Design of a Photovoltaic Power System

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Abstract

What should technology and engineering students know about renewable energy? Traditional energy technologies, such as coal-fired power plants and petroleum-based internal combustion engines, will continue to dominate modern society for the short term. However, an increased dependence on foreign energy sources, energy shortages, and environmental concerns are beginning to bring alternative energy issues to the forefront. The paper describes the design of a small photovoltaic power system that demonstrates renewable energy topics in a variety of MET and EET undergraduate courses.

Energy Use in the United States

Figure 1 illustrates several well-known trends regarding overall energy consumption and production in the United States.[1] Prior to 1950, energy production and consumption were roughly equal. The U.S. met its domestic energy requirements without foreign sources. By the early 1960's, consumption began surpassing production. In recent decades, increased use of automobiles, higher levels of industrial production, and greater amounts of comfort air conditioning allowed total consumption to easily surpass total production. In 2000, the U.S. produced only about 75% of the total energy it used.

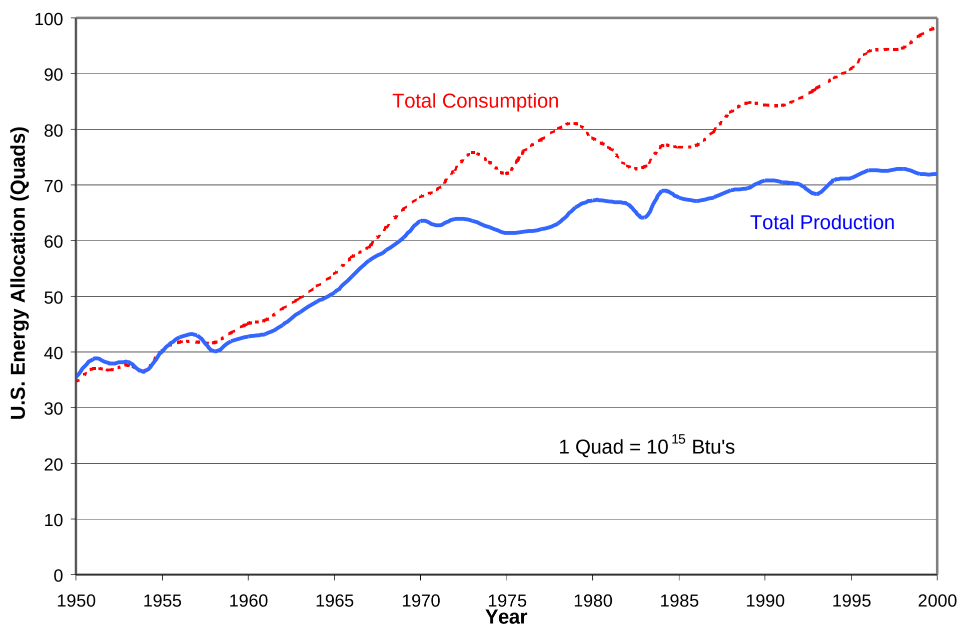

Figure 1. Energy consumption has outpaced energy production in the United States.

Figure 1 also suggests that if current trends continue the imbalance between energy consumption and production should continue to grow. Unfortunately, most of the obvious long-term implications of this trend are not helpful to the United States. Increased dependence on foreign sources jeopardizes energy stability. Global terrorism and political unrest in the Mideast, which are largely out of our control, can have a dramatic impact. Although not directly tied to the basic production/consumption problem described here, the power shortage experienced in California during the summer of 2001 clearly demonstrated that relatively minor energy supply disruptions could have serious negative economic consequences. *Any viable energy technology that increases U.S. production and reduces the need for foreign energy should be emphasized and encouraged. This "encouragement" should begin in the college classroom.*

Figure 2 summarizes energy sources used by the United States.[1] Fossil fuels have historically been the most abundant and provided the bulk of our energy needs. Petroleum, natural gas, and coal accounted for 85% of the nearly 100 quadrillion Btu's consumed by the United States in 2000. Renewable sources, which include hydroelectric, geothermal, solar, and wind energy, contributed approximately 7% to the year 2000 total. Nuclear electric sources (which the Department of Energy does not categorize as "renewable") make up the remaining 8% of the year 2000 energy supply. Figure 2 also clearly shows a trend toward increased use of fossil fuels. The production of nuclear and renewable energy has been flat for more than a decade.

