# Energy Conservation in Thermal Power Courses

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Abstract

What should technology and engineering students know about energy conservation? 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, evidence of global warming, ozone depletion, and other environmental concerns are beginning to bring energy conservation issues to the forefront. The purpose of this paper is to encourage discussions about how broad concepts like "renewable energy" is treated in undergraduate thermal power courses.

## Renewable energy use in the United States

The data summarized in Figure 1 shows that renewable sources deliver only a small part of the annual energy used in the United States.[1] Coal, petroleum, and natural gas were responsible for more than 85% of the nearly 100 quadrillion Btu's consumed by the United States in 1999. Renewable sources, which include hydroelectric, solar, and wind energy, contribute approximately 8% of the total. Nuclear electric sources, which the Department of Energy does not categorize as "renewable", make up the remaining 7% of the energy consumed. Based on this data, one might conclude that undergraduate thermal power courses should continue to focus exclusively on "traditional" thermodynamic topics. At first glance, it seems reasonable to emphasize topics that students will typically encounter during their early careers.

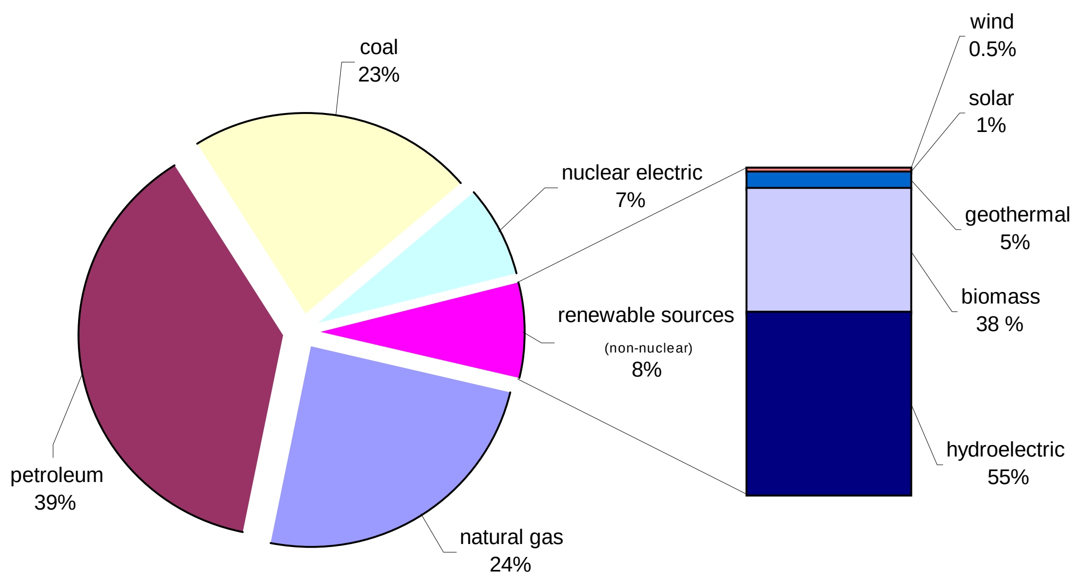


Figure 1. Renewable energy sources are a small part of total U.S. energy consumption.[1]

A four-year mechanical curriculum for technology or engineering students typically includes two thermodynamic courses. 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. However, new environmental challenges facing our power-hungry civilization should begin to influence how material is delivered in a traditional undergraduate thermodynamics course.

Mounting evidence of global warming, ozone depletion, and other environmental concerns have increased the relevance and importance of topics like "renewable energy" within traditional undergraduate thermodynamics courses. Emerging technologies, such as fuel cells, could eventually become required reading. Even if a discussion of renewable energy does not supplant conventional course topics, it can influence how thermodynamic courses are delivered. Energy conservation has become an ethic, a professional standard that should be an integral part of every energy decision.[2]

The purpose of this paper is to provide an example of how energy conservation and renewable energy topics can be integrated into a traditional undergraduate thermodynamics course. The context of this discussion is a solar energy experiment that has been developed by the Mechanical Engineering Technology Department at the West Lafayette campus of Purdue University. The experiment demonstrates basic thermal power concepts, but also exposes undergraduate thermodynamics students to an environmentally friendly energy source. The educational goal is for students to develop a greater appreciation for energy efficiency as part of their core thermodynamics coursework.

