Alternative Energy: Solar Energy

Introduction

Historical

As with hydropower, solar energy has a long history. Many pre-historic cultures used it to warm their dwellings, dry their clothes, and cure their food. The importance of solar energy was so great that most cultures revered the Sun and created rudimentary observatories to track its location in the sky (ex. Stonehenge). Some found solar energy so important that they even codified its power in their laws. Ancient Romans relied so heavily on solar energy to heat their homes and bathhouses that it was illegal to build a house or dwelling so tall so as to block the sunlight of any neighbor[1].

Ancient Rome was not the only culture to rely heavily on the Sun for energy. The Anasazi cliff dwellers of the ancient American Southwest also used their knowledge of the Sun's motion in the sky to heat and cool their homes. They built their dwellings into the sides of cliffs that faced the south. In the winter, sunlight was able to shine on their homes, while the cliffs protected their homes from cold northern winds that might blow. In the summer, the overhangs from the cliffs shaded their homes from the Sun, and thus made it cooler.

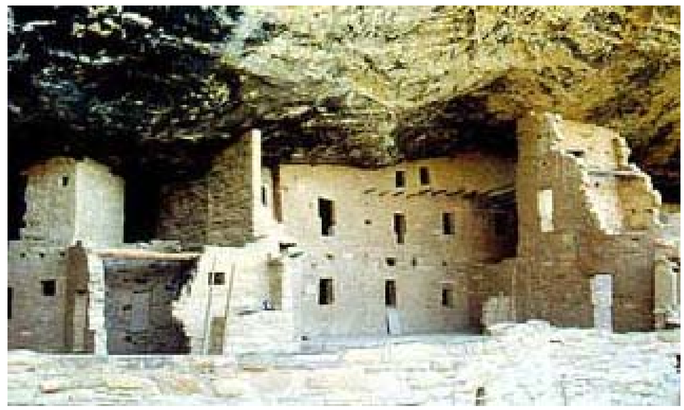

Figure 1: Mesa Verde cliff dwellings

Just as with hydropower, solar energy began to wane as a conventional energy source as fossil fuels and nuclear energy became cheap and reliable. The expense and variability of using sunlight has relegated its use to unusual situations where fossils fuels and nuclear energy are not available or where they are prohibitive to use or maintain. A perfect example of this is on satellites, which need energy to power all on board computers and instrumentation. Using fossil fuels to power a satellite over its lifetime would require quantities of oxygen and fuel that would be prohibitive to shoot into orbit. Nuclear material would be fine for powering the spacecraft, but would become very problematic when the satellites life was over and it came crashing back to Earth. An example of solar energy that is closer to home are interstate call boxes that are in remote locations. Rather than spending a lot of money to run telephone and electric lines out to these call boxes, one can use a solar panel equipped with a battery and a cell or satellite phone.

Outside of these few types of uses, though, solar energy has seen limited usage. In fact, in some parts of the U.S., the use of solar energy is prohibited. Covenants in some modern subdivisions that have homeowners associations actually forbid the use of solar panels or clotheslines for drying clothes. The reason for this is one of aesthetics: using solar systems can look "ugly" and hurt property values. Some states, such as California, have actually written state laws that prohibit subdivision convents from doing this[2].

Solar Energy Basics

At its core, solar energy is actually nuclear energy. In the inner 25% of the Sun, hydrogen is fusing into helium at a rate of about 7×10^{11} kg of hydrogen every second. If this sounds like a lot, it is because it is: this is equivalent to the amount of mass that can be carried by 10 million railroad cars. There is no need to fear, though, that we are going to run out of fuel anytime soon, as the Sun has enough hydrogen in the core to continue at this rate for another 5 billion years. This energy production, coupled with gravitational compression, keeps the Sun's center near a sweltering 16 million K, which is about 29 million ^{o}F. Heat from the core is first primarily radiated, and then primarily convected, to the Sun's surface, where it maintains at a temperature of 5800 K[3].

