Solar Collector Design Optimization: A Hands-on Project Case Study

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Introduction

Solar energy is an attractive resource for the world's ever-growing power needs. Offering a locally clean and endless source of electricity, solar cell technology has demonstrated its importance for the future. In part because fossil fuels have remained cheap, the widespread adoption of solar power generation has not yet occurred. Broader adoption of solar energy depends on reducing costs in making high efficiency cells, the result of many incremental advances in cell efficiency. To interest engineering students in solar and energy engineering, we have been working to provide a combination of solar-related research and curriculum experiences (Birnie and Berman, 2003).

As one component of our solar program, we have created a solar cell design and processing class, which has been very popular. To enhance this class we have created a solar-collector design project appropriate for beginning engineering students that utilizes a set of optical, thermal, and electrical trade-offs critical to understanding solar power generation in a broader context[1]. It is similar in spirit to other solar-related engineering design projects that involve optimization and critical thinking to capture students' attention and interest (Head, Canough and Ramachandran 2002; Gupta 2006; Pecen, Hall, Chalkiadakis and Zora, 2003; and Tester 2003) .

This paper outlines our project as a starting point for teachers interested in giving engineering students hands-on experience with photovoltaic technology. We provide a detailed account of our procedures and materials, some necessary technical background information (see Appendix), and a description of the test equipment we designed that enabled the rapid measurement and testing of the solar concentrators under a variety of optical conditions. Because our design project is one of many variants that could be created within this area, we conclude with some discussion of possible adaptations and enhancements.

Solar Collector Design Project

Good design involves many facets: information gathering, idea generation, narrowing of scope, implementation, testing, iteration, communication, and many other things. This project has been constructed to exercise many of these facets. The design assignment was to build a reflective concentrator in association with a silicon photovoltaic cell and to tune the electrical load to optimize the power output. A significant part of the project grade was also tied to presentation of the final design in combination with careful analysis of the technical performance of their devices. Identical single-crystal silicon solar cells were distributed to the students. They were required to design their concentrators to fit their cells and optimize the power output. The bare cells had an average open circuit voltage of 0.55 volts and an average short circuit current of 0.86 amps. They were square with an edge dimension of 8cm. In the following subsections we describe key parts of the project assignment and the testing apparatus, as well as practical considerations that an instructor may use in running this project effectively.

Reflector Construction

The challenges involved in designing the reflector are similar to those of building a solar oven (choosing angles of incidence and reflection, as well as reflector shape) (Johnson and Bailey, 2006). To provide for a reasonable constraint on their design, we limited the total area of reflective material in their final structures to 1000 cm^2 (about 1 square foot). Larger reflectors would present substantial difficulty because of the huge thermal consequences. The large amount of heating cannot be avoided because solar cells are typically only 10–15% efficient at

Abstract

A solar power collector optimization design project has been developed for use in undergraduate classrooms and/or laboratories. The design optimization depends on understanding the current-voltage characteristics of the starting photovoltaic cells as well as how the cell's electrical response changes with increased light illumination. Students were given the assignment of building a small reflective concentrator to match with a single solar cell—and to maximize the total power output from the system. In addition to providing practical suggestions for how to assign and run this project, we describe the design and construction of simple test equipment to help students reach their optimum designs. Post-mortem assessment of the project was done with a 30-student class and improvements for future implementation of the project are suggested, including different tasks and design constraint situations that can be assigned.

Keywords:
Solar Cells, Photovoltaics, Engineering Design, Solar Concentrators, Design Competition, Undergraduate Case Studies, Optimization

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[1] Although the technical content is suitable for beginning engineering students, the multifaceted nature of this project makes it also very challenging and rewarding for juniors or seniors. ABET accreditation emphasis on "design" units could be easily connected to this project and related activities.

converting sunlight to electricity, meaning that the remaining 85% or more of incident power must be dissipated as heat.

Many students were attracted to designs drawn from their knowledge that parabolic reflectors provide for focusing of light to a single point. However, the solar design is more suitably optimized by providing *uniform* illumination of the whole solar cell area. So, tilting of flat reflector areas works very nicely and is very amenable to simple geometric calculations and simple construction. Since the reflectance from surfaces is not 100%, and because the absorption into the silicon cell will also depend on incidence angle, there are many more advanced technical measurements that upper-level classes may also be assigned.

