Campus as a Living Lab (CALL) Project

"Solar Energy Learning Labs"

CSU, Chico

Spring 2015

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Dept of Mechanical and Mechatronic Engineering and Sustainable Manufacturing
California State University, Chico

CALL funding was used for …

- Faculty overload compensation for developing a new Mechanical Engineering elective course: **MECH 433, Solar Energy Engineering**
- Equipment expenditures for completing the OCNL Solar Lab
- Installing a weather station and activating energy monitoring on Chico State "Parking Structure II" for performance analysis of 78 kWdc solar PV array

The Course

- Very popular – 30 students enrolled
- **Lectures**
  - Solar radiation fundamentals (25%)
  - PV cell and module operation (25%)
  - Grid-tie and off-grid PV system design (25%)
  - Solar water heating and other thermal applications (25%)
- **Labs**
  - Solar site surveys using Solar Pathfinder, SunEye, and pyranometers
  - PV module electrical characteristics
  - OCNL Solar Lab (PV module cooling)
- **Team projects** …

Team Projects

- Instructor created five different campus and community-oriented projects:

1. **Grid Alternatives PV Installation and Study** (four teams, 2 students/team)
2. **Campus Solar Feasibility Study** (3 students)
3. **University Farm Solar Feasibility Study** (3 students)
4. **Campus Solar Charging Station Design** (three teams, 3 students/team)
5. **Parking Structure II PV Performance Study and Future Add-on Design** (3 students)

Team Projects, cont.

- Two students proposed their own projects and recruited team members:

1. **Napa Winery PV Design** (2 students) – grid-tie, roof-mounted system to offset 100% of PG&E cost
2. **Chico Dharma Center PV Design** (2 students) – grid-tie, ground-mounted system to offset 100% of PG&E cost

OCNL Solar Lab

OCNL Solar Lab Details

- The OCNL Solar Lab consists of a 1.6 kWdc PV array with two-axis tracking mounted in a roof alcove of the O'Connell Technology Center
- Can be run in grid-tie or off-grid modes
- The power output of each PV module is monitored so that shading, soiling, and temperature effects can be studied
- A heat exchanger mounted to one module is used to heat water in a storage tank for solar thermal studies
- Automated data acquisition reports power output, irradiance, temperatures, and flow rate to a website at one-minute intervals

Parking Structure II PV Array Project

- Irradiance and temperature sensors were installed and inverter monitoring was activated (with website reporting) to allow performance studies

Reflections

- CALL funding was very useful in developing the course and completing the two facility installations
- Working with our FMS and getting them engaged was challenging due to manpower limitations and resignations of key personnel; separate funding for their services would have been helpful
- Lori Hoffman, our VP for Business & Finance, was key in getting the FMS work done; she also took personal interest in the team projects and attended the student presentations
- All in all, the CALL project was very successful – *thank you!*

Examples from Team Projects …

Grid Alternatives PV Install and Study

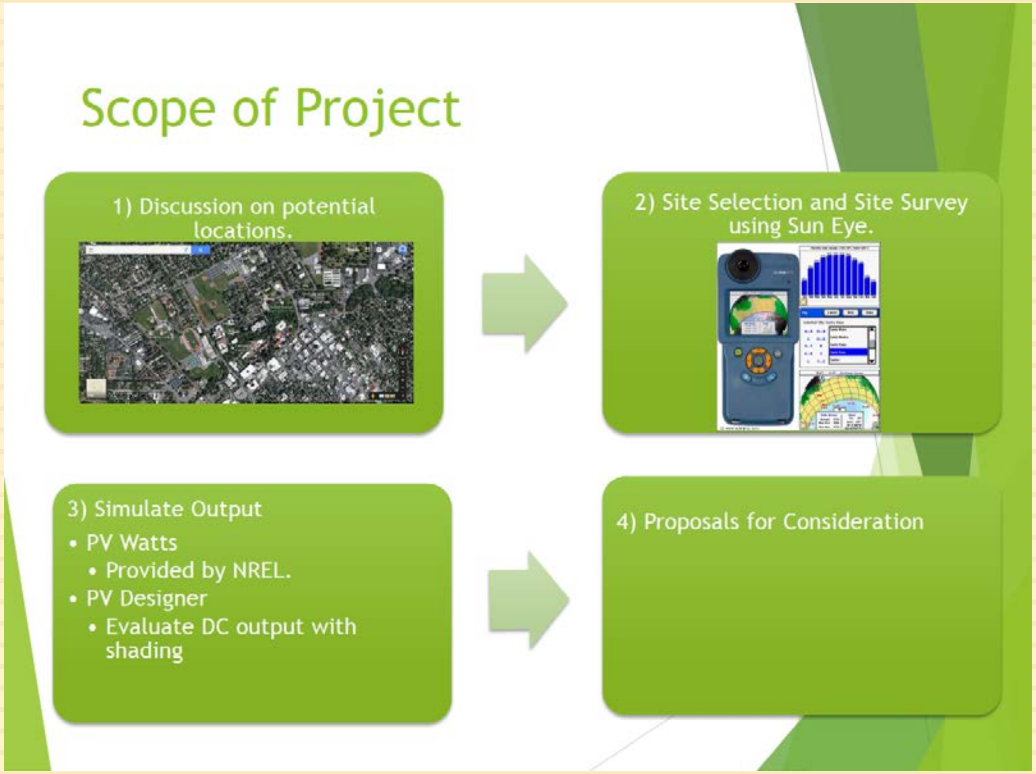
Yearly Offset Predictions			
Month	**Current Usage**	**Projected Generation**	**% Offset**
January	234	153.4	66%
February	316	187.6	59%
March	280	318.6	114%
April	275	410.5	149%
May	272	539.1	198%
June	347	555.5	160%
July	555	553.3	100%
August	843	478.1	57%
September	735	379.7	52%
October	508	276.8	54%
November	262	155.1	59%
December	332	123.5	37%
Annual	**4959**	**4131.2**	**83%**

