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## **University of Minnesota Guidebook to Small-Scale Renewable Energy Systems for Homes and Businesses**



**West Central Research and Outreach Center**

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# Table of Contents

<b>1.</b>	<b>Why Renewable Energy?</b>	<b>1</b>
<b>2.</b>	<b>Solar Energy</b>	<b>3</b>
<b>2.1</b>	<b>The Solar Resource</b>	<b>3</b>
<b>2.2</b>	<b>Electricity from Sunlight (Solar PV)</b>	<b>7</b>
<b>2.2.1</b>	<b>How does it work?</b>	<b>7</b>
<b>2.2.2</b>	<b>PV materials and panel types</b>	<b>9</b>
<b>2.2.2.1</b>	<b>Crystalline silicon</b>	<b>9</b>
<b>2.2.2.2</b>	<b>Amorphous silicon</b>	<b>10</b>
<b>2.2.2.3</b>	<b>Thin film materials</b>	<b>10</b>
<b>2.2.3</b>	<b>PV system architecture</b>	<b>12</b>
<b>2.2.3.1</b>	<b>Solar cell characteristics</b>	<b>12</b>
<b>2.2.3.2</b>	<b>Grid-tied systems</b>	<b>15</b>
<b>2.2.3.3</b>	<b>Stand alone systems</b>	<b>18</b>
<b>2.2.4</b>	<b>Performance and cost considerations</b>	<b>21</b>
<b>2.2.4.1</b>	<b>What's on the label?</b>	<b>21</b>
<b>2.2.4.2</b>	<b>Example performance calculations</b>	<b>22</b>
<b>2.2.4.3</b>	<b>PV costs</b>	<b>24</b>
<b>2.2.5</b>	<b>Solar PV Consumer guidelines</b>	<b>26</b>
<b>2.3</b>	<b>Solar Thermal Energy</b>	<b>28</b>
<b>2.3.1</b>	<b>How does it work?</b>	<b>28</b>
<b>2.3.2</b>	<b>Solar thermal collectors</b>	<b>29</b>
<b>2.3.2.1</b>	<b>Flat plate collectors</b>	<b>29</b>
<b>2.3.2.2</b>	<b>Evacuated tube collectors</b>	<b>30</b>
<b>2.3.2.3</b>	<b>Comparison of collector types</b>	<b>32</b>
<b>2.3.3</b>	<b>Solar hot water systems</b>	<b>35</b>
<b>2.3.3.1</b>	<b>System Types</b>	<b>35</b>

# Table of Contents

2.3.3.2	Configuration details .....	38
2.3.4	Space heating and cooling .....	40
2.3.4.1	Heating with air collectors .....	40
2.3.4.2	Heating with water collectors .....	40
2.3.4.3	Solar air conditioning .....	42
2.3.5	Performance and cost considerations .....	46
2.3.5.1	What's in an SRCC report? .....	46
2.3.5.2	Solar water heating performance.....	50
2.3.5.3	Solar water heating and space heating performance .....	51
2.3.6	Solar thermal Consumer guidelines.....	54
3.	Geothermal Heat Pumps.....	56
3.1	How Does It Work?.....	56
3.2	GSHP Loop Configurations .....	58
3.3	System Performance .....	59
3.4	Geothermal Heat Pump Consumer guidelines .....	61
4.	Small-Scale Wind .....	63
4.1	The Wind Resource .....	63
4.2	How Does It Work?.....	66
4.3	Performance and Cost Considerations .....	67
4.4	Small-scale wind Consumer guidelines .....	70
	APPENDIX A - Energy and Power Units.....	72
	APPENDIX B – Solar Energy Performance Data .....	75
	Sources.....	82

## 1. Why Renewable Energy?

Renewable energy includes any energy source that is replenished at least as fast as it is used. Some examples are gathering energy from the ocean due to waves, tides, or thermal gradients; geothermal energy which uses the heat of the Earth to generate electricity; biomass energy which uses plant material to create liquid or gaseous fuels to burn in vehicles or boilers; hydroelectric power which uses moving water to turn a turbine generating electricity; wind power which uses wind to turn a turbine generating electricity; and sunlight which can be collected as heat or converted directly into electricity.

