985	1,439
Total	19,196
Average	1,200

Table **1**. Daily radiation on array for consecutive cloudy days

This analysis was conducted to aid in designing and sizing PV systems with battery storage.

3.1.1 Maximum Number of Consecutive Cloudy Days

December 15 through December 30, 1985, was the longest period of consecutively cloudy days. Table 1 shows the simulated solar radiation on the PV array for each day during this period. The average is 1200 Wh per square meter per day.

The Sacramento Bee newspaper ran articles during December 1985 on the fog over the Central Valley during this period. These articles corroborate the weather data from the same period.

Table 2 shows the number of times that a period of at least "n" consecutive "cloudy days" has occurred from 1961 through 1990 for various thresholds. For example, the table shows that there have been six periods of nine consecutive days or longer, with the daily solar radiation on array less than 1500 Wh per square meter.

Note that the values in the Consecutive Days "1" column represent the total number of days that are under the threshold for the entire 1961 through 1990 time period.

Threshold	Consecutive Days Under Threshold																
W-h/m^2	22	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
2500	1	1	2	2	4	7	12	19	24	35	44	57	91	131	213	343	739
2000	0	1	1	1	1	2	2	5	11	22	30	41	65	106	164	299	637
1500	0	1	1	1	1	1	1	2	6	13	16	23	36	64	107	203	483
1250	0	0	0	0	0	0	0	0	0	0	0	2	7	18	52	119	387
1000	0	0	0	0	0	0	0	0	0	0	0	0	1	1	5	22	154
750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	29

Table 2. Occurrences of consecutive cloudy days at various thresholds

3.1.2 Worst-case Month

This analysis examined two approaches to define the "worst-case month." The first defines the worst-case month as the 30-day period with the lowest total solar radiation on array. The second approach defines the worst-case month as the 30-day period with the most days with solar radiation on the array of less than 1500 Wh per square meter.

During 1961 through 1990, the 30-day period with the lowest total radiation on the array occurred from November 24 through December 23, 1970. The total radiation on array for this period was 49,674 Wh per square meter; a daily average of 1656 Wh per square meter.

The worst-case month with the most days with less than 1500 Wh per square meter of solar radiation on the arrays was December 16, 1985, through January 14, 1986. This period had 23 days with less than 1500 Wh per square meter of solar radiation on the modeled array. The total radiation on the array during this period was 50,531 Wh per square meter; averaging 1684 Wh per square meter per day.

Table 3 shows the characteristics of the worst-case months compared with an average 30-day period from 1961 to 1990.

	Days Under 1500 W/m^2	30-Day Total Radiation on Array	Daily Average	30-Year Average for Time Span	Worst-Case/ Average
30 Day Period	Days	(W-h/m^2)	(W-h/m^2)	(W-h/m^2)	
11/24/1970 through 12/23/1970	17	49,674	1,656	91,486	54%
12/16/1985 through 1/14/1986	27	50,531	1,684	82,134	62%

Table 3. Comparison of worst-case 30-day periods

3.1.3 Worst-case Two Month Period

This analysis used the same two approaches to define the worst-case two month, or 60-day period as was used to define the worst-case month. Again, the first defines the worst-case two month period as the 60-day period with the lowest total radiation on array. The second defines the worst-case two month period as the 60-day period with the most days with solar radiation on the array of less than 1500 Wh per square meter.

The 60-day period with the least total radiation on the modeled array was November 23, 1985, through January 22, 1986. The cumulative radiation on array for that period was 119,809 Wh per square meter, or 1997 per day. There were 33 days under 1500 Wh per square meter during this period.

The 60-day period with the most days under 1500 Wh per square meter of radiation on the array was November 3, 1962, through January 2, 1963. This period had 35 days with less than 1500 Wh per square meter of radiation on the modeled array. The total radiation on the array during this period was 166,422 Wh per square meter; an average of 2774 Wh per square meter per day. The total radiation on the array during this period was 86% of the average total radiation for the two month period of November 3 through January 2 during the 30-year period of 1961 to 1990. Table 4 shows a comparison of worst-case two-month periods with the average characteristics of those same months for other years.

	Days Under 1500 W/m^2	60-Day Total Radiation on Array	Daily Average	30-Year Average for Time Span	Worst-Case/ Average
30 Day Period	**Days**	**(W-h/m^2)**	**(W-h/m^2)**	**(W-h/m^2)**	
11/23/1985 through 1/22/1986	33	119,809	1,997	176,698	68%
11/3/1962 through 1/2/1963	35	166,422	2,774	194,019	86%

Table 4. Comparison of worst-case 60-day periods

3.1.4 Worst-case November through February

November through February is the period considered to be Sacramento's "winter" and cloudiest months. This analysis examined the historical weather data from 1961 through 1990 to determine the worst November through February period.

Table 5 presents total plane of array radiation values for November through February from the lowest to the highest total. Although winters of 1985–1986 and 1974–1975 had more days with less than 1500 Wh per square meter, November 1982 through February 1983 had the least total radiation: 316,563 Wh per square meter for the 120 day period.

Winter	Total	Daily	Days Under 1500 W/m^2	Percent of Average Season
82-83	316,563	2,683	41	74.7%
68-69	337,602	2,861	29	79.7%
85-86	359,374	3,046	44	84.8%
83-84	373,100	3,162	36	88.1%
72-73	374,895	3,177	34	88.5%
73-74	375,068	3,179	37	88.5%
66-67	376,877	3,194	18	89.0%
63-64	387,355	3,283	39	91.4%
70-71	391,565	3,318	30	92.4%
77-78	398,108	3,374	32	94.0%
64-65	410,088	3,475	28	96.8%
61-62	410,101	3,475	41	96.8%
81-82	414,952	3,517	41	97.9%
84-85	426,787	3,617	29	100.7%
71-72	427,961	3,627	13	101.0%
65-66	429,342	3,638	20	101.3%
80-81	433,068	3,670	30	102.2%
67-68	440,057	3,729	23	103.9%
62-63	450,657	3,819	20	106.4%
79-80	453,122	3,840	28	107.0%
78-79	454,981	3,856	37	107.4%
74-75	455,859	3,863	51	107.6%
69-70	456,462	3,868	39	107.7%
89-90	467,170	3,959	31	110.3%
88-89	468,434	3,970	42	110.6%
87-88	479,612	4,065	24	113.2%
86-87	502,630	4,260	27	118.6%
76-77	506,654	4,294	17	119.6%
75-76	507,893	4,304	19	119.9%
Average	**423,667**	**3,590**	**31**	100.0%

Table 5. November through February radiation on array comparison

3.1.5 Module Performance

System performance is critical to off-grid applications and various module technologies perform differently under different situations. Using the worst-case weather data, RLW Analytics modeled the performance of four PV technologies: crystalline, polycrystalline, tandem layer amorphous, and triple layer amorphous modules.

