An Energy-Monitoring System for Stanford University's Leslie Shao-ming Sun Field Station

by John Scofield, Associate Professor of Physics

Biographical Information

A.B., Univ. of Michigan--Flint, 1978

Ph.D., Cornell University, 1985

When I first came to Oberlin College from AT&T Bell Laboratories in 1987, it never occurred to me that I might someday have the freedom to make a major change in my research field.

In graduate school and at Bell Labs I had studied noise in metallic thin films and metal-oxide-semiconductor (MOS) transistors, and investigated new ways for fabricating thin metal coatings and superconducting yttrium barium copper oxide (YBCO) thin films. During my first six years at Oberlin I continued research in these areas. My research was very applied, bordering on electrical engineering. Indeed, some of my research appeared in journals published by the Institute of Electrical and Electronic Engineers (IEEE). Students with engineering interests gravitated to my research program, and several of my former research students earned graduate degrees in engineering fields.

With tenure attained and my first sabbatical ahead, I began to worry less about the next grant and think a bit more outside the box. In 1993 I shifted directions and joined the thin-film photovoltaic (PV) device group at the National Renewable Energy Laboratories (NREL) in Golden, Colorado, to work on copper-indium-diselenide (CIS) thin-film solar cells. I decided to apply my expertise in semiconductor devices and thin-film materials to investigate solar cells. This change was not as dramatic as it appeared, since in my day-to-day research I used many of the same fabrication and characterization techniques that I had been using for years. I continue this work today in collaboration with the thin-film photovoltaic group at Cleveland's NASA Glenn Research Center

I first became interested in green buildings in 1993, while I was on sabbatical leave at NREL. That spring, my NREL research group moved into the newly constructed Solar Energy Research Facility (SERF). This building was one of the first to be highlighted by the Department of Energy in its High Performance Building Program. This program now features approximately 60 buildings, including Oberlin's Adam Joseph Lewis Center for Environmental Studies.

Upon returning to Oberlin I joined the Environmental Studies Program Committee during what proved to be the initial planning stage for the Lewis Center. That spring I wrote my first essay regarding that building, arguing that it should be located on Lorain Street, opposite Wilder Hall, rather than on the Elm Street site that was subsequently adopted.

In 1997 I began teaching *Energy Generation and Usage*, a course that has evolved over the years into *Introduction to Solar Energy* and, this semester, into two module courses, *Energy Technology I & II*. In these courses students learned about the many ways buildings use energy, and each year we conducted an energy audit of a local building, most often a house in town. We conducted energy audits of two Oberlin College buildings, the Wright Laboratory of Physics in 1998, and, two years later, the newly constructed Lewis Center. This latter investigation spurred another major shift in my research.

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My interest in the Lewis Center is well known in Oberlin due to numerous letters I have written to *The Oberlin Review* and, most recently, an article I wrote for the *Oberlin Alumni Magazine.* But less is known about the professional work that formed the basis for these letters. Since the Lewis Center was completed in January 2000, I have continually monitored the energy flows into and out of the building, and have documented the building's design history. Building upon the class energy audit, I constructed a mathematical model for the building and performed numerical simulations to project the amount of energy the building is expected to consume.

This work resulted in two peer-reviewed articles in engineering journals. "First-Year Performance for the Roof-Mounted, 45-kw PV-Array on Oberlin College's Adam Joseph Lewis Center," a paper co-authored with David Kaufman '03, was presented in May 2002 at the 29th annual Institute of Electrical and Electronics Engineers Photovoltaic Specialists Conference in New Orleans and was subsequently published in the conference proceedings.

The second paper, "Early Energy Performance for a Green Academic Building," presents my thermal analysis of the building and energy data for the first 24 months of occupancy. This paper was presented in June 2002, at the annual meeting of the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE), and was subsequently published in *ASHRAE Transactions*.

My work on the Lewis Center has been positively received outside Oberlin, particularly by those engaged in building research. For instance, architects at Carnegie Mellon University's Center for Building Performance and Diagnostics have expressed interest, as have members of the Building Energy Group at Lawrence Berkeley National Labs. In early October I spoke at the Political Economic Research Center's annual symposium for journalists, delivering a lecture titled "What Works–And What Doesn't Work–For the Environment."

