A Simple Laboratory Exercise Introducing Photovoltaics

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Abstract

A simple laboratory exercise teaches students important behavior of four different photovoltaic technologies and inspires debate on pertinent issues for designing solar panel arrays. Students perform experiments on monocrystalline, polycrystalline, thin film flexible, and folding flexible photovoltaic panels. They find practical influence of azimuth on performance, identifying a substantial tolerance in angle from normal. They use their laboratory skills and management instruction to gain quick but remarkably valid estimates of solar panel performance: relative energy efficiency and relative cost of each of the four technologies. Assessed results showed improved performance on exam questions relating to this laboratory work, preference for designing with solar cells as an option on their design projects, and greater enthusiasm for studying renewable energy. The students even received some unexpected recognition from their non-engineering peers. The paper presents sample costs of the equipment and typical results from four simple but insightful experiments that the students performed within a single hour-long class period using commonly available instruments in their laboratories.

Introduction

A number of universities have begun to teach topics in renewable energy. Textbooks of good quality and appropriate to support a wide breadth and depth of coursework have appeared. Some of the more advanced academic experts have even placed some superb course notes on-line.[1] Planning tools and simulation software appropriate for a host of classes in the subject are now available on-line. With these tools, creating a good course or sequence on a minimal budget is well within reach. One of the challenges is to create exciting laboratory exercises. The university was installing six megawatts of photovoltaic power generation near its south entrance at the time that this lab was being developed, so interest in photovoltaics was already quite high among engineering students on campus. The laboratory work proposed here requires a small investment to create enthusiasm or build on it in a small lab section within an hour. The lab work was created and executed for the first photovoltaics lab in an introductory renewable energy course at the United States Air Force Academy.

Four Solar Panels

With four different small photovoltaic panels, a lab section of eight electrical engineering students can investigate a remarkable wealth of introductory topics. The panels for this investigation are composed of the following closely related types: monocrystalline cells, polycrystalline cells, and two different thin film cells, one on a rigid, foldable backing and one on a flexible backing. These are easy to find on-line, including their prices, in small quantities. For example, all four types in a low wattage size, are available on amazon.com for less than a few hundred dollars total. [1]

The first panel is composed of monocrystalline cells. An example cell is shown in Figure 1. The first panel had six of these monocrystalline cells mounted on a heat sink. Overall dimensions were 40cm x 20cm x 2cm. In this case, a 5 Watt panel of an older monocrystalline technology was already on hand as a demonstrator unit in the department. For those who lack such a heritage, a 5 Watt unit from Instapark® is $36.75 with a controller. Other monocrystalline units are, for example, $109.70 for a 30 Watt unit with a controller, and $240 for 100 Watt unit with a controller. All are available in single-unit quantities on amazon.com.[2]

Figure 1. Typical Monocrystalline Cell.[3]

The second panel is a polycrystalline unit. These are the common panels with the wild grain pattern in the face of the solar cells. An example is shown in Figure 2. The test panel was a 10 Watt unit from Solartech® retailing at $58.28. Overall dimensions were 36.8 x 31.0 x 1.8 cm. Other polycrystalline solar panels are available at, for example, $59.00 for a 20 Watt panel with controller, and $290.00 for a 130 Watt panel at amazon.com.[2]

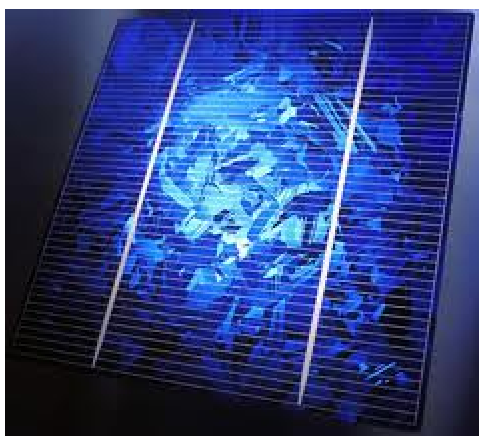

Figure 2. Polycrystalline Photovoltaic Cell.[4]

The third panel is a flexible amorphous silicon unit. It is a thin-film solar panel, a 10 Watt unit known for high efficiency. Overall dimensions are 30 x 60 x 0.2 cm. It rolls up into a neat tube that fits into the pocket on a pair of cargo pants. The manufacturer of the example in Figure 3 claims that they can manufacture panels in excess of a mile (1.6 km) long. This claim is quite credible considering the nature of the web manufacturing process that they employ to build it. Other units are available, for example, a 68 Watt panel for $189 and a 128 Watt flexible peel and stick unit for $230 at amazon.com.[2]

