Energizing the Next Generation with Photovoltaics

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ABSTRACT

Following the lead of Russian colleagues, photovoltaic (PV) lab kits are being built and experiments and curricula are being developed for use of these kits. This Photovoltaic Science Experiments and Curriculum (PSEC) is being tested in local high schools, at Lane Community College, and at the University of Oregon. The building and testing of the PV lab kits are in their initial stage. Teachers have been taught to use the PV kits and the PSEC is being tested in local high school science classes. Concurrently the PSEC is being used in a freshman science seminar and plans are to use the PV lab kit for training future solar installers at Lane Community College. Evaluation of these experiences will be used to refine the PSEC. Further testing will be done in the 2010-2011 school year with the improved kits and curricula. A similar PSEC concept is already being tested in several cities in Russia and an exchange of experiences will further help improve the package. Final evaluations will be made and the PSEC will be made available on the Web. A lending library for the PSEC will be established in the Physics Department at the University of Oregon.

1. INTRODUCTION

To understand sustainability and appreciate fully the interactions and consequences of our actions, it helps to have a background in science. Right now, renewable energy and, particularly, photovoltaics (PV) are hot topics in the news. The PV industry comprises a major renewable energy technology that is undergoing rapid deployment and stimulating growth in our region's economy. The Photovoltaic Science Experiments and Curriculum (PSEC) is designed utilize this exciting sustainable technology to harness a student's innate enthusiasm and their boundless imagination and teach the basic scientific principles in a captivating and inspiring manner.

Reducing the amount of carbon dioxide dumped into the atmosphere is a major challenge for the 21st Century. Renewable energy technologies offer a solution to this problem, and implementation of this solution will require the deployment of every type of renewable technology as well as considerable use of conservation and energy efficiency. To bring down CO_2 levels to an acceptable level, the population needs to understand how renewable technologies operate and a workforce needs to be trained to manufacture, install, maintain, and operate the renewable technologies. Photovoltaic systems constitute a key renewable technology that needs to be widely deployed if a sustainable energy mix is to be established.

In addition to teaching students about science and solar technology, the PSEC facilitates and encourages the installation of photovoltaic systems in schools. The optimum learning experience occurs when an operating photovoltaic system is combined with a classroom curriculum [1]. For example, Emerald People's Utility District (EPUD) installed photovoltaic systems at the high schools in the service territory and lesson plans developed by the University of Oregon Solar Radiation Monitoring Laboratory (UO SRML) were used to stimulate the interest of teachers at the high schools who then provided support for the installation of the systems in the high schools [2]. Without the teacher support at the high school, it would have been much more difficult for EPUD to get permission to install the systems.

2. PROJECT OVERVIEW

The existing prototype curriculum, developed by Vignola

first published in the SOLAR 2010 Conference Proceedings

Fig. 1: Russian PV lab kit for study characteristics and parameters of solar cells also principles of solar module' design.

Fig. 2: The cover of the book that analyzes the experience of introducing new school technologies in Russia

and Erickson for 9th grade students, is available on the UO SRML Website at http://solardata.uoregon.edu/LessonPlans.html. Teaching modules cover the basics of energy, how a PV cell works, testing PV cells, and how PV arrays are assembled to produce electrical power. These lesson plans serve as the basis for PSEC package that is being tested in the high schools. The PV lab kits include a PV module with two independent solar cells, meters, wires, contacts, filters, terminals and banana plugs, propellers with motors, DC lights, resisters, and lamps with incandescent and fluorescent bulbs. The electronic components are assembled onto a breadboard for ease of use, storage, and transport. Recycled materials are used to make the lab kits when possible. Sources for these recycled materials will be included in the list of components in the PSEC package. The lesson plans include introductory reading material, lab activities for testing photovoltaic cells including a description of expected results and assessment tools including suggestions for follow-up labs.

In previous papers [1, 3, 4] the overall concept of a PV lab kit was discussed and a potential curriculum was developed. Many of the concepts are modeled after work done in Russia with similar PV lab kits (Fig. 1). During 2008-2009 the Russian federal project for schools was initiated in the Moscow, Kaluga and Ryazan regions. An analysis of the Russian experience of introducing new technologies at schools is documented in a book published in 2009 (Fig. 2) [5].