Each array was sized to achieve an approximate 900 W maximum-rated output and designed for a typical remote stand-alone application with a fixed slope of 55°, azimuth 0°, and no maximum power point tracker. The Perez et al. radiation model was utilized and no deratement was applied.

The simulations were executed with Maui Software PV Design Pro application that utilizes the Sandia National Laboratories' Database of Photovoltaic Module Performance Parameters. The application is capable of modeling dc output of many commercially available PV modules given location and weather data.

The model was run for each array using 1970 Sacramento Airport weather data to simulate an average year of performance on an hour-by-hour basis. RLW Analytics then compared system performance during a randomly selected July cloud free hour[4] to determine if all four systems were performing within 5% of each other. Systems that were not performing within 5% were resized until they met the performance goal. The output of each array was totaled for the worst-case month, November 24, 1970, through December 23, 1970. All modules performed within 10% of each other. The energy output of four different PV technologies was simulated for an array rated at 1 kW_{STC}. For the worst consecutive 30 days of weather, the average energy output for all the PV technologies was a total 47,769 Wh for this simulated array.

3.2 Worst-case Summer Analysis Outcomes

RLW Analytics analyzed weather data from the summer months to determine the worst-case scenario for an air-conditioning unit operating in the Sacramento region.

The project team identified the following data points during their analysis:

- Maximum historical summer dry-bulb temperature.
- Maximum historical peak temperatures for July and August.
- Historical occurrences of a high dry-bulb temperature, high humidity.
- Probable worst-case combinations of high temperature and humidity.
- Probable worst-case conditions for cooling.
- The excess energy produced by a grid-tied PV array sized to power a 3 ton conventional air-conditioner under worst-case conditions.

4. All arrays were sized to generate a 900 W maximum output, within 5%, for a given July cloud-free hour. If the array was not within the 5% target, modules were added or subtracted in order to meet the criterion. If an array using a particular module could not be sized to meet the summer output criterion, another typically performing module of the same technology was selected and the process began again.

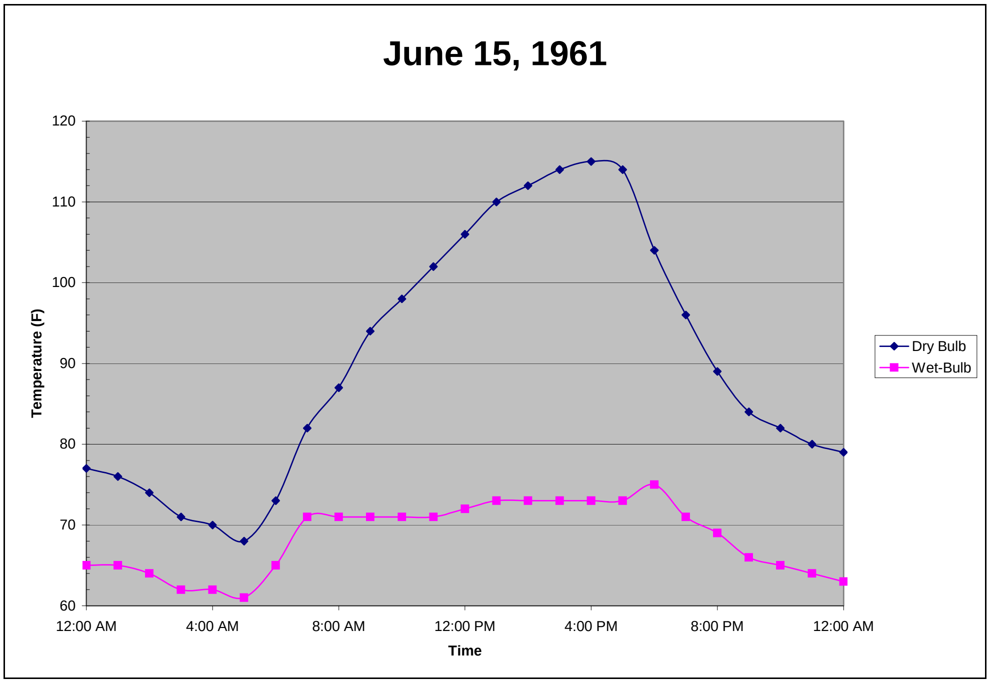


Figure **1**. Temperature plot of day with highest recorded temperature

3.2.1 Maximum Historical Summer Air Temperature

The maximum historical dry-bulb temperature recorded at Sacramento Airport was 115°F on June 15, 1961, at 4 p.m. The simultaneous wet-bulb temperature was recorded as 73°F, with a corresponding enthalpy[5] of 36.3 Btu/lbm. Figure 1 shows the temperature plot of the day.

Weather records show that June 15, 1961, began with a mild, warm breeze from the northwest that became warmer as the day progressed. After noon, the hot wind continued to blow at 10 mph from the northwest and the dry-bulb temperature increased, peaking at 4 p.m. By 6 p.m., the wind reached almost 15 mph and shifted to the southwest, cooling the air dramatically throughout evening.

Highest Average Peak July		**Highest Average Peak August**	
1988	98.4	**1996**	98.5
1961	97.5	**1967**	97.1
Average	91.9	**Average**	90.8

Table 6. Highest average daily peak temperatures for July and August

5. Enthalpy is a measure of the energy of a system, in this case the energy contained in an air mass. The enthalpy of an air mass is determined by the enthalpy of the dry air mass and the enthalpy of the water vapor. The enthalpy increases as temperature increases, and the percent of water vapor increases.

3.2.2 Maximum Historical Average Temperatures for July and August

The maximum historical average high dry-bulb temperatures for July and August were calculated by averaging the daily peak temperatures for each month. The top two results for each month are displayed in Table 6. The temperatures shown as "average" in the table are the means of the average July and August peak temperatures for 1951 through 2000.

3.2.3 Historical Occurrences of High Temperature and High Humidity

The record high wet-bulb temperature at the Sacramento Airport was 82.6°F and occurred at 3 p.m. on June 19, 1992. The simultaneous dry-bulb temperature was recorded at 93°F; this equates to an enthalpy of 46.5 Btu/lbm and a relative humidity of 65%. This is the highest enthalpy recorded during the 1951 to 2000 period, and is considerably higher than the enthalpy at the historical maximum dry-bulb temperature of 115°F.