Figure 3. Flexible Photovoltaic Panel.[5]

The fourth unit is a folding solar panel. These are quite popular with the military because they fit flat inside the cargo pocket of a field uniform. An example with desert colors is shown in Figure 4. In the experiment at hand, a 10 Watt folding panel retails for $174. It has dimensions of 8.9 x 26.7 x 3.3 cm folded. It fits into a backpack and is designed to charge phones or small laptop computers. These panels are popular for charging marine batteries. Other typical units are a smaller AA battery charging unit for $49.85 and a 26 Watt foldable array for $387 on amazon.com.[2]

Figure 4. Folding Solar Panel.[6]

Instruments

Only easily portable instruments that are common to a typical undergraduate circuits, electronics, or power laboratory are required for this laboratory. An example is a common handheld portable multimeter, measuring voltage and current, among other things. These panels are all rated at 12 Volts, so the two-Ampere capacity of many such portable multimeters is more than sufficient. Other instruments include a simple protractor and a 30cm ruler. A handheld calculator or laptop computer completes the recommended array of equipment.

Experiments

The following experiments can be run in less than a quarter hour each:

Experiment A: The effect of azimuth angle on generation. This experiment is exactly as stated. The academic building which houses electrical engineering (and everything else) at __________ University is well known for its sunny east-facing floor-to ceiling windows that run the thousand-foot length of the building on three of its six floors. Using a protractor, the angle is easy to measure. Applying a rated load resistance or a small light bulb gives an appropriate current output as a function of phase angle.

Experiment B: An estimate of maximum power output. The voltage vs. current curve of a solar cell is nearly rectangular, as shown in Figure 7.

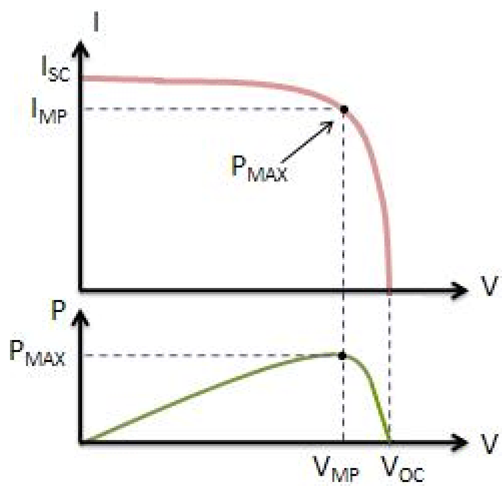

Figure 5. Typical Voltage vs. Current Curve for a Photovoltaic Cell[7]

The terminal voltage is quite close to the open circuit voltage for a range of current from zero up to typically more than 70% of the short circuit current. The power capacity is the area under the curve. Therefore, an estimate of maximum power output is the product of the open circuit voltage and the short circuit current. A range of loads is not required, just a handheld multimeter. On the voltage option, the meter impedance is large enough that the reading is quite close to the open circuit value. On the current option, the impedance is small enough that the reading is quite close to the short circuit value. Realizing this is an important discovery in the workings of a meter for most of the students.

Experiment C: An estimate of energy efficiency. This is a relative measurement, not an exact measurement, with the equipment at hand. The same rated load as described for Experiment A is applied to each panel when located with the same illumination. The product of output voltage and current is, of course, output power. Measuring the surface area with the ruler and dividing the power output by the surface area yields a power per unit area. Because the illumination (power input) is the same in each of the four cases, this power output per unit surface area is a measure of relative energy efficiency for the given illumination.

Experiment D: An estimate of the cost effectiveness of a large array of the same panels. This is an extension of the immediately previous experiment. Dividing the cost of the panel by the power output near rated conditions gives a dollars per watt figure for comparison. This, of course, is an important and readily understood value, particularly in the minds of the students at the United States Air Force Academy, whose course of instruction prepares every student for a technical leadership position upon graduation.

The class was divided into four groups. Each group was issued a panel and assigned two of the four exercises to perform. This produced two sets of data for each experiment. Because each student had already take the prerequisite two semesters of laboratory science (physics and chemistry), a brief review of appropriate experimental procedures was sufficient. The rigid panels were best suited for the solar angle experiment. By having two groups take independent observations for each experiment, the students obtained a way to compare and discuss the relative merits of each type of solar panel. With data from all four groups, a good impression of the relative merits of each panel became apparent.

Two of these experiments took about half an hour total to complete. Upon finishing, each group reported its findings in a table on the classroom whiteboard. The instructor pointed out important relationships as described above with the experiments. He had the students calculate energy efficiency and dollars per Watt, making comparisons about which panels might be better than others.