A grant from the Meyer Fund for a Sustainable Environment enabled the purchase of materials for the kits and the hiring of a graduate student and student intern to help build the kits and work with the teachers. In all, 50 of these PV lab kits will be built. The main goal is to make this PSEC package available to high school teachers for use in classrooms. This paper details the design of these lab kits, briefly describes various experiments that have been developed for use of PV kits, and discusses the lessons learned by those using the PSEC package in a classroom setting.

3. DISCRIPTION OF THE LAB KITS

Each lab kit consists of a PV module with two solar cells, two multi-meters, two lamps, four color filters, a filter opaque to visible light, a filter opaque to infrared irradiance, connecting wiring, and loads including resisters, propeller fans, and light bulbs mounted on a circuit board. The PV module consists of two unconnected photovoltaic cells sandwiched between two polycarbonate sheets. The cells are attached to the back sheet with a non-corrosive sealant. The tabbing from the solar cells is soldered to conducting tape, as are bolts holding the module together. A color-changing temperature strip is inserted between the two solar cells to indicate the approximate temperature of the cells. Banana plug spades are fastened to the bolts, and all other connec-

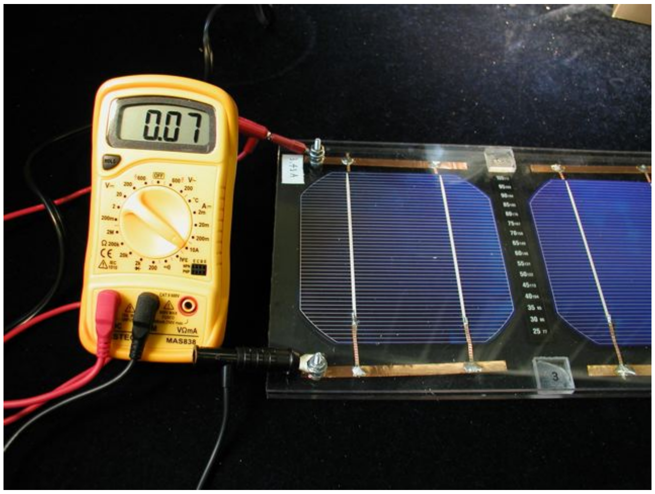


Fig. 3: Multi-meter connected to measure the short circuit current of one solar cell

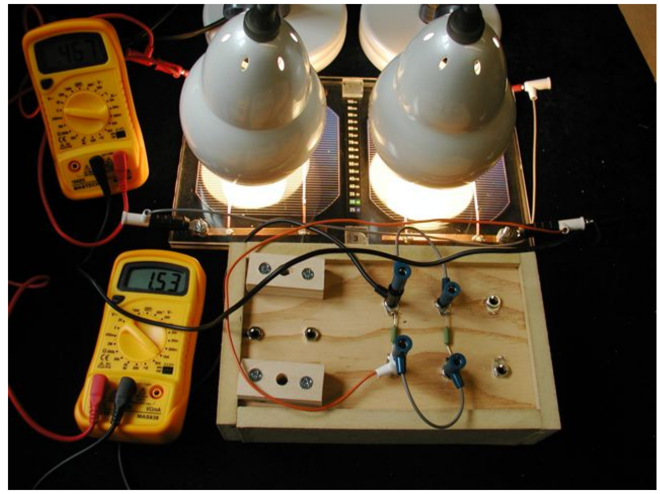


Fig. 4: Circuit board and meters measuring the effect of load on the circuit

tions use banana plugs to simplify changes in circuits and monitoring modes.

Circuit boards were made from recycled wood to demonstrate a further example sustainability. Rechargeable batteries are to be purchased for the multi-meters. Solar cells for the project were donated by SolarWorld, a local manufacturer.

An example of the PV module connected to the multi-meter for a short circuit current reading is shown in Fig. 3. The structure of the module can be seen clearly in this figure. The module is simple to construct and can be taken apart to replace broken cells or make other changes. The module is not designed for use in wet environments.