As concerns about rising fossil fuel prices, energy security, and climate change increase, renewable energy can play an important role in producing local, clean, and unlimited energy to supply Minnesota's and the nation's increasing demand for electricity, heat, and transportation fuel. Renewable energy sources address economic concerns of future fossil fuel prices by offering low to zero ongoing fuel costs especially when used to generate electricity. Of course, capital costs associated with renewable energy systems can be higher than traditional sources, but the costs are decreasing with increased manufacturing volume and advancements in technology. Eliminating the uncertainties of fossil fuel supply and demand addresses one aspect of energy security by offering facility managers long term price stability and predictability in the budgeting process.

Another aspect of energy security is reliability. Renewable sources, especially wind and solar, are well suited to distributed generation meaning the energy source is close to the load. Distributed generation can reduce power outages due to transmission problems whether accidental or deliberate. Yet another aspect of energy security comes from less reliance on foreign sources of energy. According to the U.S. Energy Information Administration, although the United States has large reserves of fossil fuels, 20% to 30%

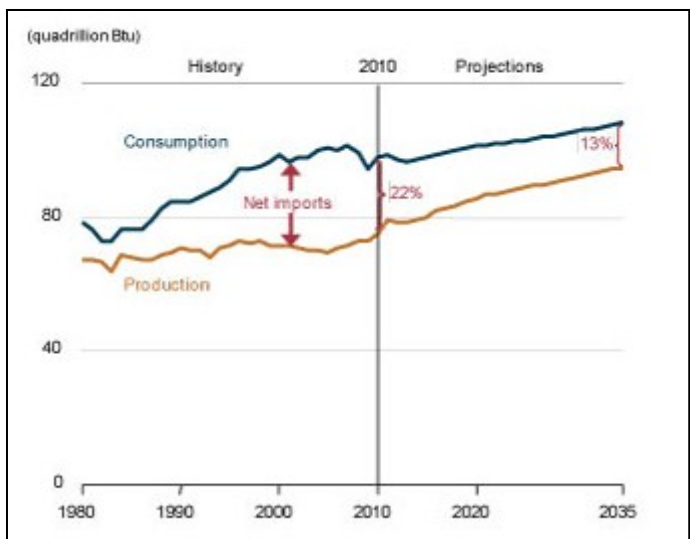


Figure 1. U.S. Energy Production and Consumption (U.S. EIA)

of the total annual energy consumption over the last ten years was from imports (Fig. 1)<sup>1</sup>.

Renewable energy sources offer an opportunity to reduce dependence on foreign energy sources because there are huge amounts of local, untapped energy even in states like Minnesota that have no fossil fuels. In fact, comparing the known reserves of fossil fuels in the world to the amount of available renewable energy (Fig. 2) shows how large these resources are - especially solar power<sup>2</sup>.

