Design of a Photovoltaic Panel Experiment for an Undergraduate Heat Transfer Lab

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Abstract

Renewable energy sources and systems have become popular topics of study for engineering students. In this article, the authors present a renewable energy project that they have integrated in a junior-level heat transfer laboratory at Indiana University–Purdue University Fort Wayne (IPFW). The project makes use of a photovoltaic panel that is mounted on a portable frame which allows adjustment of the panel tilt angle. A bank of resistors is available to provide a variable load on the device, and the panel is instrumented to read voltage and current. The incident solar radiation is also measured using a pyranometer. In the project, students are required to design an experiment to determine the resistance load that results in the maximum power output. Then, they investigate the effect of the panel angle on the power output and determine the efficiency of the panel in converting solar radiation to electrical power. This type of activity serves to enhance the students' understanding of renewable energy sources and energy conversion processes. It also provides the students an opportunity to apply knowledge acquired in an electric circuits course to a practical application.

Introduction

Due to environmental issues and limited fossil fuel resources, more and more attention is being given to renewable energy sources.[1] Radiation from the sun is one example of a renewable energy source. The sun provides an enormous amount of energy to the earth daily and engineers have long been striving to harness this energy. One often quoted rule-of-thumb is that the amount of solar energy absorbed by the earth in one hour is sufficient to meet the energy consumption of the world for one year (see for example some of the facts at www.renewablegreenenergypower.com).

In 2011, the International Energy Agency said that "the development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. It will increase countries' energy security through reliance on an indigenous, inexhaustible and mostly import-independent resource, enhance sustainability, reduce pollution, lower the costs of mitigating climate change, and keep fossil fuel prices lower than otherwise."[2] Many different systems and devices have been proposed to harness this vast energy resource (see for example some described in References [3] and [4]). Devices are necessary to convert the electromagnetic radiation from the sun into other more usable forms of energy such as thermal energy or electrical energy. The conversion of solar radiation to thermal energy can be accomplished by passive architectural systems, such as the Trombe wall to heat air, or active systems, such as solar collectors to heat water. The conversion of solar radiation first to thermal energy then to electricity can be accomplished by heliostat power plants, while photovoltaic systems directly convert solar radiation into electricity.

The focus of this paper is the photovoltaic panel. Figure 1 illustrates the solar radiation to electricity conversion process. Photovoltaic systems have been the topic of many studies over the years. Figure 2 shows a historical record of solar cell efficiencies. While the maximum efficiencies achieved in the laboratory have reached over 40%, typical commercially available solar panels have efficiencies of approximately 15%. Real-world applications, such as photovoltaic panels, studied in a laboratory setting can be useful to help certain types of student learners understand some of the important concepts.