In the summer of 2002 I received a call from Dr. Philippe Cohen, administrative director of Stanford University's Jasper Ridge Biological Preserve, a 1200-acre tract of protected land in the middle of Silicon Valley just five miles west of the Stanford campus. The university had recently completed construction of a green building at Jasper Ridge, and having learned of my work on the Lewis Center, Dr. Cohen invited me to submit a proposal to design and install an energy-monitoring system for this building. Ironically, I was being given the opportunity to do for Stanford University work similar to that performed by NREL for Oberlin College.

The Leslie Shao-ming Sun Field Station (right) is a 10,000-square-foot, single-story building that provides office, teaching, and research space for Stanford University students and faculty working at Jasper Ridge. Designers of the field station sought to minimize the environmental impact of both its construction and operation. The building makes maximum use of sunlight for both lighting and heating and boasts a 22-kilowatt photovoltaic (PV) array on its roof for generating electricity. The building is described in the recent issue of *Solar Today*.

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Designing the Energy Monitoring System

The challenge was to design an energy-monitoring system that would measure the building's total energy consumption and the amount of energy produced by the PV array, as well as other variables to ensure precise characterization of the PV array performance. The system would also need to provide real-time data for display on the World Wide Web and on a kiosk display located at the building entrance. Initial expectations also called for the system to monitor exactly where in the building energy was being used, but budget constraints prevented this, so we designed a flexible monitoring system that could be expanded with additional sensors in a later phase.

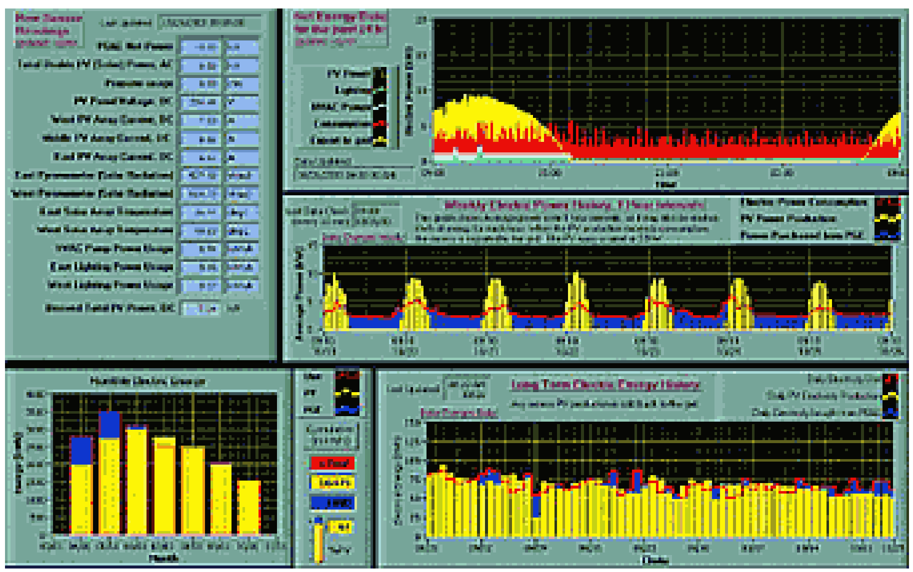
Sunlight provides much of the building's energy, directly supplying light and heat and indirectly supplying electricity generated by the rooftop photovoltaic array. Two additional "pipes" bring energy to and from the building: wires connect the building to the local power company, Pacific Gas and Electric (PG&E) and a gas pipe connects the building to a liquid propane gas storage tank. Propane is used to supplement the building's heat, as well as for domestic hot water. Electric energy may be purchased from or sold to the grid.