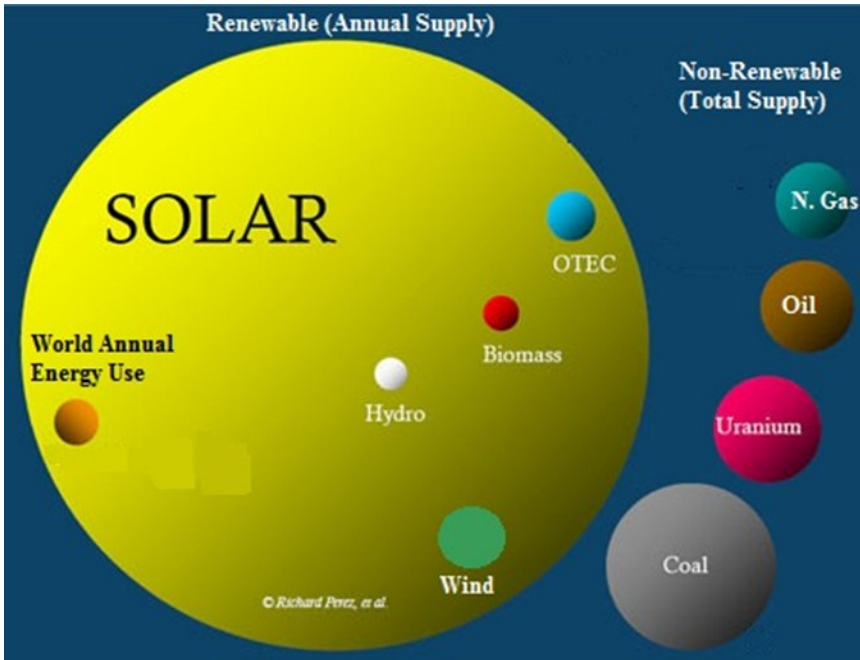


Figure 2. World Energy Resources

Moreover, the non-renewable sources represent the total known reserves of each energy type while the renewable resources indicate the amount available annually on an ongoing basis. Clearly, renewable energy can be a big part of reducing our dependence on foreign energy sources.

Renewable energy sources have the further advantage of not releasing greenhouse gasses with the exception of biomass. The burning of fossil fuels releases carbon that has been sequestered for millions of years and was not part of the carbon balance in the current ecosystem. Burning biomass, in contrast, only releases carbon that the plant absorbed from the current ecosystem, and therefore, is considered to be a net-zero emitter. However, the ultimate carbon balance of any biomass energy system depends on the carbon intensity of the biomass production system.

The U.S. Census Bureau projects world population will reach 9 billion by the year 2045 (Fig. 3). This is equivalent to adding two new countries to the world in the next 30 years, each with a population equal to China. Moreover, the International Energy Association

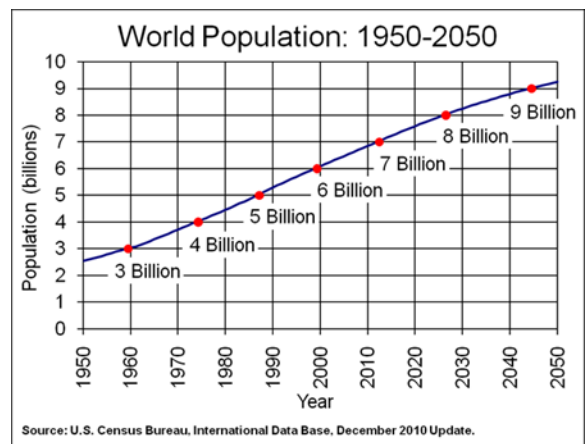


Figure 3. World Population

projects a roughly 50% increase in the world's annual energy consumption by the year 2035 (Fig. 4)<sup>3</sup> reflecting the move toward a more western energy lifestyle.

As world population and demand for energy continue to increase, it will be more important than ever to find solutions that minimize the economic and environmental demands on the world's resources. Renewable energy can be a key part of the solution to our current and future energy challenges.

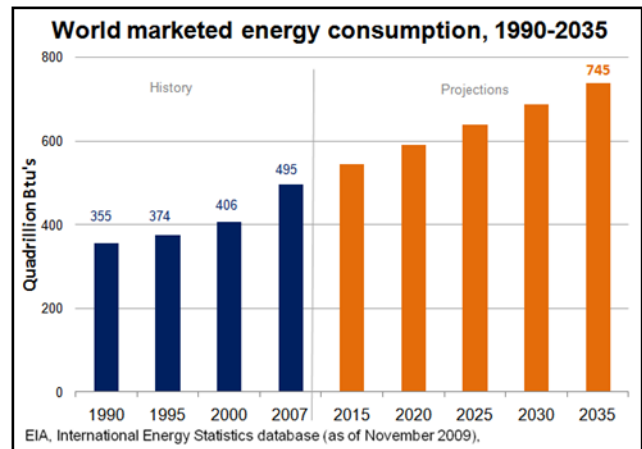


Figure 4. World Energy Consumption

## 2. Solar Energy

The sun is humanity's oldest energy source, and scientists and engineers have been trying to harness the power of sunlight for a wide range of heating, lighting, and industrial tasks for hundreds of years. Even children know that focused sunlight is hot enough to start fires; scientists know that every square meter of the Earth receives about 1 kilowatt of energy when the sun is directly overhead. Gathering and converting this energy into usable form has been explored since burning mirrors were first used in China around 700 BC for ignition of firewood. Excluding photosynthesis, energy can be collected from sunlight in two ways. It can be converted directly into electricity using photoelectric materials or it can be converted into heat.