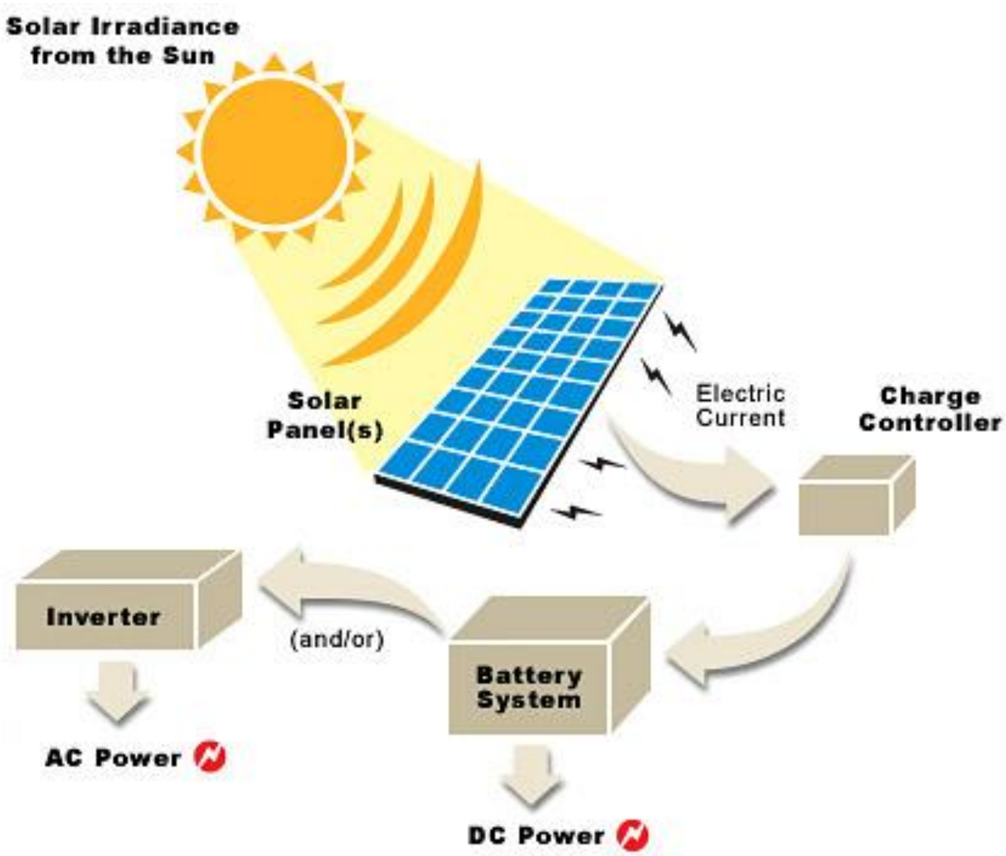

Figure 1: Use of a solar panel to convert solar irradiance to electrical power.
(www.alternative-energy-news.info/technology/solar-power)

