REAL-TIME, WEB BASED ENERGY MONITORING SYSTEM FOR A SOLAR ACADEMIC BUILDING

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ABSTRACT

We describe the energy monitoring system installed in the *Leslie Shao-ming Sun Field Station* at Stanford University's *Jasper Ridge Biological Preserve*. This system, installed in April 2003, provides real-time data on the world-wide-web from 14 sensors that monitor various aspects of energy flows to and from this building. The system also maintains an extensive database of minute-by-minute data for subsequent retrieval and analysis, and regularly updates hourly, daily, and monthly summary performance graphs.

1. INTRODUCTION

There is growing interest in green buildings, particularly in college and university environments [1]. Energy-efficient operation is arguably the most important criteria for deciding the "greenness" of a building. This can be established only by measurement.

While monthly utility bills provide aggregate energy-use information they are too infrequent to provide useful feedback for guiding building operation. Billing dates are irregular and meter readings for two or more energy vendors are not coordinated making it nearly impossible to deduce even monthly energy consumption, let alone use for shorter time scales. And, of course, monthly energy bills cannot quantify any on-site energy production. A dedicated, energy-monitoring system solves all of these problems.

There is also growing interest in generating electricity with photovoltaic arrays. Many institutions, often with state or federal subsidies, are installing small PV arrays for demonstration (i.e., educational) purposes. Both in the case of PV arrays and green buildings, the educational value is greatly enhanced by installing real-time energy performance monitoring. The *World Wide Web* makes such information accessible to a far greater audience than just those who are able to visit the actual building site.

The *Leslie Shao-ming Sun Field Station* is a 9,800 sf single-story building designed to help *Jasper Ridge Biological Preserve* fulfill its mission: to contribute to the understanding of the Earth's natural systems through research, education, and protection of the Preserve's resources. Jasper Ridge has a long tradition of basic research in the field sciences, and most recently, has been at the forefront of research in ecosystem responses to global climate change as a result of the Jasper Ridge Global Change Experiment (http://globalecology.stanford.edu/DGE/Dukes/JRGCE/home.html).

The *Sun Field Station* not only provides critically needed space for students, faculty, scientists, and staff, but represents *Stanford University's* first explicitly green, sustainable building as well an opportunity to translate the values of the Jasper Ridge Biological Preserve into the design and construction of this new facility. Hence, the building is designed to minimize its environmental footprint by being energy efficient, maximizing its reliance on renewable energy, and reducing material waste. A detailed description of the building may be found elsewhere [2].

Design goals for the building included an annual recurring energy budget of net zero carbon emissions; use of recycled and renewable materials whenever possible; low maintenance and life-cycle costs; minimize waste; and meet the project's budget. To meet these and other goals, the *Sun Field Station* incorporates passive solar cooling and active solar heating, maximizes ergonomic daylighting, and boasts a grid-connected, roof mounted 20-kW photovoltaic (PV) array.

Whenever possible, we employed sustainable materials, such as using only certified wood, minimizing cement use by replacing it with fly ash, and employing only non-volatile organic compounds in building materials. Sustainable features in this building include:

- Engineered for no load bearing walls to increase flexibility and reduce volume of materials employed.
- High performance glazing (Heat Mirror Glass by Southwall Technolgies) was used throughout the building — http://www.southwall.com/homepage.htm).
- Roof insulated on top rather than from underneath, dramatically improving efficiency by reducing thermal leaks from structural components.
- High flyash concrete, voiding over 15 tons in CO_2 emissions.
- Recycled newsprint was used for wall insulation.
- All lumber was certified as sustainably harvested by the Forest Stewardship Council (http://www.certifiedwood.org/).
- 50-year old salvaged redwood provided all the siding materials.
- Waterless urinals.
- Designed to harvest rainwater from roof for storage and use in a 25,000 gallon cistern.

Figure 1 highlights many of the building's green features.