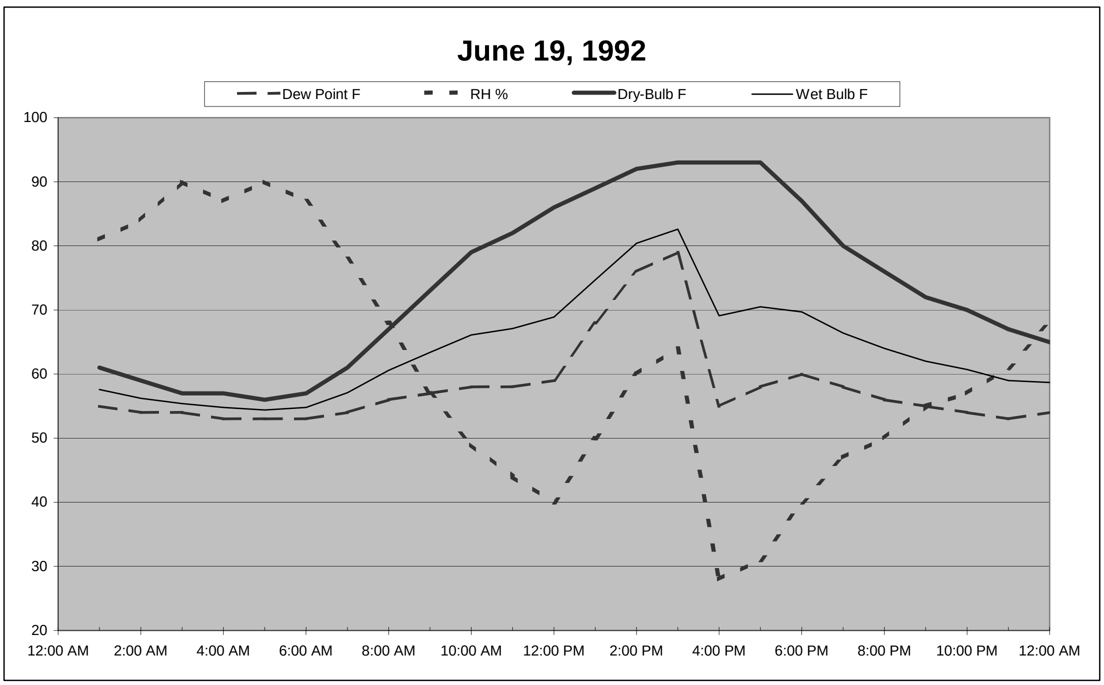


Figure 2. Temperature and humidity plots of day with highest recorded enthalpy

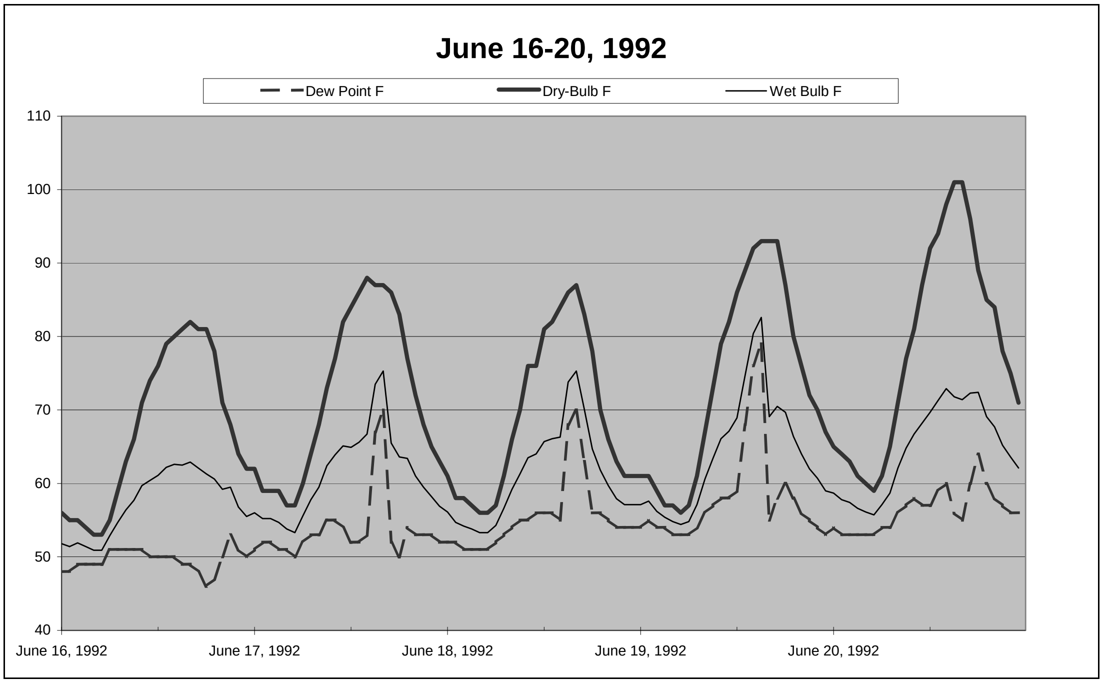


Figure 3. Temperature plots surrounding June 19, 1992, high enthalpy event

Error! Reference source not found.**Figure 2. Temperature and humidity plots of day with highest recorded enthalpy**

shows the temperature and humidity plots for the entire day. Note that the dew point temperature is a linear function of absolute humidity, or mass ratio of the air, and the wet-bulb is a function of both absolute humidity and dry-bulb temperature.

Figure 3 shows the temperature plots three days before and one day after the June 19 event. The chart shows that June 19 is the third day straight that experienced a “spike in humidity” for two hours during the day. This magnitude of fluctuation is atypical and aroused some suspicion about the validity of the data. However, the investigation of the questionable weather data is beyond the scope of this project. Humidity changes of this magnitude do occur in other locales, especially in places near bodies of water. Therefore, these data cannot be dismissed as faulty readings merely on the basis of being unusual.

The second highest wet-bulb temperature, 82.4°F, was recorded on August 4, 1986, at 3 p.m. The corresponding dry-bulb temperature was 101°F, and the relative humidity was 46%. The calculated enthalpy of the air was 46.1 Btu/lbm, the second highest enthalpy recorded from 1951 to 2000. Although the enthalpy on August 4, 1986, was lower than the enthalpy of the maximum wet-bulb occurrence, these conditions probably were less comfortable since the dry-bulb temperature was 8°F higher than the temperature on June 6, 1992. Figure 4 shows the temperature and humidity plots for the day.