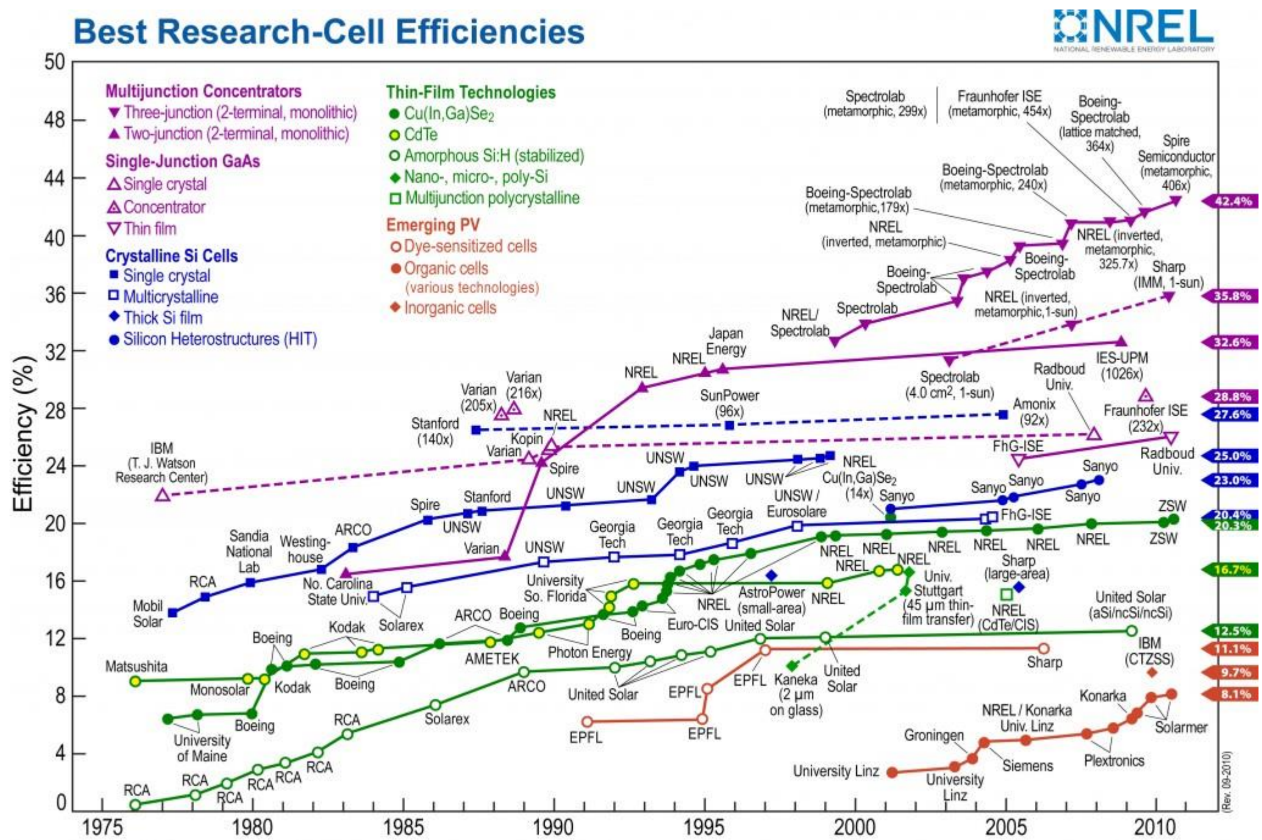

Figure 2: Historical record of PV cell conversion (electromagnetic to electrical) efficiencies. (www.nrel.org)

The Accreditation Board for Engineering and Technology (ABET) has as one of its outcomes that programs must demonstrate: (b) an ability to design and conduct experiments, as well as to analyze and interpret data. In order to partially achieve this outcome, the heat transfer laboratory has a course outcome that states: Students who successfully complete this course will have demonstrated the ability to design a heat transfer device or system to achieve a specific objective or design an experiment to characterize a heat transfer device or system; then develop a model (if appropriate), perform a test, and report the results. In recently published studies,[5,6] educators at IPFW describe a design-build-test (DBT) and design-of-experiment (DOE) activity in which students are asked to design an experiment which uses a solar collector to heat water in a reservoir and determine the efficiency of the process by doing the required performance analysis.

In this article, the authors present another renewable energy project that they have integrated in an undergraduate heat transfer laboratory at Indiana University–Purdue University Fort Wayne (IPFW). The project makes use of a photovoltaic panel that is mounted on a portable frame which allows adjustment of the panel tilt angle. A bank of resistors is available to provide a variable load on the device, and the panel is instrumented to read voltage and current. In the project, students are required to design an experiment to determine the resistance load that results in the maximum power output. Then, they investigate the effect of the panel angle on the power output and determine the efficiency of the panel in converting solar radiation to electrical power. This type of activity serves to enhance the students' understanding of renewable energy sources and energy conversion processes. It also provides the students an opportunity to apply knowledge acquired in an electric circuits course to a practical application.

Description of Apparatus

Figure 3 shows the experimental apparatus. The apparatus was designed and constructed by Jason Davis, Maurice Ralston, and John Mitchell, members of the IPFW engineering and technology technical staff.

The solar panel is a Kyocera KC85T high-efficiency, multicrystal module. The device is rated with a maximum power of 87 W, an open circuit voltage of 21.7 V, and short circuit current of 5.34 A. The panel measures 2 ft. x 3 ft. and has an effective of area of 0.59 m^2.