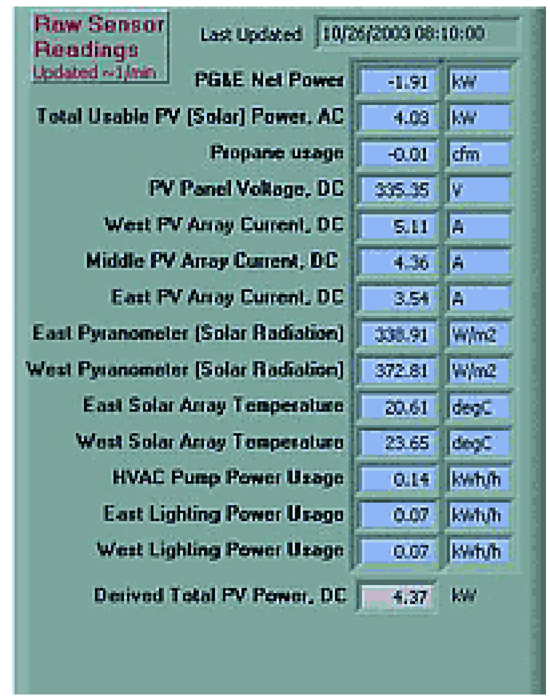
A list of desired sensors was assembled and prioritized. Initially, we decided to monitor 14 different sensors and record their measurements to a database at one-minute intervals for subsequent retrieval and analysis. Five of the sensors were chosen to characterize building energy consumption. The other nine characterize performance of the PV array.

All the sensors were connected to a [Campbell Scientific model cr23x data logger]() (right). This device is similar to those employed by Assistant Professor John Petersen for monitoring environmental variables at the Lewis Center. Both Petersen and Michael Murray '03 were extremely helpful to me in sharing information they had learned working with Campbell data loggers.

The logger, which can measure and store output from dozens of sensors, is connected to the Internet, and its data can be retrieved by authorized computers. Battery backup and internal memory allow the logger to store more than four weeks of data from the 14 sensors without outside intervention. In practice, the managing computer retrieves data every two minutes for display on the Internet and archives the data at one-hour intervals.

Both real-time and trend data are regularly posted [online]() (see below). Summary data, updated automatically every two minutes, are condensed to one web page and displayed on a kiosk at the building entrance. This page may also be accessed [off-site]().

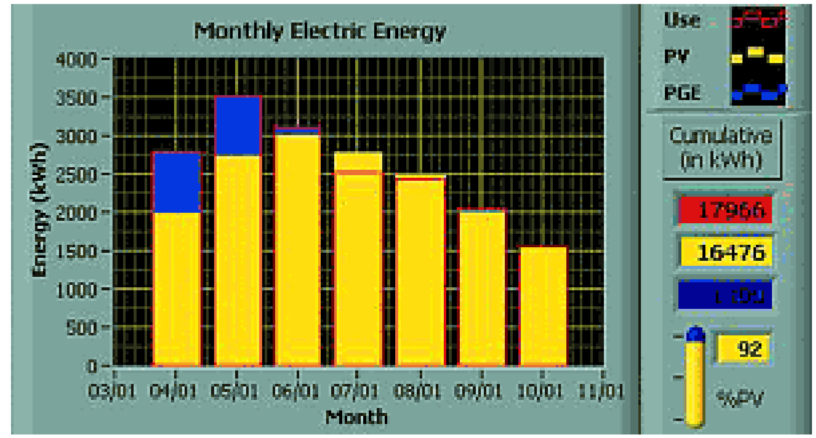




The real-time measurements of the 14 sensors are displayed on the dashboard in the upper-left corner of the kiosk. A larger image of the dashboard is shown here. The first three sensors capture energy flows into and out of the building. The first measures bi-directional energy flow to and from the PG&E electric grid. The second monitors the energy generated by the PV system, and the third monitors propane gas usage. The building's energy consumption and the amount of this energy furnished by the photovoltaic array can be determined by combining these sensor readings.

The last three sensors displayed on the dashboard measure the power consumed by the HVAC pumps and general lighting circuits in the east and west wings of the building.

Since the monitoring system began operation on April 4, 2003, the PV array has generated about 90 percent of the electric energy consumed by the building. (The propane flow sensor was not installed until mid-June, but propane usage has been minimal during these warm months.) From the perspective of PV, spring and summer are the good seasons, with long days and little need for heat. In the next six months, photovoltaic energy production will decrease and building energy consumption will increase. It will be interesting to see how well the solar hot-water-heating system works and how much propane will be required for heating.



The month-by-month electric energy summary is shown above. The red line indicates building energy consumption, the yellow bar indicates the energy supplied by the PV array, and the blue bar tracks the amount of electricity purchased from the grid.