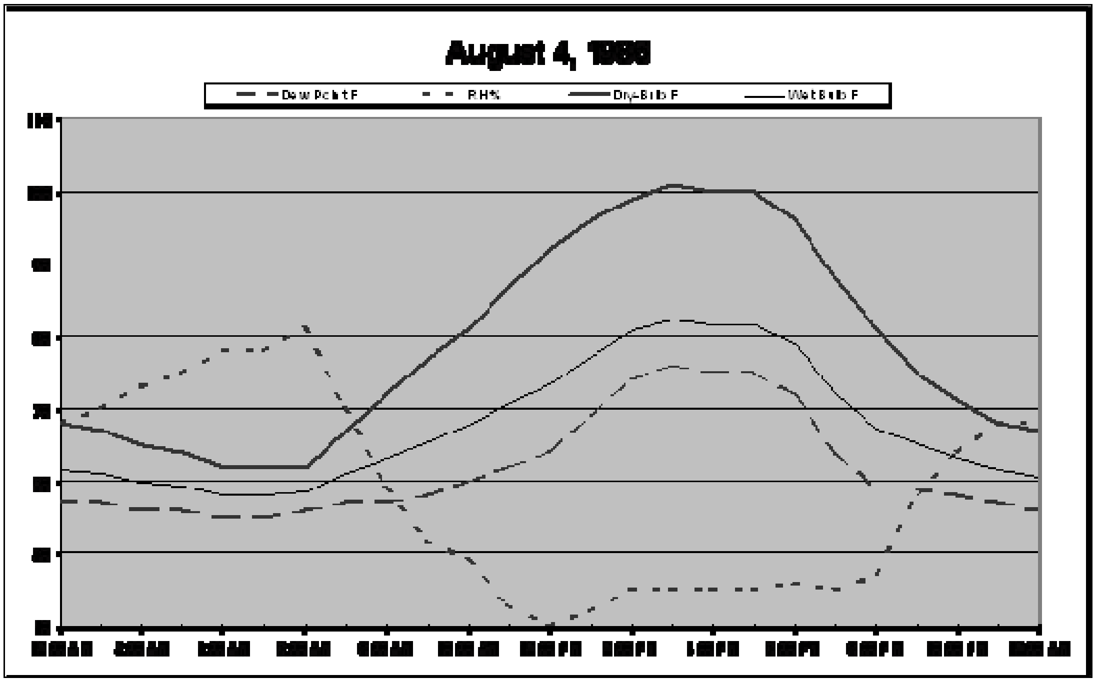


Figure 4. Temperature and humidity plots of day with second highest recorded enthalpy

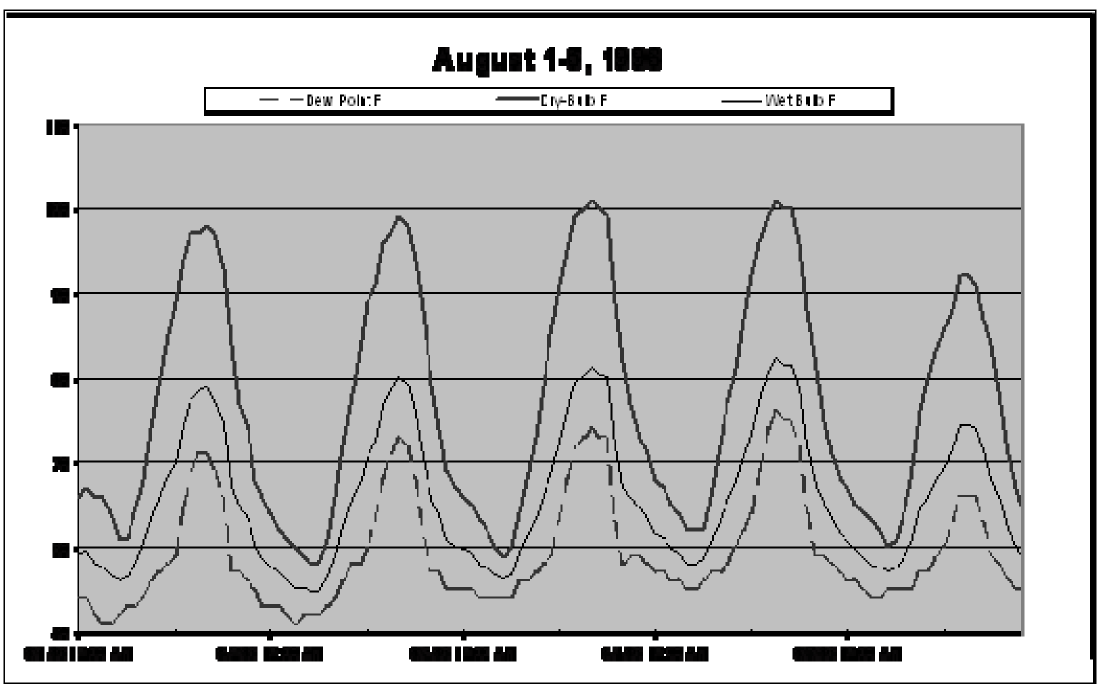


Figure 5. Temperature plots of days surrounding high enthalpy event

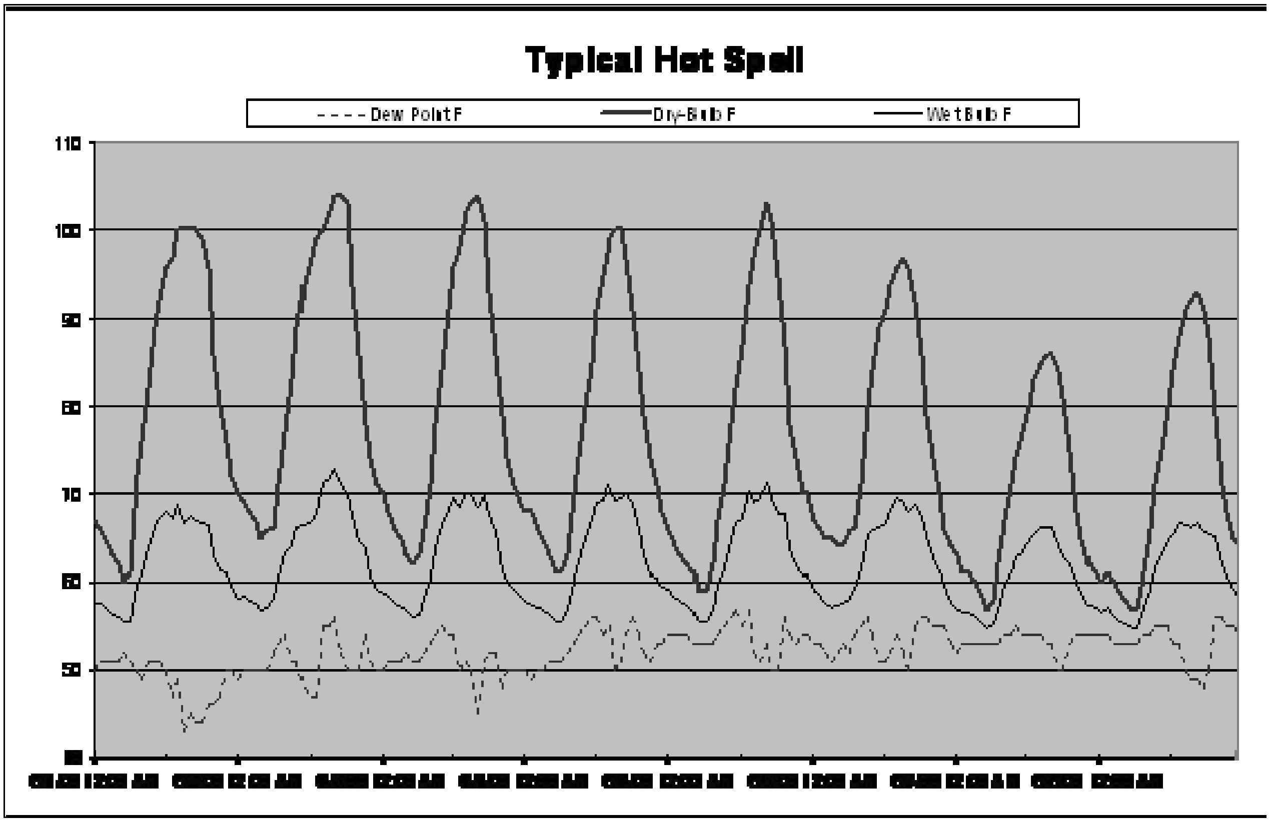


Figure 6. Temperature plots of a typical heat wave

August 4, 1986, is a more typical example of a high humidity day in the Sacramento area. The morning began relatively cool with wind out of the southeast. By 10 a.m., the wind direction shifted to the southwest and absolute humidity and dry-bulb temperature increased. By 6 p.m., the wind shifted back to southeast, the air temperature cooled, and the absolute humidity decreased.