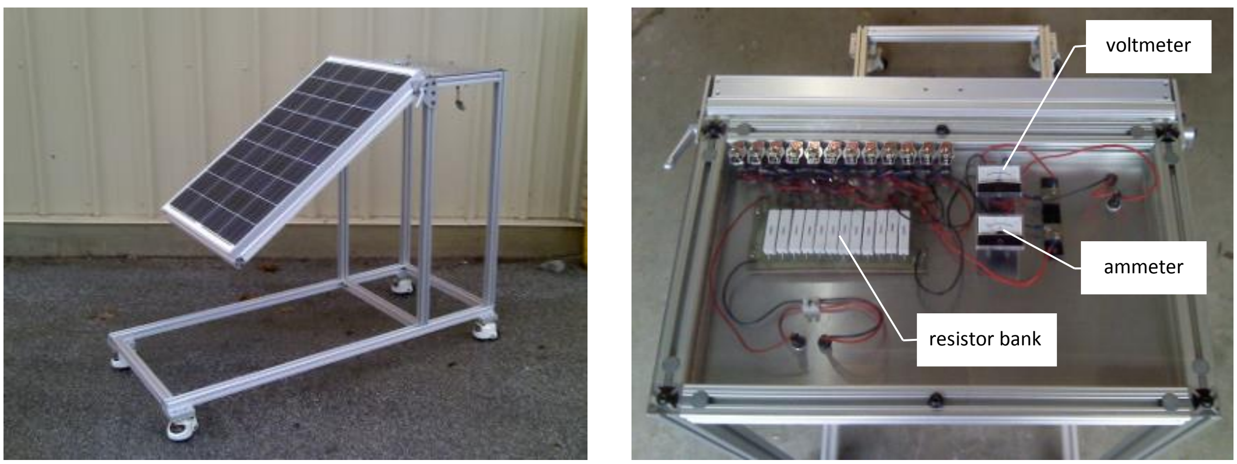

Figure 3: Photographs of the apparatus and the instrumentation.

The frame is constructed of 80/20 tubular framing (1.5 in.), and it measures 0.685 m in width, 1.52 m in length, and 1.04 m in height. The apparatus is mounted on wheels, making it portable, but it can be securely locked in place. The tilt angle of panel is adjustable from 0 degrees (horizontal) to 90 degrees (vertical).

A schematic of the electrical circuit design is shown in Figure 4. A bank of twelve, 20 ohm resistors wired in parallel is available to provide an external load to the panel that range from 0 to 20 ohms. The resistors are added to the circuit by closing the corresponding switch. An analog 30 V-voltmeter and analog 10 A-ammeter are used to measure the voltage and the current, respectively. An auxiliary connection is available to connect a digital voltmeter that can also be used to obtain measurements. Fuses are in place for safety and to protect components.

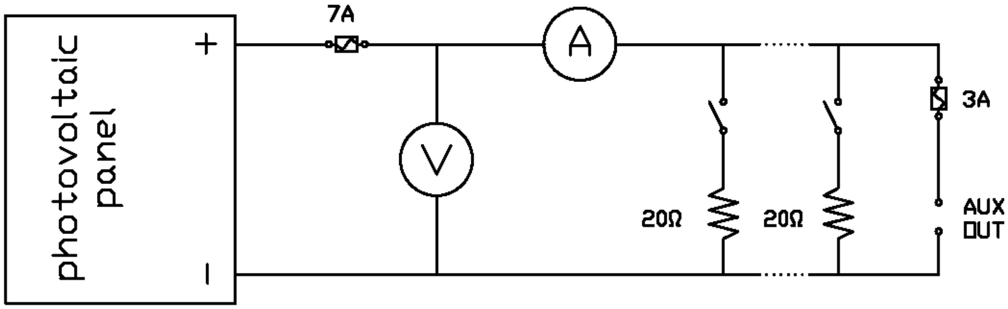

Figure 4: Schematic of electrical design. A bank of twelve, 20 ohm resistors are available to provide an external load ranging from 0 to 20 ohms to the panel.

In order to calculate the input energy to the system the SDL-1 Solar Data Logger model from Micro Circuit Labs Co.[7] is used to measure the sun's average irradiance at regular time intervals (Figure 5). It is powered by a 9 V battery and a USB interface allows the data to be loaded to the computer. The communications program RealTerm is used to capture logged data to a text file to be analyzed and plotted using a spreadsheet program. The SDL-1 also reports the cumulative incident solar energy that it receives during deployment.[7]