The circuit board is illustrated in Fig 4. The figure shows the connections for metering the current and voltage during an experiment to measure an ampere-voltage characteristic (IV) curve. Different combinations of resisters are used to get points along the IV curve.

4. EXPERIMENTS UNDER REVIEW

Many classroom experiments are possible using this PV kit: The following experiments are being tested for inclusion in the PSEC package.

1. Measuring DC current and voltage of one cell, two cells in parallel, and two cells in series
2. Measuring and plotting the change in DC current as the lamp moves farther and farther from the PV module
3. Measuring the change in DC current with different colored filters, including filters that block only the infrared (IR) or the visible wavelengths of light
4. Measuring the change in DC current with a fluorescent bulb instead of an incandescent bulb
5. Connecting resisters, light bulbs and propellers in a circuit and observing changes in performance with various loads with cells connected in parallel and series
6. Measuring an IV curve—for advanced students
7. Using a heat gun or hair drier and chilled slabs to observe the effect of temperature on voltage and current
8. Testing the effect of shading on cells hooked in series and in parallel

If it is sunny outside, the following experiments could be conducted:

1. Evaluating the effect of tilt on DC current and voltage
2. Using an aluminum foil reflector to increase the DC current

An instruction sheet is supplied with each experiment along with diagrams on how to connect the wiring and meters and a table to fill with experimental data. The following is an example of the instruction sheet for measuring short circuit current and the change of output with distance from the light source.

The first page of instructions contains a paragraph on the overview of the PV lab kit and a list of materials used that the teacher will handout. The following information is given on the cover page of the handout.

Obtain a materials kit from your teacher. Check that it contains the following materials:

- PV Cell Module
- Electrical Leads
- DC ammeter
- DC volt meter
- 1 Lamps
- activity sheets