Figure 5 shows the temperature plots of three days prior to August 4, 1986, which demonstrate a similar pattern, and the day after, which reveals the beginning of a cooling trend and a considerable reduction in humidity.

These high enthalpy events are uncommon in the Sacramento area, which usually experiences heat waves that are dry with no increase in absolute humidity during the day.

Figure 6 shows the temperature plots of a typical heat wave for the Sacramento area. The dew point fluctuates randomly, and tops out at 57°F. The corresponding wet-bulb temperature peaks near the Sacramento ASHRAE design wet-bulb temperature of 69°F.

3.2.4 Probable Worst-case Combination of High Temperature and Humidity

The worst-case scenario for humidity is primarily dependent upon the wet-bulb temperature. Therefore, RLW Analytics reviewed data to determine the highest wet-bulb temperature

Wet-Bulb (F)	Occurrences	Annual Occurences	Probability
72	726	14.52	1.00
73	441	8.82	0.98
74	245	4.90	0.86
75	153	3.06	0.74
76	84	1.68	0.56
77	45	0.90	0.36
78	32	0.64	0.24
79	15	0.30	0.12
80	11	0.22	0.10
81	6	0.12	0.08
82	3	0.06	0.04
83	1	0.02	0.02

reached at least once each year from 1951 to 2000 in the Sacramento area. Every year during that period the wet-bulb temperature reached at least 72°F, and during the same period, the wet-bulb temperature reached 72°F on 726 different days.

Table 7. Occurrences of high wet-bulb conditions during 1951 to 2000

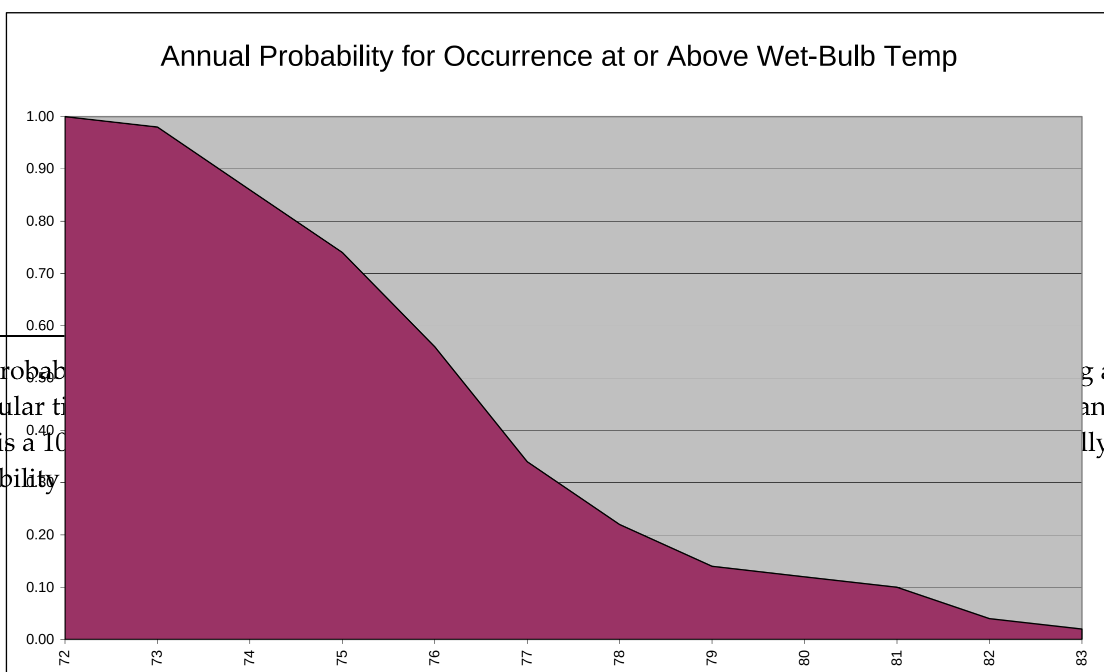
Figure 7. Probability chart that wet-bulb will reach a given temperature during any year

The probability of the wet-bulb temperature reaching the previous high of almost 83°F is 0.02.[6] The historical occurrences and resulting probabilities for all temperatures above 72°F are quantified in Table 7. Figure 7 shows a graphical presentation of the probabilities listed in Table 7.

3.2.5 Probable Annual Worst-case Conditions for Cooling

High dry-bulb temperatures present the most difficult conditions for a cooling system. Most air-conditioning systems on the market use air-cooled condensers that decrease in cooling capacity and increase in power draw as the dry-bulb temperature increases.

As noted previously, Sacramento summers tend to be hot and dry. During the period of 1951 to



6. A probab ... g a particular ti ... and there is a 10 ... lly, the probability

2000, the dry-bulb temperature reached at least 100°F in Sacramento on 620 different days—an average of 12.4 annual occurrences. The dry-bulb temperature has reached 100°F every year during that period. The high dry-bulb temperature during the same period was 115°F. The probability of the dry-bulb temperature reaching 115°F during a given year is 2%.

The historical occurrences and resulting probabilities for all temperatures above 100°F are quantified in Table 8. Figure 8 is a graphical display of probabilities shown in Table 8. This data shows that it is unlikely that the temperatures will reach 115°F in a given year, but that every year temperatures will reach at least 100°F. Based on the probability of high temperature occurrences, air-conditioning systems can be designed to provide optimum cooing.