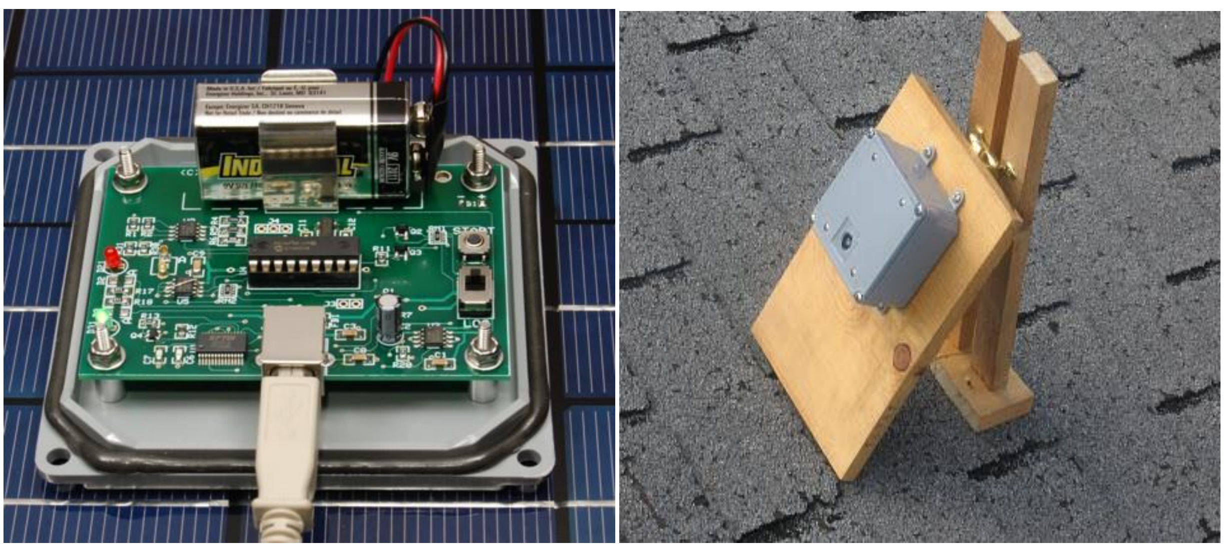

Figure 5: SDL-1 Solar Data Logger (photos from Ref. [7]).

The incident radiation on a horizontal surface could also be determined from the IPFW Geosciences Weather Station website at http://geo.ipfw.edu/geoweather/allReadings.html. The station uses a Davis Vantage Pro Plus Integrated Sensor Suite which includes a solar pyranometer to measure solar irradiance.

Problem Statement and Experimental Procedure

The apparatus is flexible and adaptable so that different experiments can be assigned each semester or to different student lab teams. For example, student teams could be asked to design an experiment:

- to determine the resistance load that results in maximum power output by using the installed bank of resistors and creating appropriate graphs for voltage, current, and power.
- to study the effect of panel angle on power output at the optimum resistance load.
- to determine the efficiency of the panel at converting solar radiation to electrical power.

Each lab group is to independently create and perform an experiment satisfying one (or a combination) of these objectives and submit a report and presentation on their work.

A typical experiment procedure to determine the optimal resistance load, observe the effect of panel angle on power output, and determine the efficiency of the panel is as follows:

1. Move the solar panel to a flat area in direct sunlight in a location without much reflected light from buildings, etc.
2. Aim the panel so it is in line with the sun's azimuth (compass direction).
3. Calculate or look up the altitude of the sun.
4. Adjust the vertical angle between the solar panel and its frame to the altitude of the sun, which makes the panel and the incoming light from the sun perpendicular.
5. Switch on each parallel 20Ω resistor one by one, recording the current and voltage each time.
6. Record the number of resistors (and total resistance) that result in the most power output.
7. Set the number of active resistors to the number that gives the most power.
8. Rotate the panel from vertical to horizontal in small increments, such as 10 degrees, taking voltage and current readings at each angle setting.
9. Set the panel's angle to that which gives the most power.
10. Record the incoming solar radiation in using the SDL-1 Solar Data Logger described in the previous section.
11. Measure the surface area of the solar cells on the photovoltaic panel.
12. Multiply the panel area times the incoming solar radiation to find the maximum possible power if the panel converted all solar radiation to electricity.
13. Divide the highest power output from the panel by the solar power hitting it to find its efficiency.