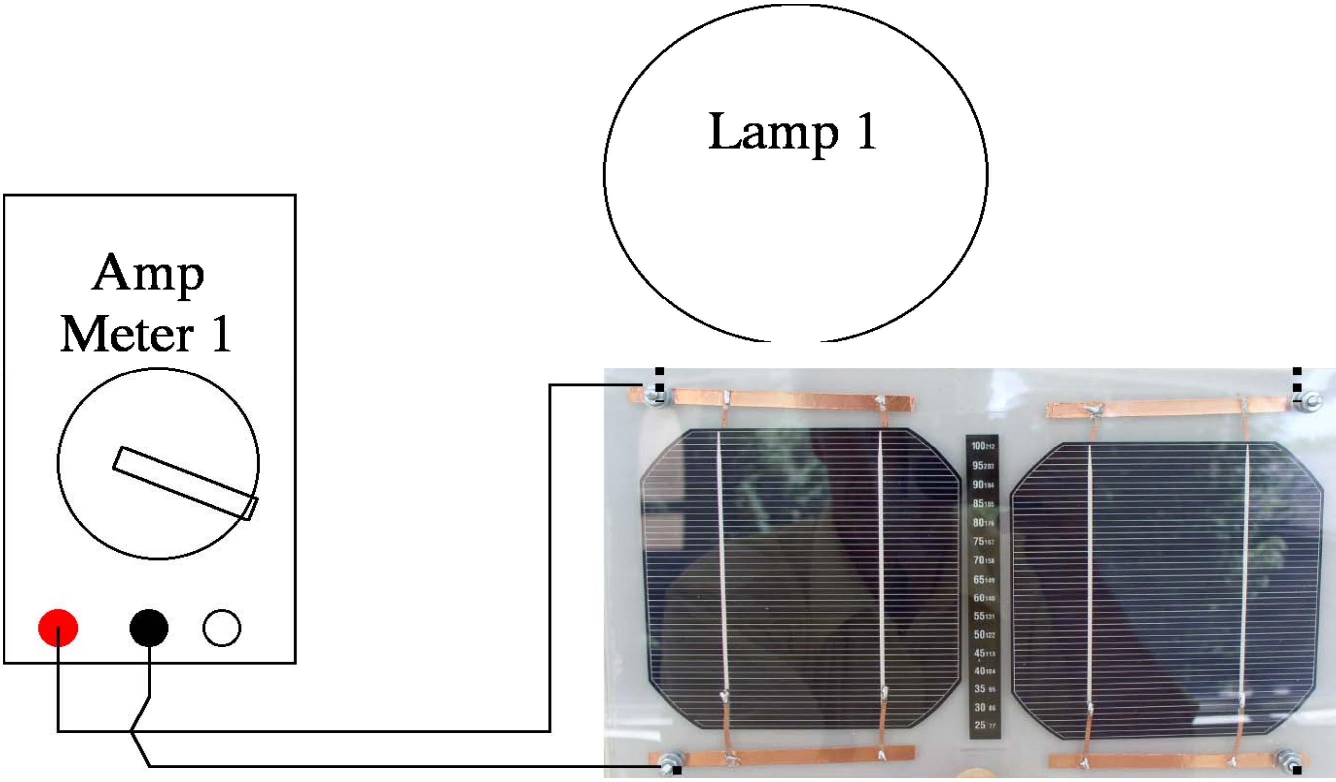


Fig. 5: Set up for current measurement of the one

The following is the description of the experiment with an explanation on how to conduct the experiment.

Part I: Short Circuit Current

1. Connect one Solar Cell to the PV Module as shown in Fig. 5. The red connector is the + output of the cell. The + output connects to the 10ADC input on the meter. The negative black output connects to the COM input of the meter input of the meter. Set the meter dial to the 10A setting. Place the desk lamp as **CLOSE AS YOU CAN** to the PV cell. Measure the distance between the bulb surface and the PV Module. You need to add 3.7cm to your measured distance to have the actual distance between the filament inside the bulb and the solar cell surface located underneath the module's protective cover. Enter the measured distance and short circuit current measured by the meter in Table 1. (If your current reading is zero check your connections and meter settings or call over an instructor for assistance.)

2. Vary the distance of the lamp to the cell by placing the lamp on blocks or books. Each time, record the distance between the lamp and the bulb and the output current in Table 1.

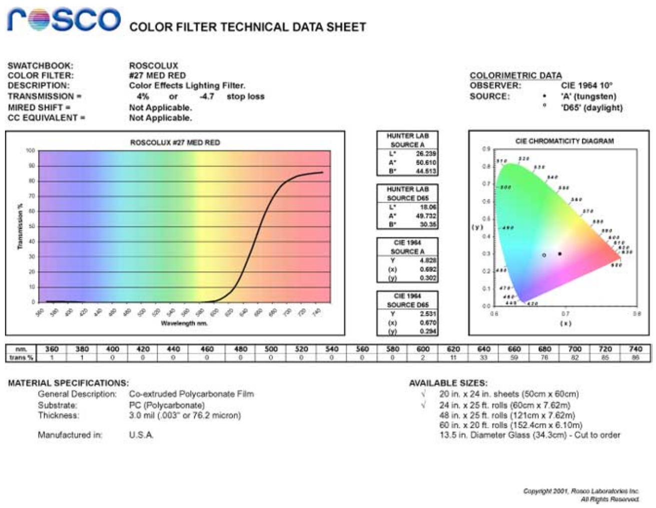
Table 1: Current and Distance

Distance between bulb and PV module (cm)	Actual Distance (Measured Distance + 3.7 cm)	Current (A)

Analysis: Plot a graph of Current vs. Actual Distance to try and see what kind of relationship exists. (You can use a graphing program or the supplied paper.)

What happens to the current when you double the distance between the lamp and the cell? Is the current half as much or is it less than half of what it was?

One complicating factor in this experiment is that the light source is not "centered" on the surface of the light bulb. In addition other ambient light can affect the readings, especially when the lamp is not near the solar cell. It is quite difficult to produce $1/r^2$ falloff, but it can be done with care-



COLOR FILTER TECHNICAL DATA SHEET

SWATCHBOOK: ROSCOLUX
COLOR FILTER: #27 MED RED
DESCRIPTION: Color Effects Lighting Filter.
TRANSMISSION = 4% or -4.7 stop loss
MIRED SHIFT = Not Applicable.
CC EQUIVALENT = Not Applicable.