### 2.1 The Solar Resource

The solar resource is the electromagnetic radiation emitted by the sun. Sunlight is an excellent energy source in that the supply is consistent, widespread, and essentially inexhaustible. Solar energy also has several challenges, namely that it is only available during the day, it varies throughout the day and year, and is less energy dense than fossil fuels. Measuring energy produces a confusing array of units and terms which are explained in Appendix A.

Irradiance is the rate of energy falling on a surface per unit area. It is commonly measured in units of Watts per meters squared ( $W/m^2$ ), and measures the intensity of the sunlight at any given time.

Insolation is the total energy received on a surface over a specific time interval. It is commonly measured in units of kilowatt hours per meters squared per day ( $\text{kWh/m}^2/\text{d}$ ), and measures the average amount of solar energy received in a day. The amount of solar irradiation that reaches the outer edge of the Earth's atmosphere varies slightly around a value of  $1366 \text{ W/m}^2$  depending on how close the Earth is to the sun. The atmosphere scatters, reflects, and absorbs solar radiation so that only about  $1000 \text{ W/m}^2$  reaches the surface when the sun is directly overhead.

Atmospheric effects result in two types of solar radiation: direct radiation, sometimes called beam radiation, and diffuse radiation. Diffuse radiation is any sunlight that has been reflected off of something like clouds, the ground, dust, etc. Most solar panels can collect both types of radiation, but any solar collector that concentrates or reflects sunlight will only be effective with the direct radiation component. That's why concentrating and reflecting collectors are typically used in desert areas where most of the solar radiation is direct. They would be less effective in Minnesota where, on a sunny day, 10% to 20% of the solar radiation is diffuse, and on an overcast day it is 100% diffuse.

The actual irradiance at any location depends on the latitude, the time of day and year, any shading from adjacent buildings or trees, and the local weather. The latitude affects the angle that sunlight makes with the ground (Fig. 5). Generally, the angle is smaller as the distance from the equator increases. The axis through

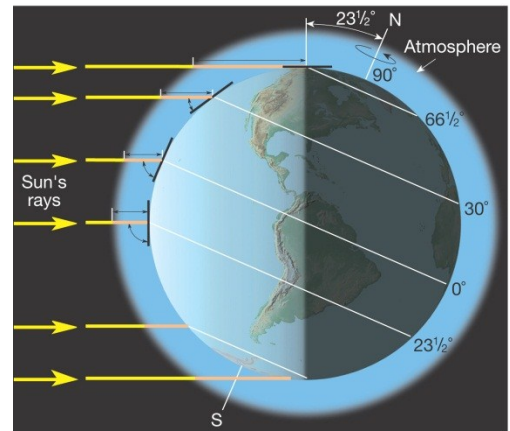


Figure 5. Earth Geometry

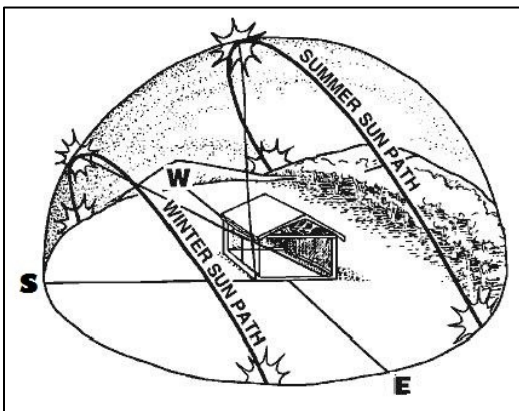


Figure 6. Seasonal Sun Paths

the North and South poles is tilted relative to the plane in which the Earth revolves around the sun. This angle, called declination, is about 23.5 degrees and is the reason the Earth has different seasons. The northern hemisphere is tilted away from the sun on the winter solstice (Fig. 5) and toward the sun on the summer solstice resulting in the shortest and longest days of the year, respectively. This is why the sun is higher in the sky in the summer, and rises and sets north of an

east/west line, while the opposite is true in the winter (Fig. 6). The optimum mounting angle of a flat

solar collector is determined by the height of the sun's east/west path since the maximum amount of energy is obtained when the collector is perpendicular to the incoming sunlight.

