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IEEE Lesson Plan:
Solar Power

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Lesson Focus
This lesson is intended to provide students with a basic understanding of what Solar Power installations are and how they work.

Lesson Synopsis

The Lesson begins by making the point that while Wind Turbines often have dead spells when there is no wind blowing, they can often produce energy no matter whether it is day or night. On the other hand, so long as it is daylight, solar panels can produce power regardless of whether the wind is blowing or not. Furthermore, if a solar array is of the more elaborate type, which includes a battery and a DC/AC inverter, it can produce energy in the dark. Such installations are of course, more expensive. Students complete hands-on challenges with mini solar cells.

Age Levels
8-14

Objectives
Students will:
- Gain a useful understanding of a relatively new energy technology, which over their lifetimes, will become more prevalent and common.
- Learn about the importance of discipline and team work.

Lesson Activities
The hands-on challenges include:
- Connect three mini solar cells in series and/or parallel.
- Measure the voltage of each cell and the three in combination.
- Measure the internal resistance of each cell and then of all three in series and/or parallel.
- See how many LEDs the array can illuminate or if it can power a mini DC motor.

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Anticipated Learner Outcomes

- Students will become familiar with the construction and application of an energy source which is to be seen on an everyday basis, but which is often taken for granted.

Alignment to Curriculum Framework

See attached curriculum alignment sheet

Internet Connections

- TryEngineering (www.tryengineering.org)

Optional Writing Activity

Write a set of comments on the various Solar Installations shown in the figures in the text which follows, also prepare a series of advantages and disadvantages of solar power.

Source

- This lesson contributed to TryEngineering by Dave Hepburn, IEEE Canada.

For Teachers:
Teacher Resource

◆ Lesson Goal

This lesson is intended to provide students with a basic understanding of what Solar Power installations are and how they work. Wind Turbines and Solar Arrays are becoming more and more a common and integral part of the fabric of our daily lives. It is important that future generations understand what they can and cannot do.

◆ Materials

- 3 solar panels
- jumper wires
- volt meter

◆ Time Needed.

Two sessions of 45 minutes each, including time at the end for students to prepare written comments.

◆ The Need for Solar Power: General Background

As will be clear after reading this text, over the last ten or fifteen years, there have been two predominant technical developments in the field of electric energy production. These have been (a) the rapid increase in the number and size of wind turbines and (b) a similar development in the use of Solar Panels. Both of these produce what is known as "renewable" or "clean" energy. These are in contrast to electricity produced from the burning of coal, natural gas or oil, all of which consume oxygen and give off large quantities of smoke, or what is known as "Greenhouse gases". These are so called because when they get into the upper atmosphere they remain there and tend to reflect back to earth any heat which may be given off by industrial or other activity. Furthermore, even some of the heat coming in from the sun and which attempts to escape again, is trapped back under this layer of "greenhouse" gas. The net result is that over time, the earth's atmosphere and the air we breathe is becoming warmer. If this process were allowed to continue over a century or more, planet earth will become uninhabitable. The situation is therefore already critical, as indicated by the melting of glaciers and the shrinking of the two polar ice caps.

◆ Non- Renewable Energy Sources

In order to provide the student with a general perspective of how solar power fits into our every-day energy production, a brief mention of the so-called "non-renewable" energy is appropriate here.

In increasing order of pollution emitted, they are:

- Nuclear Energy. Although nuclear energy when properly controlled, does not normally emit greenhouse gasses, it can have VERY serious health effects if not properly handled.
- Natural Gas.
- Oil and gasoline.
- Coal. Unfortunately, coal is available in vast quantities world-wide, and is easily extracted, which tends to make it the "Easy way out".

Renewable Energy sources

In decreasing order of energy intensity, they are:

- Hydro. Hydro is of course the most "Powerful" simply because water is a very heavy material. One cubic meter of water (approximately 3 ft. x 3 ft. x 3 ft.) weighs one ton. How much does the same volume of air weigh? Not very much. The main problem with hydro is that it often requires the flooding of large areas of good farm land and/or the spoiling of fish runs.
- Wind Power. After some initial resistance, mostly on the grounds of appearance, it now appears to be gaining acceptance
- Solar Power. Comparatively benign but somewhat expensive, although costs are coming down rapidly as technical development and mass production are reducing it.
- Tidal and wave power. Limited to sea coast areas. Also there are two High Tides and two Low tides each day, with dead periods between them. Tidal power is also linked to the lunar cycle and therefore has a shifting availability.
- Geothermal energy. As most students will know, the center of the earth is quite hot. Furthermore some countries have "hot spots" where the heat is close to the surface. In such locations, similar to volcanos, it is economic to drill holes into these hot spots and circulate water which becomes steam in quantities enough to drive steam turbines. Students may wish to look up places such as Iceland, the Philippines, New Zealand and the Rift Valley (in Africa).

Solar Power – Thermal Storage

The simplest type of solar power is the type which absorbs energy from the sun and stores it, usually in water. This heat can then be released after sunset, for use in heating or washing. This type of heat storage cannot easily be used to power machinery or lighting, and will not be discussed in detail in this lesson.