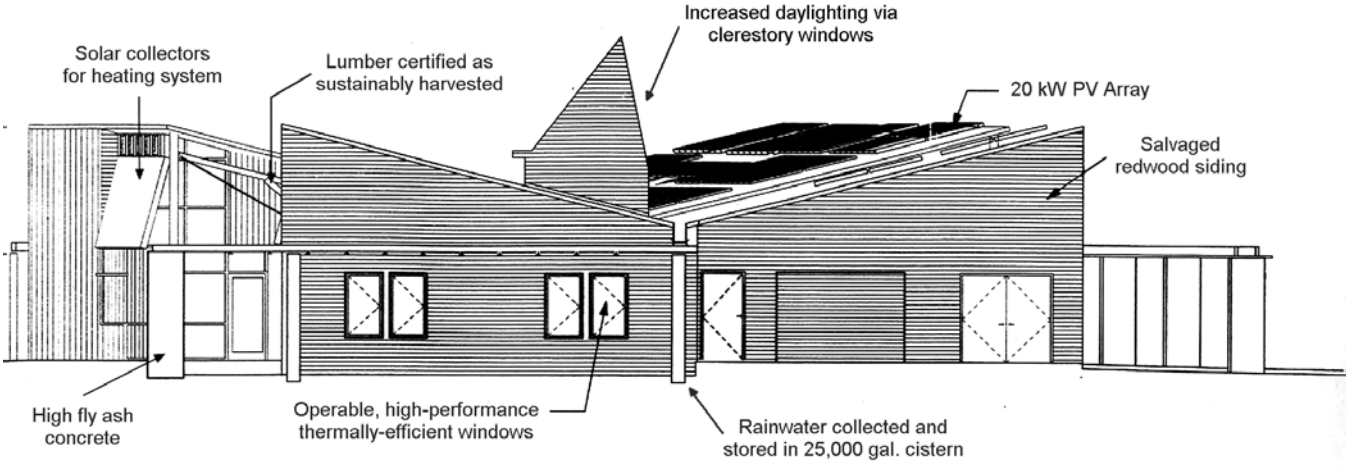

Fig. 1 Drawing illustrating various green design features of the *Leslie Shao-ming Sun Field Station*.

Two "pipes" bring auxiliary energy into the building when solar energy is not able to provide the building's energy needs. One of these is a propane gas line that is connected to an external liquid propane storage tank. A propane boiler provides backup heat to the solar hot water system. Domestic hot water (for restrooms, sinks, and showers) is provided by a propane, instant-hot water heater. The second energy "pipe" consists of wires connecting the building to the local power company, *Pacific Gas & Electric* (PG&E). This connection allows the building either to import electric energy or export it to the grid when the PV array production exceeds building demand.

2. PHOTOVOLTAIC ARRAY

The 20-kW photovoltaic array consists of 275, BP Solar, model TF-80B, 80W, prototype cadmium-telluride (CdTe) modules arranged in three sub-arrays mounted on the south-facing roofs of the building's east and west wings as shown in Figure 2. Eleven modules are wired in series to form strings. Nine strings are connected in parallel to form the west sub-array, while the middle and east sub-arrays each consist of 8 strings. All modules are mounted on the south-facing portion of the roof that has a 15º angle. The west wing faces due south. The east array is rotated 12º west of south. The middle sub-array contains modules with both orientations. Figure 3 is a photograph of the east wing roof showing PV modules and the light monitors.