Tracking systems can be used to keep a panel directed at the sun. Single axis systems follow the east-west path of the sun during the day while dual axis systems can keep a panel directed at the sun at all times of the day and year. Using a single axis tracking system or a fixed panel requires a compromise between winter and summer performance. Typically a fixed panel will be mounted facing south at an angle equal to the latitude which maximizes the energy collected over an entire year. A higher mounting angle will collect more energy in the winter months at the expense of summer performance. The opposite is true for a lower mounting angle. There are web based tools that will calculate the annual insolation for different mounting configurations based on location<sup>4</sup>. Using such a tool for the city of Morris, MN (Fig. 7), shows that a panel facing within plus or minus 15 degrees of south and at a mounting angle within plus or minus about 8 degrees of the latitude will receive 99% of the insolation available with the optimal configuration. This leeway may make it easier to adapt a solar collection system to specific roof geometry or help minimize the effects of local shading.

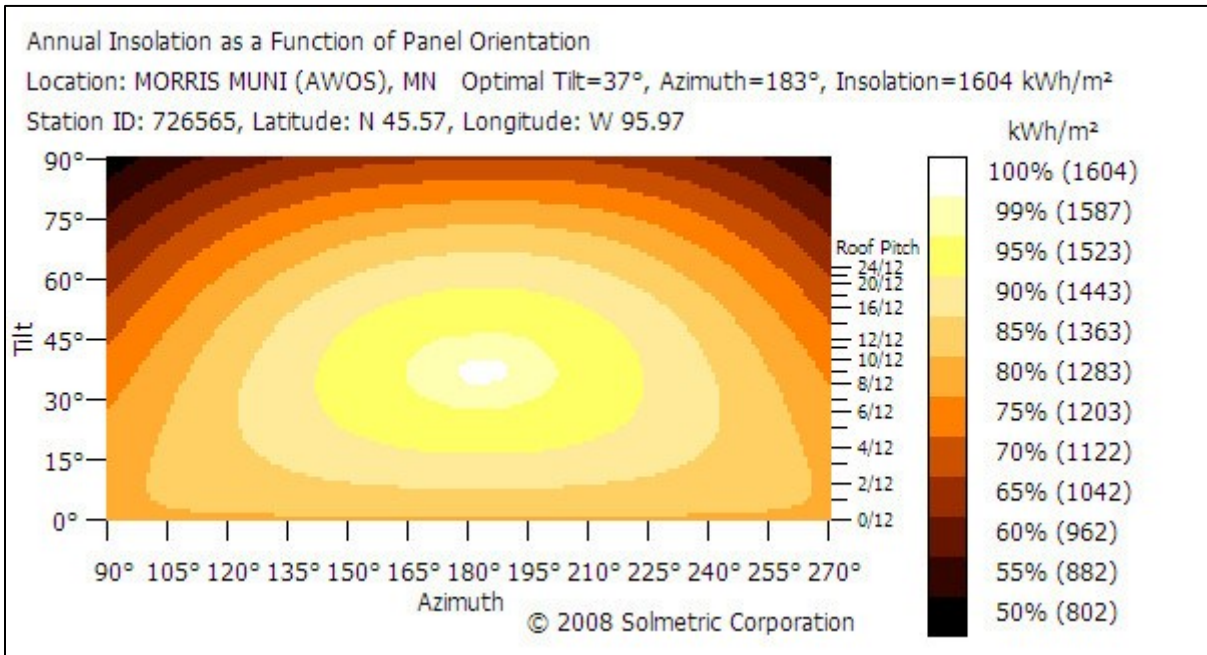


Figure 7. Mounting Configuration Effects on Insolation in Morris



Shading from nearby buildings or landscaping is another factor that affects the solar irradiance of any particular site. Before any kind of solar energy system is installed a site assessment should be completed. A competent contractor will use a tool like the Solar Pathfinder (Fig. 8) to determine if there will be shading on a potential site, and if so, at what times during the day and year. Some shading during certain parts of the year may be unavoidable, but a site analysis may allow the consumer to minimize the effects or at least understand the impact on system performance.



Figure 8. Solar Pathfinder

The final factor affecting irradiance is the local weather. A map of the average insolation in the United States (Fig. 9) shows that the insolation is much higher in the southwest than in the south east even though the two regions are at roughly the same latitude. The same is true when comparing the insolation in Minnesota with that on the northwest coast or northeastern part of the country. These differences are due to the local geography and weather patterns. On average, skies are much clearer in the desert southwest than they are in the southeast.