Dry BulbTemp (F)	Occurrences	Annual Occurrences	Probability
100	620	12.40	1.00
101	475	9.50	0.98
102	355	7.10	0.96
103	248	4.96	0.88
104	173	3.46	0.82
105	103	2.06	0.74
106	73	1.46	0.44
107	48	0.96	0.30
108	36	0.72	0.20
109	21	0.42	0.16
110	17	0.34	0.14
111	11	0.22	0.12
112	5	0.10	0.04
113	3	0.06	0.04
114	2	0.04	0.04
115	1	0.02	0.02

Table 8. Occurrences of worst-case cooling conditions during 1951 to 2000

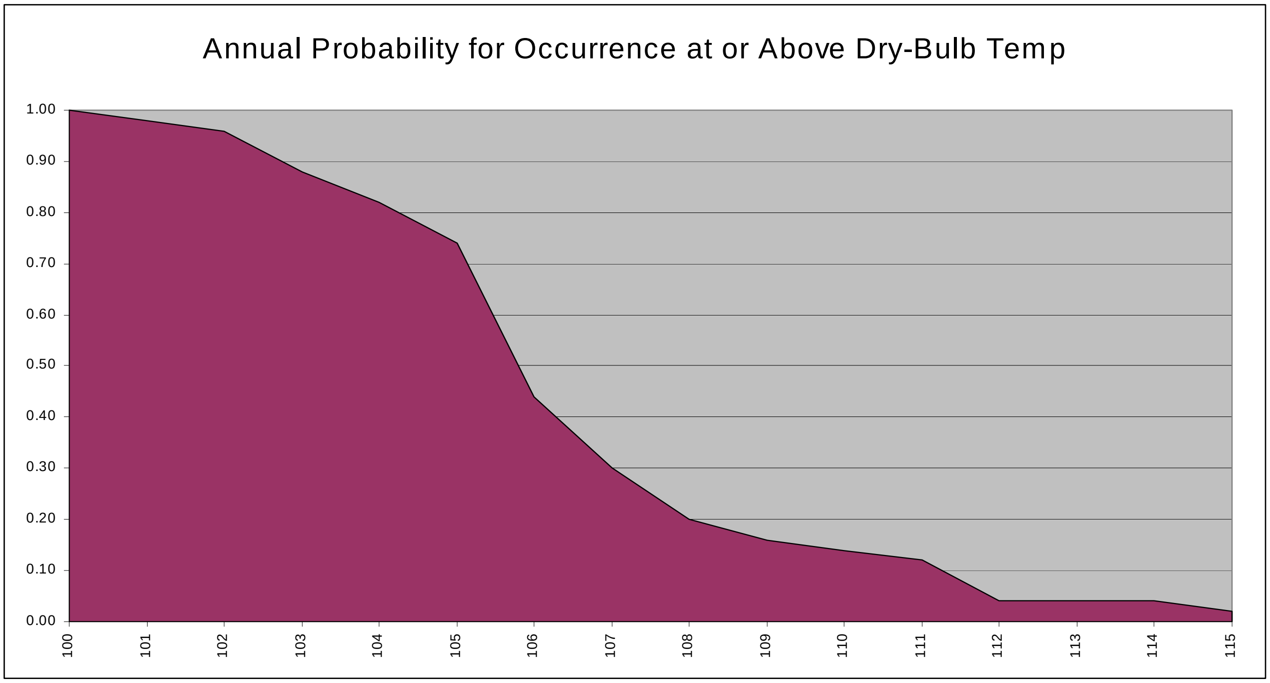


Figure 8. Probability of reaching high dry-bulb temperatures during a given year

3.2.6 Simulation Results of a Grid–tied Residential PV Application Residential Simulation

The electricity needed to power conventional air-conditioning systems[7] increases during high dry-bulb temperatures as cooling capacity decreases. RLW Analytics created a computer model[8] to demonstrate the operation of a conventional air-conditioning system during the heat of a Sacramento summer.[9] The model represents a 2000 square foot, wood frame, single family detached home with a concrete slab floor equipped with a conventional split system central air-conditioning unit and forced air furnace. This is the predominant building type and equipment combination used for new construction in the Sacramento area. The prescriptive requirements, called "Package D," include the following minimum energy related features:

- R-38 roof or ceiling insulation

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7. The term "conventional air-conditioners" refers to air-conditioners equipped with air-cooled condensers.

8. The model was built to meet, but not exceed, current Title 24 energy standards for Climate Zone 12, the zone that encompasses the Sacramento area.

9. Additionally, curve fits were calculated using regressions of manufacturer's data (Carrier 38CKC036, a popular 10 SEER split system air-conditioning unit) for total heating capacity, sensible heating capacity and energy input ratio (EIR, the inverse of coefficient of performance COP). The curves were generated as a function of condenser entering dry-bulb temperature and coiling entering wet-bulb temperature as required by DOE2.

- Radiant Barrier
- R-19 wall insulation
- Glazing, U-Factor 0.65, SHGC 0.40
- Total glazing area, 16% of conditioned floor area
- 10 SEER Air-conditioning unit with TXV (Thermostatic Expansion Valve)
- 6% Duct Leakage

Other modeling assumptions were based on the California Energy Commission's Residential Alternative Calculation Method,[10] the standardized methodology used for code compliance with simulation models. The following features were used in the model:

- 50,000 BTU per day (14,650 W per day) internal gains from occupants, lights, and plug loads (20,000 plus 15 per square foot of conditioned floor area)
- Cooling setpoint 78°F, constant
- Heating setpoints 68°F from 7 a.m. to 11 p.m., 60°F all other times

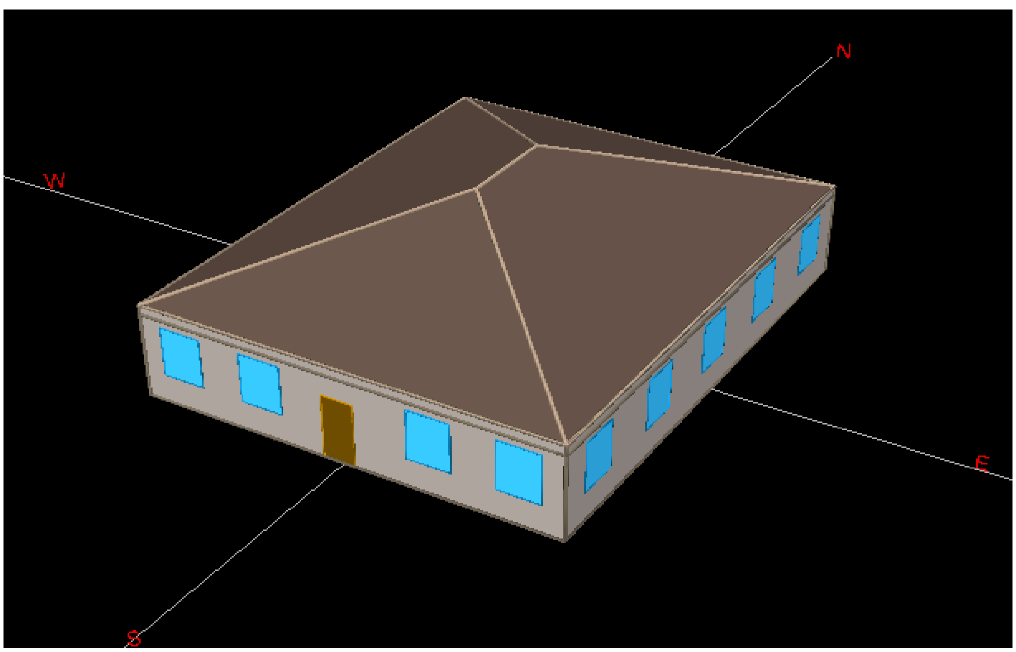

Figure 9. Three dimensional rendering of DOE 2.2 simulation model

10. *Alternative Calculation Method (ACM) Approval Manual* for the 2001 Energy Efficiency Standards for Residential Buildings, adopted by the California Energy Commission April 2001, available from http://www.energy.ca.gov/title24/residential_acm/