## Solar energy equipment

As shown in Figure 2, eight different active loop solar collectors have been installed on the roof of the Knoy Hall of Technology in West Lafayette, Indiana. Each collector consists of an insulated sheet metal box whose upper surface is double-paned glass. The glass surface is actually an inexpensive patio door, which has a durable construction and a surface area of roughly 1.7 $m^2$. The collectors are mounted on an aluminum channel frame that faces southward at an angle of roughly 55° with respect to horizontal, which is close to the optimal solar orientation for this location.

Although all the solar collectors have the same surface area, orientation, and basic construction, the interior configuration of each collector is slightly different. The five collectors to the left circulate 50% propylene glycol in a closed loop. The three collectors to the right circulate air in an open loop. Some absorber surfaces are black while others are a more reflective color. Some absorbers have ridges or fins while others are smooth. The subtle differences between collectors allows for interesting comparisons of thermal performance. Which collector is most efficient at converting radiant into thermal energy?

Figure 2. Eight solar collectors demonstrate basic thermal science along with renewable energy concepts.

A Direct Digital Control (DDC) system, similar to those used in modern commercial buildings, has improved the solar collector system's day-to-day operation.[4] The DDC system monitors and controls all sensors, valves, dampers, pumps, and fans on a continuous basis. Software algorithms determine all aspects of solar collector performance. As an example, the pump for pushing 50% propylene glycol to the rooftop collectors is programmed "on" whenever the sun's intensity exceeds 50 $W/m^2$. The operation of the pump triggers a chilled water valve "open" to dissipate thermal energy through a plate and frame heat exchanger.

Data collection has been enhanced by the DDC system's ability to automatically store sensor measurements at 15-minute intervals. It is frequently more helpful to look at a daylong temperature trend rather than an instantaneous value. The data buffer is configured to keep a running tally of all measurements for the three most recent days. On sunny days, students access real time data. When it is cloudy, stored data from a previous sunny day is more useful.

Students also benefit from the DDC system's ability to broadcast data over the Internet. Rather than collecting performance data on the roof, an entire classroom of students use individual networked personal computers to remotely monitor fluid temperature, fluid flow, and sunlight intensity. Sunlight intensity is a particularly interesting measurement. It is recorded by a solar pyranometer that is mounted next to the solar collectors. This sensor records the total amount of visible and near-visible (ultraviolet and near-infrared) radiation, which occurs in wavelengths between roughly 295 and 2800 nm. This single sensor cost $2000, by far the most expensive in the lab!

In recent years, several large renovation projects have restored the aging collector boxes, replaced the mechanical equipment for circulating heat transfer fluids, and modernized the control equipment. The total cost of the rehabilitation projects was approximately $30,000.[3] The cost of building this heavily instrumented version of a solar collector system from scratch would approach $50,000. A simpler system with comparable thermal performance, minus the internet-based controllers and electronic instrumentation, would cost a fraction of that amount.

Efficiency of active loop solar panels

One experiment for an introductory MET Heat Power course compares the efficiency of the eight active loop solar collectors. The efficiency calculation compares the thermal energy collected to the radiant energy available. Each solar collector is exposed to the same amount of radiant energy, but thermal performance varies. Although the experiment's primary goal is to demonstrate typical thermal science computations, it also introduces students to an environmentally friendly renewable energy source.

Figure 3 summarizes radiant energy data, as measured by an Eppley solar pyranometer for a typical day in early January 2001. As expected, radiant energy varies with cloud cover and time of day. The radiant energy started increasing rapidly at about 8 AM, until clouds momentarily obscured the sun. The sun came out again by noon. The radiant energy reached a peak of 900 W/m$^2$ before diminishing rapidly. By 4 PM the sun's energy was gone for the day.