Sample Results

Typical experimental results are shown in Figures 6 and 7. The data was collected from 1:37 pm to 1:55 pm on 9 January 2013. The air temperature was 34^{o}C and the sky condition was mostly sunny with thin clouds. The photovoltaic panel was oriented at a compass angle of 179 degrees and a tilt angle of 45 degrees. The solar data logger was used to determine that the average solar radiation incident on the panel during the test was 786 W/m^2. Note that the theoretical sun position altitude was 25.8 degrees and the azimuth was 193 degrees; theoretically, the maximum amount of energy would be incident on the panel if it is oriented perpendicular to the incident radiation.

Figure 6 shows the current and voltage as external loads ranging from 0 to 20 ohms are applied to the panel. As expected, the current is a minimum at the maximum resistance and as the external resistance is reduced the current increases. Note that at some of the lower resistances clouds slightly obscured the panel causing the current to decrease.

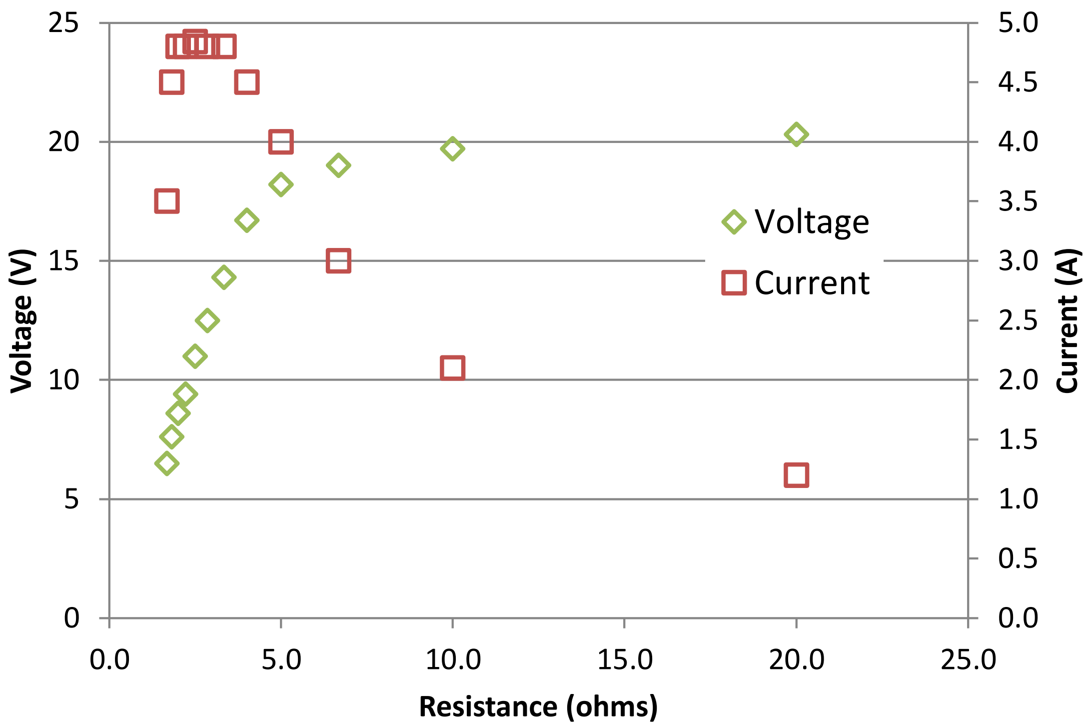

Figure 6: Variation of current and voltage as the external load on the panel is varied.

Figure 7 shows the variation of the electrical power produced as the external resistance load on the panel is varied. The electrical power is determined by simply multiplying the current and voltage. The maximum power of 75.2 W occurs at an external resistance of 4 ohms. The solar power incident on the panel is 461 W (found by multiplying 786 W/m^2 by 0.59 m^2) which results in a conversion efficiency of 16.1%. This value is in agreement with the published values for multicrystal photovoltaic panels as shown in Figure 2.