	ASHRAE Design Conditions	Historical Peak Conditions
	100 Dry-bulb	115 Dry-bulb
	69 Wet-bulb	72 Wet-bulb
Coil Load (Btu)	19,982	31,613
Cooling Capacity (Btu)	32,107	28,709
Power Draw (kW)	2.55	4.39
EIR	0.421	0.522
COP	2.37	1.91
EER(kBtu/kW)	8.10	6.53

Table 9. Comparison of peak vs. design conditions[11]

The modeled home, shown in Figure 9, has a simple rectangular shape, and no attached garage, self-shading, overhangs, or window setbacks that would reduce the cooling load of the residence. No allowances were provided for shading from trees, fences, and nearby structures. All of these aspects combined rendered a baseline model; a residence that would suffer the worst possible energy performance while still adhering to California's 2001 energy code.

Month	kWh
Jan	0
Feb	0
Mar	0
Apr	10
May	110
Jun	250
Jul	440
Aug	448
Sep	297
Oct	83
Nov	0
Dec	0
Total	1,637

Table 10. Cooling system energy consumption of simulated residence

Once the model was created, the simulation was run with Sacramento TMY2[12] data. Table 9 shows the effects of the peak conditions on the cooling load and air-conditioner performance. The ASHRAE design conditions referred to in the table are the 0.4% conditions for the Sacramento Metro area.[13] The EIR stands for "energy input ratio," the unitless rating of power

[11] Note that the term wet-bulb in Table 9 refers to the ambient wet-bulb temperature, *not* the coil entering wet-bulb temperature as is used in manufacturer's performance data.

[12] TMY2 is "typical meteorological year" dataset derived from the 1961-1990 National Solar Radiation Data Base (NSRDB), the successor to the TMY data sets that were derived from the 1952-1975 SOLMET/ERSATZ database.

[13] ASHRAE Handbook Fundamentals 2001, *American Society of Heating Refrigeration and Air-Conditioning Engineers, Inc.*

draw over cooling output, which is simply the inverse of coefficient of performance. The value is also converted into the more familiar unit, energy efficiency rating (EER), the cooling output in kBtu divided by cooling system power draw in kW. Table 10 shows the cooling system's energy consumption in the simulated home.

The cooling load of a residence is a function of the weather conditions for the previous few hours as much as the current weather conditions. Therefore, the cooling load for a given set of conditions will vary based upon the temperature profile and solar radiation profile prior to the event.

Using the actual data for the historical record peak dry-bulb temperatures, the cooling demand for the simulated residence exceeds the capacity for the cooling system. This means the system was unable to meet the demand for that hour and the temperature increased inside the home. The complete results of the annual cooling energy consumption are shown below.

Photovoltaic Simulation

The final step for the worst-case cooling analysis was to size a PV system to meet the electricity demand of a 3 ton traditional air-conditioner during the worst-case conditions. RLW Analytics ran the Maui Software's PV Design Studio program for grid-tied applications using the Sacramento weather data for 1961, the year with the historical peak dry-bulb temperature of 115°F. The program model was based on a rooftop array using AstroPower AP-1206 single crystalline modules with the following characteristics:

- 22.5° slope
- Maximum power point tracker with 95% efficiency
- No shading
- Trace SW5548 inverter

Orientation	Modules	Peak Output (W)	Watts Per Module	Rated Power (W)	Array Area (sf)
West	50	3,469	68.9	5,423	524
South	18	974	54.1	1,952	189
Total	68	4,443	65.3	7,375	713

Table 11. Sizing characteristics of simulated photovoltaic array

Because the cooling system electricity demand of 4.39 kW peaked at 4 p.m. on June 15, 1961, the initial plan was to place the array on the west side of the roof to take advantage of the afternoon sun. The roof of the simulated residence had a 590 square foot, trapezoidal west-facing roof section that could accommodate 50 rectangular PV modules with a total surface area of 524 square feet. However, 50 west-facing modules were insufficient to power the cooling system during peak conditions. Therefore, 18 modules were added on the south facing roof. The combination of the west- and south-facing modules was sufficient to satisfy the estimated cooling system demand. The rated DC power of the array was 7.375 kW. Table 11 provides a summary of the results of the array sizing.

	West (kWh)	South (kWh)	Array (kWh)
January	240	105	344
February	402	198	600
March	589	272	862
April	827	341	1,169
May	914	347	1,260
June	978	357	1,335
July	987	372	1,359
August	851	338	1,189
September	747	323	1,070
October	561	273	834
November	349	185	534
December	250	116	366
Total	7,695	3,227	10,923

Table 12. Annual estimated energy production of a simulated PV array by month

After the array had been sized to provide sufficient power for the cooling system during the historical worst-case conditions, the PV model was run with TMY2 weather data for Sacramento to estimate the energy generated by the array during an average year. The results of the simulation are shown in Table 12.

Although the west facing modules deliver more power during the late afternoon when cooling demand peaks, their overall energy production is lower than the south-facing modules. Table 12 shows the performance of individual west and south facing arrays. Overall, a west-facing module generates 86% of the energy as the same module facing south under these conditions. The tradeoff for late afternoon power production is a 14% reduction in overall output.

The rooftop photovoltaic array annually generates more than six times the energy consumed by the cooling system in a year. Excess generation is simply the array output less the energy consumed by the cooling system. Figure 10 shows the average daily production of south and west facing modules by month. The analytical results are presented in Table 13. The annual energy output of the PV obviously far exceeds the annual energy needs of the cooling system. Therefore, sizing the PV system to provide the peak power to run a 3 ton cooling is cost prohibitive.