From the surface of the Sun, the primary method of energy transport is electromagnetic radiation. This form of heat transport depends greatly upon the surface temperature of an object for the amount and type of energy. Stefan-Boltzmann's Law tells us that the amount of energy that is radiated per unit area of surface depends upon the temperature of the object to the fourth power, i.e. energy/area is proportional to T^4. This means that the amount of energy that is emitted by the Sun, and therefore, the amount of solar energy that we receive here on Earth, is critically dependent upon this surface temperature. A change of 1% in the temperature of the Sun (58 K) can result in a change of 4% in the amount of energy per unit area that we receive here. While this might not sound like a lot, it is more than enough to plunge us into brutal ice age or hellish global warming.

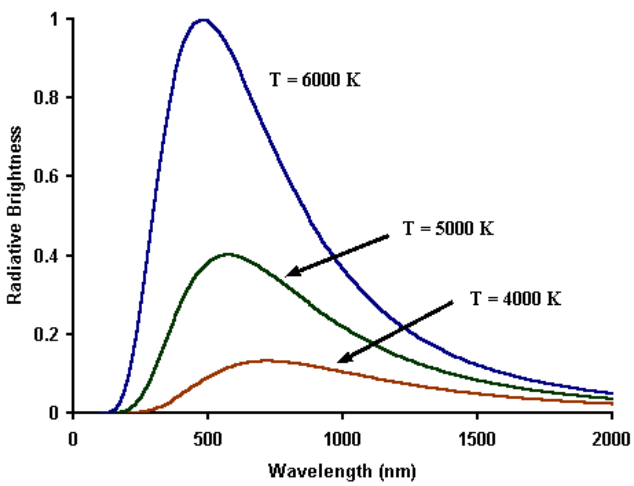

Figure 2: Brightness vs. wavelength for various temperatures

The type of radiation coming from the Sun also depends on temperature. The Sun is emitting electromagnetic radiation in wide variety of wavelengths. However, most of the radiation is being sent out in the visible spectrum due to its surface temperature. Wien's Law states that the wavelength at which the most energy will be radiated depends inversely upon the temperature of an object. Thus, as an object gets hotter, the peak radiation will come from shorter wavelengths, and vice-versa. Figure 2 shows a theoretical plot of the energy emitted by three perfect blackbody radiators of different temperature. An object that has a temperature of 4000 K has its peak energy being radiated at about 750 nanometers, which is in the near infrared. An object that has a surface temperature of 6000 K, though, has its peak energy being radiated at about 500 nanometers, which is in the green region of the visible spectrum. How these objects will appear to the human eye is determined by just how much energy is in each of the visible wavelengths. The first object will appear a very dim red, while the second (which is close to our Sun's temperature of 5800 K) will appear a bright white that has a hint of yellow.

While our Sun is not a perfect blackbody radiator, its output is fairly close to that described above. It radiates 1.6×10^7 watts of power per square meter from its surface at all wavelengths. However, by the time that it has reached the Earth's surface, this value is vastly reduced. Between the Sun's and the Earth's surfaces, the energy density of the radiation is lessened by spreading and absorption. Light travelling from a spherical object such as the Sun must spread to fill all available space. While the total amount of energy of the radiation will remain the same, the amount of energy crossing any square meter of space will be reduced by the square of the distance between the object and the area in question. Since the Sun is almost 150 million kilometers from the Earth, the energy density per unit time of the sunlight reaching the upper atmosphere of the Earth is only 1340 W/m^2.

Travelling through the almost perfect vacuum of space, there is almost nothing to absorb or reflect any of this energy. Most of the absorption of the Sun's light occurs after it enters the Earth's atmosphere. The vast majority of the visible part of the spectrum gets through the atmosphere with little attenuation. What little doesn't get through is due to scattering by nitrogen and oxygen (blue appearance of the sky is due to this) and by absorption and reflection from clouds. Large portions of the non-visible part of the spectrum do not get through the atmosphere, though. Chemical species such as ozone, water vapor, and carbon dioxide all absorb wavelengths of light in the infrared and ultraviolet portion of the spectrum. Figure 3 shows a plot of the percentage of the Sun's energy that gets transmitted through the atmosphere versus wavelength on a cloudless day. As you can see, outside of the visible and radio parts of the spectrum, there are only a few small sections in the infrared through which the energy gets transmitted. On average, only about 50% of the Sun's energy that makes it to the top of the atmosphere actually gets down to the surface.