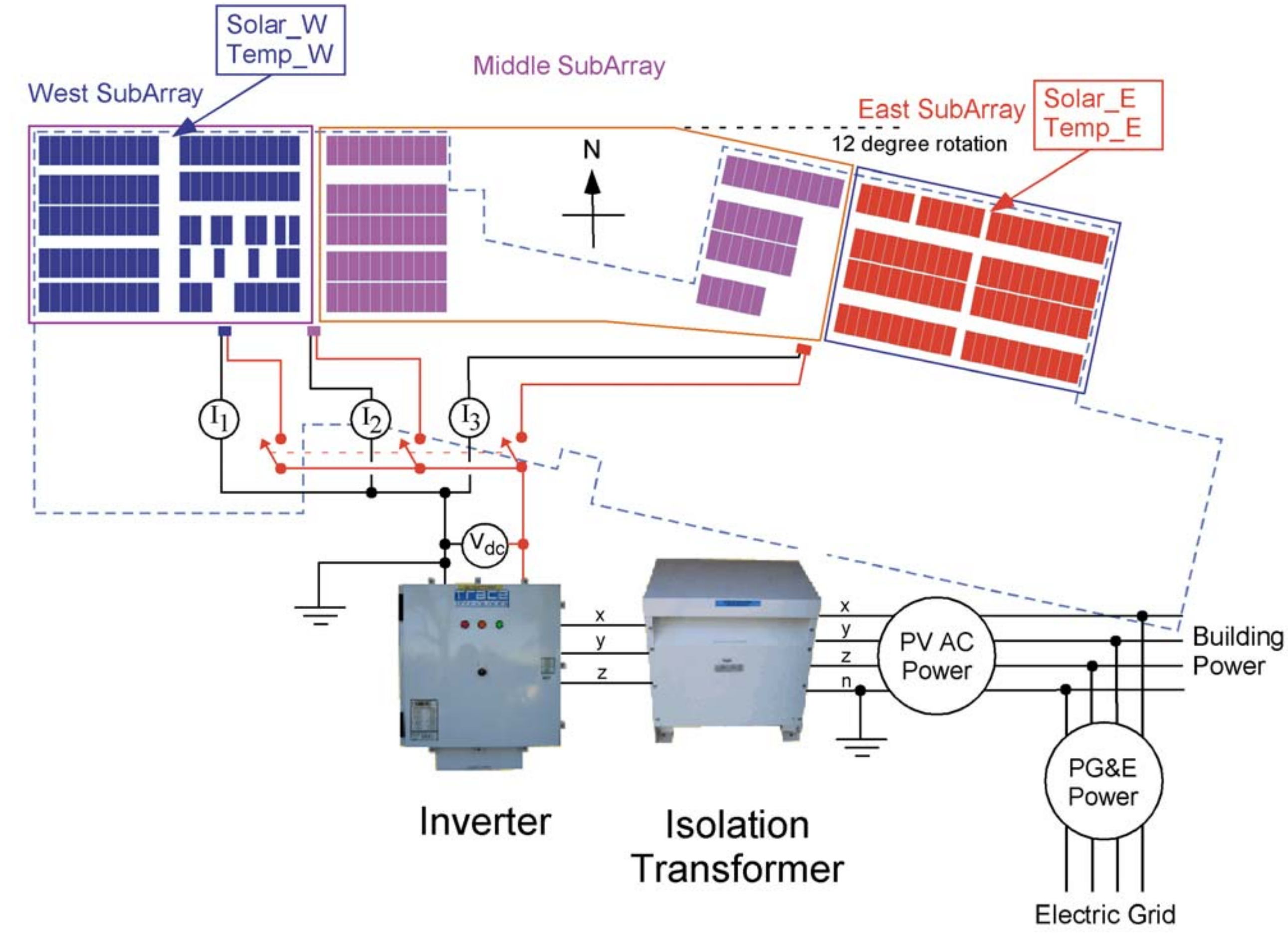

Fig. 2 Schematic diagram for the PV array and associated sensors.

Fig. 3 East wing roof PV array and light monitors.

Positive and negative wires from the three sub-arrays run to the inverter closet located in the northeast corner of the building where they eventually are connected in parallel to a Trace/Xantrex model PV-20208 inverter. The 3-phase, 208-VAC inverter output feeds the primary of a 1:1 isolation transformer, made necessary by the code requirement that one side of the PV array be grounded.

3. ENERGY MONITORING SYSTEM

In designing an energy monitoring system there were several important goals. First, we wanted to accurately monitor total building energy consumption. Second, we wanted to monitor energy consumption on sufficiently short time scale to provide useful feedback for making improvements in building operation. Third, we wanted to characterize the performance of the PV array. The CdTe thin film PV modules used in the array represent a new technology for which relatively little field performance data are available. It is important to characterize performance changes with time, temperature, and exposure to sunlight.

Fourth, we wanted to provide a kiosk at the building entrance where both occupants and visitors could view real-time and historical energy performance. And finally, we wanted to make all the building's energy information available to anyone using the world-wide-web. The number of visitors who are able to actually set foot in the *Sun Field Station* is small compared to the number who can reach the building by the internet. The educational value of the PV array and building itself is greatly magnified by making its performance data easily accessible on the web.

The energy monitoring system is designed around a *Campbell Scientific, Inc.* (CSI) model cr23x data logger and two personal computers running National Instruments *LabView 6.1* software. The logger monitors 14 sensors and stores their average values on 1-minute intervals. The logger has battery backup power and is currently able to store about 35 days of data in its internal memory. A laptop computer communicates with the logger to download new data every 2 minutes. The data are stored to temporary files on the laptop and, on hourly intervals, added to a Microsoft Access database. The laptop also runs daily queries on the database to produce and store archive files that summarize daily and monthly averages for the 14 sensor readings. The laptop computer runs ftp server software so that the various data files may be accessed by the web server and authorized users via the internet.