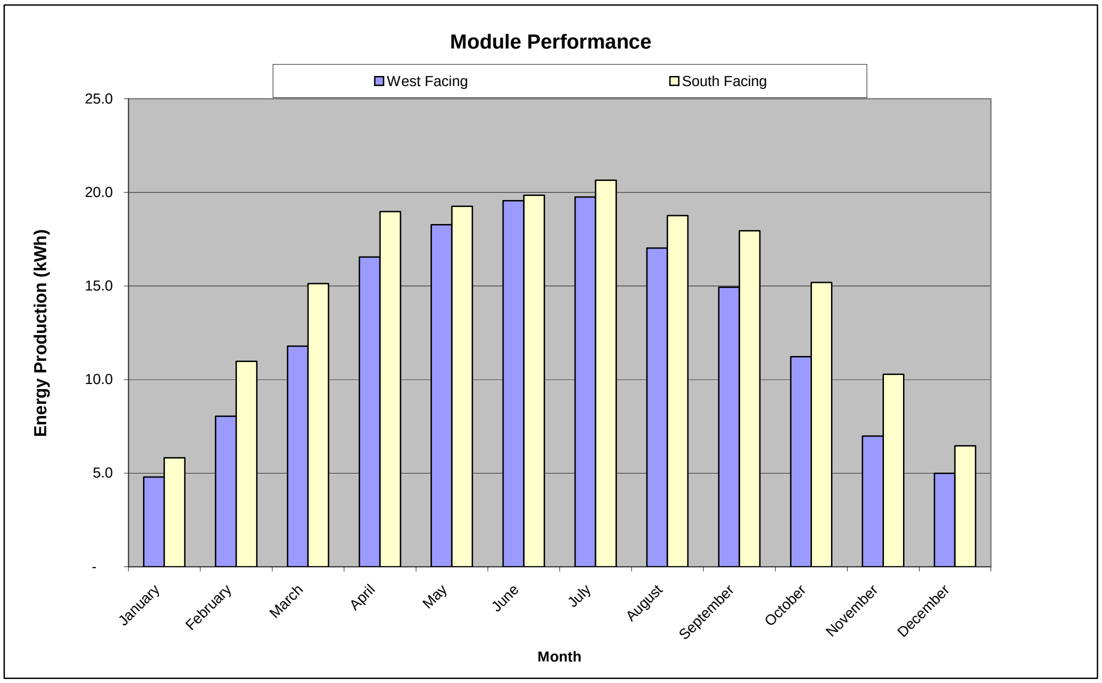

Figure 10. Monthly performance graph

Month	Array Output (kWh)	Cooling System (kWh)	Excess Generation (kWh)
Jan	344	0	344
Feb	600	0	600
Mar	862	0	862
Apr	1,169	10	1,159
May	1,260	110	1,150
Jun	1,335	250	1,085
Jul	1,359	440	920
Aug	1,189	448	740
Sep	1,070	297	773
Oct	834	83	752
Nov	534	0	534
Dec	366	0	366
Total	10,923	1,637	9,285

Table 13. Annual simulation performance comparisons

4.0 Conclusions and Recommendations

4.1. Conclusions

4.1.1 Winter Analysis Conclusions

This study has identified the worst-case weather scenarios for stand-alone photovoltaic applications in the Sacramento area. By using the solar insolation data identified in this study, a designer can develop a PV system—including the PV array and battery storage—that will not fail through periods of protracted cloudiness. In the Sacramento region, for mission-critical systems, the PV and battery system must be designed to provide sufficient and continual power during a 30-day period with a total irradiance input of 49,674 Wh per square meter, or a daily average irradiance of 1656 Wh per square meter. PV system size, efficiency, and battery storage requirements will be determined by daily and monthly load durations.

4.1.2 Summer Analysis Conclusions

The summer analysis quantified the frequency and severity of high dry-bulb and humidity events in the Sacramento region to aid in assessing the viability of evaporative cooling systems. The results show that even during the historical maximum enthalpy event, evaporative cooling technologies would provide some degree of cooling. Additionally, the occurrences of high wet-bulb events are infrequent.

The simulation of a residence cooled with a 3 ton conventional air-conditioning system demonstrated the effect of record temperatures on cooling system capacity, power draw, and residence cooling load. The simulations also showed that sizing a PV system to completely power the cooling load during worst-case conditions would be impractical because a PV system sized to meet those conditions would provide energy in excess of what the home would use during the rest of the year. This would not be a cost effective measure and would take up a considerable amount of roof-space.

4.2. Benefits for California

This study identifies worst-case historical weather conditions for stand-alone PV applications in the Sacramento region. By using this data, the designer of a mission critical stand-alone application can confidently size a battery back-up system that will continue to supply power during protracted periods of cloudiness. This additional data may facilitate the implementation of stand-alone PV applications, thereby reducing load on the grid and increasing the use of renewable energy in California. Californians will benefit from a reliable, economical option to power critical loads and from the renewable energy used for those applications.

The air-conditioning load associated from development of the Central Valley contributes to the state's peak system demand on hot days. The data from this study will aid designers and decision-makers in selecting the most efficient and effective cooling technologies. Evaporative systems use a fraction of the electricity that a conventional air-conditioning system draws on a hot day. Therefore, an increase in implementation of evaporative systems, where feasible, will reduce load on the grid during peak demand periods. Widespread use of evaporative cooling systems may reduce the need for additional generation.

Glossary

AC	Alternating Current. A type of electrical current that changes direction at regular intervals. In the US, the standard frequency is 60 cycles per second.
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning.
BTU	British Thermal Unit, equal to 0.293 Wh.
CEC	California Energy Commission.
EER	Energy Efficiency Ratio
Grid (Electrical grid)	An integrated utility system of electricity generation and distribution consisting of the wires, transformers, substations, power plants and control systems. The grid may also refer just to the transmission and distribution system, not including generation, particularly in regions where generation is owned by separate entities.
kW	Kilowatt. A standard unit of electrical power equal to 1,000 watts, energy flow at a rate of 1000 joules per second.
kWh	Kilowatt-hour. 1,000 thousand Watts acting over a period of 1 hour. The kWh is a unit of energy. 1 kWh=3,600 kilo Joules.
MW	Megawatt. 1,000 kilowatts, or 1 million Watts, a standard unit of electric power plant generating capacity.
MWh	Megawatt-hour.
NOAA	National Oceanic and Atmospheric Administration.
Peak Load	The highest electrical demand during a particular period of time. Daily electric peaks on weekdays usually occur in late afternoon and early evening. Annual peaks typically occur on hot summer days.
PIER	Public Interest Energy Research.
PV	Photovoltaic. The term used for the conversion of sunlight to electrical energy usually through the use of a PV cell, a semiconductor device.
PV Array	An interconnected system of PV modules that function as a single electricity-producing unit. The modules are assembled as a discrete structure, with common support or mounting. In smaller systems, an array can consist of a single module.
PV Module	The smallest environmentally protected assembly of solar cells.
PV System	A complete set of components for converting sunlight into electricity by the photovoltaic process, including the array and balance of system (BOS) components.
RH	Relative Humidity.
R&D	Research and Development.
ReGen	Renewable Generation RD&D program at SMUD.

SAMSON	Solar and Meteorological Surface Observation Network.
SEER	Seasonal Energy Efficiency Ratio.
SHGC	Solar Heat Gain Factor.
SMUD	Sacramento Municipal Utility District, the municipal electric utility in Sacramento, California that provides electric power to Sacramento County (and a small part of Placer County) at competitive rates that are consistently lower than investor-owned utilities in the state. SMUD is the sixth largest publicly owned utility in the country in terms of customers served. SMUD's mission is to provide value for their community while working to improve the quality of life in Sacramento.
W	Watt
Wh	Watt-hour(s)