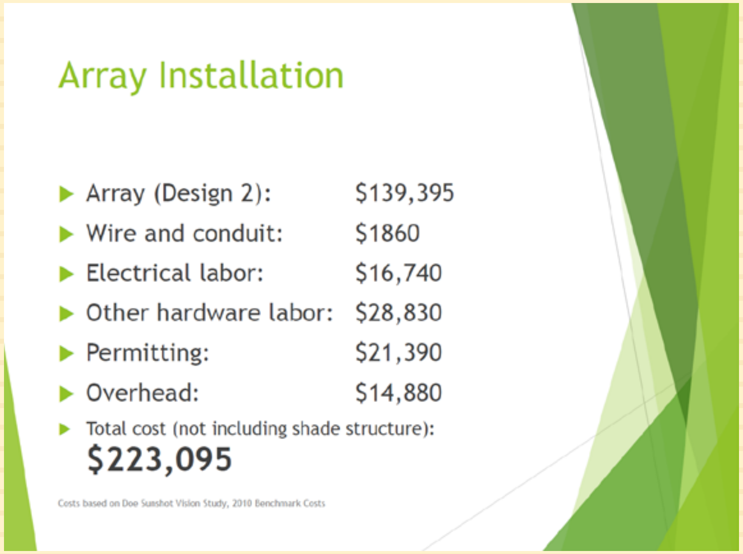
Figure 5 – Predicted System Performance

Predicted Savings	
kWh	**Dollars Saved Annually**
4131.2	**$660.99**

Figure 6 – Annual Energy Savings

Campus Solar Feasibility Study





Campus Solar Charging Station Design

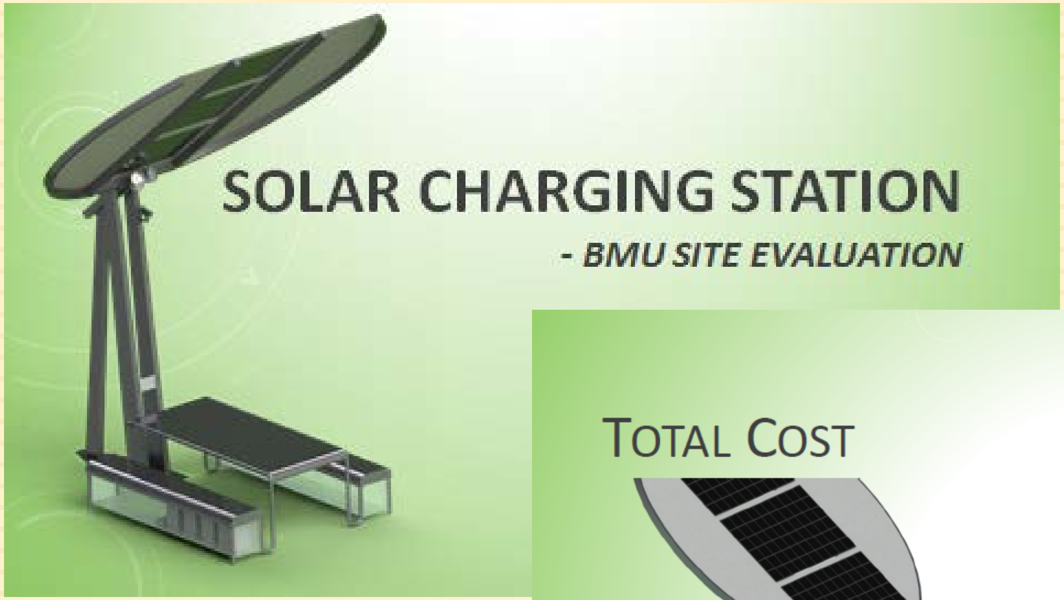
Solar Charging Station Proposal
Nelson Wheelehan
Katelyn Warner
Isai Onofre