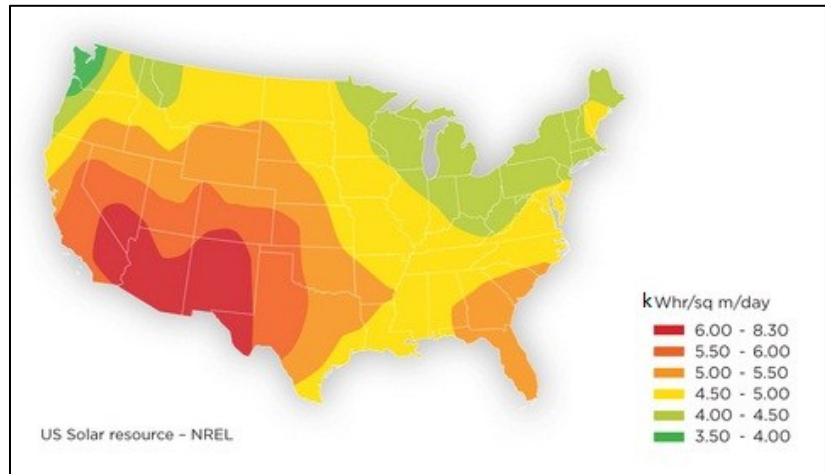


Figure 9. U.S. Solar Insolation

The average insolation in Minnesota is about 4.5 kWh/m<sup>2</sup>/day, and varies by only about 15% across the state<sup>5</sup>. Solar energy is, therefore, available to anyone with a clear view to the south. The actual amounts of irradiation and

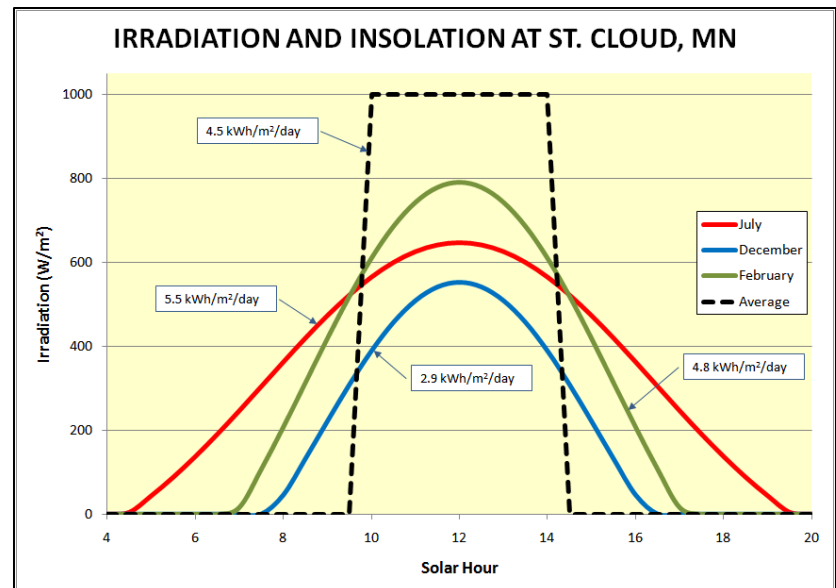


Figure 10. Irradiation and Insolation for St. Cloud (1961 -1990)

insolation vary by month, with the highest average irradiation occurring in February and the highest average insolation occurring in July (Fig. 10). It might seem odd to have the highest irradiation in February, but this is a result of the Earth being closer to the sun in winter, the relative lack of clouds, dust, and humidity in the atmosphere, and the increased reflection from snow. December is the low point for both irradiation and insolation.

## **2.2 Electricity from Sunlight (Solar PV)**

Solar cells, also called photovoltaic (PV) cells, convert sunlight directly into electricity. Solar PV gets its name from the process of converting light (photons) to electricity (voltage), which is called the PV effect. The photovoltaic effect was first noted by a French physicist, Edmund Becquerel, in 1839, who found that certain materials would produce small amounts of electric current when exposed to light. The first photovoltaic module was built by Bell Laboratories in 1954, but it was too expensive for anything other than satellites. During the energy crisis in the 1970s, photovoltaic technology gained recognition as a source of power for non-space applications. Today, solar PV systems are found everywhere from wrist watches to airplanes and thousands of people power their homes and businesses with them. Utility companies are also using PV technology for large power stations.