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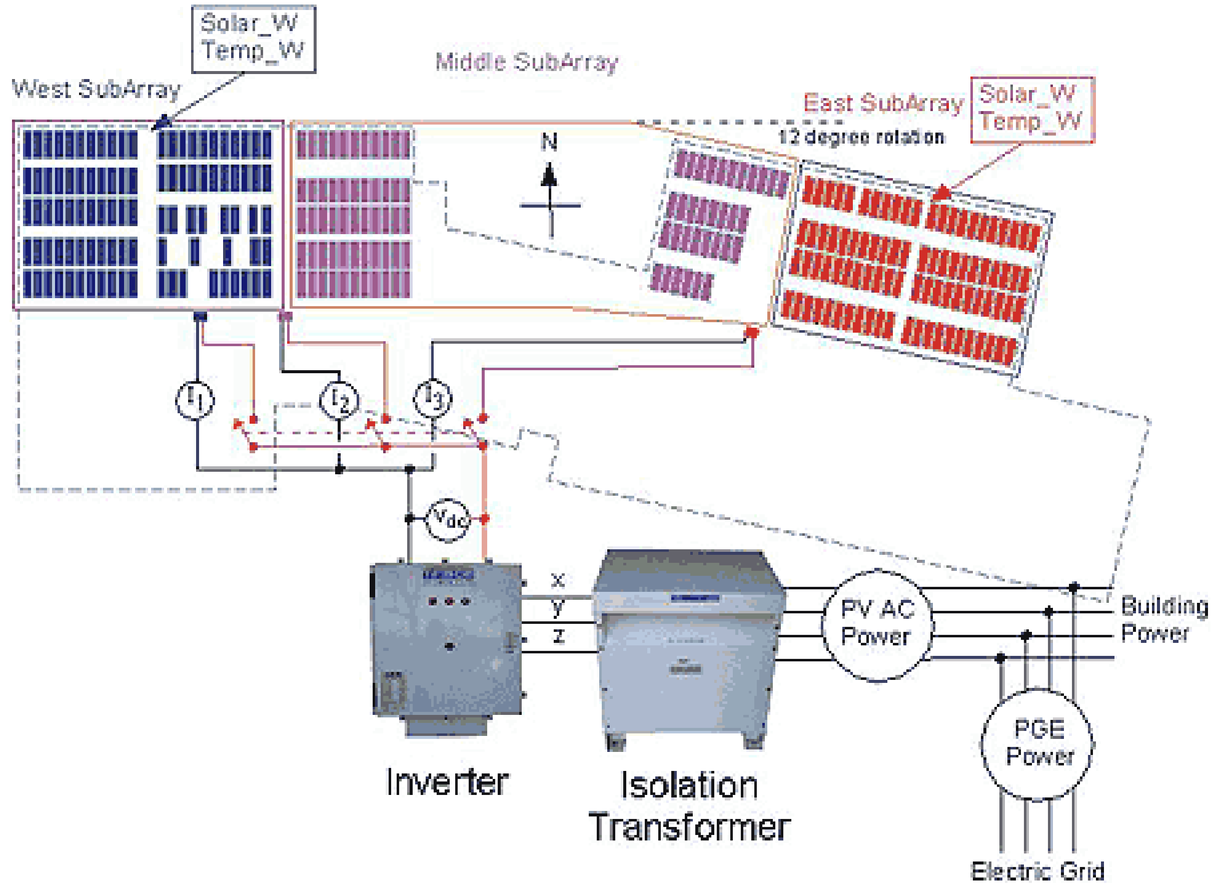
Photovoltaic Array

The eight remaining sensors displayed on the dashboard monitor the parameters associated with the PV array. The photovoltaic array (right) consists of 275, 80-watt thin-film modules made by BP Solar that are mounted on the south-facing portion of the building's inverted V-style roof.

Modules mounted on the west wing of the building are tilted at 15 degrees due south (roof angle). But the east wing of the building is rotated so that the modules on its roof are turned to the west. This means that roughly half of the modules will experience more sunlight in the morning, while the other half receive enhanced evening sun. This leads to some interesting performance issues, as San Francisco weather tends to be foggy in the morning. Two pyranometers and two thermistors were mounted to characterize the incident solar radiation and module temperature respectively for the two module orientations. The last four sensors record the array's DC voltage and the DC currents produced by the three subarrays. These sensor values are combined to calculate the DC power produced by the array before the inverter (last display on the dashboard). The array's layout is shown below.