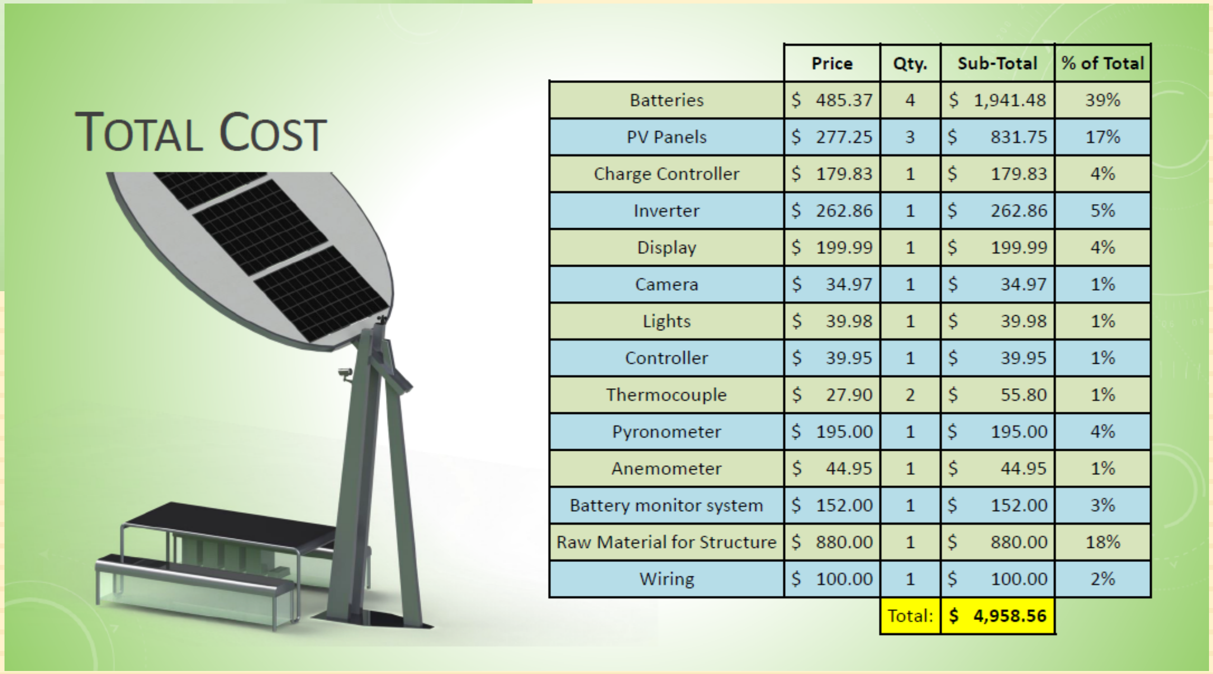
COSTS

TOTAL COST TO BUILD: $6,157

	ITEM	COST/UNIT	# UNIT	TOTAL COST	VENDOR
1	EXPANDED METAL OUTDOOR TBL	$849.00	1	$849.00	BELSON OUTDOORS
2	ASTRONERGY 310 6612P-310	$315.00	4	$1,260.00	WHOLESALE SOLAR
3	MIDNITE CLASSIC 250 CC	$604.00	1	$604.00	WHOLESALE SOLAR
4	COTEK SK100 INVERTER	$364.00	1	$364.00	WHOLESALE SOLAR
5	UPG UB8D AGM BATTERY	$450.00	4	$1,800.00	WHOLESALE SOLAR
6	POLE RACKING	$600.00	1	$600.00	ROCKWELL
7	ELECTRONICS CONTAINER	$200.00	1	$200.00	FAB IN HOUSE
8	FANS	$40.00	3	$120.00	
9	WIRING	$270.00	1	$270.00	
10	DUPLEX OUTLETS	$15.00	4	$60.00	HOME DEPOT
11	Arduino 1.77" SPI LCD Module	$30.00	1	$30.00	ALLIED ELECTRONICS
				$6,157.00	