Resistive Load Optimization

In addition to maximizing the amount of sunlight hitting the cell, it was necessary to optimize the resistive load to achieve the maximum power out of the system; this was the key metric that we used to scope the design competition aspect of this project. As described in more detail in the Appendix, the current and voltage that are generated are functionally interrelated in a predictable, but nonlinear, way. Generally speaking there will be some intermediate resistive load where the product of current and voltage will be maximized. This operating point is the “peak power point.” For smaller resistances the current will be large but the voltage too small. For larger resistances the current will be limited but the voltage will be nearer its saturation value. Determining this interplay between current and voltage is one of the key challenges we posed for our students. By adjusting the load resistance the students can map out the I-V curve for their cell-reflector system and look for the peak power point. This process of mapping out the I-V curve was simplified by having easily switchable resistor sets and simultaneous measurement of current and voltage. One useful assignment for the students is to have them convert their I-V curve into a power-versus-resistance plot (calculated from the known R values used and the measured I and V values). This is especially nice because it shows the students how quickly the power drops off if the resistance value is chosen poorly. Further description of the customized test equipment is given in a later subsection.

Thermal Management

As noted above, a substantial majority of the incoming solar energy flux will be converted to heat and not electricity—even for extremely efficient photovoltaic devices. This could lead to significant (and possibly damaging) temperature rise during use—at least in a reflective concentrator configuration. Unfortunately for photovoltaic devices, the temperature rise causes a measurable reduction in the key electrical output constants. For example, typical cells like those we used have a fractional reduction in open circuit voltage of almost 0.4% per degree Celsius (Sharp, product literature). This reduction is rooted in key factors of the semiconductor’s electronic structure: the band gap, the structure of the conduction and valence bands, the electron and hole mobilities, and other factors (Sze, 1981); therefore, it provides a wonderful avenue for connecting the macroscopic device performance to the material’s structure and bonding. Thus, at several levels the power reduction with temperature could be an important factor for students when optimizing their designs: with any specific temperature rise there will be a different peak power point, so students might want to seek this maximum after their reflectors have been constructed.

Although we hadn’t envisioned it, some of our inventive students decided that they could reduce the temperature rise of their solar cells by using some kind of heat sink in close contact to the backside of the solar cells[2]. Then consideration of airflow becomes important to allow for cooling of the heat sink’s fins.

Design Competition

When running design projects, where students or teams are each trying to optimize their designs, it is beneficial to construct the project as a design competition. This helps the students focus their energies and reach higher efficiencies and often builds a fun interactive classroom spirit. To emphasize that several designs or devices may reach similar power scores, it is useful to design a grading system that rewards all high achievers, not just the absolute best project. (More discussion of scoring and grading is given below in another subsection.)

Technical Analysis

The current-voltage response trade-off when picking a system load, and the change

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[2] The students scrounged heat sinks from microprocessor cooling systems in PC’s! These happened to be a similar size to the solar cells we were using.

in that response with light intensity and temperature are factors of critical importance for student understanding of photovoltaic optimization in the real world. Therefore we made it a project requirement that the students trace out a current-voltage curve for their cell/device and include that graph in their final project report/poster. This helped ensure that they worked through the steps of seeking out the peak power point for their design. We also required a self-assessment of the reflective material area used in their projects. This helped keep students serious about their concentrator designs. Another key technical component of their final poster/presentation was an analysis of the angles and shapes utilized in their reflector designs.

Presentation

Students were required to present their designs in a manner that would be visible and clear to passers-by who might happen across the combined set of solar collectors when we were having the class contest (it had to be outdoors on a sunny day, of course!). This presentation was specified to be a poster that could be lying on the ground next to their concentrator and that would give the relevant technical description. It was required to have a current-voltage response curve for the device as well as a basic description of particular “design innovations” that the students had employed.