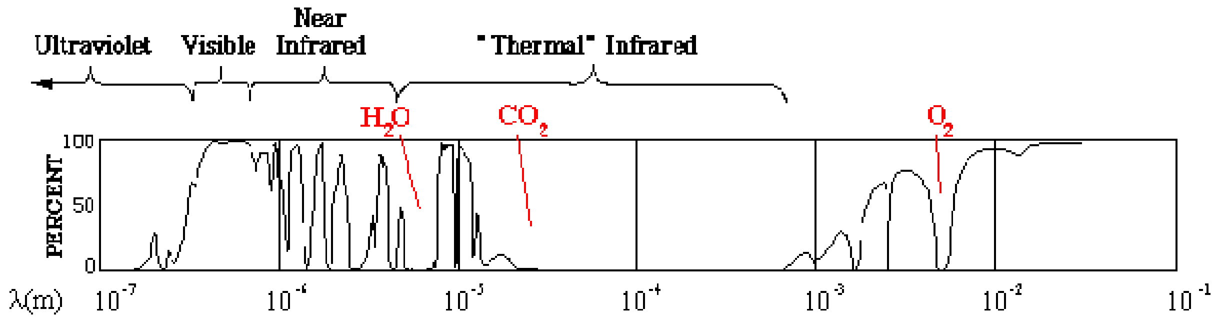

Figure 3: Sunlight transmitted through the atmosphere versus wavelength (*Source: NOAA*)

Latitude and Longitude

These are not the only factors that affect the total amount of energy that a solar system receives. One factor that seriously impacts it is the number of hours of sunlight a location receives in a day. If sunlight is striking a spot for more time during a day, then more total energy will be delivered, and vice versa. The amount of time that sunlight is shining during the day depends both on the location and the time of year. This is due to the fact that the Earth is a sphere that is spinning with its axis at an angle of 23.5^o with respect to the vertical to the plane of its orbit around the Sun. This means that the path that the Sun will take in the sky on a given day changes. Figure 4 shows a diagram of a typical situation found in the continental U.S. As you can see, the length of the path that the Sun follows on these four different days varies, as does the noonday angle of the Sun. These different lengths correspond to different travel times, which means different amounts of daylight.

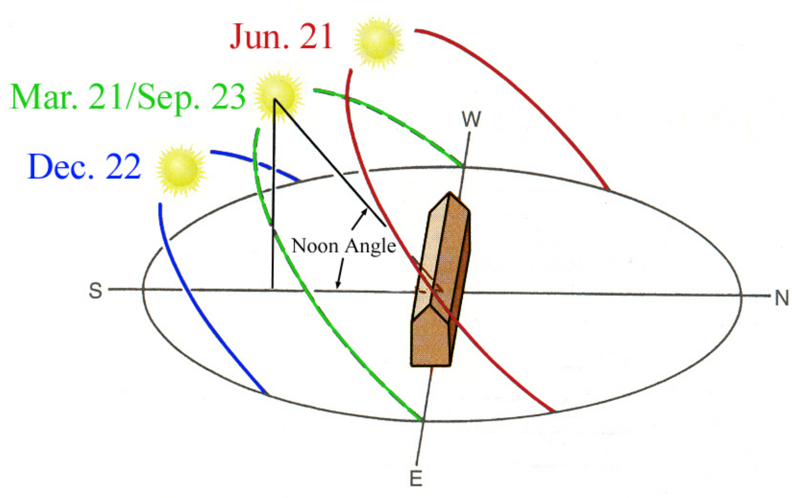

Figure 4: Diagram of the Sun's path in the sky on different days

In the continental U.S., there are about 8-10 hours of sunlight on the Winter Solstice (Dec. 22nd) and 14-16 hours of sunlight on the Summer Solstice (Jun. 21st), depending upon at what degree of latitude you live. Sites that are further north have shorter days in the winter and longer days in the summer. If one were to live at the equator, the length of the path across the sky would not vary, which results in 12 hours of daylight everyday. At the Poles, the situation is even stranger. There, the Sun is up for 6 months at a time, followed by 6 months of darkness.