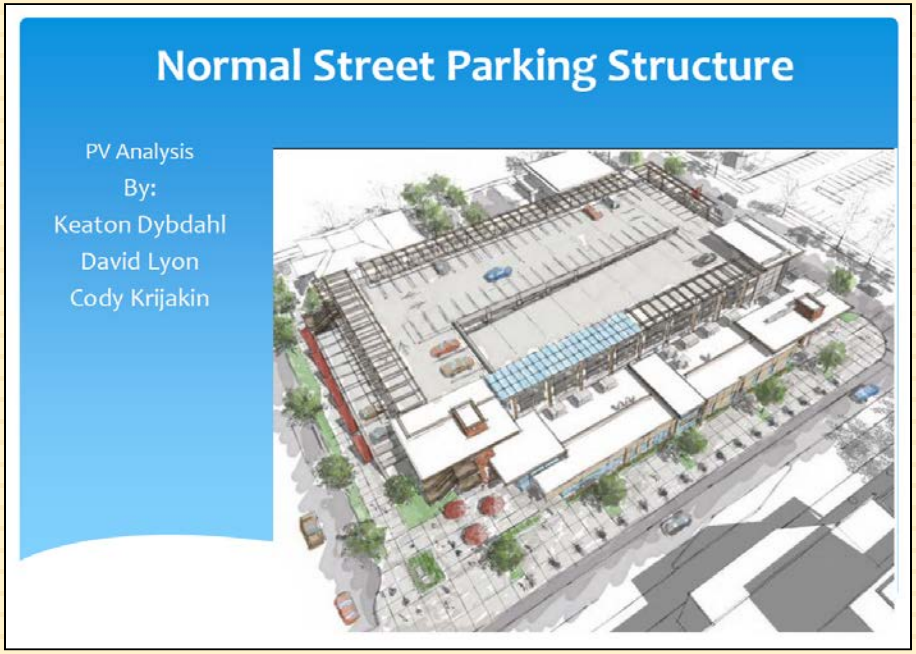
Campus Solar Charging Station Design

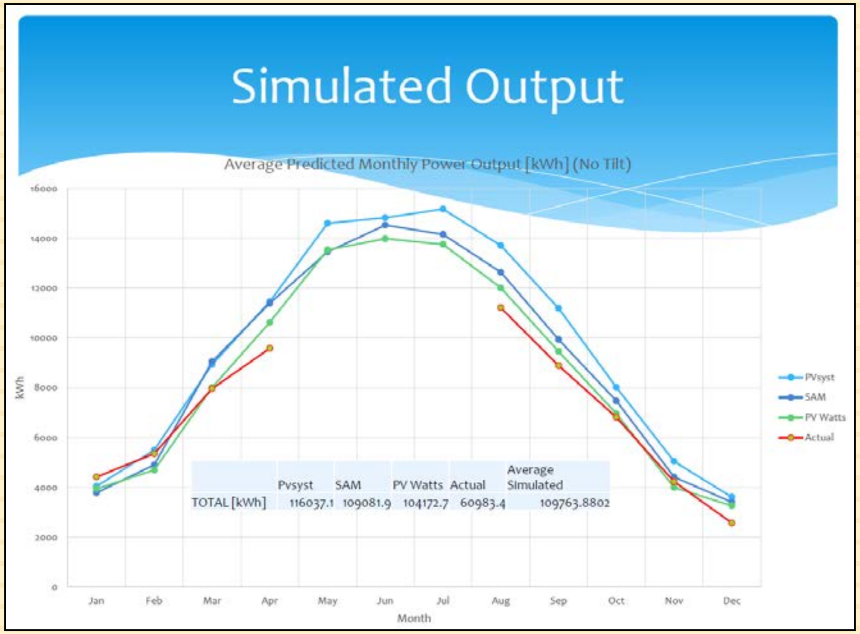




	Price	Qty.	Sub-Total	% of Total
Batteries	$ 485.37	4	$ 1,941.48	39%
PV Panels	$ 277.25	3	$ 831.75	17%
Charge Controller	$ 179.83	1	$ 179.83	4%
Inverter	$ 262.86	1	$ 262.86	5%
Display	$ 199.99	1	$ 199.99	4%
Camera	$ 34.97	1	$ 34.97	1%
Lights	$ 39.98	1	$ 39.98	1%
Controller	$ 39.95	1	$ 39.95	1%
Thermocouple	$ 27.90	2	$ 55.80	1%
Pyronometer	$ 195.00	1	$ 195.00	4%
Anemometer	$ 44.95	1	$ 44.95	1%
Battery monitor system	$ 152.00	1	$ 152.00	3%
Raw Material for Structure	$ 880.00	1	$ 880.00	18%
Wiring	$ 100.00	1	$ 100.00	2%
		Total:	$ 4,958.56	

Parking Structure II PV Study





Final Report

CSU "Campus as a Living Lab"

Date: September 30, 2014

Reporting Period: 9/1/2013 to 8/31/2014

Project Title: Solar Energy Learning Labs

Principal Investigator: Dr. Gregory A. Kallio
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California State University, Chico

Neil Nunn
Interim Associate Director, Facilities Management & Services
California State University, Chico

Marie Patterson (no longer employed at CSUC)
Former Manager of Energy & Sustainability, Facilities Management & Services
California State University, Chico

Chico Electric, Inc.
Chico, CA

NARRATIVE:

The primary focus of this project was the development of a new undergraduate elective course entitled Solar Energy Engineering (MECH 433) to be offered by the Mechanical Engineering program at CSU, Chico during Spring 2015. The grant funds were used to help establish two learning laboratories that will provide practical, hands-on experiences for students enrolled in the course. One laboratory is an off-grid, solar photovoltaic (PV) system located in the roof alcove of the O'Connell Technology Center (OCNL) building. The second laboratory is a grid-tied, solar PV system located on the new Normal Avenue Parking Structure. Each lab offers unique teaching/learning experiences as described below. Some funds were also used to purchase solar-related tools for the course.

Off-Grid Tracking Solar PV Lab

This facility will be a primary experimental lab for the MECH 433 course, allowing students to operate and test a stand-alone solar PV system. The array consists of six, 270W PV modules attached to a pole with two-axis tracking. Energy is stored in a 24v, 400Ah battery bank and a 3500W inverter provides ac power to loads. One PV module is fitted with a heat exchanger that provides cooling and hot water storage. Power optimizers on each module allow individual monitoring of dc power in real-time via a live website; hence, students can investigate the effects of cooling, soiling, and shading on individual module performance.

The facility also has solar irradiance, temperature, and flow rate sensors for evaluating the overall efficiency of the PV array and solar hot water system. PV power output data has been collected and preliminary analyses performed (see Appendix A). Plumbing for the PV cooling and hot water storage is expected to be completed by October 31.

The off-grid solar lab has been in development for several years, aided by the support of Facilities Management and Services (FMS) personnel and expertise of College of ECC staff technicians. This grant provided funds to purchase electrical and plumbing hardware to complete the project. It also provided salary compensation for PI-Kallio to test the system and begin developing lab experiments for the course.

This one-of-a-kind lab facility will support several learning objectives of the course as well as provide a test bed for future research. Figures 1, 2 and 3 show the PV array and battery bank, pole-mounted tracking mechanism, and electrical components. Figure 4 shows a sample display of dc output power from the live website.

Grid-Tied Solar PV System – Normal Avenue Parking Structure

The Normal Avenue Parking Structure (Parking Structure II) was completed in 2012 and houses a 78 kWdc grid-tied solar PV array with a 60kWac Solectria inverter. The inverter output is net-metered by PG&E and networked to Solectria's SolrenView data logger and web-based monitoring system. This system allows for real-time, seamless recording and reporting of PV array production; as such, it is a valuable learning laboratory for this course.

This grant provided funds to purchase and install a weather station near the array that reports solar irradiance, ambient temperature, and PV module temperature to the SolrenView monitoring system. The SolrenView Weather Station was installed by Chico Electric, Inc. The grant also provided salary compensation for PI-Kallio to manage the installation and coordinate it with FMS and the CSUC networking staff.

Having weather data in addition to PV power output will allow students to perform detailed system analysis which includes computation of overall PV array efficiency and Performance Ratio (PR). This analysis is critical to evaluating system performance and detecting malfunctioning components and system degradation. Performing this analysis will give students valuable experience and a key ingredient to managing and maintaining larger PV installations. The results of this analysis will also be useful to FMS and the University in maintaining maximum return on investment (ROI).

Figures 5 and 6 show the Parking Structure PV array and the installed weather station sensors. Figure 7 shows a typical data display from the SolrenView website. Data is recorded every minute and can be downloaded to Excel spreadsheets for analysis. Currently, there is intermittent data being sent from the weather station to the SolrenView server. This communication problem appears to be a firmware issue and will hopefully be resolved soon.

Other Course Equipment Purchases

The following equipment was also purchased with grant funds for the MECH 433 course:

- Solar Pathfinder Shade Tool and PV Studio Software – allows students to perform solar site surveys and calculate solar exposure for specific locations, array tilt, and array azimuth. This tool will be used to size PV arrays for a particular energy demand.
- Sun Runner Stirling Engine – a solar dish heat engine that demonstrates the operation of solar-powered Stirling engines. This technology will be covered in the course as an alternative to PV systems for generating utility-scale electric power.