COLORIMETRIC DATA
OBSERVER: CIE 1964 10°
SOURCE: • 'A' (tungsten) ° 'D65' (daylight)

ROSCOLUX #27 MED RED

HUNTER LAB SOURCE A: L* 26.239, A* 50.610, B* 44.513
HUNTER LAB SOURCE D65: L* 18.06, A* 49.732, B* 30.35
CIE 1964 SOURCE A: Y 4.828, (x) 0.692, (y) 0.302
CIE 1964 SOURCE D65: Y 2.531, (x) 0.670, (y) 0.294

nm.	360	380	400	420	440	460	480	500	520	540	560	580	600	620	640	660	680	700	720	740
trans %	1	1	0	0	0	0	0	0	0	0	0	0	2	11	33	59	76	82	85	86

MATERIAL SPECIFICATIONS:
General Description: Co-extruded Polycarbonate Film
Substrate: PC (Polycarbonate)
Thickness: 3.0 mil (.003" or 76.2 micron)
Manufactured in: U.S.A.

AVAILABLE SIZES:
√ 20 in. x 24 in. sheets (50cm x 60cm)
√ 24 in. x 25 ft. rolls (60cm x 7.62m)
48 in. x 25 ft. rolls (121cm x 7.62m)
60 in. x 20 ft. rolls (152.4cm x 6.10m)
13.5 in. Diameter Glass (34.3cm) - Cut to order

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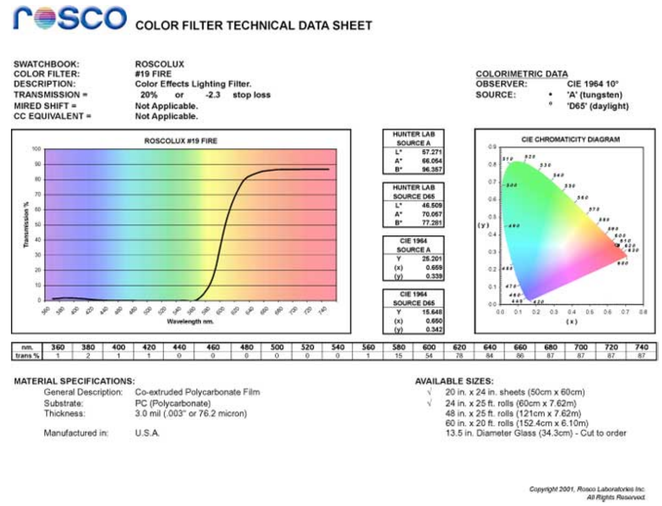
Fig. 6: Colored filter transmisivity. #27 Medium Red blocks wavelength less than 620 nm.



COLOR FILTER TECHNICAL DATA SHEET

SWATCHBOOK: ROSCOLUX
COLOR FILTER: #19 FIRE
DESCRIPTION: Color Effects Lighting Filter.
TRANSMISSION = 20% or -2.3 stop loss
MIRED SHIFT = Not Applicable.
CC EQUIVALENT = Not Applicable.

COLORIMETRIC DATA
OBSERVER: CIE 1964 10°
SOURCE: • 'A' (tungsten) ° 'D65' (daylight)

ROSCOLUX #19 FIRE

HUNTER LAB SOURCE A: L* 57.271, A* 66.054, B* 96.357
HUNTER LAB SOURCE D65: L* 46.509, A* 70.067, B* 77.281
CIE 1964 SOURCE A: Y 25.201, (x) 0.659, (y) 0.339
CIE 1964 SOURCE D65: Y 15.648, (x) 0.650, (y) 0.342

nm.	360	380	400	420	440	460	480	500	520	540	560	580	600	620	640	660	680	700	720	740
trans %	1	2	1	1	0	0	0	0	0	0	1	15	54	78	84	86	87	87	87	87

MATERIAL SPECIFICATIONS:
General Description: Co-extruded Polycarbonate Film
Substrate: PC (Polycarbonate)
Thickness: 3.0 mil (.003" or 76.2 micron)
Manufactured in: U.S.A.