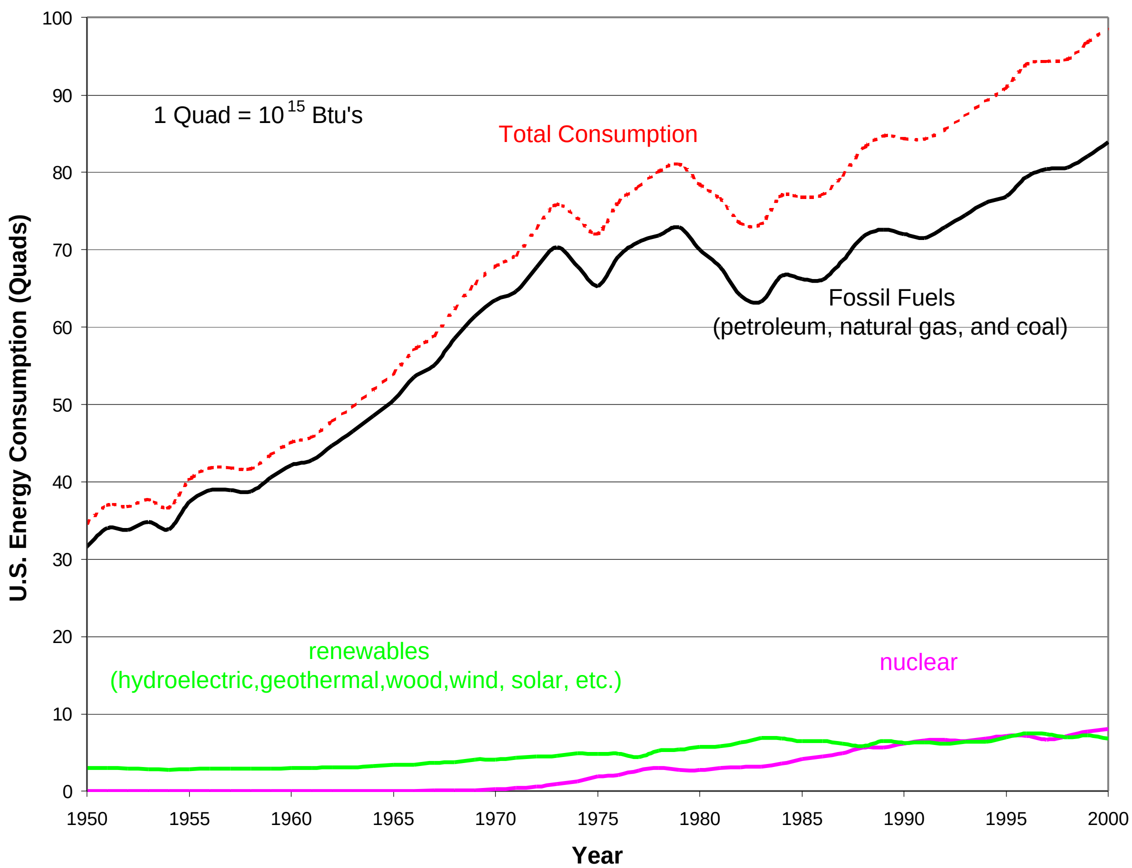

Figure 2. Renewable sources supply a small part of the energy used in the United States.

Based on the data shown so far, one might conclude that undergraduate technology courses should continue focusing on traditional energy topics. It seems reasonable to emphasize topics that students will typically encounter during their early careers. A four-year curriculum for Mechanical Engineering Technology students typically includes two thermodynamics courses with an ”energy” focus. After covering crucial concepts such as conservation of mass and conservation of energy, there is a limited amount of time left over for specific applications. Traditional topics such as the Rankine Cycle for steam-driven power plants, the Otto Cycle for internal combustion engines, or the Vapor Compression Cycle for mechanical refrigeration systems have been taught for the past 50 years. It is particularly tempting to stick with these tried and true subjects since they are key ingredients of most popular thermodynamics textbooks.