MECH 433 Course Syllabus

A preliminary syllabus has been developed that includes a topical course outline and specific learning objectives (see Appendix B). Input to course coverage is being solicited from engineers working in the solar energy industry. In addition, invitations have been sent out to three CSUC alumni to present guest lectures pertaining to their experience in the solar energy field. A project to perform a Campus Solar Feasibility Study is tentative at this time. It may be replaced with a volunteer, residential PV installation with the non-profit organization Grid Alternatives. There is considerable interest among the Mechanical Engineering student body in this course and I expect at least 25 students to enroll this coming Spring.

Figure 1. PV array and battery bank in OCNL building roof alcove.

Figure 2. Pole-mount tracking mechanism.

Figure 3. PV electrical components.

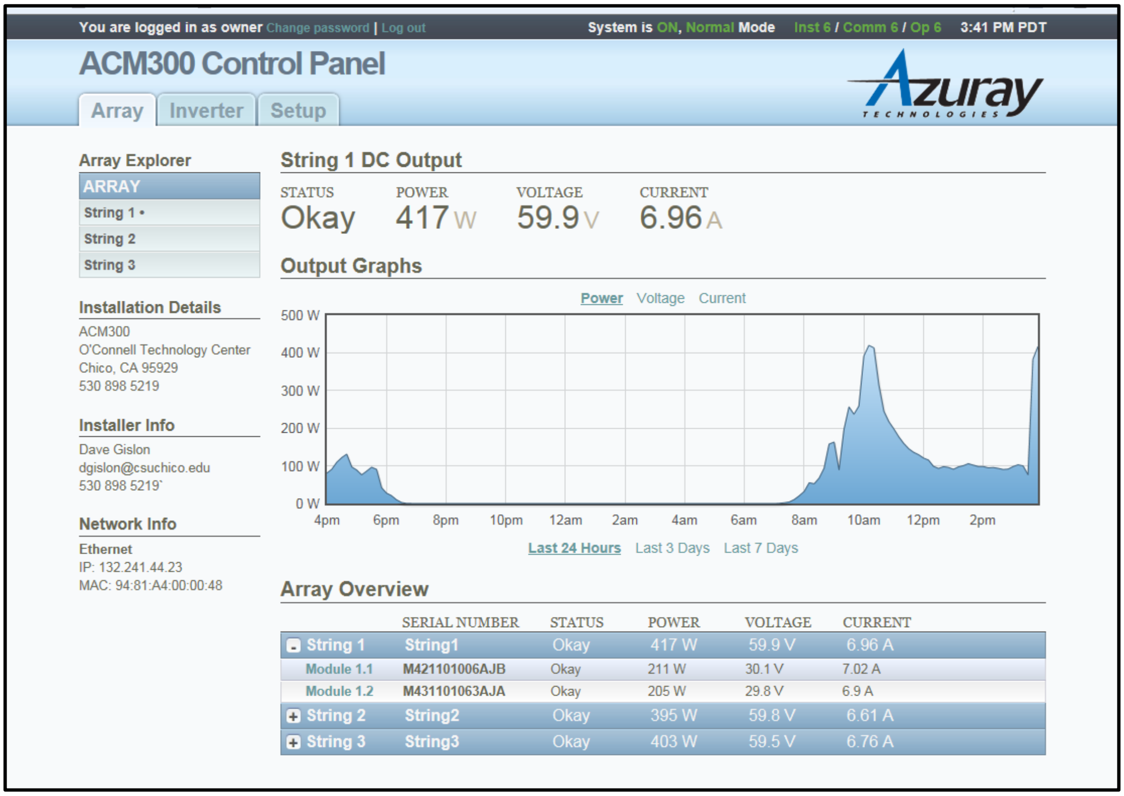


Figure 4. Live website showing real-time power output from off-grid solar PV lab.

Figure 5. 78 kWdc PV array on Normal Avenue Parking Structure.

Figure 6. Installed weather station sensors.

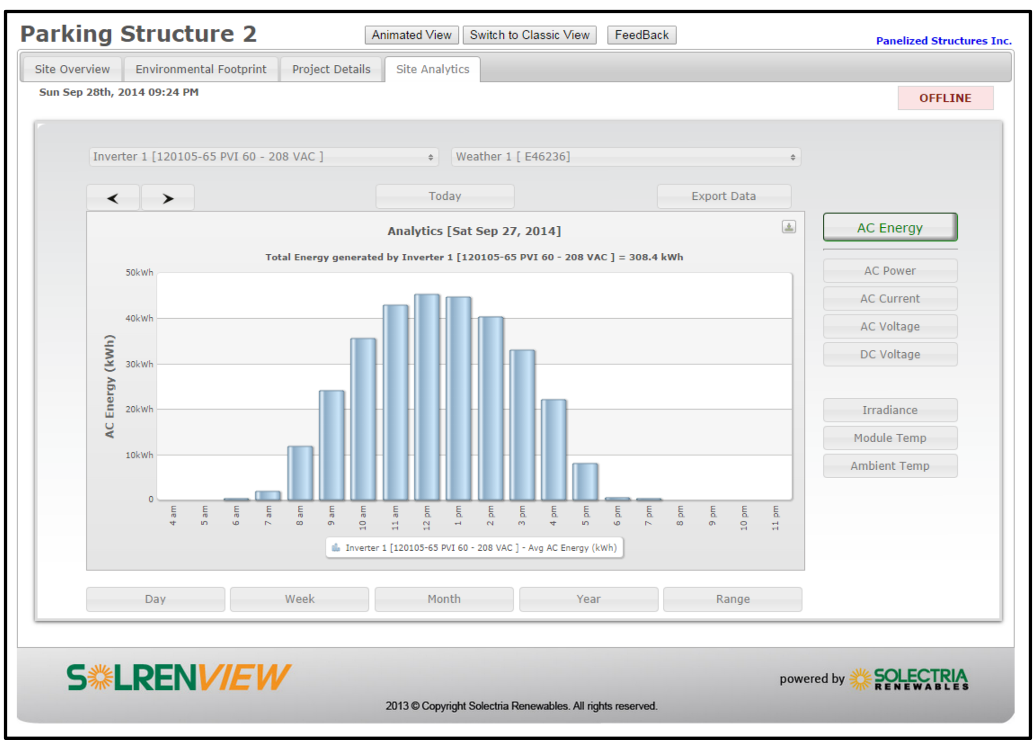


Figure 7. Data display from SolrenView website.