Figure 3 displays both "instantaneous" and "average" solar intensity. The instantaneous value is the real time data from the sensor, which can be very erratic on days with significant cloud cover. The average reading is integrated over a 30 minute time interval so it is largely unaffected by an occasional cloud. The average reading typically lags the instantaneous reading by approximately 15 minutes. Accounting for this lagging effect is crucial during later analyses.

The radiant energy is computed by multiplying the average solar intensity by the active surface area of each collector. At 2 PM on January 5, each collector saw about 1394 Watts (820 Watts/m$^2$ x 1.7 m$^2$). The average (rather than instantaneous) solar intensity is used for most calculations because it less susceptible to errors associated with the momentary peaks and valleys highlighted in Figure 3.

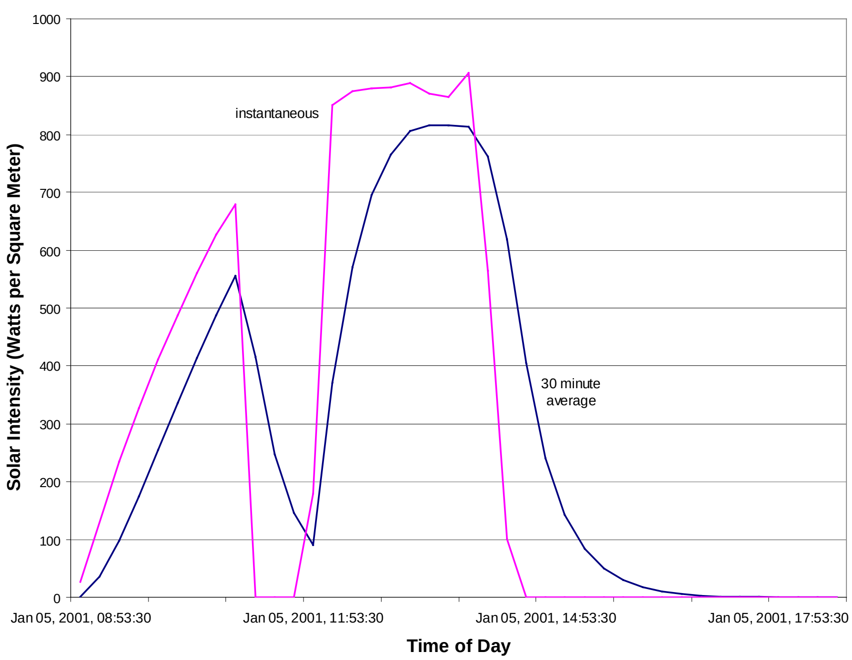


Figure 3. Solar intensity fluctuates with cloud cover and over the course of a typical day.

Figure 4 illustrates the thermal performance of three air-based collectors on the same January day used in Figure 3. The graph shows the temperature difference between the air entering and leaving each collector. Each collector has a small centrifugal blower that delivers a steady airflow of approximately 35 cubic feet per minute. As expected, the temperature differential increases as the solar intensity increases, reaching a peak at about 14:00 (2 PM). The perforated plate collector appears to be the best performer since its temperature rise peaks at 75 °F, more than 20 °F higher than the second place flat plate collector. The thermal performance of the air collectors was not influenced by the mid-day cloud cover detected in Figure 3.