Electrical Engineering Technology courses face the same challenge. EET power courses have emphasized the same basic topics for many years. If EET power graduates are expected to work on large-scale electrical distribution systems, it makes sense to emphasize that topic in their coursework. However, educators must recognize the long-term challenges facing our power-hungry civilization. Technology used today may not be the best solution for tomorrow. This recognition should begin to influence what new material is delivered in traditional undergraduate courses. Emerging technologies, such as fuel cells used as part of a smaller decentralized power system, could eventually become required reading.

The purpose of this paper is to provide one example of how renewable energy topics can be integrated into undergraduate MET and EET courses. The context of this discussion is a small photovoltaic array that was designed by students at the West Lafayette campus of Purdue University. The design project exposed undergraduate students to an alternative energy source that is not typically addressed in an undergraduate curriculum. Once the photovoltaic system is operational, the long-term educational goal is for MET and EET students to develop a greater appreciation for alternative energy sources as part of their core coursework.

Planning the Photovoltaic Project

Table 1 illustrates that the student-lead photovoltaic project has spanned three academic years. The work has taken a significant amount of time because of the 1) expense in purchasing individual components, 2) limited amount of design time available to MET students, and 3) time required for technicians to fabricate, install, and commission the system. The drawn-out schedule has not been a major hurdle. That is how the project was originally envisioned. However, it will be a relief when the system is fully operational!

Two different groups of senior-level Mechanical Engineering Technology students completed the design. Both student groups performed their work as part of the requirements for a senior-level Air Conditioning & Refrigeration course (MET 421). Each group spent about four weeks out of a 15-week semester on this project. In the spring of 2000, the first student group completed a feasibility study. Their preliminary evaluation was used to justify the purchase of some basic electronic control components. In the spring of 2001, the second student group completed a detailed design. Their recommendations were used for purchasing the photovoltaic panels and other balance of system components. Fabrication and installation will be completed in 2002. The entire photovoltaic system should be functional by the summer of 2002.

Table 1. The photovoltaic project spans three academic years.

TASK	2000			2001			2002	
	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer
student feasibility study	■							
first equipment purchase		■						
student detailed design				■				
second equipment purchase					■			
fabrication & installation							■	
wiring & commissioning								■

Photovoltaic feasibility study

What photovoltaic equipment is needed to power the three small blowers and one small circulating pump shown in Figure 3? MET students tackled this first question in the spring of 2000. Since the instructor and students knew very little about photovoltaic systems at this point, the investigation focused on fundamental photovoltaic concepts. A preliminary understanding about the components, physical size, and cost of a photovoltaic system was needed as a precursor to a more detailed design.

The blower and pumps are part of a separate solar heating system that is used in the MET Department's Applied Energy Laboratory. Other than the fact that these components use electrical power during operation, the details of this equipment are not relevant for the current discussion. If the reader is interested, references 2 and 3 provide extensive documentation on the solar heating apparatus.