Appendix A – Efficiency Analysis of Off-Grid Solar PV Lab

OCNL Solar PV Lab module efficiency calculations					
Date:	9/4/2014			1.1	1.2
Module:	Suntech STP270-24/Vb-1			PV1	PV2
Active area:	1.94	m^2		2.1	2.2
STC Power	270	W	STC = 25°C, 1000 W/m^2	PV3	PV4
STC Efficiency:	13.9	%		3.1	3.2
PTC Power	244.7	W	PTC = 46.4°C, 1000 W/m^2	PV5	PV6
PTC Efficiency	12.6	%			

Comments: 1500W space heater load, Tamb = 38.7°C (102°F), Sundrum collector on PV3 (no coolant)

Module	**PowerOpt S/N**	**Date**	**Time**	**ModTemp (°C)**	**RefCell1 Irrad (W/m^2)**	**V_in (V)**	**I_in (A)**	**Power_in (W)**	**Eff_in (%)**	**V_out (V)**	**I_out (A)**	**Power_out (W)**	**Eff_out (%)**
1.1, PV1	M421101006AJB	2014-9-5	15:00:00	68.36	905.40	29.70	7.11	211.29	10.89	29.56	7.02	207.51	10.70
1.2, PV2	M431101063AJA	2014-9-5	15:00:00	68.95	905.40	28.89	6.99	202.01	10.41	28.78	6.89	198.43	10.23
2.1, PV3	M431101029AJ2	2014-9-5	15:00:00	80.50	905.40	28.19	6.67	187.95	9.69	28.08	6.57	184.59	9.52
2.2, PV4	M461101120AJF	2014-9-5	15:00:00	69.96	905.40	30.34	6.75	204.94	10.56	30.19	6.67	201.41	10.38
3.1, PV5	M461101053AJ8	2014-9-5	15:00:00	68.84	905.40	29.05	6.92	201.06	10.36	28.92	6.82	197.37	10.17
3.2, PV6	M461101194AJ0	2014-9-5	15:00:00	69.73	905.40	29.14	6.96	202.73	10.45	29.02	6.86	199.14	10.27

Appendix B – MECH 433 Course Syllabus

COURSE SYLLABUS FOR
MECH 433, SOLAR ENERGY ENGINEERING - 3 UNITS

California State University, Chico
Spring Semester 2015

Instructor: Dr. G.A. Kallio, OCNL 417, 898-4959
email: *gkallio@csuchico.edu*

Office hours: TBD

Class hours: Two 75-min lectures per week

Catalog Description: This introductory course covers the design and operation of solar photovoltaic (PV) and solar thermal systems. Foundational topics include solar radiation characteristics, solar materials, and heat transfer. Solar PV systems include cell operation, I-V characteristics, module design, maximum power-point tracking, charge controllers, batteries, inverters, design of grid-tied and off-grid systems, and system performance evaluation. Solar thermal systems include flat-plate collectors, concentrating collectors, passive and active solar water heating, solar space heating and cooling, and solar thermal power systems.

Prerequisites: CIVL 321, Fluid Mechanics; MECH 332, Thermodynamics; EECE 211, Linear Circuits.

Corequisite:	MECH 338, Heat Transfer.
Primary Textbook:	***Solar Energy Engineering,*** Kalogirou, 2^{nd} Edition, Academic Press (2013) ISBN: 9780123972705 (tentative)
Reserve Textbook:	***Photovoltaic Systems Engineering,*** Messenger & Venture, 3^{rd} Edition, CRC Press (2010) ISBN: 9781439802922 (tentative)
Software:	***EES: Engineering Equation Solver***
Internet:	Lecture slides, text problem homework and solutions, lab and project descriptions, and other course material are posted on Blackboard Learn.

Grading:

Homework Problems	20 %
Labs & Projects	40 %
Midterm Exam	15 %
Final Exam	25 %

Homework: There will be approximately four homework problem sets assigned during the semester. Problem solutions must be neat, legible, numbered, arranged in assigned order, written on only one side of the paper, and stapled.

Homework is due at the beginning of class on the due date. **Late homework is not accepted.**

Labs: The new Solar Lab on the OCNL roof will be used for several experiments that will investigate the performance of an off-grid photovoltaic system, the benefits of tracking, the benefits of module cooling, and solar water heating. Specific procedures and lab report format will be given for each experiment.

Projects: Two class projects will be assigned to student teams. One project involves performance evaluations of the Normal Avenue Parking Structure Solar PV Array from web-based data monitoring. The second project will be a Campus Solar Feasibility Study to locate candidate sites and perform basic design for future solar PV installations. The projects will culminate with written reports and class presentations.

Examinations: There will be a 75-min midterm exam and a 110-min final exam. Use of the textbook and one, 8½” x 11” page of notes are allowed during the exams.

Guest Lectures: Engineers working in the solar energy industry have been invited to present guest lectures. Dates to be announced.