Simple Test Equipment

It was important for the students to have a convenient method for testing their devices during the design phase as well as in the final competition. To facilitate rapid testing, it was necessary to have easily switchable resistive loads and the ability to measure both current and voltage without reconnecting or rearranging the wires. Therefore, test equipment was designed to meet these constraints. Figure 1 shows a photograph of our testing apparatus. The figure illustrates the three key parts of the equipment: one multimeter set to measure voltage, one multimeter set to measure current, and a switchable resistor network (in the small metal switchbox—note inset with wiring schematic). The clipboard allowed for easy attachment of a logging sheet for the current and voltage data that were measured. The wires were arranged so that both measurements are logged simultaneously after the two leads are attached to the solar collector leads using alligator clips. There were five resistors in each load box. Each resistor could be placed in the circuit (and act as a load) or bypassed by toggling a switch (using SPDT switches). When creating test equipment for a project of this type, the range of resistor values used must be appropriate for the I-V responses of the cells or modules being used. For the solar cells that we used, V_{oc} was just over 0.5 volts and I_{sc} was almost 1 amp under noon-time illumination. With the reflective concentrator increasing the possible current output, the optimum load was expected to be less than 0.5 ohm. Therefore these resistor values were chosen for creating the load boxes: 0.05, 0.10, 0.15, 0.27, and 0.56 ohms. These were chosen to climb by approximately a factor of 2X each step with the constraint that they be able to withstand the current generated by the solar cell when illuminated. Using different combinations of these resistors, the load could vary from zero (all bypassed) to 1.13 ohms (all included in series). Several sets of these test arrangements were provided so that testing would not be a bottleneck. It is certainly possible for more sophisticated gear to be procured and more complete I-V curves to be traced, but for introductory projects they only needed equipment at this level of cost.

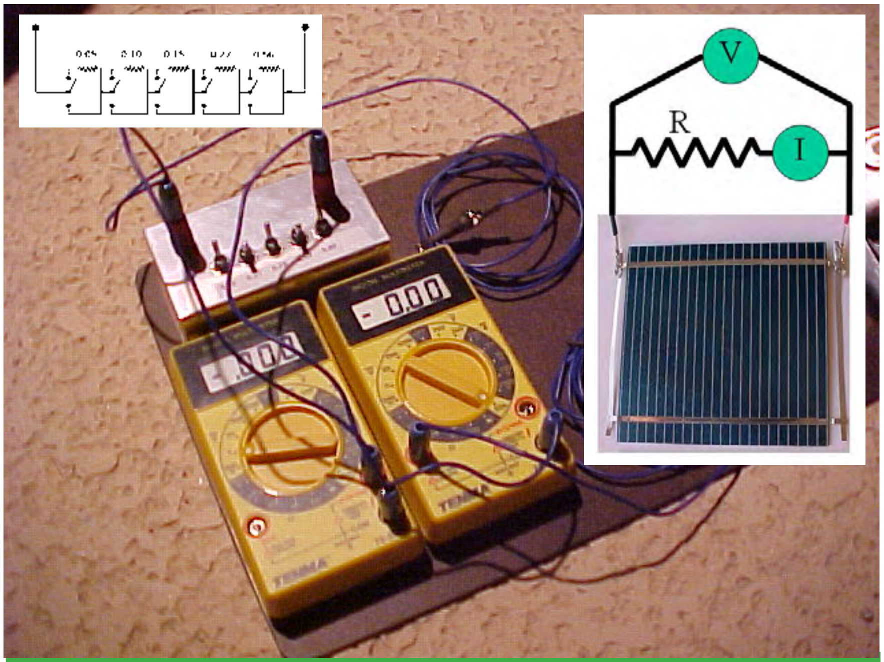

Figure 1: **Custom-built test equipment for solar design project assessment. Upper left inset shows the resistor network used to achieve easy fine-tuning of the load resistance. Upper-right inset shows how the voltmeter and ammeter must be connected. Wires were pre-arranged to clip easily to the solar-cell output leads.**

Results

Figure 2 shows the final output results for the projects constructed in our first year’s com-