The noonday angle of the Sun in the sky can also have an effect on a solar energy system unless it has a way to track the Sun. A system that can do this can always keep its collecting surface perpendicular to the Sun's rays, thereby allowing the most energy to strike it. If it cannot do this, then sunlight will always strike the system's collecting surface at some angle, thereby spreading the energy over a greater area and reducing the amount that actually strikes the surface. As we see from Figure 4, the angle of the

Sun's rays changes throughout the year, as well as throughout the day. As previously stated, these angles will depend upon the location of the system on the Earth's surface.

Types of Solar Systems

When most people think of solar energy systems, they imagine photovoltaic panels like those found on solar-powered calculators or satellites. These devices are very portable and useful, as they convert light directly into electricity via the photoelectric effect. This ability to directly output electricity means that they can power a tremendous number of modern devices that we use. However, they do have one very serious drawback: low efficiency. Most commercially available photovoltaic panels only have efficiencies in the 10-20% range, with the ones having efficiencies close to 20% being the most expensive[4]. The reason for these low efficiencies has to do with the fact that 1) not all frequencies of light are able to free electrons from the atoms in the panels and 2) those frequencies that are able to free electrons from the atoms do not do so in a 100% efficient manner. Given the expense of materials and the process for creating the panels, the low efficiencies mean that photovoltaic cells create electricity at about 3-5 times the cost of coal or natural gas powered electrical plants. This leads to their use in only special circumstances, such as in satellites in orbit around the Earth.

Photovoltaic systems are not the only way to convert sunlight into electricity. Solar thermal electrical systems use sunlight in order to boil water for a turbine generator, much like what happens in a normal power plant. In order to boil water using sunlight, one has to concentrate the light from a very large area into a very small area. This can be done with a magnifying glass, as any child who has ever attempted to burn leaves or paper on a sunny day can verify. However, for a large system that is going to create electricity, magnifying glasses are not useful, as such a large lens would have glass so thick that a great deal of the light would be absorbed by it. Instead, light is magnified by using curved mirrors to reflect the light to a focal point. Figure 5 shows a picture of such a system that is used for testing in New Mexico.

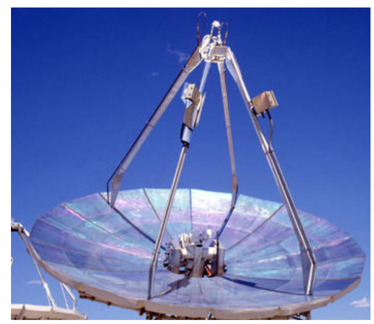

Figure 5: Solar thermal collector (*Source: DOE*)

Solar thermal systems have efficiencies comparable to those of a coal, nuclear, or natural gas powered plant. The main impediment to their widespread use has to do with the cost of construction and upkeep. As it currently stands, these systems produce electricity at a cost that is slightly more than $.10/kWhr, which 1.5-2 times that of coal or natural gas[5]. The price on these systems has been coming down, but it must continue to come down in order to make them economically feasible. If it does, large systems built in the desert southwest could supply a large percentage of the total electrical demand of the U.S.

Just as it was almost 2000 years ago, the greatest use of solar energy in the U.S. today is for heating. In most situations, it is used to either heat the air in a home or office or to supplement or replace the hot water system. This can be achieved by doing something as simple as installing a glass window on the south side of a house, or as complicated as a roof-mounted hot water system (See Figure 6). Because of the great flexibility and individuality in designing and building such system, there are no hard and fast numbers as to how much solar energy is being employed in this manner. The only data that can actually be measured is from industries that we know for sure are involved in the business of building solar thermal systems. In 2001, these companies sold over 11 million square feet of solar thermal collectors in the U.S[6]. However, we know that there is much more solar thermal energy that is being employed in the U.S. than just that being produced by these types of systems, which means that these figures represent a very low estimate to its use.