<u>Specific Course Outcomes</u> - what a student should be able to do at the end of this course:

1. Calculate the terrestrial solar radiation on an arbitrary tilted surface.
2. Identify and describe the basic instruments used to measure solar radiation.
3. Describe the interaction of solar radiation with opaque and transmissive materials: calculate solar absorption, reflection, and transmission energy rates.
4. Identify and quantify the important heat transfer modes (conduction, convection, radiation) in a solar energy system.
5. Describe the operation of a PV cell and module, and their I-V characteristics.
6. Describe the function of a charge controller, batteries, and inverter in a PV power system.
7. Conduct a solar site survey using an appropriate instrument and software.
8. Design a basic stand-alone solar PV power system.
9. Design a basic grid-tied solar PV power system.
10. Calculate efficiency and performance factors of grid-tied PV systems from monitored data.
11. Use a flat plate solar collector mathematical model to predict performance.
12. Describe the different types of solar hot water and space heating systems.
13. Design a basic flat plate solar collector and water heating system.
14. Describe the different types of passive solar heating designs for buildings.
15. Describe the different types of solar cooling technologies.
16. Describe the different types of solar thermal power systems.

Tentative Course Outline:

Week	Topic	Activity
1	Introduction to renewable energy technologies, solar radiation basics	
2	Available terrestrial solar radiation	Homework 1
3	Photovoltaic effect, cell I-V characteristics	Lab 1
4	Module and array design, types of PV technologies	Lab 1
5	Batteries, inverters, charge controllers, MPPT operation, trackers	Homework 2
6	Design of grid-tied and off-grid PV systems	Project 1
7	PV system data monitoring and performance evaluation	Project 1
8	Introduction to solar thermal systems	Midterm Exam
9	Heat transfer basics	Homework 3
10	Solar irradiation on opaque surfaces and glazing materials	Lab 2
11	Design of flat-plate collectors, concentrating collectors	Lab 2
12	Modeling and performance of solar collectors	Homework 4
13	Solar water heating systems – passive and active	Project 2
14	Solar space heating and cooling	Project 2
15	Solar thermal power systems	Project 2
16	Project presentations	Final Exam

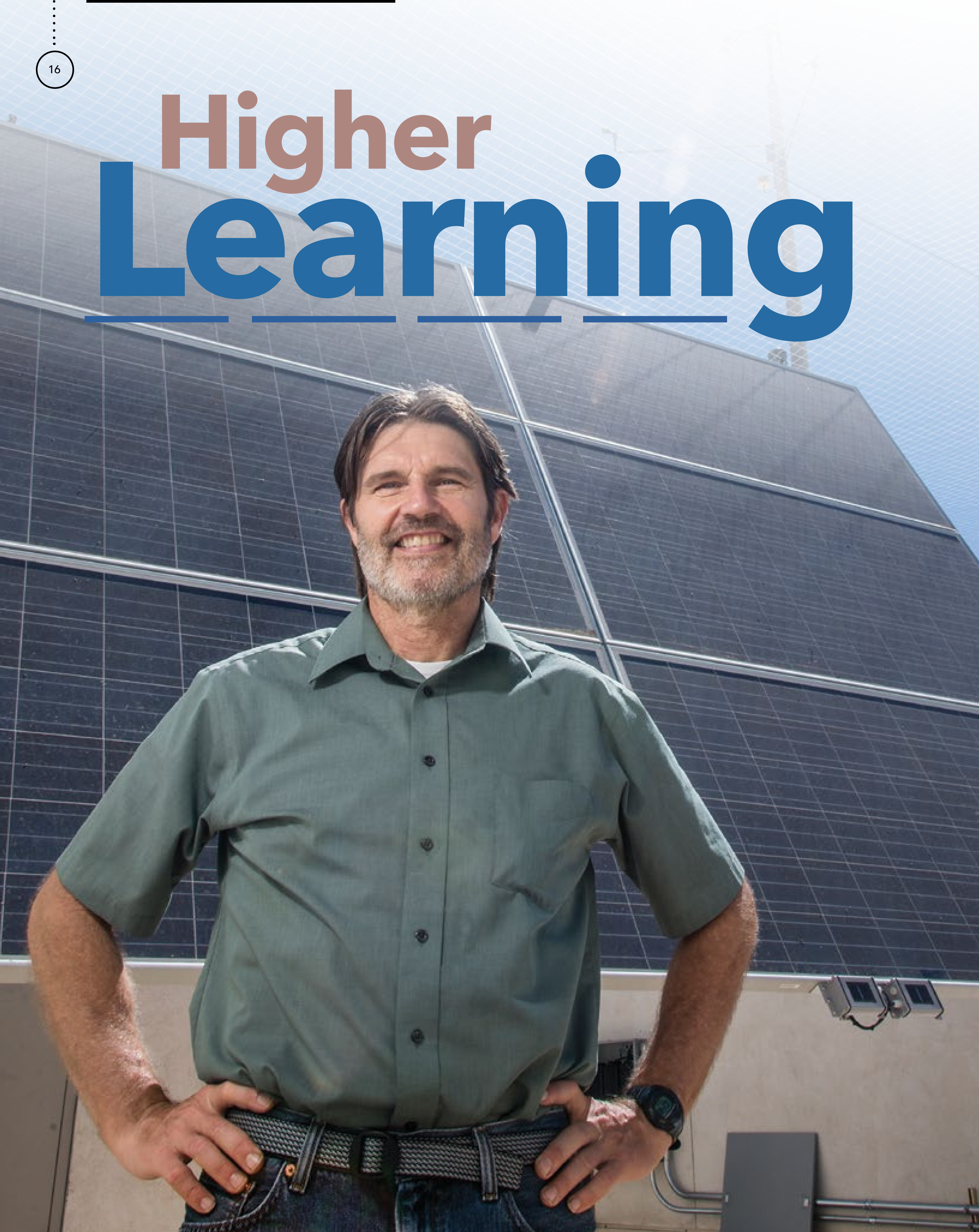
CONNECTIONS

College of Engineering, Computer Science, and Construction Management CSU, Chico 2014