Requiring written answers to followup questions that apply and extend the important points of the experiment is important in a laboratory exercise of this nature. For example, the instructor asked for an estimate of the cost per Watt, with numbers and justification, of a 6.0MW photovoltaic array being built at the same time near the university's entrance. The students had to look up the project's cost from press releases available on the Internet and calculate the result ($3.16 per Watt). They then commented on whether this seemed reasonable from their data. (It was quite close.) Another question asked for the power per unit area of the same 6.0MW array. (95 Watts per square meter)

The simplicity of the lab perhaps hides the remarkable amount of learning available. For example, Experiment B requires two easy measurements with a common multimeter and a basic knowledge of the voltage-current characteristic of a photovoltaic cell. When the simple procedure became known, the operation of the meter was reinforced in the students' minds. Experiment C uses the result of Experiment B and some data about illumination quickly accessible from the NOAA website. Each group that did either of these two experiments learned how to gain a relative comparison of energy efficiency. The groups that did both of them reinforced the learning.

Results

Experiment A. The monocrystalline panel proved to be best for this experiment. Its 12V output gave 350mA when positioned normal to incoming solar radiation. This varied remarkably little for about 20 degrees on either side of normal, then tapered off in an approximate sinusoidal relationship. There was an ambient bias of about 10%.

Experiment B. The four panels gave estimated capacity somewhat below expectations. It was a late winter day in a location that experiences some seasonal attenuation of solar flux. Results varied from 4 Watts per unit for the folding panel to nearly 6 Watts per unit for the monocrystalline panel.

Experiment C. Energy efficiency ranged from 9% for the folding panel to 14% for the monocrystalline panel.

Experiment D. Dollars per Watt ranged from about 5.0 for the monocrystalline panel to 19.5 for the flexible panel.

Assessment

Assessment of the effectiveness of this laboratory exercise is based on student comments from the lab and from student performance on a subsequent examination. Students were initially confused by the nature of the lab. It was not tightly structured and the data came from estimates from hasty experiments, not carefully structured, well-controlled laboratory work. On the other hand, every student at the United States Air Force Academy is learning to be a leader and a technical manager; it is central to the nature and purpose of the school. When they realized that this was designed to play to their strength of quick assessment of technical information based on incomplete data, they rose to the occasion.

Each group was assigned a white board in the laboratory. They posted their results and performed their calculations in full view of their peers and the instructor. When they got stuck, they turned around and solicited help from their peers first and then the instructor. Lively debates occurred. The instructor made note of who figured out each concept first and then used that in the discussion.

For a written report, each group answered the following:

1. Rank the panels in order of relative energy efficiency, best to worst. On what basis do you know this?
2. Rank the panels in order of cost per unit of energy converted. How did you determine this ranking?
3. How much does azimuth affect power generation? What tolerance would you recommend on setting the azimuth of a solar panel?

The results of the written report were encouraging. Of the eight students, six gave reasonable answers for question 1, all gave reasonable answers for question 2, and five gave a reasonable assessment for question 3. Everyone correctly calculated the cost and power per unit area of the university's solar project.

Enthusiasm for the course had flagged during the first several weeks of the course. This appeared to be due most likely to the review of basic power concepts and little apparent connection to renewable energy. Summative comments on student evaluations reinforced this notion. This lab seemed to renew excitement. Several students commented on this being the first renewable energy thing that had been done so far. This noticeably improved enthusiasm remained throughout the next unit on wind power and beyond.

On the examination that followed this experiment, scores on the questions relating to issues addressed in this lab were significantly higher than scores on the balance of the exam.

On the course's final design project, there were several options to complete a renewable energy design: solar, wind, microhydroelectric, biomass, etc. All eight students chose the solar power option for their design. Their cost calculations and their practical energy estimates strongly correlated to conclusions on the issues that they addressed in this laboratory exercise.

An unexpected benefit of this lab appeared while the students were doing the experiments. Students taking measurements while holding photovoltaic panels up to sunny windows along the heavily traveled main hallway of the university's largest academic building attracted attention. This became great advertising for the renewable energy course.

Conclusions

A simple laboratory exercise to generate enthusiasm and understanding quickly with minimal investment has been described in this paper. Using four different solar panels created with different technologies, totaling less than a couple hundred dollars, students evaluated the behavior of solar panels. They estimated power output capacity, they determined relative efficiency, they found cost per Watt, and they estimated the effect of azimuth on the performance of a solar panel. Results were consistent with published data. They debated these issues with their peers. All this was accomplished within a single hour-long lesson. As a result, enthusiasm for the coursework improved and performance on subsequent work indicated a preference for the technologies encountered in this laboratory exercise.

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