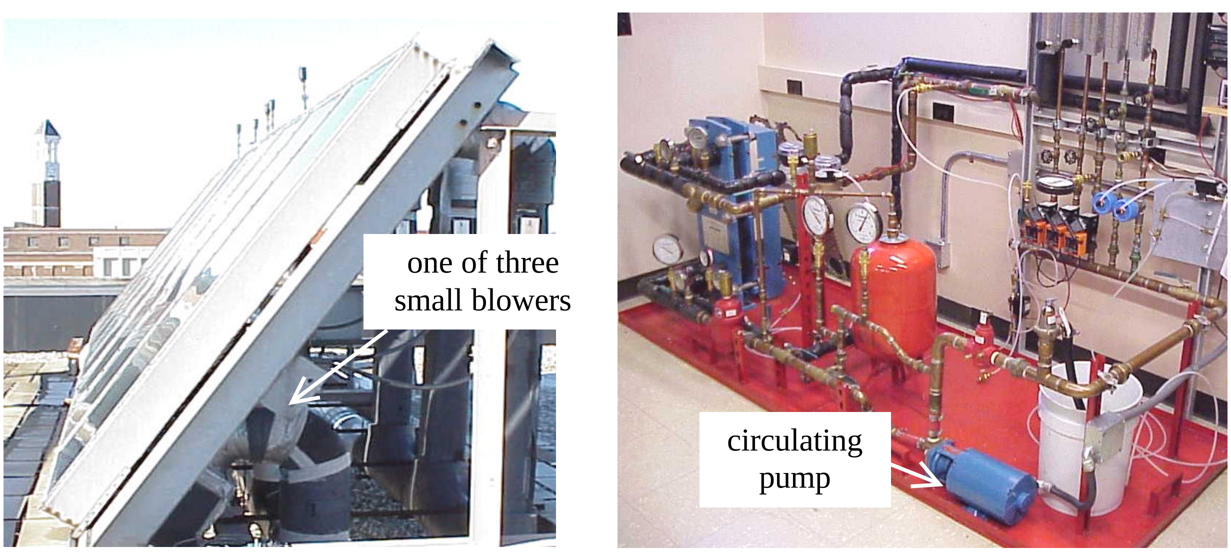

Figure 3. How much electrical power is needed for 3 blowers and a circulating pump?

Figure 4 summarizes the results of the feasibility study. This work represents the efforts of 10 students working over approximately four weeks. The students found that photovoltaic panels convert the sun's radiant energy into electrical energy, in the form of DC power. The power center shown in Figure 4 is a catchall term for an electrical panel box that includes a battery charger, circuit breakers, fuses, and connections to an inverter. The inverter converts the DC power generated by the photovoltaic cells into AC power, which ultimately drives the pump and three blowers. The deep cycle batteries store electrical power to support the AC loads when the photovoltaic cells are not able to produce the required amount of electrical power.

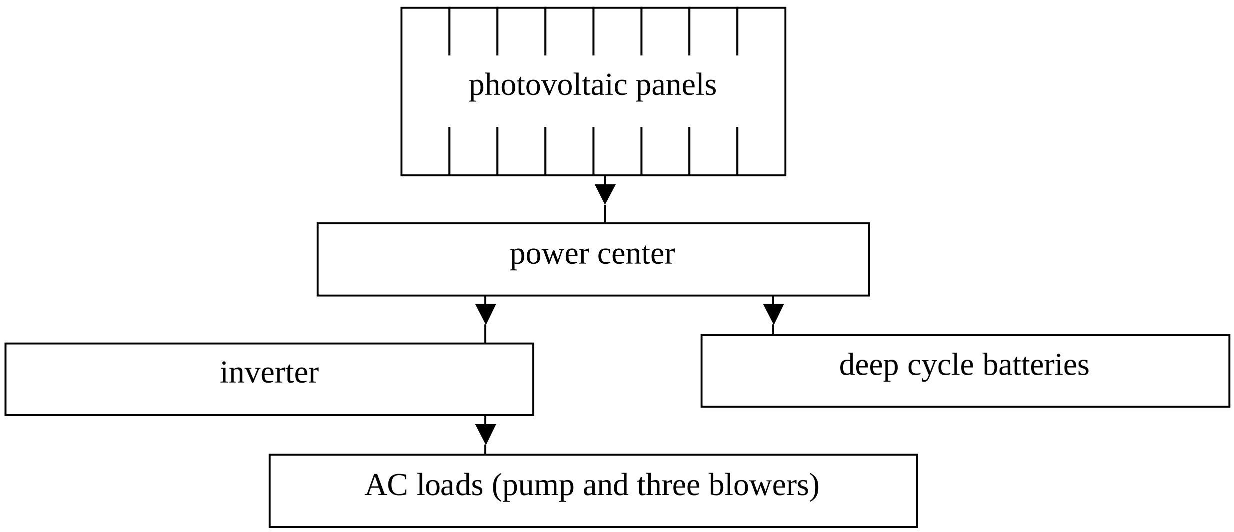

Figure 4. A photovoltaic system generates electrical power from the sun.