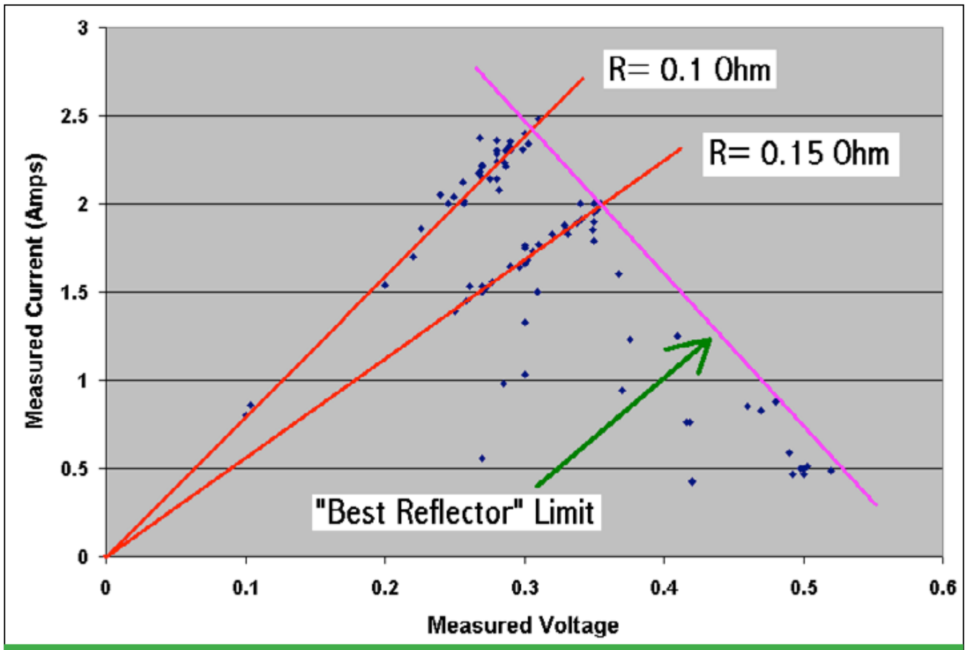

Figure 2: Final current and voltage output values from students' solar collectors. Each device was measured with three different load resistance values—selected by the students as part of their design optimization. The best performances were logged with quite low resistance value (either 0.10 or 0.15 ohm), and for reflectors that were well aligned. The best current values were up to about three times higher than the I_{sc} measured for a bare cell.

petition. Each student's collector was measured three times with different load resistance values that they selected. They were measured with three different sets of the test equipment to allow for any slight variations in reading that might have come from the equipment or slight resistor differences. Note that the current values are quite higher than the I_{sc} value for a bare cell. The best currents represented around a factor of three in brightness enhancement using the reflectors that they built. The best power values were achieved with the two load resistance values indicated. Two red lines have been drawn in to highlight these load conditions. One other line has been superimposed that shows our estimation of the best IV values that could have been achieved. Data points that fell well below or to the left were representative of reflector devices that didn't point the light at their solar cells very effectively. The maximum power output was about 0.75 Watts.

Discussion

While a design project assignment must certainly include scoring/grading that would reward all of the features described above (technical analysis, design presentation, and power output), we chose to give the largest weight to the power output generated. We assigned half of the possible points by scaling the student's best power output (of the three specific measurements of their device) in comparison to the best power achieved among all the data in class. Thus, the best performing device won full score on this attribute. Assignment of other scores should be based on a rubric that students would know beforehand: value for the IV characterization of their cell, value for poster/presentation quality and clarity, value for the geometric analysis of the reflectors, etc. We found, though, that with such a rubric defined, most students aced this part and major differences in their overall scores were really derived from the power output performance differences. For example, for the 30 students in the class, the standard deviation of the score value for "Presentation" was 3.2 points (of the 20 points possible in this category that included a poster with their IV and a description of their chosen design characteristics); and for "Creativity" their standard deviation was 1.3 points (of the 30 possible in this category); on the other hand, the standard deviation of the score value for "Power Points" was 9.7 (of the 50 points possible here). Clearly the real, objective, current-times-voltage performance of their devices was a much bigger decider of any student's final project score.

Generally speaking, students in this class understood the design objectives quite well. This can be seen by the large cluster of points near the peak power along the 0.10 and 0.15 ohm lines in Figure 2. Only a relatively few students chose substantially larger resistance value (resulting in much lower currents, but slightly higher voltages). For example, the cluster of points at the far right come from resistance choices of about 1 ohm and resulted in total output power near 0.25 watts, only a third of the power achieved by the best devices. Note that most of the power reduction in this case is a result of poor resistive load choice rather than poor reflector construction—emphasizing the importance of optimizing all aspects of a design.