AVAILABLE SIZES:
√ 20 in. x 24 in. sheets (50cm x 60cm)
√ 24 in. x 25 ft. rolls (60cm x 7.62m)
48 in. x 25 ft. rolls (121cm x 7.62m)
60 in. x 20 ft. rolls (152.4cm x 6.10m)
13.5 in. Diameter Glass (34.3cm) - Cut to order

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Fig. 7: Colored filter transmisivity. #19 Fire blocks wavelengths less than 580 nm.

ful measurements. The estimate of the distance between the filament and the surface of the light bulb is necessary along with an estimate of the distance between the module cover and the solar cell, and this information is supplied in the example. Figuring out why the inverse square law is not working if one uses the distance from the light bulb to the module could be a challenging test for advanced students if the actual distance is not provided.

Part II of this experiment is performed using a similar setup and measuring the open circuit voltage as the distance from the lamp to the cell varies. The only difference is that the multi-meter setting and connections are changed to voltage from current. The open circuit voltage decreases fairly slowly as the lamp moves away, but does start to change more rapidly when the lamp is about 20 centimeters from the solar cell. It can be interesting to see how the students interpret these results after seeing how the short circuit reacts to distance from the light source.

5. OVERVIEW OF EXPERIMENTS

A brief overview of some of the suggested experiments should be useful background for a discussion of students' and teachers' reactions to the PSEC package.

5.1 Measuring DC current and voltage from cells in series and parallel

The experiments that measure DC current and voltage for one and two cells in series and parallel are expected to show that solar cells act as batteries. The voltage adds when the solar cells are connected in series and the current adds when the solar cells are connected in parallel. However, the total power is the same in both cases. This is a difficult concept for some students. Clear instructions are necessary so that students get results that are accurate enough to see the appropriate difference.

5.2 Shading of solar cells in series and parallel

The solar module also reacts differently to shading when the two cells are connected in parallel versus in series. When the cells are connected in parallel, the decrease caused by shading is proportional to the area covered. When the cells are connected in series, the current goes to near zero when one cell is shaded. In this experiment, one has to use cardboard or other material that doesn't pass the light. A piece of paper lets too much light pass and the expected results will not be realized.

5.3 Filter experiments

There are a number of experiments that can be done with filters. Solar cells are responsive to a specific band of wavelengths. If the filters block that wavelength region, then the current and consequently the power production are significantly reduced. The transmisivity of the two filters are shown in Figures 6 and 7. There should be some differences in the current produced when employing different filters. However, only small changes are seen in experiments with a lamp using an incandescent light bulb. A fluorescent light bulb, while producing considerably less current, is more affected by the filters.

Tests with a spectral radiometer on these filters is planned to help explain such behavior. The transmisivity shown in the charts (Figures 6 and 7) does not show the transmisivity for the wavelengths in the near infrared.

An alternate approach is to use a filter that is opaque to visi-

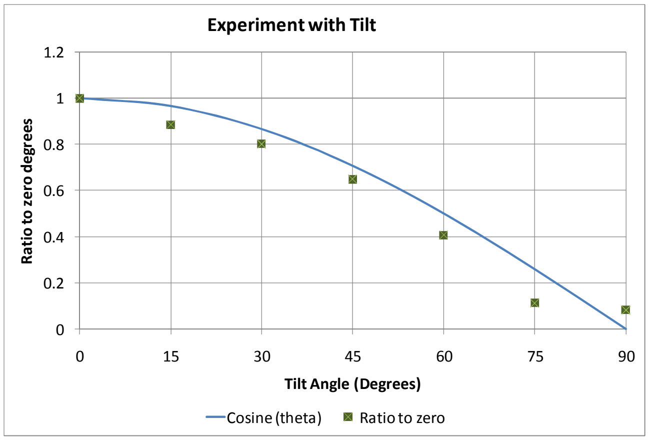

Fig. 8: Experimental results of DC current verses tilt. Solid line is cosine of tilt. Squares are ratio of measured DC current at tilt divided by DC current tilted zero degrees.

ble light but transparent to IR and another filter that is opaque to IR but transparent to the visible light. Experiments with these two filters show that the incandescent light contains a large infrared component, especially when compared to fluorescent light. Student are usually amazed when they are shown that something they cannot see through can still transmit energy, as shown by the current on the solar cell. When contrasted with the filter that appears transparent but is opaque to the IR students start to realize that there is something more than meets the eye.