The students took the feasibility study one step further. They performed preliminary design calculations to size and select each individual component of the photovoltaic system shown in Figure 4. This provided insight into the overall power requirements, physical size, cost, and complexity of the system. For example, the students who focused on the photovoltaic panels estimated that roughly 24 panels, each rated at 120 Watts of peak power, would be needed to drive the pump and three blowers. The 24 panels would have a surface area of approximately 25 square meters and fit nicely within the space available on the roof of the Knoy Hall of Technology. It was interesting for the students to discover that a comparable system located in the desert southwest could be completed with 30% fewer photovoltaic panels. The increased amount and intensity of the sun's rays in a place like Albuquerque, NM allows photovoltaic power generation with significantly fewer panels.

Students also recognized the limited economic benefits of photovoltaic power in a place like Indiana. They estimated the cost of photovoltaic components alone, not including design or labor, would be approximately $25,000. Assuming that electrical power costs $0.10/ kW-hr, the simple payback for the system could exceed 50 years! As noted by one group of students in their final report "*The benefit of the photovoltaic system will not pay for the initial cost over its predicted life. In spite of this, it is justifiable to continue with this project. The value of the project is the learning tool that it will be used for, not the economic factors*".

Detailed Photovoltaic Design

What photovoltaic equipment should be purchased and how/where should it be installed? In the spring of 2001, after a 6-month hiatus, a new class of MET students tackled these specific questions. The feasibility study from the previous year provided background information to jumpstart this phase of the work. Although none of the current students had experience with photovoltaic systems, the feasibility study from the previous year made it clear what components were needed. With this information in hand, the focus quickly shifted to optimizing the design.

Standardized photovoltaic design worksheets, published by Sandia National Laboratory, were used for this detailed systems design work. The worksheets are perfect for students (or faculty members) who lack photovoltaic design expertise. The worksheets have been widely used since they were first published in 1988. The instructions are easy to follow and make it highly unlikely that a key design component will be overlooked. The worksheets can be found on-line at http://www.sandia.gov/pv/sysd/Wkshts1-5.html.

The Sandia photovoltaic worksheets integrate equipment selection with typical electrical power calculations. When a 120 Watt Kyocera KC-120 solar panel was being considered, the solar panel worksheet helped determine the total number of panels needed. In addition, the worksheet helped determine the peak array power (kW), array short circuit current (A), and array open circuit voltage (V). This basic electrical information was subsequently used in several other Sandia worksheets for selecting the charge controller, inverter, fuses, and wire size.

The methodical approach provided the Sandia worksheets allowed students to properly select the components shown in Figure 5. The picture to the left shows a Trace 4 kW inverter and a Pulse 60 Amp power center mounted inside the Applied Energy Lab. The picture to the right shows a partially assembled aluminum frame holding two 120 Watt Kyocera solar panels. When the installation is complete, six frames on the roof of the Knoy Hall of Technology will hold a total of 24 solar panels.

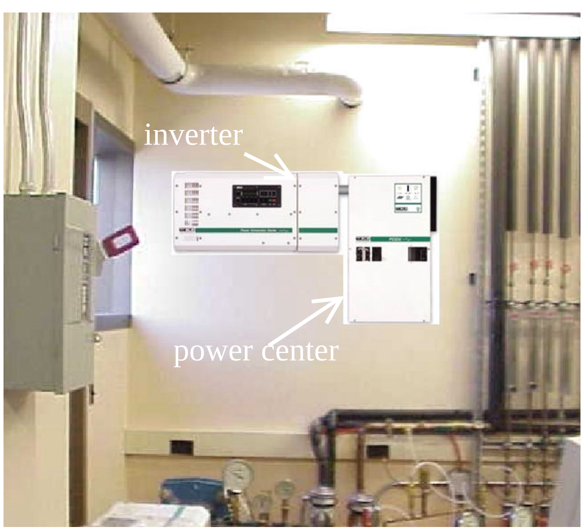

Figure 5. The electrical controls and photovoltaic panels are currently being installed.

Cost Effectiveness of the Photovoltaic System

It was somewhat disappointing to find out that the cost of photovoltaic power equipment is very expensive for places like Indiana. There is simply not enough sunlight to make photovoltaic systems cost effective. As summarized in Table 2, the equipment for the small photovoltaic system will cost more than $22,000. The cost is only for materials and excludes the installation costs.

Table 2. The photovoltaic equipment, excluding design and installation, cost $22,100.

