Efficiency of a Photovoltaic Power System

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Abstract ? A new solar energy experiment for Mechanical Engineering Technology students at Purdue University illustrates basic efficiency computations. Efficiency is defined as the electrical energy delivered by a photovoltaic array with respect to the total radiant energy available. The experiment achieves two objectives. Students are exposed to energy conversion concepts that are important for all thermal power courses, but they also get a better understanding of how photovoltaic systems operate.

OUR ENERGY FUTURE

What happens when the demand for energy exceeds the supply? This is a very real (and scary) prospect for the United States. The U.S. Energy Information Administration predicts that in just two decades we will need 175 quads (1 quad = 10^{15} Btu's) to meet anticipated annual energy demands. That is 75% more energy than is used today. Even more alarming, 175 quads is 250 % higher than current U.S. levels of energy production. Solar energy is one of several promising technologies with the potential to reduce the demand for diminishing fossil fuels. Despite being abundant, renewable, and non-polluting, solar energy is not widely understood or deployed. It is surprising that solar energy contributes less than 0.1% of the energy annually used in the U.S. [1]

Figure I shows a new photovoltaic array and an older active loop solar heating system that teach students about the importance of renewable energy. They are located on the roof of the Knoy Hall of Technology on the West Lafayette campus of Purdue University. The 3 kW photovoltaic array was designed and built by Mechanical Engineering Technology students during 2001 and 2002. It consists of 24 120 Watt Kyocera panels that are wired to produce a 48 Volt array voltage. The array current varies with sunlight intensity. Reference [2] provides additional information about the layout and design of the new photovoltaic array.

The 30,000 Btu/hr active loop solar heating system shown in Figure I has been in place for many years. Reference [3] describes the solar heating system and explains how it is used to demonstrate basic thermal energy calculations for students in Heat Power (MET 220), a required laboratory course for sophomore students in Mechanical Engineering Technology. It is interesting to note that the new photovoltaic system provides the electrical energy for the fans and pumps on the older active loop solar collectors. Since being "unplugged" from the utility grid, all the solar energy equipment is totally self-contained.

FIGURE. I
3 kW Photovoltaic Array and 30,000 Btu/hr Solar Heating

MEASURING INSTANTANEOUS PV PERFORMANCE

The remainder of this paper discusses a new experiment for MET 220 that computes the energy conversion efficiency of the photovoltaic array at one time of day. Although an efficiency reading averaged over an entire day would probably be more representative of overall array performance, instantaneous measurements allow the experiment to be completed in one laboratory session. Students are asked to consider cloud cover, time of day, and seasonal factors in the "discussion" section of the lab report.

Before starting this experiment, students are reminded about the potential danger associated with electrical equipment. Even though students have taken a required lab-based Electrical Engineering Technology course before MET 220, this initial safety caution is always important. Students determine the output power by measuring the instantaneous DC current and DC voltage coming from the photovoltaic array. A handheld Fluke model 337 clamp meter is used for these measurements.

The array input power is measured directly from the sun. Students use a data acquisition system to monitor an Eppley Model PSP solar pyranometer. This sensor is permanently mounted at the same angle as the photovoltaic array and records the total broadband (sun and sky) radiation in units of Watts per square meter. The pyranometer measurement is not an instantaneous reading, but is averaged over a short time interval. The average reading helps smooth out erratic readings that can occur on cloudy days.

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Table I is an example of data used for computing the instantaneous energy conversion efficiency of the photovoltaic array. The measurements were made on a sunny day in January of 2003. Column 1 shows that readings were made approximately twice each hour between 9 AM and 3 PM.

Columns 2 and 3 of Table I show the DC current and voltage readings from the array. Column 4 shows the electric power from the array in Watts, which is computed by multiplying DC amps by DC volts. As expected, the array output power peaks between noon and 1 PM.

Sunlight intensity is shown in column 5 of Table I. Rather than displaying an instantaneous reading, which is strongly affected by momentary cloud cover, the sunlight intensity in column 5 is averaged over a 30 minute interval. Column 6 converts sunlight intensity to power in Watts by multiplying by the surface area of the array. The total area of 24-120 Watt Kyocera panels is 22.32 square meters. As expected, the sun's energy peaks between noon and 1 PM.

TABLE I
PHOTOVOLTAIC PERFORMANCE ON A SUNNY JANUARY DAY

Time of Day	Array Performance			Sunlight Performance		Overall Efficiency
	Amps	Volts	Watts	Watt/m^2	Watts	%
9:30 AM	3.1	49.1	152	64	1428	11
9:45 AM	3.3	47.8	158	111	2478	6
11:00 AM	8.5	47.7	405	390	8705	5
11:30 AM	25.7	50.6	1300	522	11651	11
12:00 PM	41.4	52.9	2190	866	19329	11
1:00 PM	32.4	63.6	2061	910	20311	10
1:30 PM	20.2	71.0	1434	787	17566	8
2:00 PM	17.5	73.1	1279	806	17990	7
2:15 PM	15.9	61.4	976	806	17990	5
3:00 PM	13.2	73.8	974	182	4062	24

The last column shows the calculated efficiency of the photovoltaic array. The efficiency term is all-inclusive. It is a direct comparison of radiant energy available to electrical energy delivered. It specifically includes transmission losses between the rooftop array and the final point of use. Table I does not contain enough data to accurately assess trends in solar energy performance. The instantaneous efficiency does not appear to vary uniformly over the course of a day or as a function of sunlight intensity.

The efficiency values fall within published limits for commercially available photovoltaic systems. Efficiencies as high as 15% are relatively common. The last efficiency value (24%) is an outlier that should probably be disregarded. As indicated by the high array voltage for the 3:00 PM computation, the electrical power measurement was made after the battery bank was fully charged. This tends to inflate the overall efficiency because a large voltage leads to a correspondingly low current, which minimizes significant transmission losses. The sunlight performance at 3:00 PM presents another problem. The 182 W/m^2 measurement was made towards the end of the day, when the sun's intensity was rapidly declining. It is difficult to get an accurate reading under these dynamic conditions.

IMPACT ON STUDENT LEARNING

In the "discussion" section of the lab report, students are asked to describe their impression of the role of solar energy in meeting future energy needs. Three representative comments are listed below:

"I believe solar energy will become a much more widely used source of energy. However, this will not happen until solar cells become more efficient, available, and cheaper."

"In the future solar energy will be a great source of power. As for the present, getting the efficiency to a higher percentage (over 20%) is one of the hardest things to do."

"It is my belief that solar energy will increase and become much more important to the future. I believe the only reason why we have not adopted more to using this plentiful source of energy is because oil and other resources are much easier to use."

The student comments suggest a realistic understanding of the strengths and weaknesses of photovoltaics. While students were impressed with the potential of solar energy, they also understood the challenges. Photovoltaic systems will have to become cheaper and more efficient before they will be more widely deployed.

CONCLUSION

A relatively simple photovoltaic efficiency experiment has some important lessons for Mechanical Engineering Technology students. It forces students to recognize that energy conversion processes are not perfect. In the case of a photovoltaic array, efficiencies less than 15% are always somewhat disappointing. The low efficiency and relatively high cost of photovoltaic equipment are the primary reason solar energy systems are not more widely deployed. This experiment also provides a useful opportunity for classroom discussions about renewable energy, which will become increasingly important for our energy hungry society.

REFERENCES

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