Higher Learning

O'CONNELL TECHNOLOGY CENTER ROOFTOP BECOMES SOLAR LAB FOR ENGINEERING STUDENTS

Higher Learning



O'CONNELL TECHNOLOGY CENTER ROOFTOP BECOMES SOLAR LAB FOR ENGINEERING STUDENTS

When mechanical engineering professor Greg Kallio wanted to design a lab where students could study solar electric and thermal systems, his first thought was to look up. He knew that the roof alcove of the O'Connell Technology Center would be the perfect location for a new 1.6-kilowatt (kWdc) solar lab that would be used by students to complete hands-on projects associated with the courses that Kallio and others teach at CSU, Chico. The lab would be just steps from the fourth-floor location of the Department of Mechanical and Mechatronic Engineering and Sustainable Manufacturing faculty offices and classrooms. "Because the lab is viewable from the department office lobby, it also serves as a useful demonstration and showpiece for visitors," explained Kallio.

Widely recognized by other universities and organizations for its early and continuing commitment to sustainability, CSU, Chico is one of the seven founding members of the American College and University Presidents' Climate Commitment to reduce global warming. Over the last decade, the campus has shown leadership in sustainability through the completion of campus projects that divert waste from landfills through recycling and composting and conserve energy by more efficiently heating, cooling, and lighting campus facilities. The campus also hosts the annual This Way to Sustainability Conference, the nation's largest student-run conference of its kind.

Somewhat incongruent with its leadership in sustainability, as of 2013 there were no dedicated solar energy courses taught at CSU, Chico by engineering or any other department faculty. "Solar energy is one of many topics included in my Energy Systems course, but the coverage is cursory at best," said Kallio. Citing the need for a stand-alone course to provide students with opportunities to secure good jobs in the growing field of solar energy, Kallio worked with others in his department to create a new elective course titled Solar Energy Engineering.

As he designed the new course to include ample opportunities for students to apply what they learn in the classroom to real-world projects, Kallio searched for a space that could serve as a primary lab for the course. When, in spring 2013, the CSU Chancellor's Office issued a request for proposals for funds that would support faculty and facilities management partnerships in their efforts to integrate sustainability into undergraduate curricula, Kallio jumped at the chance to submit a proposal. His project was selected for funding, and for the past year, he has collaborated with CSU, Chico facilities management staff to create two solar energy "living labs" —one on the rooftop of the O'Connell building and the other on the Normal Avenue parking structure. The O'Connell solar lab is nearing completion.

The O'Connell lab consists of a pole-mounted, six-module photovoltaic (PV) array with a two-axis tracking unit to give perfect alignment with the sun. Each PV module has a power optimizer that allows the array to produce maximum power and provide module-level monitoring via the Internet. One module is water-cooled with a heat exchanger to improve electrical performance; this also provides an additional experiment for students to study PV-thermal solar water heating. The system is presently configured for off-grid operation with a charge controller, battery bank, inverter, and an automated data acquisition system that records power, solar irradiance, water flow rates, and temperatures. The stored energy can be used for a variety of purposes such as charging stations for student laptops and phones. "This is a one-of-a-kind lab, and it would not have been successful without the expertise of the College of ECC technical staff, namely Steve Eckart, Dave Gislon, and Scott Vanni," said Kallio.

The rooftop lab will be used by students enrolled in the course to learn how solar electric and thermal systems operate by conducting experiments with automated data acquisition. Through classroom assignments and projects, they will understand the design of an off-grid solar PV system and be able to investigate the effects of

–continued on page 18

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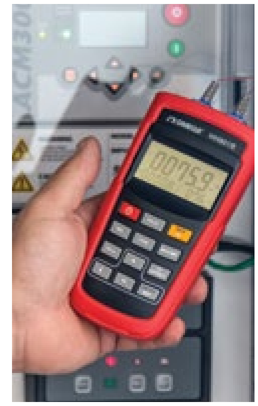
array tracking, module cooling, shading, and soiling on performance. They will also learn how to conduct a solar site survey and learn how to design PV arrays and support structures, attach to building roofs, and select electrical balance-of-system equipment.

In addition to the new lab on the O'Connell rooftop, students taking the new Solar Energy Engineering course will download data collected from the 60-kWdc grid-tied solar PV array on the campus's new Normal Avenue parking structure. Completed in 2013 and fitted with the solar PV array during construction, the parking structure needs only a modest investment in sensors and a communication gateway for "live-site" web page monitoring to serve as a living lab. Once fitted with the new equipment, students will be able to download archived data and evaluate system efficiency, look at seasonal trends, evaluate cell temperature effects, and create "what-if" scenarios to evaluate improved array configurations. Students will gain an understanding of the importance of PV monitoring and how environmental factors affect power output.

Kallio is enthusiastic about the learning opportunities that the new lab space above O'Connell and the newly acquired data mining capacities from the parking garage array will provide to students.

"The planned activities associated with the new course in solar energy engineering will be challenging, hands-on, open-ended, and will prepare students for the real-world system design that they will see as engineers in the solar energy field," he said.

Greg Kallio joined the CSU, Chico engineering faculty in 1988. Since then, he has taught courses in the areas of thermodynamics, heat transfer, energy systems, and air pollution control. His research interests include residential building energy efficiency, performance benchmarking of solar PV systems, solar energy applications in agriculture, and designing labs for undergraduate education in renewable energy, energy efficiency, and diesel engine emissions. In addition to his teaching and research, he is a faculty associate of CSU, Chico's Center for Water and the Environment and a regular presenter at CSU, Chico's This Way to Sustainability Conference.



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