The second computer functions as the web server to make graphs of real-time and summary data available on the web. This computer also runs *LabView*, using its built-in web server capabilities. It accesses the archive data and the most recent sensor data from relevant files on the laptop using ftp protocols. The building kiosk is actually a second laptop computer that simply displays and updates one of the many energy web pages posted by the web server.

The building is served by a 208VAC, 3-phase electric system, connected to the grid through a high-voltage transformer located outside the building. Bidirectional power flow on the secondary side of the transformer is monitored with an *Ohio Semitronics, Inc.* (OSI) model GW5, AC watt transducer with three CTX-100A current transformers (CT's). The 0-1 mA transducer output is fed to an analog voltage input on the logger, terminated by a resistor. A second OSI GW5 transducer with three CTX-50A CT's measures bidirectional power in the secondary of the PV isolation transformer (see Figure 2).

The DC characteristics of the PV array are also monitored. *Empro Current Shunts* (20A/200mV) are installed in the negative leads of each sub-array, producing analog voltage signals to the logger that are directly proportional to the currents, I_1, I_2, and I_3. A 100-to-1 voltage divider across the array allows V_{dc} to be directly monitored by the logger.

Incident solar radiation is also monitored to more fully characterize PV system performance. Two pyranometers were installed, one for each of the two module orientations. Our thin film CdTe modules have a different spectral response from the less expensive, Si pyranometers. To avoid calibration issues [3] we chose to install Kipp & Zonen model CM3 thermopile pyranometers with flat spectral response from 305 to 2,800 nm. Thermistor temperature sensors were also fixed to the back of two modules to measure module temperatures for each of the two module orientations (see Figure 2).

Propane use is monitored with a Rosemount, model 8800C vortex flow meter installed in the propane gas line from the external storage tank. Installed on June 17, its integrated readings yield numbers 50-100% higher than those obtained from liquid propane delivery information. This remains an ongoing problem.

Three additional power transducers were installed to further characterize energy consumption. *Continental Control Systems* (CCS) Wattnode transducers were installed to monitor energy consumption by lighting circuits in the west wing, east wing, and for pumps P1, P2, and P3 associated with the solar hot water heating system. These transducers have pulse outputs that are monitored by the logger.

The monitoring system, which may be readily expanded, presently monitors 14 sensors. Sensor readings are recorded five times per second and used to calculate 1-minute, 15-minute, 60-minute, and 1440-minute averages (or sums in the case of pulse signals) that are stored to the logger's internal memory.

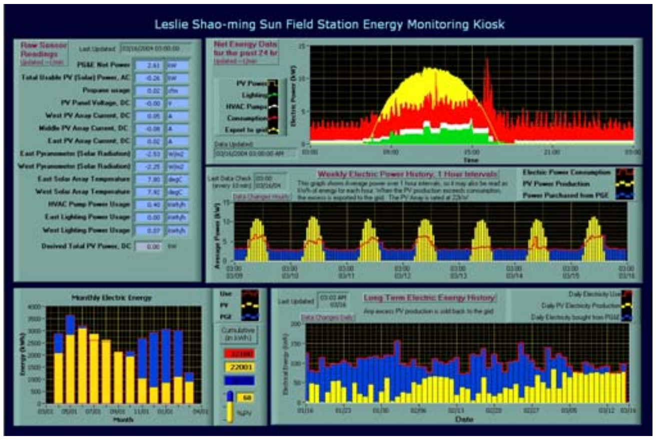

Fig. 4 Kiosk display showing various energy graphs. Graphs display energy budget on minute, hour, day, and monthly intervals. Real time data available at http://jr-solar.stanford.edu/kiosk/slow_kiosk.html.

Real-time data and summary performance graphs accessible on the web at http://www.jr-solar.stanford.edu. The kiosk, located at the building entrance, is simply a laptop computer that displays the page shown in Figure 4. This 5-panel page automatically updates every two minutes displaying the latest data. Data from other sensors are regularly graphed on other web pages for similar time scales, all accessible from links on the main energy monitoring page.