5.4 <u>Measuring DC current produced by incandescent and fluorescent light bulbs</u>

A simple experiment is to replace the 60W incandescent light with an equivalently bright fluorescent light. The brightness appears about the same, but the fluorescent light uses about 1/4 of the energy. The DC current that is measured from the solar module with the incandescent light is higher than that measured with the module in front of the fluorescent light. Of course the incandescent light produces a lot of IR and some of this IR is used by the solar cell to produce electricity. This helps explain why incandescent bulbs are less efficient than fluorescent bulbs. Use of the filter with the two different light sources can also help make the point and can emphasize the spectral nature of light.

5.5 <u>Connecting resisters, lights, and propellers</u>

Student enjoy connecting propellers and lights to the PV circuit. Given free reign they will see how many lights or propellers they can connect to the circuit, and they will experiment with a variety of connections. The speed of the propellers is a more salient clue to some students than a change in current reading on a meter.

Fig. 9: Students in a freshman physics seminar are measuring the DC current with the lamp at different heights from the solar cells.

5.6 <u>Measurements with tilt</u>

On a clear day, the PV module and ammeter can be taken outside to measure the solar radiation. The student gets the most current while pointing, assuming that clouds are not affecting the readings. Student can then use a protractor to measure the tilt of the PV module with respect to the sun.

Measuring the DC current as a function of tilt was one of the more successful experiments. Students were able to produce results similar to those expected (Fig. 8).

6. <u>REVIEW OF PV LABS</u>

The PSEC package was used at Crow High School as part of the physical science curriculum. The following are observations by Sadie Thorin on how the kits were used and what went right and what could be improved in her general science class. This was the first time the PSEC package was used in a classroom setting.

Prior to doing the labs, the class discussed and learned about different types of alternative energy sources. Thorin found that more time should be spent on *how* PV panels work, with perhaps a little more preparation involving the hardware than occurred the first year. The labs took too long a time to get through and students found it increasingly difficult to pay attention as the labs proceeded. If the labs were to be shortened or streamlined, then more time could be spent on the curriculum.

6.1 <u>Part I – Packet I</u>

The class went through four labs, including the experiment in which the angle of the PV module to the sun was varied, and they answered the questions attached to the instructions for each lab.

The teacher recommended several changes to the instruction sheets. The need for improvements in the instructions was also the main complaint from students. They were confused by the instructions, particularly those involving the fluorescent and incandescent light bulbs. Thorin wrote revised lab instructions, adding a space for the color of each filter and documentation on how to calculate the percent transmittance.

Experience showed that a more thorough discussion of the labs would be useful. This would include more training on how to use the meters, how to connect the meters to make voltage and current readings, and how to connect the solar cells in parallel and in series. Students worked through the labs at differing paces, and this made it difficult to discuss problems as they arose. While assignment questions were asked, enquires about the questions had to be answered individually. This was a constant task through the assignments.

6.2 Part II – Effects of Temperature on PV panels

Students designed their own experiments to explore this phenomenon. Most did well and got some data. One group chilled their panels overnight and ended up getting significantly higher current and voltages the next day.

The PV modules proved to be sturdy and stood up well, without damage. However, the effort to come up with individual experiments took up a great deal of time, and Thorin questioned whether it was worth the effort. This is one experiment that might be cut.

Instead of evaluating the effects of temperature on solar cells, it is recommended that more time be allotted for students to design aluminum foil reflectors as part of an independent experiment. Unfortunately, there were not a lot of sunny days when this could be done outdoors.