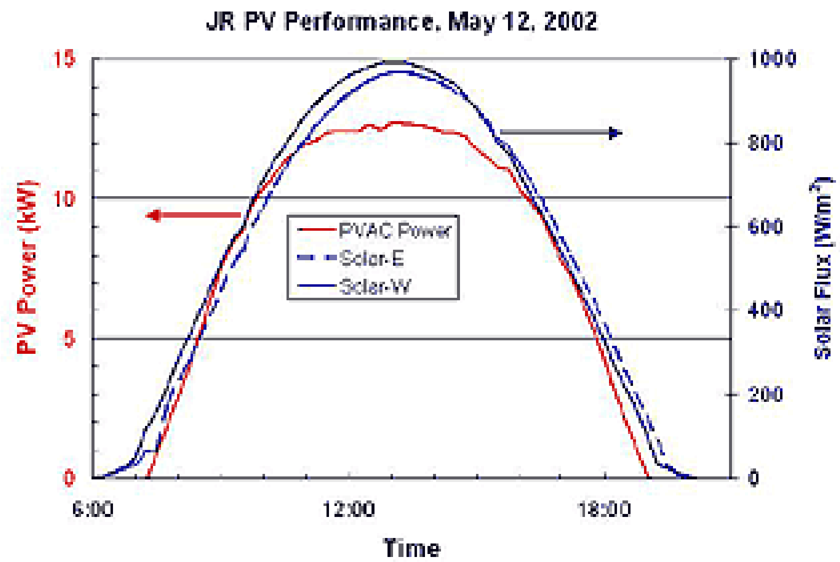


The array is unusual in that it is one of the first thin-film cadmium-telluride (CdTe) arrays to be installed on a building. Crystalline silicon modules, like those installed on the Lewis Center, are a mature technology and have been widely used for many years. Competing thin-film technologies, such as a-Si, CdTe, and CIS, offer the promise of low manufacturing cost and building integration, but of these, only a-Si has been used significantly in the marketplace. CIS modules and CdTe modules have only recently become commercially available. Considerable interest exists in the thin-film PV industry to learn how the CdTe array performs.

Scofield and Stanford graduate student Bryan Palmintier run a cable for one of the two pyranometers.

One of the immediate benefits of an energy-monitoring system is that it can reveal performance problems that otherwise might go unnoticed. Such was the case with the PV array. Operating since the building opened in April 2002, the array clearly reduced electric bills because there were times during the day when the PG&E electric meter actually ran backward. But there was no information about how much energy the PV array was producing until our monitoring system was installed in April 2003. Within weeks, it was clear that the PV array was generating between 10 percent and 30 percent less energy than expected.

The problem is illustrated in the May 12 data graphed below. The bell-curve-shaped blue lines reflect the measured incident sunlight for the east and west pyranometers. At solar noon the intensity of the incident sunlight peaks near 1000 W/m2. The power output of the PV array is graphed in red; it peaks at about 13 kilowatts, well below the 20-kilowatt inverter capacity. In early morning, the PV array output increases with the increased sunlight. But after 10 a.m., although the incident sunlight increases further, the PV array output flattens, failing to increase with the incident sunlight. For this reason, the PV power curve has a flattened top, rather than the usual bell-curve shape.



Further investigation revealed the origin of the problem. As the array temperature increased, its optimum operating voltage dropped below that achievable by the inverter. The inverter (a device that converts direct current to alternating current) could not track the maximum power point and, instead, operated the array at its minimum allowable voltage of 330V, well above the array's optimum voltage. The problem is being addressed by rewiring the PV array to yield a higher voltage.

What Comes Next?

Because the building's energy consumption and the photovoltaic energy production vary with the seasons, it is necessary to collect 12 months of energy data before any significant conclusion regarding performance can be drawn. When these data have been collected, they will be compared with theoretical calculations to see how well actual performance aligned with expectations. The building designers are hopeful that the PV array will generate more energy than the building consumes. But the sub-optimal performance of the PV array thus far is not encouraging.

As it is now configured, the energy-monitoring system does not collect information about the performance of the solar hot-water-heating system. Its overall performance can be inferred, however, by tracking the amount of propane that is consumed. In the next year, we expect to install a second group of sensors to monitor various parameters associated with the HVAC system. These will provide much better information for characterizing this aspect of building performance.

Bryan Palmintier, Cary Tronson, John Scofield, and Philippe Cohen take a break from the system installation and testing on April 4.

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