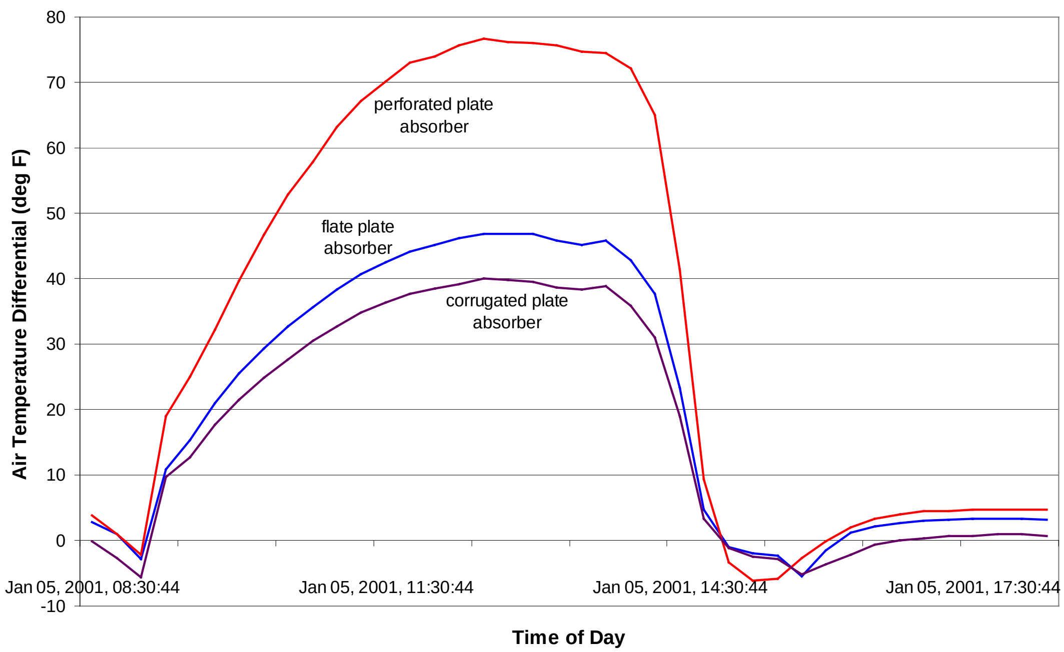


Figure 4. The temperature differential for air moving through active loop solar collectors varies with construction and time of day.

The raw data in Figure 4 can be used to estimate the thermal energy absorbed by each collector using basic specific heat equations. "Q = 1.1 x cfm x ΔT" is a simplified calculation for air at atmospheric conditions that is commonly used for HVAC work. Q is the energy transfer in Btu/hr, 1.1 is a conversion factor, cfm is the flow rate of atmospheric air, and ΔT is the temperature differential displayed in Figure 4. At 2 PM on January 5, the perforated plate collector absorbed approximately 2849 Btu/hr (1.1 x 35 cfm x 74 °F) of thermal energy.

The efficiency calculation is made by comparing thermal to radiant energy. As noted earlier, the radiant energy at 14:00 on January 5 was 1394 Watts, which is equivalent to 4759 Btu/hr. Since the thermal energy of the perforated plate collector was 2849 Btu/hr, its overall efficiency is 60 % ($\eta$ = thermal energy collected / radiant energy available = 2849 / 4759). This calculation means that 60% of the total radiant energy striking the collector is converted to useful thermal energy. Some energy is lost by light waves reflecting off the solar collector's glass surface. Unwanted heat transfer through the walls of the collector box also adds to the losses.

Figure 5 illustrates some of the factors that complicate the interpretation of solar collector efficiency. The graph is a two-hour snapshot that summarizes the January 5 data discussed in Figures 3 and 4. At first glance it appears that solar collector efficiencies vary dramatically over the course of a day. Even more startling, it appears that the efficiency of the perforated plate collector exceeds 100% early in the day. Students in the thermodynamics course are challenged to come up with a rational explanation for these unexpected results. A deeper understanding of the basic solar energy calculations is necessary to make progress on this task.

With some help from the instructor, a solution becomes apparent. The efficiency calculations are not reliable when solar intensity is changing rapidly. The denominator of each efficiency term is an "average" solar intensity that is computed over a 30-minute interval. The integral creates a problematic lagging effect. The average solar intensity is unrealistically small at noon and unrealistically large after 14:30. Figure 5 identifies a time period between 12:30 and 14:30 when the efficiency calculations are relatively stable and trustworthy.