In the future, for those who field a solar collector project of this style, here are a few recommendations and considerations for improvement or enhancement.

Heat management: While the discovery of the utility of a heat sink was fortuitous in our case, it would make more sense to simply provide students with some type of standardized heat sink—or prohibit them altogether[3]. If the competition is to be conducted with regard to practical applicability of the students' work, it ought to be done on a level playing field. If heat management is chosen as a design variable then it might be useful to even measure the steady-state temperature rise of the cells and to coach students about airflow and heat-transfer considerations that would apply.

Other geometries: Most of the projects that our students completed were upward facing cells with reflectors that steered more light onto the cells. It would be an interesting twist to *require* that the students mount the cells in a downward facing orientation and use the reflective area to bounce light up to the cells. This would put a much more difficult geometric constraint on their designs and force them to put more thought into optimizing the use of their reflective material.

Iterative design: One key aspect of "the engineering design process" is assessment and iterative feedback to make improved designs. It would be worthwhile to include two design cycles in the semester and "allow" the students to learn from the mistakes they make during the first round.

One suggestion mentioned by a student was that, to make things more exciting, the cells should be used to power some active device like a small electric motor, an LED display, or another kind of gadgetry. This could be included as one of the deliverables (i.e., the students would have to bring in a device the cells could power). This would open up even more room for creativity and diversity among finished products—an added bonus if one is hoping to attract attention from onlookers. One challenge is finding gizmos that actually run well on one half volt or less—or to provide each student or team with enough cells to string them in series to bring the voltage up to more useful levels.

One final practical note: Silicon wafers and solar cells are usually very brittle and fragile; many students needed replacement cells during this project, so an abundant supply of cells is needed to start with. Alternatively, flexible, thin-film technology cells could be acquired, which would make it easier for students to build them into robust structures.

Conclusion

Solar power is an important technology for the future. The present paper illustrates how photovoltaic devices can be used in fun and informative hands-on student design projects that can spark the creativity and interest of students. Practical issues of the interplay between current and voltage were discussed and integrated into the parameters that students needed to characterize and understand when optimizing their devices and systems. These hands-on projects are a fun way to emphasize the optimization process and to provide ample room for students to develop creative design solutions.

Acknowledgement

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[3] We found that the use of the heat sink was important, but since temperature values were not measured it is hard to know how effective they actually were. As a group, the student designs that incorporated a heat sink generated, on average, 32% more power than those that did not use heat sinks. However, it might be argued that students who went beyond the normal design scope had probably also put more attention into the base design features.

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Dunbar P. Birnie, III Professor, Rutgers University Department of Materials Science and Engineering Professor Birnie is actively involved in using solar power and renewable energy from many angles. His solar "start" was supported by NSF under a Combined Research and Curriculum Development program – and helped him create a solar technology class that continues and improves with time. Present work includes modeling of solar power for commuter transport (for both cars and buses) as well as solar cell fabrication work aimed at substantially lowering the cost of solar cells by using various printing technologies.

David M. Kaz received his BS in Engineering Physics at the University of Arizona in 2003 where he worked on solar cell optimization in miniature satellites and solar powered cars. He is currently finishing his PhD in soft condensed matter physics at Harvard University, and will be taking a postdoctoral position at the University of California at Berkeley in the fall. His interests currently include design, fabrication, and optimization of novel measurement techniques for experiments in soft matter and biology.

Elena A. Berman now retired, was Director of Assessment for Student Life and Associate to the Vice Provost for Assessment at the University of Arizona at the time when this work was carried out.

Appendix: Background Information and Definition of Terms

The basic electrical characteristics of most typical solar cells can be quantified with a current-voltage response when measured while illuminated at some fixed intensity. Specific points in this response have names that are frequently used in the literature to rate or understand the performance of cells. Some important terms are: "open circuit voltage", "short circuit current," "fill factor," "peak power point," "optimum load," and "efficiency." These terms are defined briefly below and presented more completely in the literature (Sze, 1981).