The Combination of Wind Energy and Solar Power

From the above very brief outline, it will be seen that these two sources have considerable potential if used in "tandem". Wind power can often blow just as well at night as in the day, while Solar Power, especially if provided with a battery, can provide power even when there is no wind.

The obvious limitation of solar power is that it simply does not produce energy at all during the night, unless provided with a battery

But put the two together and you can usually get useful energy, 24-7.

Specifically:

At night, wind energy can often make up for the lack photo electricity at night and, Photo-electric power can often make up for the lack of wind power during a calm period during the day.

But it will be seen that to get the best out of both systems together is very much a juggling act. The Lesson entitled "Working with Wind Energy" in this series deals in detail with wind energy. It is recommended that it be read in conjunction with this lesson, if a clear understanding of both is to be obtained. All lessons are listed in alphabetical order.

◆ The Development of Early Electric Power Systems

Over the last 150 years or so, since the time of Thomas Edison, George Westinghouse and Nicola Tesla, Ferranti, and others in that group, the need for, and convenience of, electricity has multiplied many times over. In that period industrial scale electricity has been produced by three primary sources:-

- Burning fossil fuels,
- Damming rivers for hydroelectric plants, and
- Nuclear energy.

But like many other technologies, these three have reached a plateau and are now facing resistance, mostly for environmental and climate change reasons. A partial exception to this is Nuclear energy. While the consequences of a nuclear accident can be serious, the fact remains that since the 1950s, there have only been 3 really serious nuclear accidents – Three Mile Island (USA 1979 no fatalities), Chernobyl (USSR 1986, total fatalities unknown – USSR was very secretive - but probably several hundred), and Fukushima (Japan, 2011, one fatality by heart attack). On the other hand one must consider (a) the number of people who die from traffic and flying accidents each year and (b) the fact that nuclear plants do not emit any greenhouse gases. The bottom line with nuclear energy is that it requires absolutely cast iron discipline with regard to safe operation and maintenance.

Today the two rising alternative power sources are wind power and solar power. The use of wind turbines has been covered in a companion Lesson Plan in this series.

This current lesson plan will provide a basic general outline of how photo electric cells work and how they fit into the general scheme of things.

◆ The Early Photo Cell

Like most things which are now taken for granted in modern technology, one of the primary constituents of a photoelectric cell was discovered almost by accident. In the case of Selenium, it was discovered in 1817 (two hundred years ago) by the Swedish Chemist Jons Berzelius while he was attempting to improve the quality of the sulphuric acid (of all things) he was making for some other industrial activity. He discovered that Selenium was in fact a discrete element. Subsequently it was given its own elemental symbol as Se and was found to have an Atomic weight of 79, as compared with aluminum at 28, iron at 55, lead at 207, and Uranium at 238. So in other words, a typical Selenium photo cell would seem comparatively heavy considering its' small size.

Subsequent experimentation by others revealed the interesting feature that the electrical resistance of selenium decreases significantly as the light in which it is placed increases. This of course soon led to an early application of selenium, maybe 80-90 years ago, as a handy accessory to photographers, as even a very small amount of selenium, suitably mounted in a pocket-size case with a small flashlight battery, could be used to measure the brightness of the surrounding light and of course, how to set the shutter speed in his camera. Eventually even the flashlight battery was dispensed with as it was found that the Selenium could in fact produce its' own (but ultra-small) electric source.

In 1835 the first practical photocell was built by Jens Becquerel, who was incidentally one of the early investigators of radio-activity. (Check that in the net under Nuclear Power. His arrangement was a combination of Silicon and Gallium arsenide.

In 1873 Willoughby Smith published a paper entitled "The Effect of Light on Selenium During the Passage of Electricity".

Subsequent investigations by many others brought to light the fact that numerous combinations of chemicals (mostly metals) could produce small amounts of electricity when exposed to light. And importantly the light could be either sunlight or artificial light. Today anyone who searches online will find that there is almost an alphabet soup of materials which are in use. However the important feature is that photo electricity requires the bringing together of thin wafers of two different materials. A few examples include Selenium/Gold, Copper Oxide/Silver, Indium/Tin, Cadmium/Telluride and many others, depending on the application.

From probably the 1890's to about the 1960's, Selenium seems to have soldiered on in a niche of the photography market as "Exposure Meters". People used to see photographers with a camera in one hand and a small exposure meter on a cord around his/her neck. Eventually these meters were miniaturized and built into the camera itself. Today of course, the whole camera is electronic.

Figure 1 shows a typical small solar panel suitable for demonstration purposes in a School Classroom. Under a bright fluorescent light, it will produce about 2.2 Volts DC, and cost about US$15.00 (in 2019). The voltage will of course decline as the brightness of the lighting is reduced. $15.00 may seem expensive but such items are robust and durable and will last some years. The internal arrangement comprises two separate metals, usually Silicon and some other metal in electrical contact with each other. The exterior is simply a thick coating of epoxy, which is translucent, watertight, and physically strong. Price is declining rapidly as mass production takes effect. On the other hand, an interesting feature of solar panels is that their output does not decline significantly with age – unlike flashlight batteries, which last less than an hour if used continuously.

Figure 1

◆ A Mobile Solar Panel

Figure 2, below, shows something which is a common sight on many streets and highways. It is a pair of medium size solar panels mounted on a two-wheel trailer. This particular one is arranged to supply a trio of yellow flashing traffic warning lights. But it could probably operate a small warning sign, such as "Construction" or "Lane Closure Ahead". The box on the back of the trailer will also carry a rechargeable battery sufficient to keep the sign working throughout the night.

Figure 2

◆ What are Solar Panels made of?

Over the last several decades, progress has been made in the field of the photo-cell itself, it was found that besides Selenium, several other materials, notably Cadmium Sulphide (CdS) and Silicon (Si) were both cheaper and more responsive to exposure to light. Silicon, of course is the material at the heart of transistors and printed circuit boards computers and cell phones. The important feature of all photo "cell" is that it comprises two wafers of slightly different material, pressed tightly together. It is therefore a diode, meaning it will only pass current in one direction. But the fundamental difference between a transistor (which is also a diode) and a solar cell, is that when it is exposed to light the two wafers begin to exchange electrons. If there is no external circuit, these electrons manifest themselves a a DC voltage. The amount of voltage it will produce varies with the intensity of the light in which it is located. In bright daylight the output is about 2 volts dc. If there is an external circuit, say for example a flashlight bulb, a current will flow and the bulb will light up. But this is no limitation because individual photo cells can be connected in series to produce the voltage desired and groups in parallel to provide the current desired. For example, to provide 120 Volts DC would require about 60 cells in series, and to supply a 1,000 Watt (1 kW) electric tea kettle would require about 8.5 amps, or say 100 cells in parallel. These figures are approximate because allowance has to be made for internal resistance and losses in the cells themselves. But they are quoted here to illustrate the general principal.

Such an arrangement of 60 cells in series and 100 in parallel can be encapsulated in a translucent epoxy resin. This epoxy is translucent, hard, tough, weather proof, and durable. Such an assembly is known as an Array, and take the form of a flat panel measuring about 36” x 36” x 1” thick The epoxy material can be drilled for mounting holes – provided none of the electrical circuits inside are damaged. The internal arrangement would be in the form a printed circuit as in a pocket calculator, only of course much bigger.

The weight of the individual silicon photo cell is not particularly heavy, but the panel itself, which is epoxy resin, is hard, stiff and comparatively heavy. A typical individual panel such as those shown in Figures 3, 4 & 5 probably weighs about 50 lbs (20 kg).

Greater power output can easily be obtained by adding more arrays in parallel or in series, depending on the need.

◆ A Tough Piece of Work

Figure 3

Figure 3, above, may look a little strange, but is included here simply to show how robust solar panels are. Note in particular that the top row is projecting at least 12” (30 cm) above the ridge of the roof and is completely unsupported. Such panels can in fact be walked on without damage. To the knowledge of the author, these particular panels have been in place for at least 5 years.

A more conventional arrangement is shown in Figure 4, which is actually a church.

Figure 4

◆ How to "Read" Solar Panels

Refer first of all to Figure 4 above.

Power Output. You will notice that in the above installation there are a total of 48 panels. Because of their unitary construction, solar panels can be arranged in a wide range of "Series" and "Parallel" combninations. Since solar panels are mainly used for lighting and heating, they are usually rated in **Watts** of heat output. Each panel shown here is rated at 250 Watts. Hence the total power output would be 48 x 250 = 12,000 W or 12 kW. (Churches and Mosques generally need a lot of heat because of the high ceilings).

Voltage Output. Solar panels produce only direct current (DC). Virtually all electric power systems world-wide, operate using alternating (AC) current. In North Americe the frequency is 60 cycles per second (60 Hz). Most other systems operate at 50 Hz. The standard domestic voltage in North America is 120 Volts AC. However, because this is an alternating current systyem, the figure of "120 V" is actually only an average of a sine wave. But to attempt to match the DC system from a solar panel with the AC system in the house, one must know the maximum height (the "crest") of the AC sine wave. It so happens that you can get pretty close to this figure by multiplying the average figure by 1.4. Thus the crest of a 120 V AC wave is 120 x 1.4 = 168 Volts. In other words each solar panel needs to have a rated output voltage of 168 Volts, if it is to have any hope of working alongside a 120 V AC domestic system.

Given, however, that in North America at least, all somestic appliances operate either at 120 Volts, or two 120 Volt systems together to give 240 Volts, in most cases the 120/240 Volt operating level is taken for granted and is usually ignored in solar panel work. Thus the installation shown in Figure 4 would be referred to as a 12 kW array.

Summary of "Reading" Figure 4

If you were to knock on the door of this church and ask the Pastor, he will probably tell you that his installation gives 12 kW and leave the voltage unstated. But more on this later. See Figure 9 below.

◆ Application of Solar Panels

Students should of course, appreciate that solar panels are only a part of the picture. Although they are an invaluable "Green Revolution" they have two main limitations

- They can only produce direct current power, and,
- They don't work at all after sunset.

To enable them to usefully integrate themselves into a modern power system they need:

- What is known as an "Inverter" which is an electronic device which can convert DC into AC electricity, and,
- A quite large common-or-garden rechargeable battery which can take DC energy from the solar array during the day, and release it to the inverter for conversion to AC power during the night. Both of these items are relatively expensive. Batteries, in addition, depending on type, require careful maintenance.

Inverters, being what is known as "solid state" devices are generally efficient and reliable. But they are nevertheless part of the cost of setting up a comprehensive solar power system. Batteries on the other hand are a known technology with known limitations. For example automobile batteries are what are known as "Lead Acid" batteries, and contain sulphuric acid, which is a serious health hazard and dangerous. The acid also causes corrosion, and during the charging cycle, gives off large quantities of hydrogen gas, which is explosive.

Both these features are discussed later in this lesson.

◆ General Discussion

Figures 5 and 6 show an alternative method for mounting solar panels. The advantage is that, with limitations, they can be so positioned as to optimise their orientation with regard to the sun. Understand that the orientation of panels mounted on roofs of houses are very much a compromise depending on the orientation of the house.

Figure 6 shows details of how such panels are mounted. A further improvement would be to add a tracking mechanism at the back of the panel to keep the panel always in the best position with regard to the sun. But like most things in life, they cost money. So you pays your money and you gets your choice.

In this installation, the house it serves is out of sight behind the trees.

Another consideration about roof-mounted solar panels is that they are comparatively heavy. In addition, they should not be in direct contact with the roof shingles, but should have maybe 2" (5 cm) clearance for ventilation. In summary therefore, solar panels are generally mounted with rubber grommets between the shingle and the underside of the panel. And of course, once mounted they are not easy to remove. It is generally a good plan to have the roof re-surfaced before mounting the panels.

CHALLENGE. How do you "read" this installation??

Figure 5

Figure 6

Pros and Cons.

As you will see, this sort of installation casts a big shadow on the ground. This will limit ability to grow crops. An ideal location is to mount large arrays on the roofs of existing buildings. Word has it that large corporations such as Walmart and CostCo are already beginning to do this.

◆ Three Basic Installations

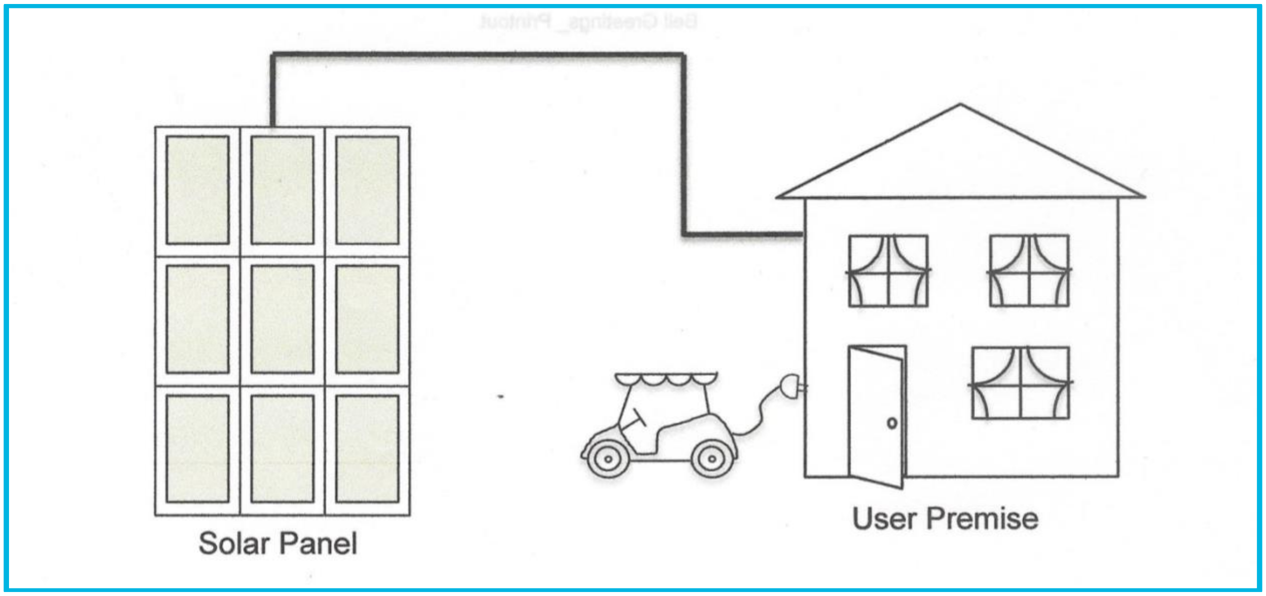

Figure 7

Figure 7, above, shows an absolutely minimum cost installation. But frankly, it wouldn't get you very far. Yes, it does have a good size solar array. But that's all it does have. It does not have an inverter, so the DC voltage it produces would not mix with the 120 Volt AC in the house. Furthermore it does not have a battery, so it would not be much use at night. About all this installation could achieve would be to charge the Golf Cart shown.

◆ Next Step Up

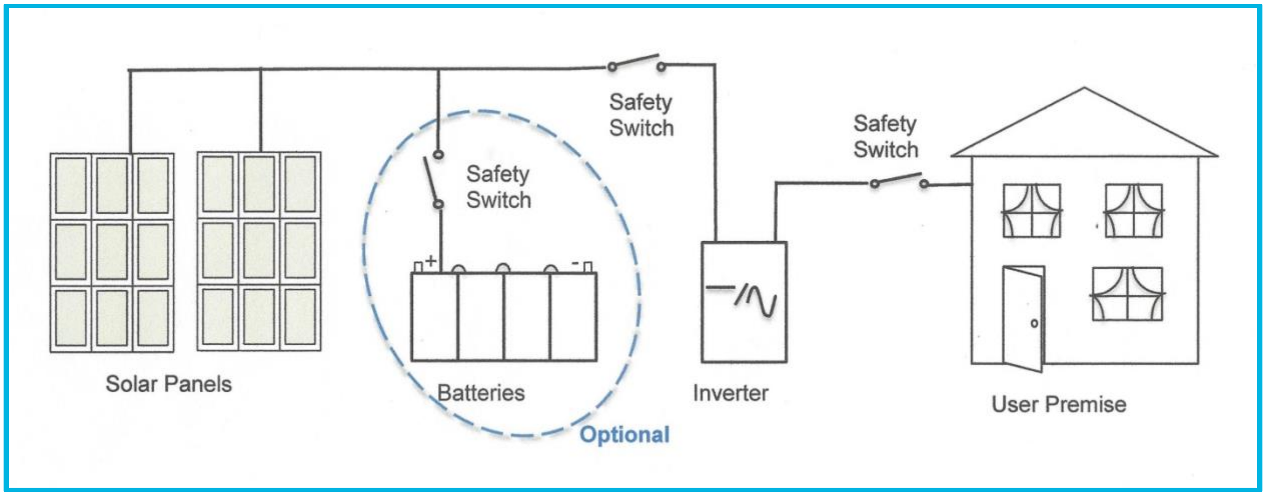

Figure 8

In Figure 8, you will see the two additional items of equipment which are required if you want a useful installation (in a house or in a factory).

- An inverter – to convert the 168 Volt DC to 120 Volt AC in the house.
- A Battery – assuming you will want electricity after dark. The battery is shown here as "Optional" but in general one would think it would be worth the additional expense.
- You will also need an electrician to do the installation work.

These items will add considerably to the cost. Given that costs are decreasing rapidly as mass production takes effect, it is difficult to give even an approximate figure. But as of early year 2020, the above set-up would probably cost at least US$15,000. And this is based on the assumption that it represents the addition to an existing house. Significantly less if it was being included in the construction of a new house.

Class Challenge: Try and find out how much that might cost in your local area.

Sale of Surplus Energy

The "ultimate" solar installation is one in which the owner can install more plant than he will probably need, with the objective of selling any surplus energy back to the power supply company. In many cases it is possible to do this at a modest profit – depending on the financial. Such an installation is shown in Figure 8. Note the additional equipment required. As before, a solar array, a DC/AC inverter and a battery. Note that if energy resale is intended, the solar array and the DC/AC Inverter will need to be somewhat larger than before. The battery will only be for the house and will therefore be the same size as before.

Additional equipment will include the additional safety switch #1 in the diagram - about which more later. The remainder of the additional equipment, including the transformer to step up from 120 Volts to the system voltage (probably about 15,000 Volts, and the 15 kV wood pole line would have to be paid for by the power company. The need for the safety switch #1 is very important. Examine Figure 9 closely. The normal procedure in a power company in such circumstances is that if they need to work on the wood pole line, they will open switch # 2 at the Grid Substation. But if there is a live solar array feeding into the house, it also means that it will also be feeding back into the power system via the transformer. In other words, the transformer will be acting as a 120 V/15 kV step-up transformer, feeding into the wood pole line. Note: transformers work equally well as "Step-Up" and "Step-Down." This is most important because if the lines-man does not know that and climbs the pole, he will be electrocuted. Both safety switches #1 and #2 is therefore required and both must be "Locked and Open" before any repair work is started. Electric Safety Codes are very strict about such matters and will probably require that signed clearance notes be issued and both switches carry appropriate safety notices.

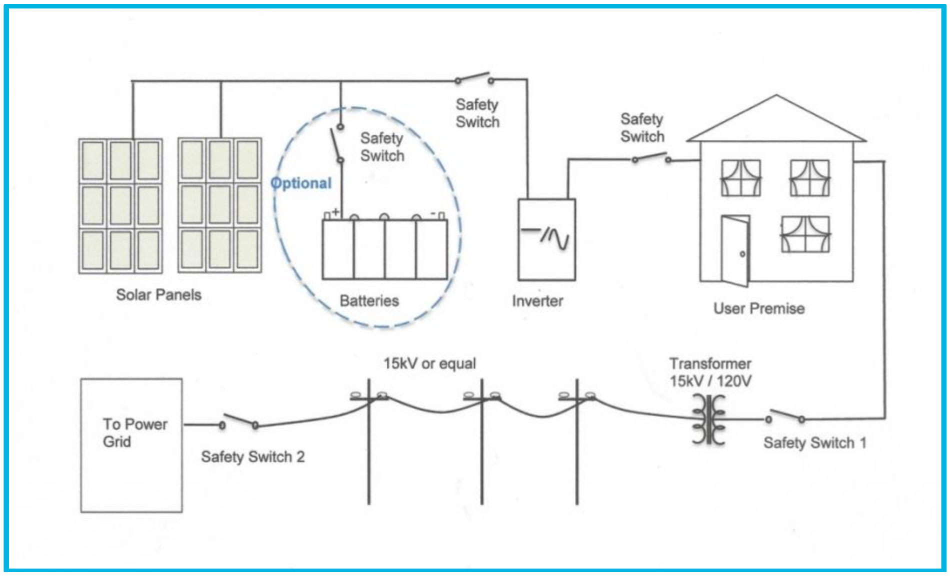

Figure 9

Figure 9 shows a second view of the church previously shown in Figure 4 above. As mentioned earlier, since this church is relatively little used during the week, it makes a good candidate to "export" energy back to the local power company. For example, the photograph shows two circular objects, which are actually billing meters. One meter will record how much energy (kW.h) has been consumed in the Church. For this energy, the church will of course have to pay. The second meter records how much energy has been sold back to the power company. Safety switch #1 is presumably in the large grey boxes. Not seen, and presumably in the basement, is the DC/AC inverter.

Figure 10

Some Important Considerations with Solar Panels

It is most important to realize that the Solar Panel itself only produces direct current (DC). Most domestic appliances require alternating current (AC) to function correctly. However, incandescent lights and LEDs will function satisfactorily on either AC or DC supply. Possibly most appliances with a commutator motor will also operate on dc, provided the voltage is suitable. But other items such as TV and clocks will not. Hence if full interchangeability is required, an additional piece of equipment known as an "inverter" is required, and such items are expensive.
As a general statement, Solar Panels can either be mounted on the roofs and walls of buildings, or on free standing frames just above ground level. See Figures 3, 4, 5 and 6. But in the case of free standing frames it is not possible to use the ground underneath for agricultural purposes because the solar panels block the sunlight required for plant growth. However, extremely large solar arrays fit well in desert areas such as Arizona and Africa. Some can be a 1,000 ft (300 m) or more either direction. There are many interesting photographs to be seen on the net.

A Note about Roof Mounted Panels

It should be noted that most roofs in North America are made of asphalt "shingles", which are comparatively soft, particularly when heated by the sun. Thus asphalt shingles tend to dry out and become brittle after about 20 years or so.

Roof mounted solar panels are generally bolted directly through the shingles into the wood beneath, separated only by rubber grommets (one in each corner of each panel and placed there to provide ventilation). It therefore makes sense to check the condition of the roof before adding solar panels. For obvious reasons it would be tedious and expensive to have to remove the panels and set them on one side while the roof is re-shingled.

A Significant Disadvantage of Solar Power

One significant disadvantage of a solar panel is that the voltage it produces varies widely with the intensity of the light in which it is located. And moreover, this variation can take place within a matter of minutes, depending on how fast the wind blows the clouds past the sun.

The reader is encouraged to read the companion lesson in this series entitled "Basic Electricity and Magnetism".

Safety Considerations with Feed-Back systems

Refer to Figures 9 & 10. It is important that the local fire brigade know that there are solar panels on the roof. As mentioned previously solar panels are heavy, and if the house has been seriously damaged, the weight of the panels on the roof could cause the roof to collapse and injure the people below.

◆ The Ultimate Domestic Installation: All-Solar Operated

If you decide you wish to have your house completely run by solar energy, you better make sure you or your parents have a big check-book. To be quite honest, to convert an existing house is probably not viable economically unless you live in a location, such as an Island, where energy is already expensive., But if you are building a new house from scratch, today's costs are probably reasonable, especially taking into account that once built, the house will essentially be operated for zero cost. Another advantage would be that all the electrical components would be free of moving parts and silent.

The following components will be required.

A solar system capable of producing about 10 kW of power at all times. (By inspection, it is estimated that the array in Figure 9 would be capable of producing about 10 kW). For this system, you have three main choices:- (a) On the roof, fixed, (b) On a separate fixed stand somewhere in the garden, or (c) A stand somewhere in the garden, but capable of rotating to keep track of the movement of the sun as the days and the seasons go by. This latter arrangement would provide maximum efficiency, but obviously would cost money. Most systems are fixed, and are therefore a compromise.

And again, the inclusion of a battery can be considered as optional.

◆ The International Space Station

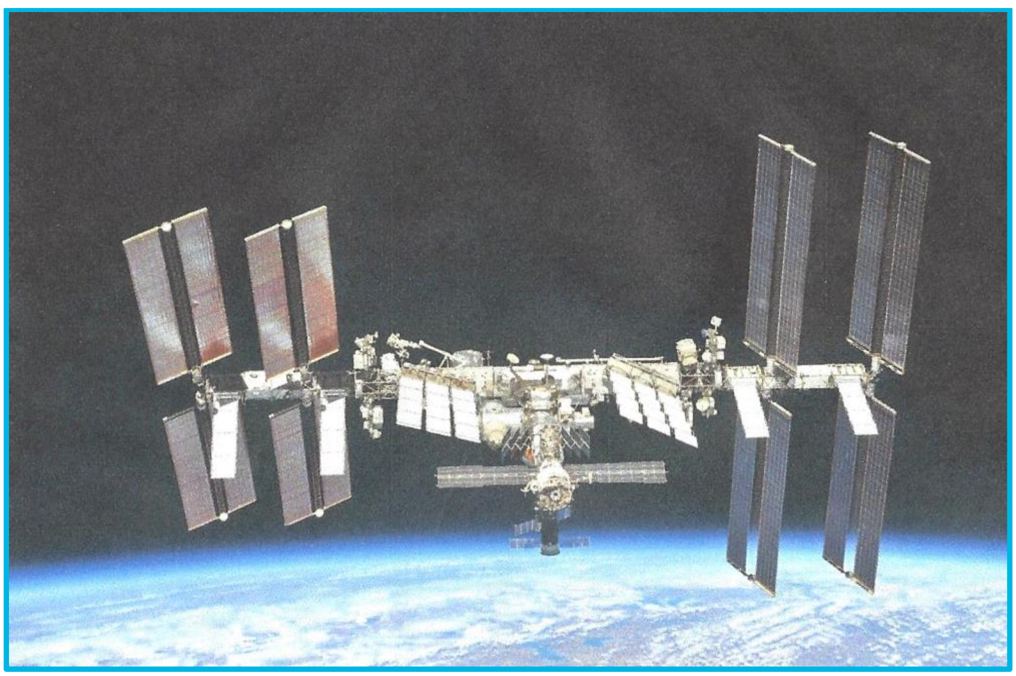

Figure 11

◆ The Ultimate Solar Array.

Although strictly speaking not related to this present lesson, the matter of the International Space Station, or ISS is worth a brief examination here because of its' large and very specialised array of solar panels, and to the interest in all school students. See Figure 11**.** The ISS is extensively detailed on the Net, but a few points here are worth mentioning.

- The Net will say that there are 8 arrays, but to the uninitiated there would appear to be 16. This because the individual panels are connected in pairs. But whether the pairs are connected in series or parallel is not clear.
- These panels are not what you might buy in your local hardware store. As mentioned above, domestic solar panels are rigid and relatively heavy. On the ISS, for obvious reasons, they have to be as light as possible. Moreover, they are very flexible, so much so in fact that when not required they can be folded down like a venetian blind. When fully extended, each pair measures 112 ft x 39 ft (34 M x 12 M).The schedule of power requirements on the ISS is, like most of the rest of the space craft, "different". The power requirement for laboratory and ordinary living purposes is about 80 kW. During the 60 minutes of "sunlight", this is, of course, supplied by the solar array. During the 30 minutes when the ISS is in the earth's shadow, this same 80 kW of power has to be supplied by the batteries. But then, when the sunlight returns, the batteries have to be re-charged. Hence the total power requirement from the solar array is about 80 kW for the working load, plus 40 for battery recharge which makes for a total of 120 kW. Note here that since one circuit of the earth is 90 minutes, comprising 60 minutes of "sunlight" and 30 minutes of "shadow", there is roughly twice as much time for recharge as there is drain on the battery. In other words the recharge load can be half the drainage load or half of 80 = 40 kW. For a comparison, an electric kettle takes about 1.5 kW, and therefore the total working load on the ISS is about 53 kettles. Battery voltage is roughly 169 volts.

You may ask, why 169 Volts? Good Question. Most North American appliances, computers etc., use 120 V, 60 Hz. Thus the DC output of the solar panels has to be converted to AC. As you may know, alternating current (AC) is a wave which reverses polarity 60 times a second. The term "120 V AC" is actually only an average figure. But in actual fact the highest point of the wave is 169 Volts. The ratio between the two is 1.4 (i.e. 169/1.4 = 120). So if the solar panels are to be able to cover the full spread of a 120 volt wave, it must be capable of reaching 169 volts.

In most other respects the ISS solar panels have to perform in much the same way as on earth. Specifically, when it gets dark, you need a battery large enough to keep you going until the next day. In the ISS however, the average "Day" is only 92 minutes, with about 60 minutes of light and 32 minutes of darkness. For this the ISS needs a battery large enough to keep all the equipment going for 32 minutes. Furthermore, the solar panels have to be able to support two functions simultaneously – the "Daytime Working Load" plus recharging the battery.

To summarise, the paragraph above notes that the ISS takes 90 minutes to rotate around the Earth. During 60 of those minutes it is in full sunlight, but for 30 minutes it is in the Earths' shadow and in darkness. What this amounts to is that only about 80 kW of the solar panels are available for "real work", with the other 40 kW required for recharging the battery.

A Very Interesting Feature of Solar Panels

To an approximation, a solar panel which is 20 years old will still be able to produce about the same amount of energy as when it was new. How can this be when there has been no discernable change in the internal arrangements of the cell? The answer is surprisingly simple. Think of a transformer which takes energy from the primary winding and transfers it to the secondary winding, (with only 1 – 2 % loss in transit). The situation is very similar with a solar panel. It takes energy from the sun, converts it to electricity, and sends it out to the inverter or whatever, with only 1 – 2% loss in transit. So it is really not making energy out of nothing, it is really converting one form of energy to another in a very efficient manner. In other words, you still can't get something for nothing. Or put another way, just as for 150 years there have been electric transformers, now we have solar transformers.

◆ Progressive Thinking

Students are probably aware that in many places there is a general reluctance to adopt new ideas and equipment. Not so in the State of California. In 2019, the State Legislature adopted a modification to the building code, which requires all new construction domestic houses up to 3 floors high, to be built with roofs which incorporate Solar Panels. It will be interesting to see how, when or if other jurisdictions follow this development.

◆ General Summary

Over the last decade, the application of photo-cells has developed at a rapid pace. Solar panels are now not simply used for domestic and industrial application. They are now used for light aircraft (one has flown non-stop around the world", cars, ships and many other uses which were not thought of ten years ago. The reader is encouraged to turn to the Wikipedia article on this topic, where some 50 photographs are to be found.

Written Exercises.

- Prepare a list of conventional domestic AC equipment which will also operate satisfactorily on a DC supply. Include comments as to the difference.
- Prepare a similar list of conventional domestic AC equipment which will not work on a DC supply. Give reasons.
- List some of the advantages of solar power.
- List some of the disadvantages of solar power. What have you learned about the ISS?

Hands-on Exercises

Unlike other lessons in this series, there are only a comparatively few exercises which can be put together using one or more photocells as a basis. For example, photo cells are comparatively expensive considering the rather low power output they offer.

The demonstration photo cell shown in Figure 1 costs about $5.00. Three such cells were purchased for comparison purposes. Hence it will be evident that to purchase sufficient cells to permit a class of 30 students, working in pairs would cost 15 x 3 x $5 or about $225 probably too much for most schools. And probably at most there would be only two or three demonstrations a year. On the other hand it was observed that the cells are robust and should last quite a long time.

It is therefore suggested that just three cells be bought and that the teacher does most of the demonstrating, while challenging the students to explain some of the discrepancies which will become evident as set out below.

Option 1.

Have the teacher allow the students to connect all three cells in series. Note the cells have positive and negative markings.

Measure the voltages produced. They will probably somewhere between 1.3 and 1.6 volts each for a total of about 4.5 volts in the classroom. Then have them place the three together in bright sunlight, which should increase the combined voltage to as much as 6.7 volts total. Write down the results.

Take 3 LEDs and see how many, one, two and three photo cells in series and then in parallel, will light up. (LEDs cost $0.50 each). Write down the results.

The class could buy a very small DC motor. Motors as small as 2 volts can be bought for about $2.00. Connect the motor across one, two or three photo cells. In all probability it will not turn over, even though it is a 2 volt motor connected to 5 or 6 volts. The same 2 volt motor connected across a 6 volt dry cell will spin like crazy. Challenge the class to answer why this should be).

(Reason: These photo cells appear to have a very high internal resistance. Have the class check this).

Then have the students measure the RESISTANCE of each photo cell. In all probability they will find a wide spread, anywhere from 10 – 50 Kilo Ohms (10,000 - 50,000 Ohms) for each cell. And of course, three photo cells in series will amount to between, 30 and 150 k ohms total Explain to them even though the motor is very small and probably draws only about a few milliamps, to attempt to pass 1 milliamp through that sort of resistance would require anywhere from 30 to 150 volts. In other words the internal resistance of the photo cells is simply too high to support anything more than solid-state equipment such as LEDs and thiresistors. (But conventional lamp batteries have much lower internal resistance, and so-called lead-acid batteries have extremely low resistance. See associated lesson "Basic Electricity and Magnetism").

Have a student hold three cells in series, close to a window in bright sunlight. Or better still take the cells outside on a sunny day. You will probably find some variation between the three cells, both with regard to voltage output and internal resistance. It should also be noted that the $10 photo cells used above are probably built to the cheapest possible standards, and certainly not to ISS standards.

Discuss with the students why the International Space Station has such a large solar array.

In short, even though the opportunities for hands-on exercises are limited here, there are nevertheless some valuable lessons to be learned.

Option 2

- Connect the three photo-cells in parallel.
- Measure the voltage of each cell and the three in combination. Write the values down.
- Measure the internal resistance of each cell and then of all three in parallel. Write them down before you forget.
- See how many LEDs the array can illuminate. You will probably find that none will light up. Why? Because these LED's need about 4 or 5 volts to illuminate, but the voltage available from 3 cells in parallel will still only be about 1.5 volts.

Final Question. Do solar panels work on a foggy day? Answer – yes, but not very well.

For Teachers:
Alignment to Curriculum Frameworks

Note: Lesson plans in this series are aligned to one or more of the following sets of standards:

- U.S. Next Generation Science Standards (www.nextgenscience.org)
- U.S. Common Core State Standards for Mathematics (www.corestandards.org/Math)
- International Technology Education Association's Standards for Technological Literacy (http://www.iteea.org/TAA/PDFs/xstnd.pdf)
- Computer Science Teachers Association K-12 Computer Science Standards (http://csta.acm.org/Curriculum/sub/K12Standards.html)

◆Next Generation Science Standards

4-PS3-4 Energy

- Apply scientific ideas to design, test, and refine a device that converts energy from one form to another.

MS-PS3-3 Energy

- Apply scientific principles to design, construct, and test a device that either minimizes or maximizes thermal energy transfer.

◆Standards for Technological Literacy (All Ages)

Technology and Society

- Standard 5. Students will develop an understanding of the effects of technology on the environment.

Design

- Standard 9: Students will develop an understanding of engineering design.
- Standard 10: Students will develop an understanding of the role of troubleshooting, research and development, invention and innovation, and experimentation in problem solving.

The Designed World

- Standard 16: Students will develop an understanding of and be able to select and use energy and power technologies.