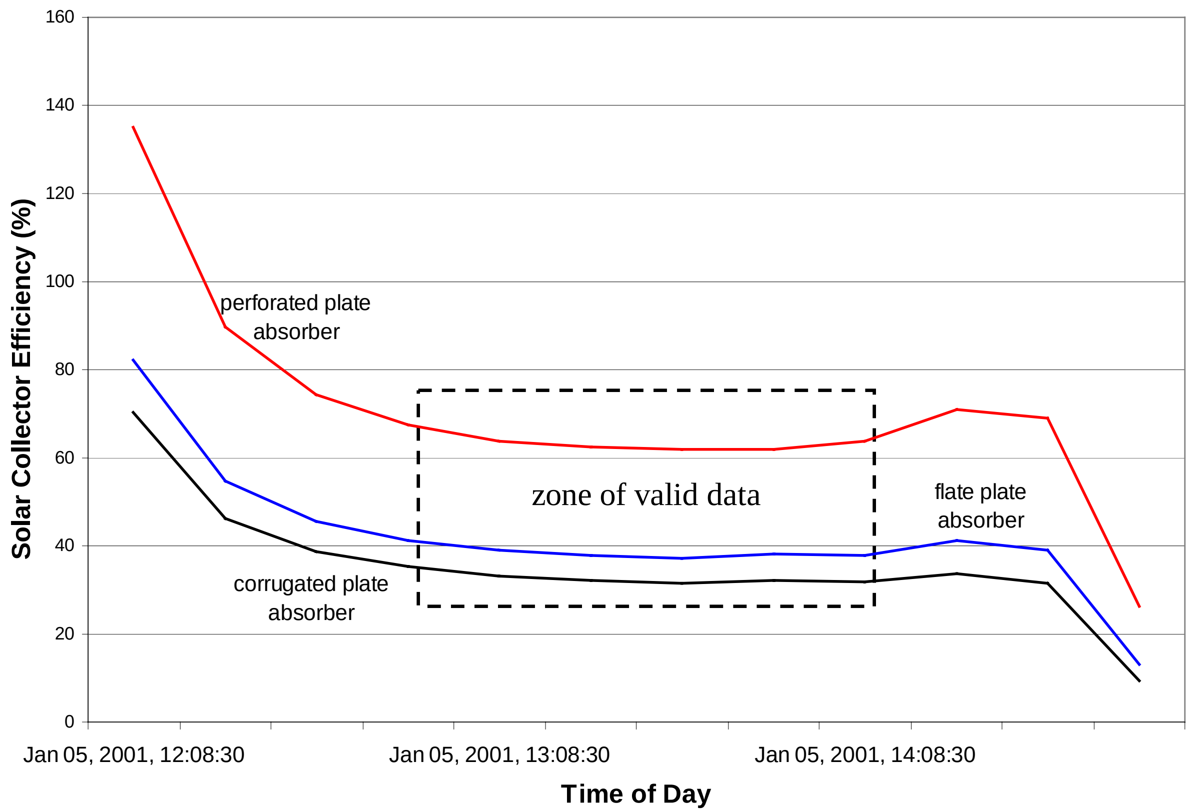


Figure 5. Use caution when interpreting solar collector efficiency data!

It is important to recognize that these basic solar efficiency calculations are a strict comparison of thermal energy collected to radiant energy available. They purposely exclude the electrical energy consumed by small centrifugal fans that push air through the rooftop collectors. Although the fan energy is easy to account for numerically, the results can be misleading. The efficiency for each collector decreases by approximately 6% when the fan energy is included. However, the 6% efficiency penalty does not convey a realistic picture of what is actually occurring. What is the nagging problem here?

In terms of an energy audit, it is not fair to compare the "high grade" electrical energy, which has a multitude of uses, to the "low grade" thermal energy that the collectors provide. A solar collector's thermal energy can only be used for local space heating and is only available when the sun is shining. Until a fair accounting of the difference between electrical and thermal energy can be made it is better to leave the fans out of the analysis.

The slight oversimplification (leaving out the fan energy) is "ok" in this case. This solar energy experiment is one of twelve laboratory projects in the introductory Heat Power course. Some concessions must be made to complete the experiment within the two hours that are allocated for the project. Upper level MET elective courses take a more sophisticated look at solar collector performance.

## Impact on technology and engineering education

It is important for educators to emphasize technical topics that reflect current industry practice. Although traditional thermodynamics topics remain most important, it may be possible to begin adding topics like energy conservation and renewable energy to the thermal sciences curriculum. The solar energy experiment described in this paper may allow educators to kill two birds with one stone. A significant number of thermal science computations are required to complete the project. At the same time, students must develop a basic understanding of solar energy to resolve some of the subtle problems with the analysis.

## References


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## Biographic information

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