While there does exist a wide array of design types, we distinguish between the different systems for heating based upon whether they need an external power source to distribute the energy. An active solar heating system is one in which a pump or fan is used to transfer heat within the dwelling, while a passive solar heating system uses only the natural means of convection, conduction, and radiation to do this. Figure 6 shows an example of both of these systems. There are three elements in common in these two systems: a solar collection area, a heat transfer fluid, and a storage unit. The variety of materials and construction for these three is endless. Collection units can be boxes on a roof, windows on a home, or greenhouses attached to the home. The heat transfer fluids can be water, antifreeze, or air. Storage units can hot water heaters, a box of rocks, or an aquarium. The list of things that can be used in building a heating system is almost endless.

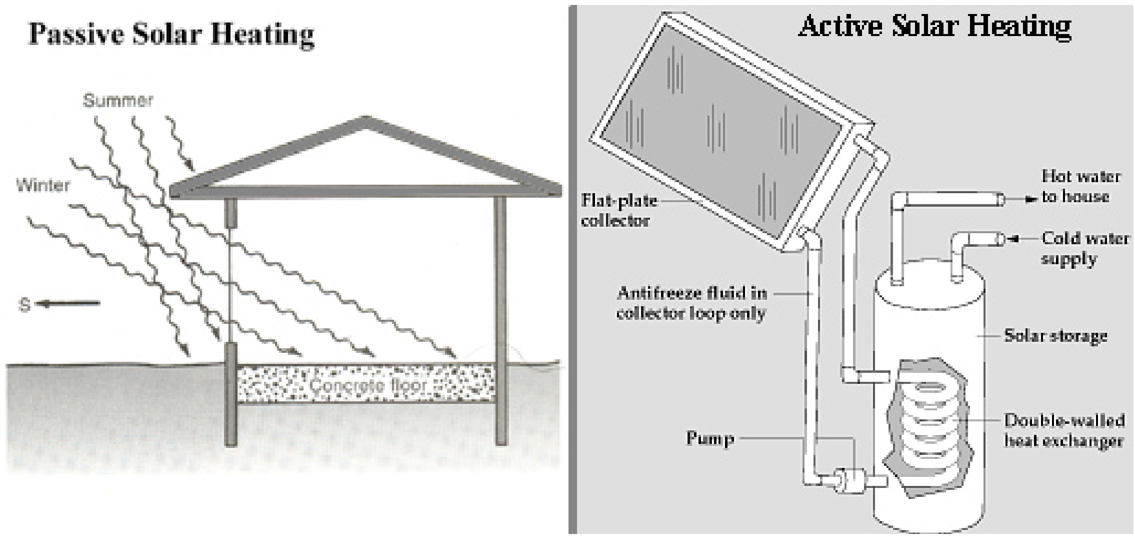

Figure 6: Example diagrams for active and passive solar heating systems (*Source: DOE*)

Activity

This week's activity is going to investigate the effects of color and collection area on the amount of solar energy absorbed by a system. While this sounds like a very simple task, it is complicated by several factors that can seriously impact results. The biggest of these factors is that a solar collector will begin to lose energy via heat transfer as soon as its temperature increases above its surroundings. Any system that we place in sunlight will begin to conduct heat through its support, convect warm air from its surface, and re-radiate energy in the infrared to its surroundings. Therefore, if you are going to attempt to test the relative abilities of different solar collectors, you must account for the heat loss.