	Manufacturer	Specifications	Quantity	Cost
photovoltaic panels	Kyocera	12 VDC / 120 Watt	24	$12,600
panel mounting frames	Two Seas	aluminum channel	6	$2,800
deep cycle batteries	Concorde	12 VDC / 210 AH	4	$1,300
inverter	Trace	48 VDC / 4000 W	1	$2,500
charge controller	Pulse	48 VDC / 60 A	1	$1,500
battery rack	in-house	steel tube & plexiglas	1	$500
conduit / wiring	-	-	-	$900
			total equipment cost:	$22,100

Importance of Real World Design Projects in Technology Education

As mentioned earlier, the purpose of this project was to provide an opportunity for students to gain real world design and implementation experience. One aspect of engineering technology education is the students' ability to integrate existing technologies to improve a current system. This skill does not require component level design of each subcomponent of the system. Students will have to work with devices that come with standard input-output specifications as well as devices with non-standardized input-output specifications. The most effective way to learn this type of system integration is by doing.

This project was part of an elective course where students are expected to explore beyond their major areas. It is expected that though this type of project both electrical and mechanical engineering technology majors would learn the important skills that they should be familiar with in the other discipline.

Project designs with off-the-shelf devices are preferred in interdisciplinary learning activities. These projects can be tailored to combine different disciplines. For example, an elective course in telecommunications where telephony is emphasized can be very beneficial to majors from electrical disciplines and majors from computer networking disciplines. Hands-on activities may include telephone switching devices and other off-the shelf telecommunication devices. This allows students to develop interesting communication networks for transferring data from a local area network to another LAN or for teleconferencing between two locations via a fiber-based transmission medium. Similarly, students from electrical engineering technology and mechanical engineering technology can be combined using alternative energy projects.

Why Renewable Energy?

Everybody talks about energy today. The California energy crisis and President Bush's National Energy Policy re-ignited decades-old energy conservation and environmental degradation dialogs. College students are willing to tackle this challenge but find they lack skills needed. A survey done by the Association of Energy Engineers (AEE) reveals that one of the fastest growing areas in the energy field is distributed generation.[4] In distributed generation, attempts are made to supplement the energy use in a facility via locally generated energy. Solar energy systems play a vital role in such generating systems. The topic of renewable energy brings other subordinating topics, such as energy conservation and environmental protection, into the learning environment. It is very important to include energy conservation and pollution prevention measures into undergraduate student projects. Existing technologies allow the design of such systems.[5] Finally, Figure 1 shows a significant gap between the energy consumption and energy production. There is a window of opportunity to enhance renewable energy awareness and conservation among engineering and technology graduates, which could eventually become a national priority.

This student project described in this paper involves designing a system using products from off-the-shelf. When it comes to constructing an alternative energy system such as photovoltaic, students are challenged to deal with aspects of system design and development that they would encounter in the real world. Some of these aspects are to: evaluate the existing power system capacity, determine the capacity of the alternative power system, implement the interfacing guidelines if the system is designed to be operated as a distributed power system, evaluate possible power quality interferences, perform the cost analysis, perform the actual construction, test the system, and determine the pros and cons of the design. These tasks become very challenging because there are no set standards among alternative-energy component manufacturers.

Integrating Photovoltaic Equipment to Courses

An expandable and modular PV lab provides continuing benefits to the courses and other departmental missions, such as outreach activities. The lab setup described in this paper could be included in Facilities Engineering or Energy Management courses. Students may recalculate the entire system, reinstall all subcomponents, and verify the performance or they may chose to use only one load available and redesign the system. For example, the major components shown in Figure 4, except the inverter and power center, consist of small modules. When the pump is selected for the load, the optimized design may not require all 24 panels and the entire battery bank. In another level, students can be asked to investigate newer components such as more efficient solar panels or an inverter from a different vendor and redevelop the entire system. Some manufacturers are willing to loan their products fro these types of comparisons.

With little additional effort, the setup can be used as a platform for outreach and applied research activities. The flexibility of the lab can also be enhanced. A flat plate solar collector will open up new opportunities to investigate electrical power generation from thermal energy. By adding a grid interface unit and meters, the lab can be used as a distributed power system.

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