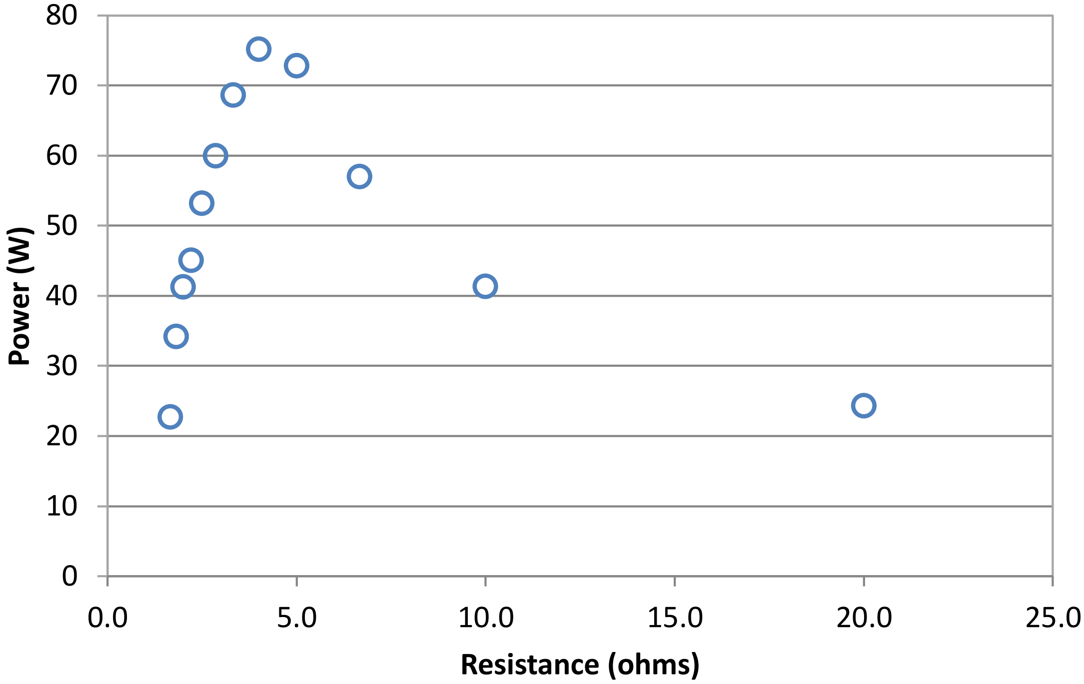

Figure 7: Variation of power as the external load on the panel is varied.

Concluding Remarks

This paper describes the implementation of a common energy conversion device and activity that involves a renewable energy source. The set-up is flexible to avoid repeating the same activities from semester to semester or from group to group. The set-up and the activity can be used to initiate discussions involving renewable energy and other contemporary issues.

While no formal survey was given to the students to assess specific learning from this activity, established assessment tools indicate that students are pleased with the experience. Through the assessment process and student surveys, both the students and the instructor felt that the students were able to design and model a heat transfer system to meet a specific objective; then test and report results.

Acknowledgement

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References

1. D. Y. Goswami, S. Vijayaraghavan, S. Lu, and G. Tamm, "New and emerging developments in solar energy," *Solar Energy,* Vol. 76, 33–43, 2004.
2. International Energy Agency, *Solar Energy Perspectives: Executive Summary*, www.iea.org, 2011.
3. B. K. Hodge, *Alternative Energy Systems and Applications*, Wiley & Sons, 2010.
4. F. Kreith and J. F. Kreider, *Principles of Sustainable Energy*, CRC Press, 2011.
5. H. I. Abu-Mulaweh, D. W. Mueller, and A. McCormick, "Integration of Design-Build-Test Concept in Undergraduate Engineering Education," *World Transactions on Engineering and Technology Education,* Vol. 9, No. 3, 2011.
6. A. Saleh, D. W. Mueller, and H. I. Abu-Mulaweh, "Design of a Solar Collector Experiment for an Undergraduate Heat Transfer Lab," *American Society for Engineering Education*, Valparaiso University, 2012 IL/IN Sectional Conference, 2012.
7. Micro Circuit Labs, *SDL-1 Solar Data Logger: Assembly and Operating Manual*, www.microcircuitlabs.com, 2010.

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