The best way to minimize the heat loss would be to suspend the collectors in a vacuum chamber from a super-insulated thread. Unfortunately, not very many people can afford to construct a device. Instead, we will attempt to minimize the effect of heat loss by making all of the factors that we are not testing as close to the same as possible and by limiting the temperatures of the collectors. For the purposes of this study, the only two factors that need to change are color and the surface area exposed to sunlight. Factors such as construction materials, total area in contact with ground, etc. should be kept as close to constant among the collectors. There are going to be some factors, though, that we cannot keep the same. However, if we do not allow the temperature of the collectors to increase too much above their surroundings, the rate of heat flow (which depends on the size of the temperature difference) should be limited.

If this activity is being done on your college campus, your instructor should be able to make available to you the necessary equipment to achieve this. If you are doing this at home or in the field, it will be a little more difficult to account for these factors. One set of collectors that we could recommend would be different sized aluminum pie and serving pans. A check of your neighborhood store will show that aluminum pans come in several sizes and shapes. What you will need to do is to get two pans that are identical and a third one that has the same shape, but is a different size. As an example, one could use one 5-inch and two 8-inch pie pans. One of the identical ones needs to be painted black, while the other one is painted white. The third pan that is of different size will need to be painted black. To complete the collectors, you will need some transparent cling film like Saran Wrap to cover the openings to limit heat loss by convection.

Once three different collectors have been obtained, the procedure is quite simple. Measure the surface area of the collector that will be facing the sunlight. Pour an equal amount of water into each of the containers, and place a thermometer into each container so that it can be read during the experiment. Seal the container with a transparent material such as cling film. Place each container in sunlight such that the collection surface is pointing straight up. Measure the temperature of each collector every 2 minutes. Continue to do this until one of the collectors increases its temperature by 30 ^{o}F above air temperature. It should be noted that the sunlight is not striking the surfaces of the collectors at a 90^{o} angle as it would if we were trying to maximize the amount of energy absorbed. This should not interfere with our study, since the angle between the surface and the sunlight is the same for all collectors.

Since the water does not undergo a phase change, the increase in the temperature of the water is directly proportional to the amount of energy absorbed by the collectors. Therefore, if we are able to neglect the amount of heat that is lost by the collectors, the amount of the temperature change should allow us to compare the relative effect of color and size on a solar collector.

Additional Reading

The links below go to the U.S. Department of Energy's Energy Efficiency and Renewable Energy division. This is the section of the DOE that researches and tests solar energy systems. The three links will give you the latest developments in photovoltaic, solar thermal electrical, and solar heating systems.

Department of Energy	**Topic**: Photovoltaic Systems **Summary**: Energy Efficiency and Renewable Energy division's photovoltaic systems homepage **Link**: http://www1.eere.energy.gov/solar/photovoltaics.html

Department of Energy	**Topic**: Solar Thermal Electric Systems **Summary**: Energy Efficiency and Renewable Energy division's concentrating solar power systems homepage **Link**: http://www1.eere.energy.gov/solar/csp.html

Department of Energy	**Topic**: Solar Heating Systems **Summary**: Energy Efficiency and Renewable Energy division's low power solar collectors systems homepage **Link**: http://www1.eere.energy.gov/solar/solar_heating.html

References

1 http://www.abc.net.au/rn/science/earth/stories/s225110.htm, August 4, 2003.

2 http://www.eere.energy.gov/state_energy/policy_content.cfm?policyid=28, August 4, 2003
Updated 2006-Aug 1: New URL is http://www.eere.energy.gov/states/alternatives/

3 http://www.nineplanets.org/sol.html, August 4, 2006.

4 http://www.eia.doe.gov/cneaf/solar.renewables/renewable.energy.annual/backgrnd/chap11i.htm, August 4, 2003.

5 http://www.energylan.sandia.gov/sunlab/research.htm, August 4, 2003.

6 http://www.eia.doe.gov/cneaf/solar.renewables/page/rea_data/chapter2.html, August 4, 2003.

ESA21: Environmental Science

Activity Sheet
Solar Thermal

Name: Professor:

Collection Area:

Collector 1 = _______ Collector 2 = _______ Collector 3 = _______

Time	Collector 1	Collector 2	Collector 3	Time	Collector 1	Collector 2	Collector 3

Plot Data: