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INTRODUCTION

One can certainly argue solar energy is at the heart of all energy available here on the surface of the Earth. Solar energy allowed the organisms that eventually became our fossil fuel supply to live, grow, and store energy in their tissues. We are now releasing that stored energy – at a rate far greater than the Sun is capable of replacing it in biological reserves. In many ways, this use of fossil fuel represents the ideal source of solar energy. It's highly concentrated, stored rather conveniently beneath our feet, and is available any time we desire. Ideal, that is, except for the fact that releasing the energy requires combustion of hydrocarbons which in turn leads to various pollutants finding their way into the environment.

Using solar energy before it is linked to various forms of matter is not necessarily a space, or time efficient process. Solar energy is diffuse and fickle. While the total amount arriving at the planet far exceeds what we (as technological societies) could possibly use, energy available at any one place in a short time is often not very impressive. A possible result of unchecked world population growth is that we will not be able to afford the "luxury" of looking to a diffuse energy supply to satisfy human desires. Using solar energy requires a significant amount of space, and therefore material. A sound scientific argument could be made that with sufficient population pressure we may be forced to depend on the most highly concentrated energy source – nuclear fission (fusion technology being far from today's reality).

The technology used to collect and store solar energy is refreshingly simple, and proven through decades of use and study. Either we collect the it directly, as in the case of thermal energy and photovoltaics, or we use methods to capture indirect results of the Sun's effects on Earth's natural processes (hydrodynamic and wind energy). All of these technologies have the ability to be widely distributed in small-scale operations – close to the end user of the energy. Most regions of the world have access to substantial amounts of solar resources (hydrodynamic being a possible exception). This has the added political benefit of allowing most societies to refine their own energy, using local human and technological resources.

The purpose of this primer is to introduce both the solar energy resource and the technologies available, now and in the near future, to produce useful energy from that resource.

THE SOLAR RESOURCE

Designing systems to effectively use solar energy requires a detailed knowledge of the behavior and quantity of solar radiation. We'll start the discussion at the source (deep inside the Sun) and move our way through space, the Earth's atmosphere, and finally down to the Earth's surface.

THE SUN

The Sun, a modest star by all accounts, is essentially a large thermonuclear fusion reactor that contains energetic reactions with immense gravitational forces. It sits at the center of our solar system, an average of 93 million miles from Earth. Even though there's no solid matter in the Sun its mass is 333,000 times greater than that of Earth. The diameter of the visible surface is more than 109 times that of Earth, which results in a "surface" area almost 12,000 *times* larger than our planet's area. Since radiant energy is proportional to surface area, this figure is important. If the Sun weren't so big, we wouldn't be so warm.

The Sun's structure can be said to consist of several zones. Figure 1, below, indicates a core with a radius about 25% that of the photosphere. In that zone, which represents only 15% of the Sun's volume, about 90% of the energy is released – mainly in the X- and gamma-ray portions of the spectrum. The density there is extremely high, about nine times that of lead. Keep in mind that this is not what we would call a solid, because the astronomical temperatures prevent even electrons from associating with atomic nuclei. In the radiative zone successive absorption and reradiation by particles occurs, lowering the temperature by several orders of magnitude. At the outer edge of the radiative zone (about 70% of the Sun's radius) the density is low enough for convection heat transfer to play the dominant role in moving thermal energy from the core to the "surface." The density of material in the convective zone is only about 1/10th that of liquid water. The photosphere, or visible surface, defines the end of convection. The density here is so low that fluid motion is no longer apparent, and beyond it the density is too low for us to see visible light. The temperature has dropped precipitously to approximately 5700 °C. The photosphere is particularly important to solar energy utilization because the vast majority of radiant energy reaching the Earth starts here. It is interesting to note that the Sun's

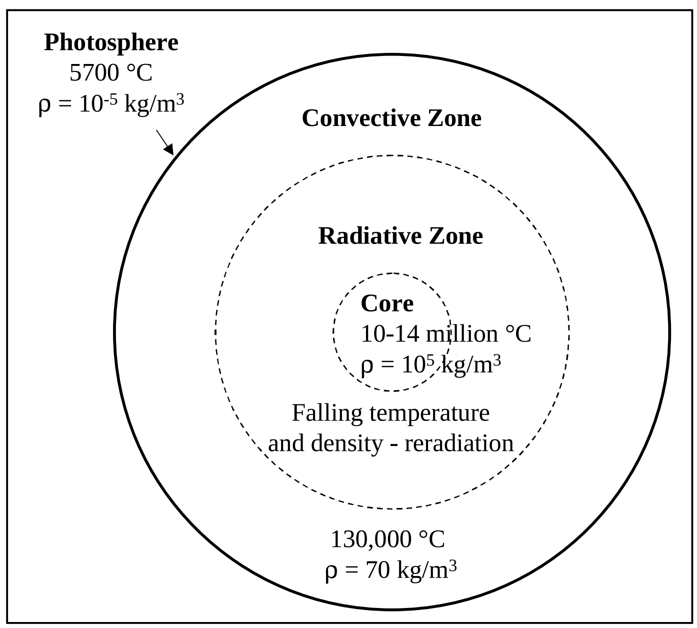

Figure 1 Structure of the Sun

density drops by 10 orders of magnitude (10 billion times) from the core to the photosphere. That's an amazing variation!

ENERGY PRODUCTION IN THE SUN

At present about 73.5% of the Sun's mass is hydrogen, 24.8% is helium, and 1.7% represents a wide variety of trace elements. Hydrogen, by far the most abundant element in the universe provides the fuel for fusion reactions that combine two hydrogen nuclei and produce a single helium nucleus while converting a tiny fraction of the hydrogen mass to energy. When the hydrogen is used up, the Sun essentially goes out. Even though the Sun loses about 4.2 million tons per second of mass (to energy conversion) the available hydrogen should be able to fuel it for 6 billion more years. Not something to worry about on a human time scale.

The chemical representation of the nuclear fusion reaction is as follows.

$$4\,H_{nuclei} \rightarrow 1\,He_{nucleus} + Energy$$

The mass lost in the reaction is converted to energy according to Albert Einstein's famous equation,

$$E = mc^2$$

where "c" represents the speed of light, which is then squared to result in an absolutely huge number to be multiplied by the converted mass (m). Energy (E) conversion from this type of reaction is the most efficient in the universe.

The problem now is getting the energy from the Sun's photosphere to Earth. Not an easy proposition, as 93 million miles is certainly *not* a walk in the park. Beyond the photosphere, the density of particles in space is too low to allow any heat transfer by conduction or convection. Luckily, radiant energy easily travels at the maximum speed of light in the near vacuum of space. This electromagnetic radiation is made up of a variety of wavelengths. Shorter wavelengths are associated with more energetic radiation (e.g. ultraviolet) and longer wavelengths refer to less energetic radiation (e.g. infrared).

SOLAR ENERGY ON EARTH

The amount of energy intercepted by the Earth is extremely small due to the Earth's size and large distance from the Sun. Only 2 billionths of the radiant output ends up here. Even so, that's about 35,000 times the total amount of energy required by all the people on the planet. In order to quantify how much energy arrives at the outer reaches of Earth's atmosphere we define the Solar Constant.

$$\text{Solar Constant} = 1367\ {}^{W}\!/\!{}_{m^2}$$

This means that if you were to take a sheet of material with an area of one square meter above the atmosphere 1367 watts of power would land on it as long at it was oriented perpendicular to the Sun's incoming radiation. That's about 30% more power than a trained athlete can deliver in short bursts.

That number is fine for satellite photovoltaic power system calculations, but does us almost no good down here on Earth's surface. Unfortunately the atmosphere is responsible for large losses in the amount of radiant energy landing at ground level. First of all, about 35% of the incident energy is reflected right back out to space. Most of this occurs in the upper atmosphere, but some is a result of reflections (during clear sky conditions) from water, snow, and sand. The latter portion could be available for collection, if necessary. Whatever energy isn't immediately reflected to space is subjected to scattering and absorption in the atmosphere. Atmospheric particles and pollutants scatter light with a preference for shorter wavelengths, thus the blue portion of the spectrum is diffused, resulting in a blue sky dome under clear conditions. Certain constituents of the atmosphere absorb selective wavelengths of radiant energy as well. Water vapor, carbon dioxide, and ozone absorb 10-15% of incident energy. Note that humid climates will suffer greater losses of solar energy due to higher water vapor contents.

Figure 2 shows the energy difference between solar radiation arriving outside the atmosphere and that measured at the Earth's surface. The solid line represents energy

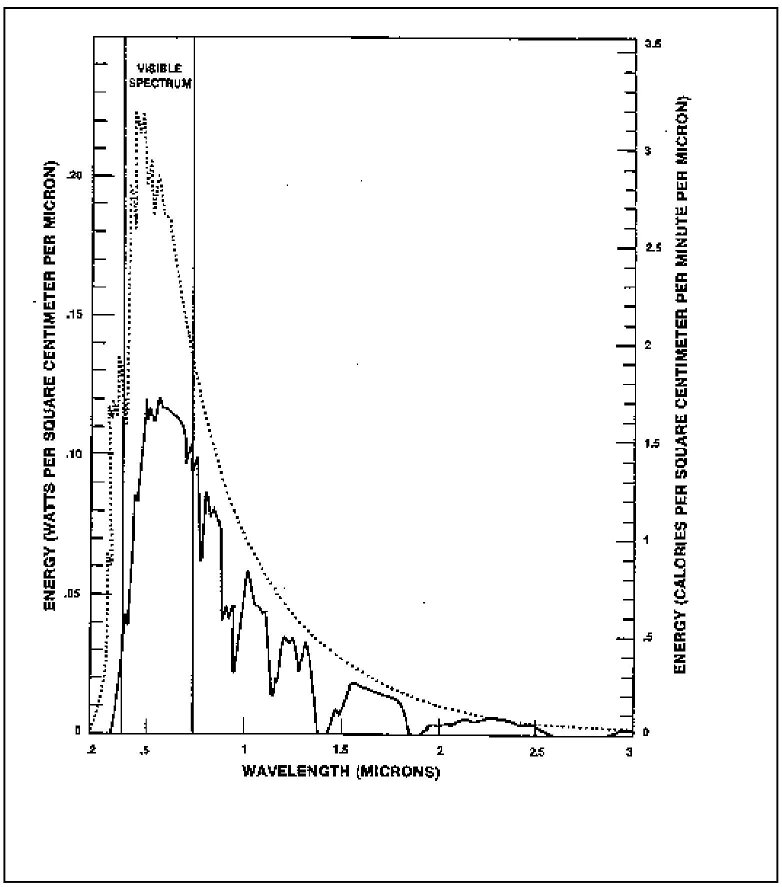

Figure 2 Spectral Characteristics of Solar Radiation

available after atmospheric effects are subtracted. The visible light portion of the spectrum extends from 0.35 to 0.75 micrometers (microns, or 10^{-6} m) of wavelength and is indicated by the two vertical lines. Note that by the time the Earth is reached a significant fraction of the short wavelength (high frequency, high energy) radiation has been removed. This is good for our health, but hampers energy collection. Also, the visible region represents about half of the total energy available at ground level. The other half is almost exclusively infrared (thermal) radiation. The sharp dips in the solid line represent wavelengths that are selectively absorbed by atmospheric compounds (water vapor, carbon dioxide, etc).

Of the 1367 W/m^2 striking the atmosphere, we would be fortunate to have 1000 W/m^2 make it to sea level. On a clear dry day when the Sun is at its highest altitude it is not unusual to record 1200 W/m^2, especially at higher elevations. Under these conditions most of the energy is arriving as *direct beam* radiation. This is the radiation you feel on a clear day. On cloudy days, and in mornings and evenings, *diffuse* radiation makes up the majority of energy. Direct beam radiation is most useful in energy conversion devices, but the diffuse energy can be significant. Diffuse radiation will work quite well in low temperature thermal collectors, built for cloudy tropical climates.

Since direct beam radiation is so important to solar energy collection, it makes sense to focus there for a moment. When determining the amount of beam radiation available at a particular site the most significant factor is the length of atmosphere radiation had to travel through to get there. If you stood on the equator and waited for the Sun to be overhead (an altitude of 90°) you would be witnessing the shortest path of radiant energy through the atmosphere. The only way to increase beam energy would be to climb in elevation. That said, think about all the factors that would affect the atmospheric travel length. They would include:

- Time of day
- Latitude of location
- Time of year (for locations north and south of the equator)

Remember that the more atmosphere, the more energy will be scattered and unavailable for direct beam collection. Obvious examples include sunsets and sunrises. The atmospheric path is so long at these times that the majority of visible light energy is scattered, leaving only longer wavelengths (red and infrared). All three of the above factors must be included in design calculations.

SOLAR TIME AND MOTION

The only time that truly makes sense for living organisms (and solar energy collection) is solar time. Solar time recognizes that at noon, the Sun should be as high in the sky as it gets during daylight hours. So when we refer to solar noon we mean maximum solar altitude. The invention of time zones marked a human attempt to link all the world's site-specific solar times. It is, though, just an approximation. Since the Earth rotates at a rate of 15° per hour, a one hour time zone difference is seen every 15° of longitude. Divide 360° (a full circle) by 15° per hour and you get 24 hours – a time zone for every hour of the day. Since solar altitude is of utmost importance to the designer, special charts are available for specific latitudes. Figure 3 shows one such chart for 36° north latitude (equally useful for 36° south). The latitude of Farmington, NM is 36.8° north.

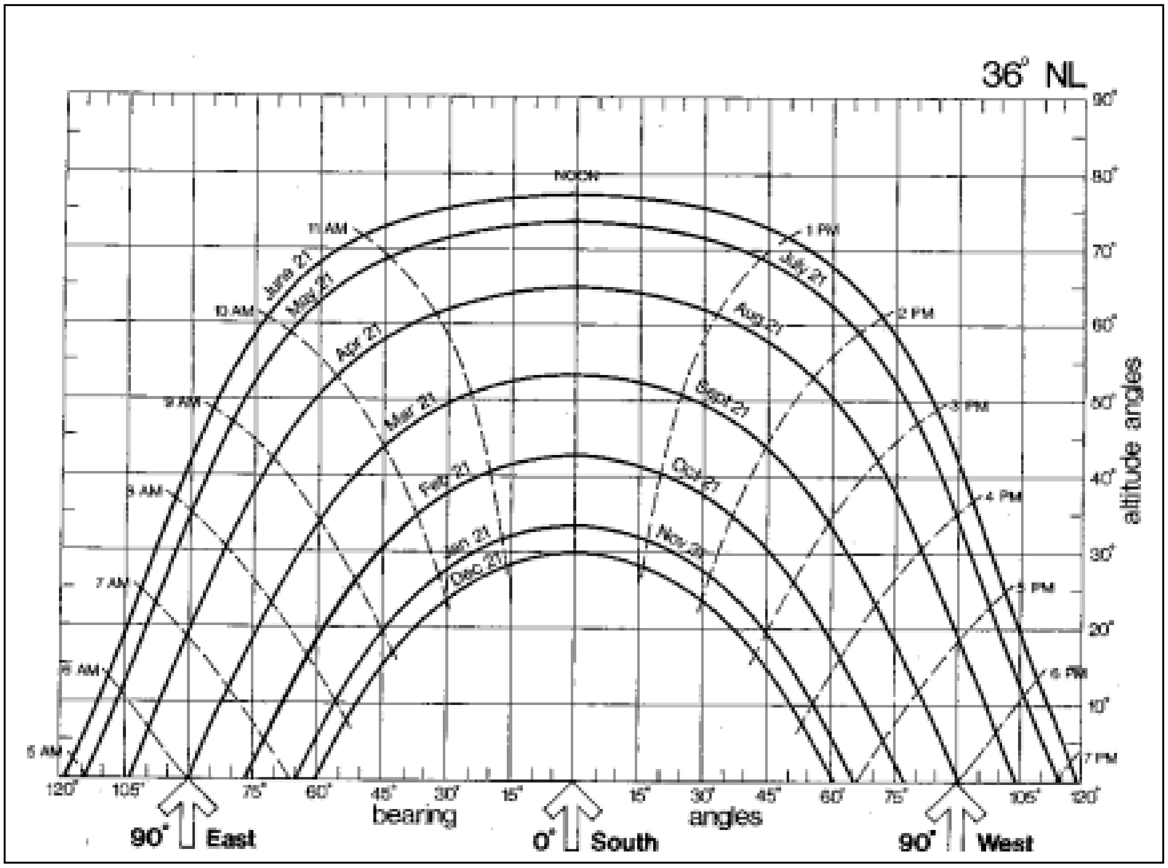

Figure 3 Solar Path Chart for 36° North Latitude

The major function of a chart such as Figure 3 is to determine if your solar collectors (or windows in a passive solar structure) will be shaded from direct beam radiation during critical times of the day or year. As a rule of thumb, it is advisable not to have any shading between 10 AM and 2 PM at any time of the year. The curved solid lines represent the Sun's path during the day. The top and bottom lines are drawn for the summer and winter solstices. The lines in between are each applicable for two days during the year, one spring and one fall. The dotted lines represent solar time of day. It is a simple matter to check a given location. You will need a compass, and a way to measure altitude. A protractor with a small weight hanging from a string attached to the protractor's center is sufficient for simple altitude measurements. Use the steps below to judge the merit of a solar site.

1. Place yourself at the proposed center position of the collectors

2. Use the compass to locate a bearing of 90° East (be sure to account for magnetic declination – approximately 12° East for NW New Mexico)
3. Sight along this bearing with the protractor to determine the altitude of any obstructions (vegetation, buildings, geographic features, horizon, etc)
4. Mark the obstruction altitude on the chart
5. Rotate 15° towards the West and repeat steps 3 & 4
6. Continue steps 3, 4, & 5 until you have reached 90° West
7. Connect the obstruction marks on the chart and shade everything below the line
8. A good solar site will have no shading between 10 AM and 2 PM on any day during the year

SOLAR ENERGY QUANTIFICATION

In order for any design work to be successful, it must incorporate numerical representations of incident solar energy. There are many ways to do this, and data for particular sites are readily available in solar energy references, and on the Internet. We have already seen a number associated with solar energy, the Solar Constant: 1367 W/m^2. However, this figure doesn't account for any atmospheric effects, weather or otherwise. The simplest method of including these effects is to measure incident radiation at a site every day for a year and then average the energy collected over the entire year landing on a specific area. Such a number is given below.

$$\text{Horizontal Annual Mean Daily Solar Radiation, Farmington, NM : } 20.05 \ \frac{\text{million Joules}}{\text{m}^2 \ \text{day}}$$

That means if we added up the collected energy for every day during the year that landed on a 1 m^2 horizontal plate and then divided by 365 (days/year) we'd arrive at the 20.05 million Joules quoted above. So, we would expect a horizontal 1 m^2 plate to collect 20.05 * 365 = 7,318 million Joules over a year's time. That's enough energy to heat 14,420 gallons of water from 50 to 140°F (the job your water heater is charged with), an average of almost 40 gallons per day. Remember, however, that every energy conversion incurs an efficiency penalty.

However, no one in their right mind would just place a solar collector horizontally on the ground (unless you live near the equator). Tilting any surface toward the Sun will improve collection energy. The real question is how closely does that surface have to "track" the Sun to be useful? The first step if your location is in the northern hemisphere is to point the surface south (since the Sun will be in the southern sky for most of the day). This would, of course, be just the opposite if you were located in the southern hemisphere. Now the choice is how far up from horizontal the collector should be angled. Ideally, parallel rays from the Sun would strike the collector at an angle of 90°. Let's investigate a few situations here in Farmington. Leaf back to the path diagram and determine the altitude of the Sun on December 21st from 10 AM to 2 PM. You should see a range of values from about 23° (10 & 2) to 30° (noon). If we set up the collector to operate at one angle for the entire day we'd choose a number in between – say 26.5°.

That relates to collector tilt angle as shown in Figure 4. Looking at the shady side of the collector it should be apparent that the tilt angle will equal 90° minus the solar altitude. For our December 21st example the tilt angle would equal 90° - 26.5° = 63.5°. Therefore, on that day, with the collector pointed due south, you would want to tilt it up 63.5° from horizontal.

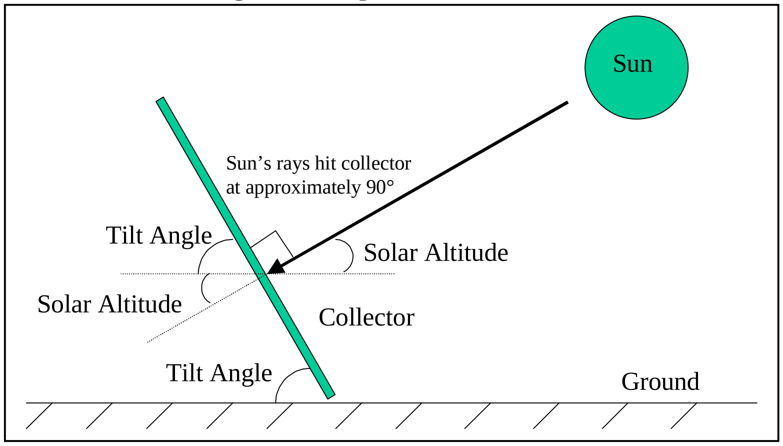

Figure 4 Solar Collector Tilt Angle

Hopefully, you're starting to see the consequences of this procedure. What would we want for collector tilt on June 21st (summer solstice)? The average solar altitude between 10 AM and 2 PM is about 70°. That makes the tilt angle about 20° above horizontal. So, do you really want to go out there *every* day and change the tilt? Does it matter *that* much? Luckily, the answer to both questions is "no." There's a fairly direct mathematical relationship between *incident angle*, which is the angle between the Sun's rays and an imaginary line extending perpendicularly from the collector, and the amount of energy intercepted by the collector surface. Figure 5 shows the distribution. Obviously, if the collector is pointing directly at the Sun (incident angle equals 0°) all the energy should land on it, and if it's pointing 90° away from the Sun no energy lands on the surface. The numbers in between, however, tell an interesting story.

Incident Angle [°]	Solar Intercepted [%]
0	100.0
5	99.6
10	98.5
15	96.5
20	94.0
25	90.6
30	86.6
35	81.9
40	76.6
45	70.7
50	64.3
55	57.4
60	50.0
65	42.3
70	34.2
75	25.8
80	17.4
85	8.7
90	0.0

Figure 5 Radiation Striking a Surface

Hopefully you see why it's not important to constantly adjust the collector to follow the Sun. If the surface stays within 20° of incoming radiation you still collect 94% of the energy. This is the main reason why time-of-day solar collector adjustments are rarely made, it's just not worth the hardware expense in most cases (especially for solar thermal applications). However, it is very often worthwhile to make seasonal adjustments. The tilt angle should be changed at least twice a year, at the equinoxes, if the collector is easily accessible. Keep in mind that even when changing the tilt angle we usually leave the surface pointing due south.

There are cases where tracking the Sun across the sky may be necessary. Locating solar electric panels in questionable areas (e.g. deep north south running valleys, highly variable weather) is often cost effective. Since the electrical wires bend easily (as opposed to copper piping or ductwork in solar thermal) tracking is not a mechanical nightmare. In addition, the high cost of solar electric panels usually outweighs the cost of the tracker. Solar thermal collectors designed to concentrate (focus) the incident radiation must track the Sun to be effective. Dish-style solar collectors are notoriously fickle about direction.

Trackers come in two varieties, single axis and double axis. Single axis devices use a fixed tilt angle (adjustable manually by season) and only track the Sun east to west. Double axis units follow the Sun both east to west and south to north. Single axis trackers are far less expensive and have the added benefit of passive mechanical control (no electric motors or electronics). Double axis trackers must incorporate elaborate feedback control systems and active motors. As a result, double axis units are only used for collectors designed to focus solar energy on a point (as opposed to a line). Single axis trackers are widely used with solar electric panels.

An example of the variation in collected solar energy based on collector orientation can be gleaned from Figure 6, which lists monthly average collections (per day) for collectors pointing directly south with tilt angles fixed at site latitude (36.8° for Farmington, NM), site latitude minus 15°, and site latitude plus 15°. Note that these numbers do not represent active tracking, only changes in tilt angle. The last row represents a yearly averaged day's worth of energy. Note some of the trends indicated by the numbers. In the winter months it's much better to have a steeper tilt (no surprise). In the summer, latitude minus 15° is much better. Notice that if you don't ever want to touch the collector a tilt angle equal to the location's latitude is the best option. Design decisions may change depending on the application. If the system only heats a building in the winter, latitude minus 15° is optimal and won't need to be adjusted. Tracking can increase the collected energy dramatically. On an annual basis a

Farmington, NM	Lat - 15°	Lat	Lat + 15°
January	15.1	17.1	18.2
February	18.3	19.8	20.1
March	22.0	22.5	21.7
April	25.3	24.4	22.2
May	27.3	25.2	22.0
June	29.0	26.2	22.4
July	27.6	25.4	22.1
August	26.8	25.8	23.6
September	25.4	26.1	25.3
October	21.7	23.7	24.3
November	17.1	19.6	21.0
December	14.2	16.5	17.9
Annual	22.3	23.8	21.6

Figure 6 Mean Daily Energy [MJ/m^2]

single axis tracker can increase collection by approximately 30%. The tracking advantage is larger in summer than in winter because of the Sun's extreme east and west positions during morning and evening hours.

So, you may be asking, "How does one get those fancy numbers in the first place?" Most major weather stations around the country (often located at airports) have instruments, called pyranometers, to measure incident solar radiation on a horizontal surface. Pyranometers come in several varieties. The ones designed for high quality measurements use two concentric silver rings protected from the environment by glass covers. One ring is coated with a highly reflective material (magnesium oxide) and the other is coated with Parson's black, an excellent absorber. The difference in temperature between the rings is a measure of incident solar radiation. Less accurate units (far less expensive) use a small silicon solar cell whose output current is proportional to incident radiation. Both types measure total radiation, the sum of direct beam and diffuse, landing on a horizontal surface. Data detailing radiation incident on tilted and/or tracking surfaces can be calculated, using very involved geometrical relationships, from the horizontal radiation data. While many sites only monitor total radiation (direct beam plus diffuse) some use a mechanical shadow arm that periodically swings over the pyranometer so it measures only the diffuse component. From that reading, direct beam radiation is calculated from the total. Much of this data is available in handbooks or on the internet.

In order to prevent an anomalous year from skewing the weather data, the practice of developing a Typical Meteorological Year (TMY) was initiated. In the TMY weather data is averaged for every hour of every day for a significant number of years (we currently have 30 year TMY data available for 239 US sites). This averaged weather data can be downloaded for free from the National Renewable Energy Lab's website (http://rredc.nrel.gov/). The hourly TMY data is particularly useful in passive solar building design simulations where you can model actual performance for every hour of the year and quickly determine the effectiveness of any particular design.

SOLAR ENERGY CONVERSION

As with any energy conversion designed to produce useful work (heat, mechanical, electrical) the goal of the technology is to improve thermodynamic quality of the energy. In order to satisfy the second law of thermodynamics (and not decrease the entropy of the universe) the process must involve inefficiencies – how else could you make a disordered system more ordered? Thus we must always factor these inefficiencies into design decisions involving energy conversion devices. Solar energy conversion devices fall into two categories: solar to thermal, and solar to electric. The two technologies are very different and need to be discussed separately.

SOLAR THERMAL CONVERSION

Solar thermal systems are designed to convert incident solar radiation directly to thermal energy, which can then be transferred by fluid to various locations for use. A variety of applications are available for the heat generated. However, these can all be divided into two categories: direct use of heat (building and process heating) or indirect use of heat (powering a heat engine for mechanical/electrical work). We will focus first on direct use of thermal energy as it the most basic and widespread.

Direct solar thermal systems are generally composed of three parts: solar collector, heat transfer fluid, and energy storage.

Solar Collectors

Most solar collectors take advantage of the greenhouse effect. Short wavelength (high frequency) solar radiation penetrates glass and is absorbed by solid material inside the collector. As this material heats up it reradiates energy in the form of long wave (low frequency) radiation that is not capable of passing back out through the glass cover.

The simplest solar collector is often overlooked in the race for a technological solution to the problem of heating. South facing windows are quite efficient at adding thermal energy to a building. Although it improves heat collection to tilt the windows up, they are much easier to install and control if they stay vertical. Vertical windows can be designed with overhangs so that summer Sun does not penetrate the building envelope, but still allow winter Sun to enter when the extra heat is needed. Although more glass surface results in greater heat loss during nighttime hours, south windows generally provide a net heat gain (more energy in than out). It is important to specify efficient windows (usually double pane), but not too efficient. The new generation of “low-e” windows is not appropriate for solar applications, as they do not let enough energy in through the glass to be effective. “Low-e” windows are best used in situations where passive solar energy is not a strong player. It is not necessary to use clear glass in solar windows, if you don’t require a view. In fact, diffuse glass will distribute the energy more evenly and with less loss. Additionally, you will reduce problems with glare and the fading of colored materials.

The most popular active solar collector (windows are considered passive) is called a flat plate collector. Not surprisingly, is uses a flat surface to collector solar radiation. This type of panel has been used successfully for decades and is very reliable. Incident radiation enters through single or double pane glass and strikes a dark surface designed to transfer the thermal energy into a fluid (air or liquid) that flows in close contact with the absorber surface. Recent advances in coatings technology have resulted in a “selective surface” for the absorber. This means that the dark surface absorbs energy much better than it emits radiation – essentially trapping more heat where it’s most needed. Flat plate collectors are best used for applications requiring relatively low fluid temperatures (200° F or less) and are ideal for space and water heating.

Concentrating collectors are designed to focus incident solar energy on a small area or point. Common types are either trough (curved polished surface that focuses on a line) or dish (curved polished surface that focuses on a point). The only version ever used for domestic water heating is called an evacuated tube collector. This type uses clear glass tubes with the air removed for better insulation (like a thermos bottle). Light is focused on a darkened copper pipe running through the center of the glass tubes. All concentrating collectors are good at producing higher temperature fluids than their flat plate relatives. These temperatures are rarely necessary in residential applications.

Heat Transfer Fluid

Now that we've collected thermal energy from the Sun we need to move it to either a storage area or the point of use. There are several acceptable options. Air is, perhaps, the easiest to work with. Ductwork is readily available and only a low power fan is needed to circulate it. Plus, no damage occurs if the system leaks. However, air isn't very dense, so it can't carry much thermal energy and storing the energy from hot air is not easy. Water is a much better and more compact heat transfer fluid. More energy is required to pump it though, and leaks can lead to structural damage over time. A more disturbing concern, though, is freezing – which will definitely lead to major leaks. In order to protect water systems from certain disaster, an anti-freeze solution must be added in cold climates. Ethylene glycol is readily available, proven, and doesn't drastically disturb the heat transfer properties of the water. However, it's toxic – not a good mix for potable water heating systems. If you run ethylene glycol a double walled heat exchanger is required by code, which drastically reduced thermal performance. A more environmentally friendly answer is to use propylene glycol (advertised for non-toxic automotive use). Propylene glycol is sometimes used as an additive in ice cream to prevent crystallization, so it's definitely non-toxic and you can easily dispose of it. Single walled heat exchangers are acceptable with propylene glycol systems, but you still need to check local building codes. In more exotic, high temperature applications oils are often used as heat transfer fluids because they can operate at much higher temperatures.

Energy Storage

Energy storage is one of the most important, and often most under-designed, aspects of a solar thermal system. The ability to store thermal energy for use at night or during inclement weather is critical to successful operation. Active solar systems (ones that use a heat transfer fluid) need to bring their heat transfer fluids into intimate contact with the storage medium. Air systems commonly run through large insulated boxes full of fist-sized rocks. Once these rocks are warmed the forced air heating system can move the energy from the storage rocks to the building with ducts. Water systems usually heat tanks of water either through direct circulation or by means of a heat exchanger. The recent widespread acceptance of radiant

Material	Specific Heat [kJ/kg°C]
Water	4.18
50/50 Ethylene Glycol	3.32
50/50 Propylene Glycol	3.53
Concrete	0.653
Brick	0.790
Clay	0.920
Stone	0.800
Sand	0.800

Figure 7 Specific Heats at Room Temperature

floor heating has given a boost to active liquid solar systems, for it is an ideal application that involves minimal storage concerns.

Almost all storage strategies involve using thermal mass to hold heat energy until it is needed. Thermal mass can take many forms (water, rocks, concrete, brick, etc.) but the elegant use is found in passive solar heating of buildings. Any material with a large specific heat will work. Specific heat is a material property that describes the amount of thermal energy need to raise the temperature of that material. Water has the highest specific heat of any common substance by a very large margin, making it the most space efficient storage material. Figure 7 shows the specific heats for various materials in kJ/kg°C (how many thousands of Joules are required to warm a kilogram of the substance by 1°C) at room temperature. Notice that concrete, the most common thermal mass in passive solar buildings is not very effective at storing heat. However, it is easy to work with and relatively inexpensive.

Domestic Systems

A few simple diagrams of typical domestic solar heating systems should clarify many of the issues discussed above. We'll start with an active system whose heat transfer fluid is circulated by a pump or fan. Figure 8 shows such a system, and although the components indicate a liquid system, they could easily be exchanged for air systems without disrupting the basic design.

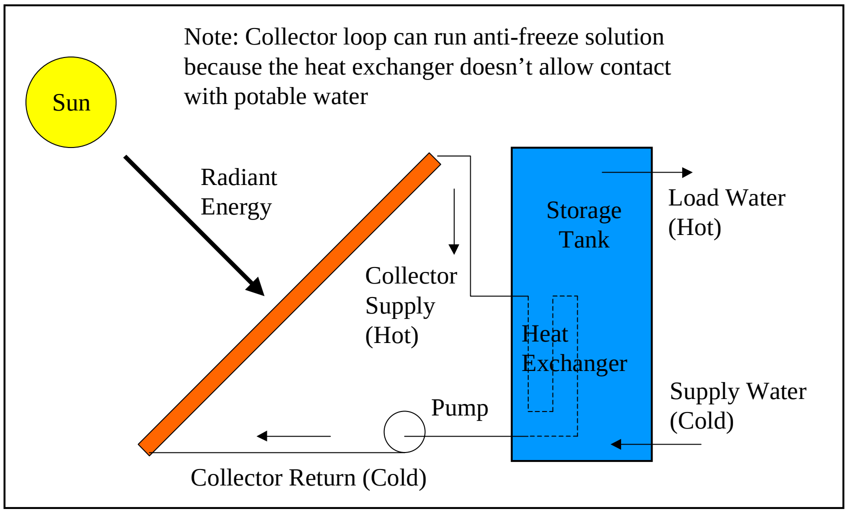

Figure 8 Active Solar Heating System

Figure 9 is a schematic diagram of a *thermosyphon* water heater. The thermosyphon effect circulates heat transfer fluid without using a pump. As the collector warms the heat transfer fluid the fluid's density decreases causing it to rise in the system. Colder fluid (more dense) drops down from the tank and replaces the warm fluid in the collector. These systems are very reliable as no moving parts are required. However, the tank must be mounted above the collector, making design of these systems difficult. Often the storage tank must be mounted outside on the roof of a building, which means heat loss will be much more of a problem during cold weather. If the roof pitch is steep enough, it is possible to mount the tank in the attic and still locate the collector in a lower position.

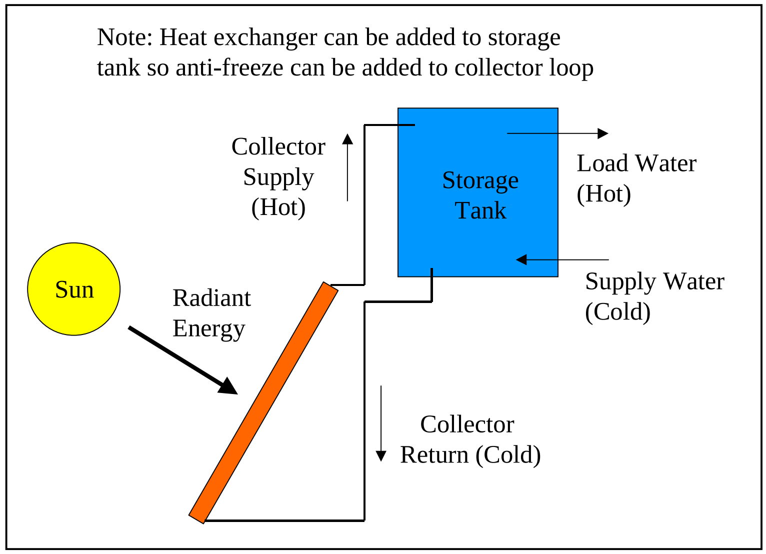

Figure 9 Thermosyphon System

Passive solar space heating requires windows installed on the south face of the building. Figure 10 illustrates typical building design. The area of south windows must represent a significant percentage of the building's floor area (20% is minimal). The energy entering the space is either reflected or absorbed (or a combination of both) by the surfaces is hits. Surfaces designed to directly intercept solar radiation should include thermal mass to store that energy. All surfaces that don't have thermal mass should be a light color to reflect that energy. Thermal mass surfaces should be dark for better absorption and cannot be covered with other materials (carpet, paneling, etc.). Diffuse coatings on windows will cut down on glare and fading. The most common problem with passive solar buildings is the lack of sufficient thermal mass. Large, uncomfortable, temperature swings in a 24 hour period will result. More thermal mass moderates temperature swings. Hourly thermal modeling of passive solar buildings is strongly recommended to prevent undesired results.

Indirect Use of Heat

All of the previous solar schemes captured incident radiation and used thermal energy directly to heat some form of mass. Indirect uses of that thermal energy usually require a much higher thermodynamic quality, that is, much higher temperatures. Most indirect systems use the energy to run a heat engine, which will have significant second law inefficiencies.

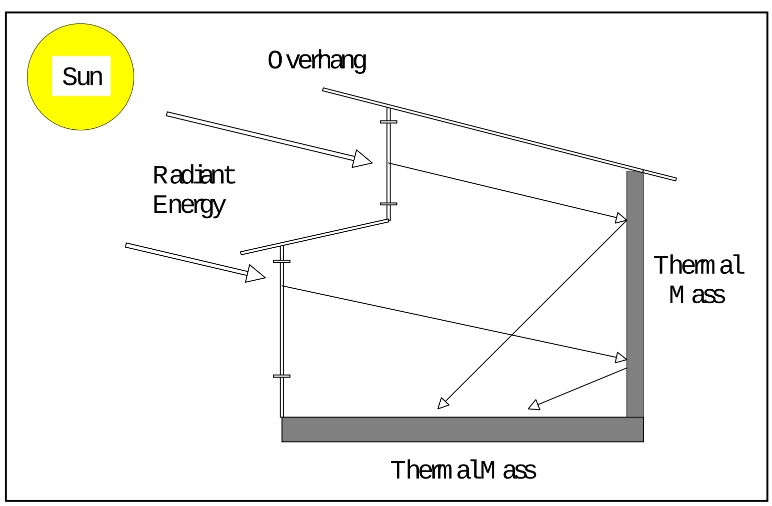

Figure 10 Passive Solar Construction

Typically, the mechanical energy from the heat engine is used to turn a generator and produce electricity as shown in Figure 11. As mentioned in the collector section, in order to produce higher temperatures you need to concentrate solar energy by focusing. The concentrating collectors can be built from troughs, dishes, or power tower configurations. Figure 12 shows the focusing effect of a trough or dish collector. The heat transfer fluid must pass through the point or line of concentration in order to be effective. This small detail results in a large mechanical problem. Concentrating collectors must remain pointed at the Sun throughout the day. A trough collector need only track on one axis, but a dish needs to track two axes, making complex control systems and strategies necessary. The power tower configuration is illustrated in Figure 13. Solar energy is reflected from an array of two-axis tracking mirrors onto a single absorbing surface located above the mirrors in a tower. The tower is required so that the mirror field can surround it and keep mirrors from interfering with each other.

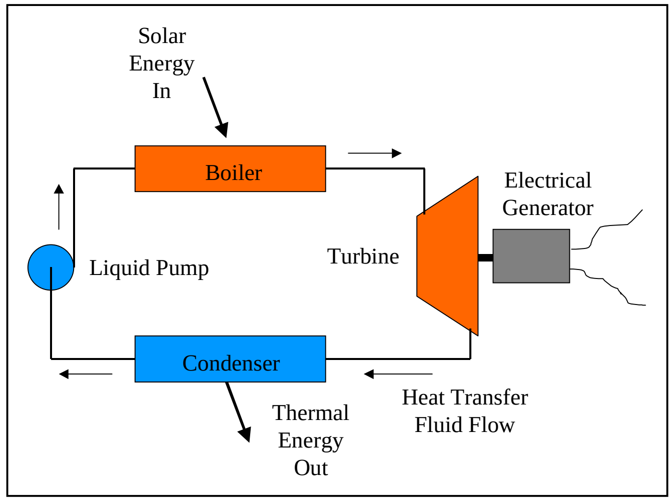

Figure 11 Thermal Electrical Generation Cycle

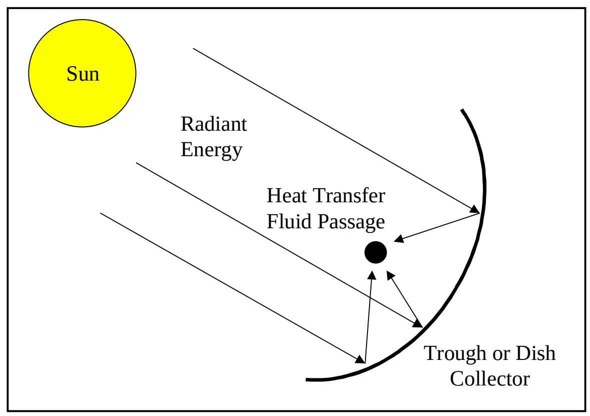

Figure 12 Concentrating Collector

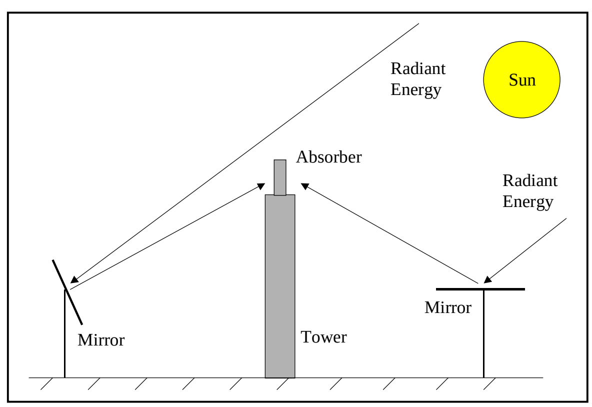

Figure 13 Power Tower

Performance data for various solar thermal electric generation strategies are summarized in Figure 14. The rightmost column indicates the ideal size for each strategy. Both trough and power tower systems are better for centralized utility operation, while the dish system can be used for small scale remote power (though still larger than for a single residence). Since concentration is far superior in dish collectors the resulting temperatures are much higher, and that leads to greater efficiencies. All three systems have been built and tested in the United States. Large trough and power tower units have been operated near Barstow, CA.

Dish-Stirling engine units are now competitively marketed for remote power applications.

System type	Concentration [Suns]	Operating T [°C]	Annual Eff. [%]	Optimal Size [MW]
Trough	80	350	10-14	200
Power Tower	800	560	15-20	100-300
Dish-Stirling	3000	800	24-28	0.025

Figure 14 Solar Thermal Electrical Cycle Performance

Wind Power

Another indirect use of solar energy (very indirect) is to capture the atmospheric energy generated by uneven heating of the Earth's surface. Wind energy technology has made dramatic advances in the last 20 years. At present it is the most economical source of renewable electric energy and is the fastest growing energy source in the world – a 36% increase during 1999. The new large wind turbine designs are appropriate for utility scale generation, and many installations around the country are already selling "green" energy through local utilities.

Currently, there are approximately 2000 MW installed in the United States, 13,400 MW worldwide. New projects are either planned or under construction in 23 US states. The most recently completed projects are generating electrical energy at between 4 and 5 ¢/kWh, which is close to conventional technology. And this low cost can be had without environmental damage. In the mid-western US, where several of the newest large installations have located, family farmers and other land owners are leasing small plots to utilities, and still using the land as before. New Mexico ranks 12th among the 50 states for wind energy potential (directly behind Colorado). Presently, there are only 0.66 MW installed and running (Clovis, NM). The US Army plans to install an additional 10 MW at Fort Bliss in the next several years.

A new generation of small wind turbines (10,000 Watts or less) is now on the market, allowing efficient installations at individual residences. These units generally produce AC electricity, which is then rectified to DC for storage in battery banks or use by inverters. The inverters change DC energy to clean AC, which closely matches the power quality supplied by utilities. Plans for producing small turbines that can be connected directly to your current electrical service and sell excess electricity back to the utility are progressing rapidly. They should be available in the next several years. All small wind turbines make good partners for photovoltaic electrical systems. In most parts of the US wind resources are better than solar during winter months. Then in summer, when winds are light and variable, the PV system is at it's most efficient.

SOLAR ELECTRIC CONVERSION

Photovoltaic (PV) modules convert some of the electromagnetic energy in solar radiation directly to DC electricity. Figure 15 shows a generic diagram of a PV cell and associated wiring. These devices need only be made of semiconductor materials and have no moving parts, resulting in reliabilities unsurpassed by any mechanical technology. Currently, modules on the retail market are advertising 25-year performance guarantees. Some early devices have been functioning with minimal maintenance for 50 years. Reliabilities like these make PV technology attractive for extraterrestrial applications. Until recently, however, the cost has been prohibitive for many uses here on Earth. Large scale manufacturing and market acceptance has resulted in dramatic cost reductions in the last 20 years. It is now possible to buy PV modules at retail prices for less than $6 per rated Watt. While this is still expensive compared to traditionally generated power the long lifetimes, minimal maintenance, zero emissions and ability to locate in remote areas make PV a good choice in certain circumstances. Even traditional utilities are beginning to use PV installations to offset peak demand and eliminate the need to construct additional power generating facilities.

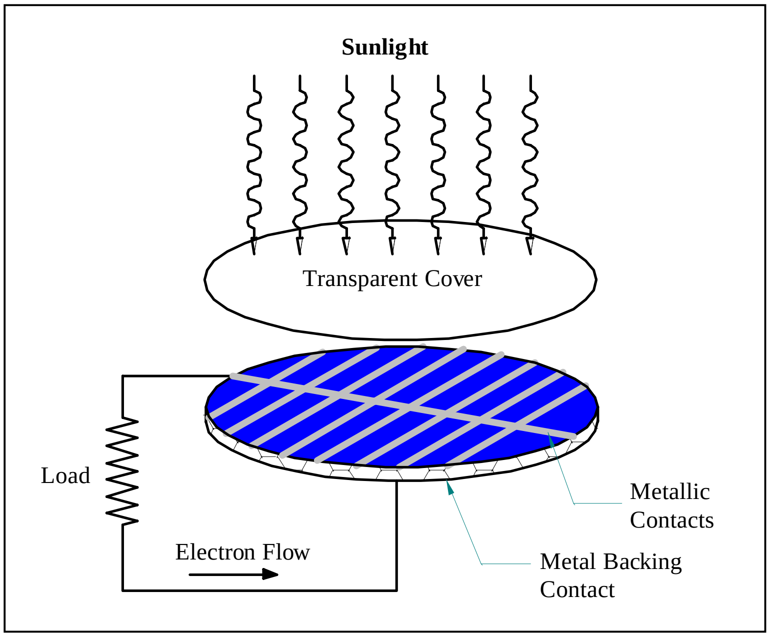

Figure 15 Generic PV Cell and Circuit

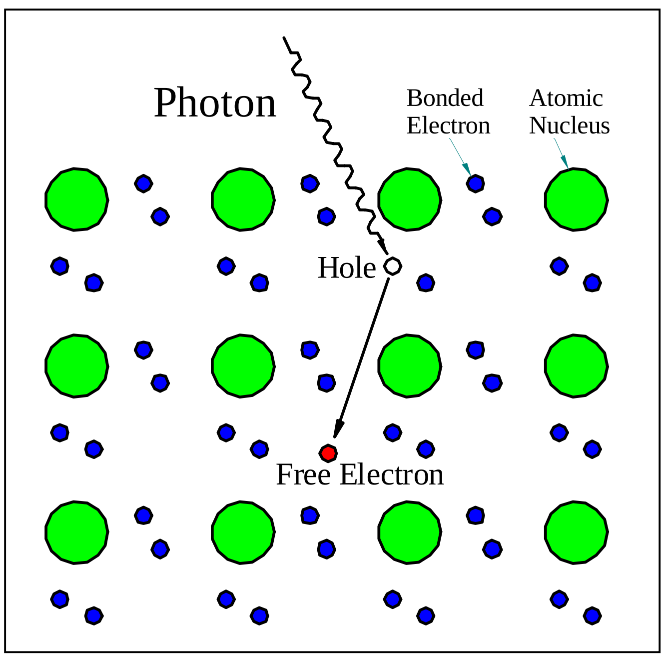

Figure 16 Photoelectric Effect

The Photoelectric Effect

Solar radiation can be used to disturb the energy balance of electron activity in certain solid materials. The so-called "photoelectric effect" (for which Albert Einstein was awarded a Nobel prize in Physics) describes a mechanism by which small packets of energy (photons) from incident radiation penetrate a material and can, under the right conditions, transfer that energy directly to individual electrons. These electrons now have more energy than they need to orbit their respective atoms and make themselves available for electrical conduction in a non-metallic material. Figure 16 shows an electron being shifted from a stable chemical bond to the conduction zone. The electron's former location is referred to as a "hole." Semiconductors, such as Silicon (one of the most plentiful elements in the Earth's crust) are particularly good at taking advantage of the photoelectric effect.

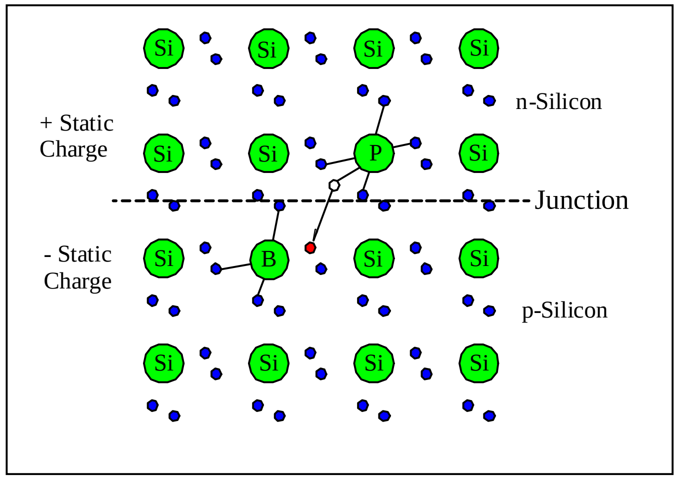

Figure 17 PV Cell Junction

If things were just as simple as placing a sheet of silicon out in the Sun, however, we would have had viable PV technology long ago. Unfortunately, the electrons promoted to the conduction zone badly want to jump right back into the more mundane chemical bond from which they were rudely removed. When this happens the extra energy is released without promoting conduction and ends up as thermal energy in the material. Heating of PV panels due to this type of loss mechanism still leads to large inefficiencies even in modern designs. So, how can we modify the silicon material so that all those free electrons don't jump right back into their respective holes? The solution involves simple static electricity. Since electrons possess negative charge they can be redirected with static potential, moving away from other negative charges and toward positive ones. In essence you're herding electrons through a one-way gate. Once they're cornered in the "conduction corral", they're ready to work for you.

In order to create static potential in an electrically neutral material we add impurities to the silicon. This process is called "doping." Traditionally, phosphorous and boron are used to dope silicon. Phosphorous has one more electron (5) than silicon in its outer shell, and boron has one less (3). As a result the extra electron from the phosphorous atom jumps over to the hole created by adding a boron atom. Figure 17 graphically shows the process. Since electrons migrate toward the boron-doped silicon that layer gets a net negative charge, and the phosphorous layer, which lost electrons, has a net positive charge. The doped layers create a region called the n-p junction (n-negative, p-positive). This junction acts as a one-way valve, herding the electrons knocked into the conduction zone from incident solar radiation. At this point the PV cell starts to act like any chemical battery, separating charge and creating negative and positive terminals. Metallic conductors at the terminals allow wires to connect the PV cell to an electrical path. Electrons on the negative terminal will take this new path in order to return to holes – a lower energy state. Figure 18 shows a complete PV cell circuit with solar radiation energizing electrons.

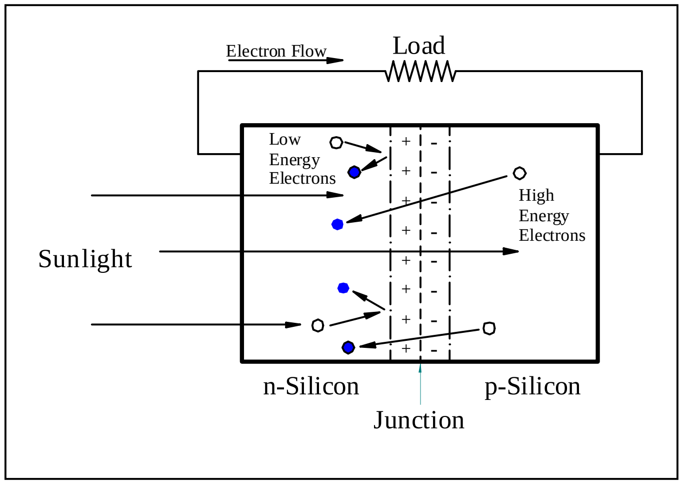

Figure 18 PV Circuit Operation

Each individual silicon PV cell is capable of generating an electric potential of only about 0.5 volts. This voltage is not usually sufficient to power useful devices. The solution is to wire several PV cells in series to increase the voltage at a particular current level. Current is largely determined by cell surface area. Figure 19 shows a series connection of two PV cells to create a one-volt module. The current capacity is not increased by this method. Modules designed for electrical power usually connect 36 cells together in series. The idea is to create a module with a nominal voltage around 12 volts. Ideally the 36-cell module would produce 18 volts – and it can when relatively cool and not connected to any load. However, hot climates (the American Southwest) and high current conditions reduce the voltage output. The nominal 12-volt module was chosen as an industry standard because of the availability of 12-volt storage batteries. System voltage is always a multiple of 12 volts, with 24 and 48 volts being common as well. Obviously, a PV array producing 48 volts (nominal) will require a storage system wired for the same voltage. System voltage is chosen early in the design phase based on considerations such as the length of wire runs (higher voltages result in lower losses), load voltage, and inverter (changes DC to AC) capacity. Combining PV modules (or individual cells) in parallel satisfies the desired load current. Figure 20 indicates an increase in current capacity without changing the voltage.

Applications for PV power systems are expanding as the cost of the technology decreases. Only a few years ago the thought of heating water with PV generated electricity was unthinkable, as it was *much* cheaper to heat water with solar thermal collectors. However, those systems are now available on the consumer market. They eliminate the cost and complexity of running pipes and circulating heat transfer fluids, and are easily incorporated into re-model projects.

Residential power systems generally fall into one of three categories. The simplest is the DC stand-alone. It only requires a PV array sized to meet the load, a battery bank sized for the required inclement weather period, and a charge controller to monitor and maintain the battery bank. Such a system is as efficient as possible – generating, storing, and supplying DC electrical power. However, it's not easy (or inexpensive) to find DC appliances, so this type of system is mostly found in seasonal use "cabins" where traditional appliances are either unneeded or unwanted. An AC stand-alone PV system consists of the same components previously mentioned with the important addition of an inverter, which converts DC energy from the batteries to AC (usually 120 volts nominal). The major advantage here is that nothing in an existing house needs to be modified. The electrical infrastructure (wiring, circuits, etc.) remains the same. While modern inverters produce excellent power quality (true sine wave and exact frequency matching) they do provide another source of inefficiency and greatly increase the system cost. It's not unusual to pay almost $1 per watt for an inverter, and a large system may require 8000 W of available inverter power (hence the absolute need for efficient appliances). Since it is not economically feasible to size such a system for the absolute worst case scenario, a back-up generator is usually added to maintain the battery bank when insolation is insufficient. The third system type is AC grid-intertied. Since the residence's electrical service remains tied to the utility grid, the need for battery storage can be eliminated. Since battery technology is lacking in many areas (particularly maintenance) this is a significant advantage. An inverter is still required to convert DC from the PV array to AC in the house. However, since the grid is available to provide coverage for surge loads (starting motors, etc.) the inverter size can be greatly reduced. In addition, many parts of the United States allow you to sell the extra electricity you generate back to the utility at the same rate you buy it. This arrangement is call net metering. When you generate more electricity than you use, your electrical meter spins backward. If necessary, this system type can still incorporate a battery bank and operate when the electrical grid goes down. However, there are many safety requirements that must be met to protect line workers in case of grid outage since your house may be back feeding electrical energy into the local utility system. Figure 21 shows the components necessary to build an AC grid-intertied PV system with battery back up for emergency power outages.

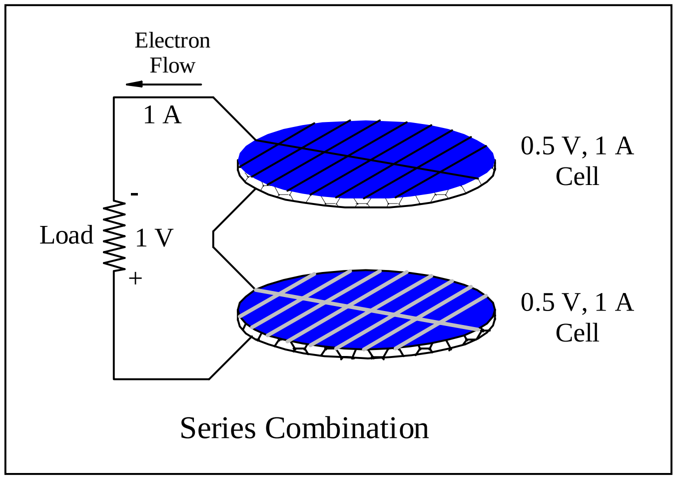

Figure 19 PV Cell Voltage Addition

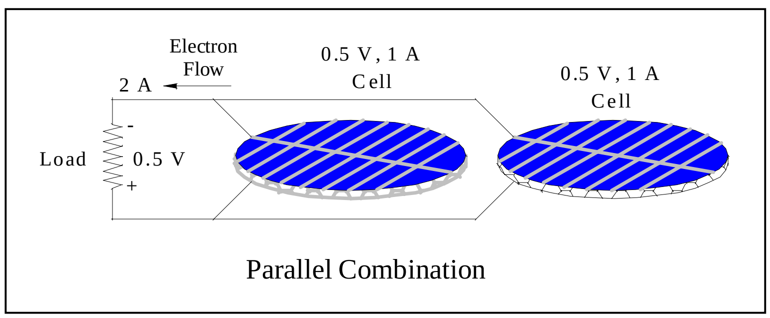

Figure 20 PV Cell Current Addition

Other uses for PV systems include communications (a big industry in the San Juan Basin), pipeline cathodic protection, utility demand-side management, lighting, and commercial building load offset. The communications industry has always been a large user of PV power. Whether repeating telephone signals across microwave towers, providing cellular coverage, or just monitoring remote industrial sites (natural gas and oil wellheads in our area) PV makes sense not only in terms of first cost, but in reliability as well. The utility grid does not usually serve these sites, and emergency communications cannot depend on grid power. A small DC current running through an underground steel pipe can prevent oxidation (rust) to a large extent. This is especially important if the fluid carries moisture with it. This process is referred to as cathodic protection and is ideally suited to PV systems because of the low power level and direct current requirement. Many small businesses around the country make a living with this one specialized application. Parking lot and security lighting can take advantage of PV power and avoid dependence on the utility grid and having to run underground wiring at great expense. Utility demand-side management involves building a network of distributed PV systems that supplement the grid during peak use hours (during the business day). This allows the utility to avoid having to build expensive new generation facilities that often take a decade or more to return on the investment. Locating PV systems close their point of use also lowers distribution losses for the utility. The Sacramento Municipal Utility District (California) has used this philosophy extensively. They lease PV systems to residential users, which lowers the customer's bill and reduces the load on traditional energy production facilities. This option is becoming popular as many utility districts grow and reach the limits of fossil fuel production equipment. Finally, some large commercial buildings are opting to offset their daytime energy use with PV systems. Since large facilities often have time-of-day price contracts (always higher during peak business hours) a PV supplement can reduce electrical costs while advertising an ecologically friendly image to the public.

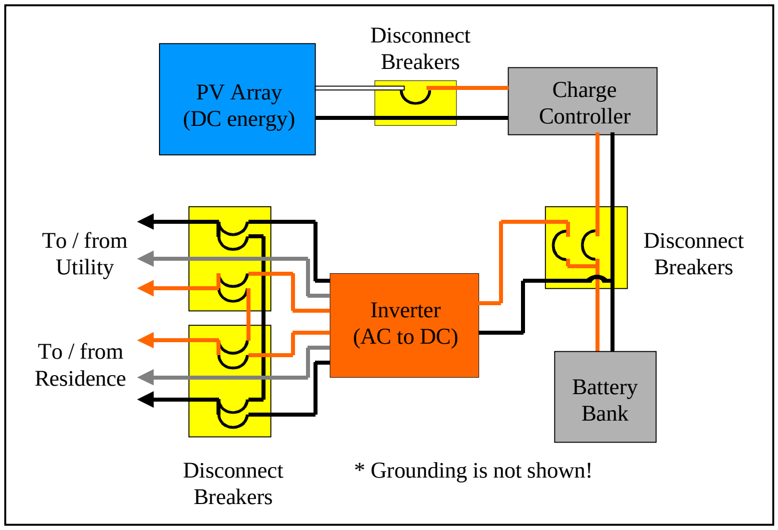

Figure 21 Residential Power System

On a larger scale, PV and other renewable energy production methods may help increase the reliability of the entire US electrical grid. As our infrastructure ages and increased usage taxes design limits, reliability becomes a significant problem. Experts predict a rise in the occurrence of "brownouts" and power failures as deregulated utilities try to compete on the open market using aging equipment. Renewable energy systems not only provide reliability, but are also economically attractive as the public's mind turns increasingly to environmental issues. The great success of current wind power projects in attracting customers willing to pay above-market value indicates that there is room to expand all aspects of renewable energy. It remains to be seen whether the highly-political energy industry will embrace environmental concerns and capitalize on them, or race to produce the absolute lowest cost product with whatever technology is cheapest. Our health, and our future as human beings on this planet, may depend on the choice of energy technology in the next century.