The monitoring system component costs are estimated in the table below. In our case we purchased a new laptop computer and used an existing workstation for the web server. The system could have been implemented on a single computer. The software costs include licenses for LabView and Microsoft Office – minimal for our installation due to university site licenses. The table below does not include labor costs associated with software and web site development nor system installation and testing.

TABLE 1: SYSTEM COMPONENT COSTS

CSI logger, software, network interface	$4,000
Pyranometer & temperature sensors	$2,000
OSI Power tranducers and CT's	$2,000
CCS Power tranducers and CT's	$1,300
Empro current shunts	$200
Rosemount gas flow transducer	$2,400
Computer hardware	$2,000
Computer software	$1,000
Total	$14,900

4. PRELIMINARY PERFORMANCE DATA

They system began operation on April 4, 2003 with all but the propane sensor connected. The propane flow sensor was installed on June 17 but, as noted above, continues to have problems. The PV array dc measurements gave inconsistent results, which turned out to be related to electrical noise problems associated with the inverter. The inverter noise introduced as much as a 10% error in the PVAC measurement as well. These problems were solved on August 22 and electric energy data are reliable since then.

Figure 5 shows the monthly electric energy consumption and generation (from the PV array) from April 5, 2003 through March 10, 2004. The 341-day total electric energy produced by the PV array and purchased from PG&E were 21,782 and 10,141 kWh respectively. Scaling the April 2003 and March 2004 data to account for the missing days, the projected annual amounts are 23,500 and 11,000 kWh respectively [4]. Hence, for the first year of operation it is projected that the building consumed 34,500 kWh of electric energy, 68% of this supplied by the PV array.

The energy produced by the PV array displaces electric energy that would have otherwise been purchased from the grid. It is useful to consider the additional carbon emission that would have occurred had this electric energy, instead, been furnished by a natural gas peaking generator operating at 37% efficiency. The 23,490 kWh annual PV-generated electric corresponds to a source energy of 241million Btu [5]. If supplied by the burning of natural gas this would release 3,490 kg of carbon – the equivalent of 28,000 pounds of CO_2. This represents the deferred carbon emission associated with the 12-mos. production of the PV array.

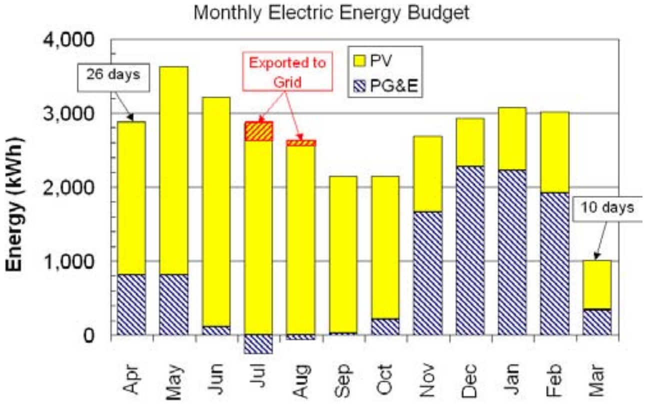

Fig. 5 Monthly electric energy produced by PV array and purchased from (or sold to) PG&E.

Propane energy use remains a weak link in the energy monitoring system. Our most reliable data come from delivery logs which show that 1,414 gal were used for the 12-mos. period Mar. 2003 through Feb. 2004. This corresponds to a use of 51,400 cf of propane gas, assuming each gal. of propane produces 36.35 cf of propane gas. Assuming an energy content of 2,880 Btu per cu. ft. of propane, the total propane consumption corresponds to both a source and site energy of 148 million Btu.

The projected 12-mos electric energy consumption corresponds to site and source energies of 118 and 318 million Btu, respectively. Combining these with the propane data and dividing by the 9,800 sf size of the building we arrive at annual site and source energy intensities of 27,000 and 48,000 Btu/sf, respectively. Since carbon emissions and true environmental costs are associated with source rather than site energy we choose this metric. Using the *Cal-ARCH* building energy tool we find this to be lower than the source energy intensity of 90% of comparable buildings [6].

Measurements on shorter time scales have proved to be useful for evaluating system performance. Figure 6 shows PV performance data for May 12, 2003. The dashed bell curve represents the average of the two pyranometers. The solid bell curve represents the total AC power produced by the PV system. The flat curve is the PV dc voltage.

The data show that the inverter is not able to track the maximum power point, resulting in sub-optimal array performance. This problem went unnoticed for the first year of PV operation, but was diagnosed about 1 month after the monitoring system began recording data.

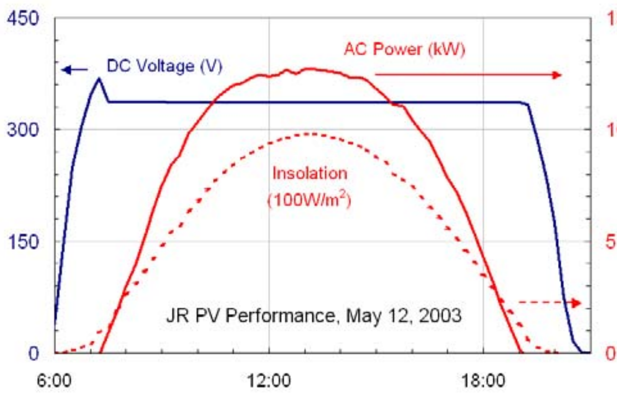

Fig. 6 PV performance for May 12, 2003. Dashed "bell curve" show incident solar radiation (left scale). Solid bell curve (left scale) shows PV AC Power output. Flat curve (right scale) is PV array dc voltage.

5. DISCUSSION

The building performance data presented here are preliminary. During this first year of monitoring two important issues have been identified which, when addressed, should lead to improved energy operation. First, the PV array is under-performing due to problems with power tracking. The plan is to rewire the array to yield 12-module strings, moving the array voltage back into 330-600V operating window of the inverter. This is expected to increase annual energy production by 20-35%. The second problem is poor performance of the solar hot water heating system, which has resulted in excessive propane consumption. This problem has been traced to a design flaw that is being addressed.

The first year with the monitoring system has also yielded some important lessons. As mentioned earlier, initial electrical measurements were plagued by inverter noise. The problem was solved by elimination of ground loops. And electrical power measurement accuracy was improved by increasing the logger sampling rate from 1 to 5Hz. The fast sampling rate is made necessary by the < 1sec integration time for the OSI transducers.

The decision to acquire data with a dedicated data logger rather than pc has been vindicated by its reliable performance. Only 1 minute of data has been lost in the 340 days of operation whereas the pc's have locked up, and required rebooting, on several occasions. Early on the web server was crashing roughly once per week. This chronic problem was solved by turning off web-logging in LabView. With this change the web server typically runs about a month before it requires rebooting.

The minute by minute energy consumption data, graphed for the latest 24-hour period are quite useful. The data reveal anomolous energy use associated with lights being left on at night, or excessive use of drying ovens. Pump energy consumption graphs make it easy to confirm HVAC system performance. The results of small adjustments can be determined in minutes rather than hours.

6. SUMMARY AND CONCLUSIONS

Here we have described an energy monitoring system for the *Leslie Shao-ming Sun Field Station* on Stanford University's *Jasper Ridge Biological Preserve*. The system was installed in early April 2003 and has been recording data from 13 sensors (14 as of June 17) on 1-minute intervals. Real-time data are updated on the world wide web every 2 mintues and all data are archived to a database for subsequent retrieval and analysis.

The first year of data show that, even though several systems are not performing optimally, the annual building source energy consumption has been 48,000 Btu/sf, lower than 90% of comparable, conventional buildings. The building's PV array has supplied 68% of its electrical energy needs.

ACKNOWLEDGEMENTS

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ENDNOTES

1. Perrin, N., The Greenest campuses: an idiosyncratic guide, Chronicle of Higher Education, April 6, 2001.
2. Alex Wilson, "Green building: a natural for this biological preserve," Solar Today, Sep/Oct 2003, pp.60-63.
3. Thevenard, D.; Dignard-Bailey, L.; Martel, S.; Turcotte, D., "Performance monitoring of a northern 3.2 kWp grid-connected photovoltaic system," Proceedings of 28th IEEE Photovoltaic Specialists Conference 2000 p.1711-14.
4. The accuracy of these numbers is no better than 5%, particularly due to the 10% uncertainty in PV energy prior to August.
5. Most electric energy is produced from heat energy at plants with efficiencies ranging from 30-35%. Here we adopt the convention used by LNBL that source energy is 2.7X site energy.
6. The CalArch building energy tool may be found on the web at http://poet.lbl.gov/cal-arch/compare.html. Comparison data are from 40 educational buildings in the same geographical region.