6.3 Part III – Packet IV – Series and parallel circuits under load

Students were not very successful with this packet. Clearer instructions are needed along with better diagrams illustrating how to connect the multi-meters and cells for different tests. Often with two multi-meters, one meter would not give a reading at all and the student had to switch between a current and a voltage mode. This required changes in the circuit and made the testing difficult. The circuitry diagram was incomplete for this activity and all variations should be diagrammed.

This part of the curriculum is more appropriate for a physics class and not as appropriate for physical science students. Thorin recommended revising the diagrams to give more complete current and voltage connections.

6.4 Part IV – Propellers with series and parallel connections

This activity was fun for students because they got to hook up several propellers and try out a number of different wiring configurations. However, this lab needs revised instructions because the students didn't understand the differences in series and parallel cell hookups. The propellers (fans) were a good idea, and with simpler instructions the students can really see differences with one and then two solar cells connected to the circuit.

6.5 The assessment

Students were asked to provide some short answer to questions and then multiple choice questions were asked covering general information taught in class. The PV Technology questions from the prototype curriculum developed by Mr. Erickson [6] were quite useful.

Thorin is interested in using the panels next year in the Physics class. The PSEC is a good way to demonstrate solar cells as an alternative 'battery' when doing series and parallel circuit labs. In addition, the PSEC is useful in demonstrating the abilities of solar cells themselves.

Alternative energy sources are going to be increasingly important to teach in class and solar modules will allow just that.

One idea that was found to be unsuitable for this physical science class involved computing the surface area of panels needed to supply all the energy for a student's household; this might be interesting to do in physics the next year.

An examination of the student labs sheets shows that more effort is needed to teach students how to read a meter. Many students did not place the decimal point properly, if at all. However, the instructions were not clear or complete enough for many students. In addition, future instructions should be developed for a single experiment at a time.

The Short Circuit Current curriculum discussed in section 4 of this article was revised based on feedback from teachers and students. Crucially important, when developing any curriculum, is the involvement of teacher in development process and to get their feedback after they have used the curriculum. Students in the freshman seminar are shown conducting this experiment in Fig. 9.

7. NEXT STEPS

One teacher has used the PSEC package and a couple of other teachers are in the process of using the package. They will be building on the experience of those who have already taught the curriculum and are also providing feedback and recommendations for improvement. During the summer of 2010, all the critiques will be analyzed and the high school teachers involved in the project will help write an improved curriculum.

After the revised PSEC package is tested in the 2010-2011 school year, it will be made available on the UO SRML Website along with assessment questions and other useful information for teachers.

Workshops are being considered to promote the curriculum and to also receive feedback for the further development of the PV kits. Equipment lists and assembly procedures will also be available to promote adoption of the PSEC package in other parts of the state and country.

Part of the problem with the instructions is that they are being used by many diverse levels of students from freshman high school students to freshmen college students. It is essential to identify a common set of instructions that can be provided for all groups and then identify levels of experiments that are appropriate for each group.

After initial feedback from the teachers we have found that the experiments and instructions should be separated rather than grouped together. This would help teachers select from a menu of options to address the particular needs of their classes.

Basic lessons covering how solar cells work are already provided on the UO SRML web site. However, background information tailored to what is being taught with each experiment needs to be developed. Working with the science teachers is the best way to develop the appropriate information.

The needs of community colleges are different from high schools, especially for courses training future solar installers and technicians. The UO SRML is working with Lane Community College on such a curriculum and we hope to develop appropriate experiments for this group.

The genesis for this project came from an exchange of ideas with Professor Igor Tyukhov following his time as a Fulbright Scholar at the University of Oregon, and this exchange is continuing with Professor Tyukhov and his colleagues. The discussion between colleagues with different cultural perspectives provides for new ideas as we learn from each other's approach.

The challenge is to build on the excitement students have for popular technologies like photovoltaics and to provide intriguing experiments while stimulating their interest in science. As important as teaching about renewable energy is, teaching sound scientific methodology and principles is just as vital. This is an exciting challenge, especially rewarding when one sees that the students suddenly comprehend a new concept.

8. ACKNOWLEDGEMENTS

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