The open circuit voltage, V_{oc}, is defined as the voltage measured between the positive and negative terminals of the cell when no current is allowed to flow (typically by not touching the contacts to any electrical load and with nothing connecting the terminals—i.e., "open" circuit). The open circuit voltage is measured under the direct illumination of light of a known intensity (e.g., if the light level matches what would be found after sunlight passes through 1.5 thicknesses of atmosphere, as would be found with a morning or afternoon sun inclination, then we designate the illumination conditions as having "air mass" of 1.5 or AM1.5). The open circuit voltage is the highest meaningful voltage that would be associated with a particular cell, though typical operating conditions would necessitate generating a voltage that is somewhat smaller than V_{oc}, as discussed below.

The short circuit current, I_{sc}, is defined as the current passing through a perfectly conducting wire connecting the two terminals under the same specified illumination conditions. This is the maximum current that the cell is capable of generating, but because the opposite terminals would be grounded to each other, the voltage generated in this case would be zero. For many well-optimized cells, the short circuit current will vary nearly linearly with the intensity of the illumination.

These two values place upper limits on power output for any given cell. However, neither of these values corresponds to what one might see in an operating cell; in both of these cases either the current is zero (open circuit) or the voltage is zero (short circuit), and hence the power output is zero. In fact, in real operating conditions the current, I, will be somewhat less than I_{sc} and the voltage, V, will be somewhat less than V_{oc}. The interplay between I and V provides an interesting optimization problem since power is defined as the product of current and voltage:

$$P = I * V \tag{A1}$$

And the effective load, R_{load}, of the external system governs how I and V adjust—and the ultimate power that is recovered. Current and voltage will obey Ohm's law:

$$V = I * R_{load} \tag{A2}$$

For various loads ranging from zero to infinite ohms, the current passing through the load and the voltage across the load will vary. For small resistance values the voltage is low and the current approaches I_{sc}, and for large resistances the current drops, kicking the voltage up close to V_{oc} (but the current drops rapidly as the resistance rises).

Somewhere in the middle of the I-V curve lies what is known as the peak power point (V_{pp}, I_{pp}). This is the point at which the product of the voltage, V_{pp}, and the current, I_{pp}, results in a maximum power output. This point corresponds to the optimum load, and is found by rearranging Ohm's Law:

$$R_0 > {}^{V_{pp}}\!/_{I_{pp}} \tag{A3}$$

This is also the inverse of the slope of the line connecting the origin and the peak power point.

The fill factor "FF" is defined as the ratio of the peak power generated to a hypothetical power represented by the product of the open circuit voltage and the short circuit current:

$$FF > {}^{I_{pp} * V_{pp}}\!/_{I_{sc} * V_{oc}} \tag{A4}$$

Typical values for fill factor might be in the neighborhood of 0.7 or so, but could be much lower for a poorly designed cell.

The efficiency of a cell quantifies the portion of incident solar energy (often evaluated at 1000 W/m^2 illumination using AM1.5 spectral variation) that is converted to electrical energy. Cell efficiencies vary widely and depend on the kind of solar cell, but they might range from 10–20% and work is progressing feverishly to improve this important metric. (Be careful: efficiency values quoted in the literature are sometimes misleading, especially if they are measured at only one wavelength or under unrealistic loading conditions.)

Under more intense illumination, the I-V curves are shifted upwards, increasing I_{sc} proportionally, but increasing V_{oc} only slightly. Similarly, under lesser illumination the value of I_{sc} is pushed down almost linearly with reduced brightness. Hence, under differing illumination conditions, the peak power point (along with the optimum load) will change. This is a consideration especially in cloudy, unpredictable, or shady areas. It is also an especially crucial concept for this particular project where illumination is being deliberately enhanced with a reflector. So, the I-V curve that characterizes the unmodified solar cells will not likely suffice to choose the optimum load. Instead students should try to optimize their reflectors to max out the I_{sc}, but then seek resistive load that will achieve the peak power point for those illumination conditions.

Finally, temperature has a rather pronounced effect on cell efficiency. As temperature increases, the open circuit voltage diminishes, and the peak power point drops. This is an important issue with the solar concentrators—after all, approximately 85% of the incident light is being converted to heat.