### **2.2.1 How does it work?**

Solar cells are made of the same kinds of semiconductor materials used in the computer industry – typically silicon. Semiconductors can be used to transform sunlight into electricity because of their atomic structure. When electrons have enough energy, they can leave their atom and move freely through the material. This is what it means to conduct electricity. Materials like metals that have some electrons with enough energy to escape their atoms are called ‘conductors’ and will conduct electricity if an external electric field like a battery is applied. When electrons do not have enough energy to escape their atom, the additional amount of energy needed to escape is called the band gap. In some materials the band gap is so high that under ordinary circumstances electrons cannot accept enough energy to conduct. These materials are called ‘insulators’. Materials that have a small band gap that can be overcome if external energy like sunlight is supplied are called ‘semiconductors’.

To make solar cells, a thin semiconductor wafer is specially treated to form an electric field, positive on one side and negative on the other. This process involves introducing a small amount of another element into the silicon crystal. Some of these other elements cause the crystal to have an excess of electrons, making an n-type semiconductor, and some cause it to have a deficit of electrons, making a p-type semiconductor.

Sandwiching these two types of semiconductors

together creates the weak electric field that makes a solar cell work (Fig. 11). When light particles (photons) enter the solar cell, some electrons are freed from the atoms in the n-type semiconductor and forced to the surface by the electric field. If electrical conductors are attached to the positive and negative sides of the cell, forming a circuit, an electric current will be produced.

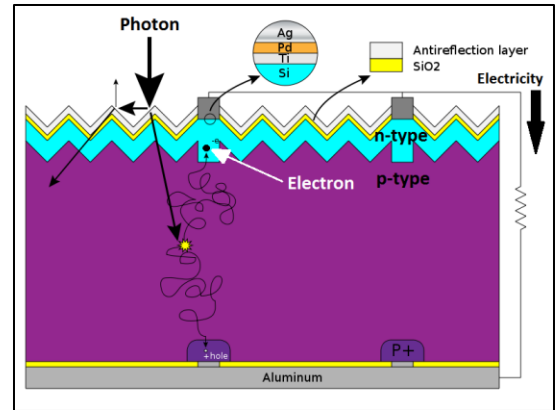


Figure 11. Solar Cell Structure

The size of the band gap is a property of the semiconductor material and determines what kind of solar radiation will have enough energy to free electrons. Photons can be absorbed or reflected by the semiconductor, or they can pass through. Only one electron can be freed by each photon and if the photon has more energy than needed, the extra energy becomes heat. If a photon is absorbed by the semiconductor, but does not have enough energy to free an electron, its energy also becomes heat. This is why PV cells have relatively low efficiencies and heat up during use.

If the energy in solar radiation is graphed against the wavelength of the radiation (Fig. 12), it can be seen that most of the energy reaching the surface falls within the visible light region. Different

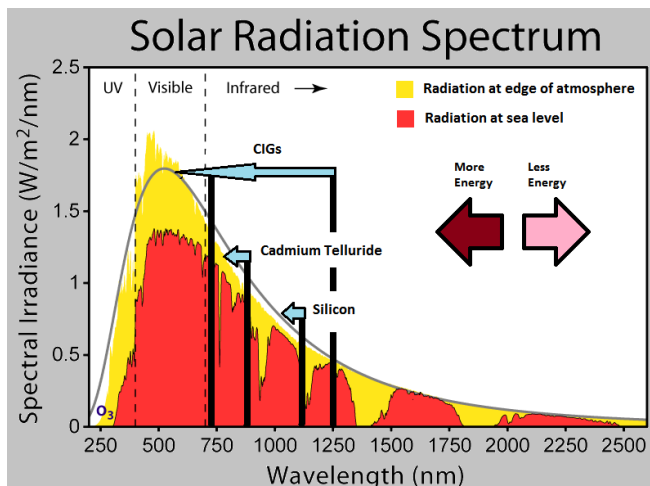


Figure 12. Sunlight Energy VS. Wavelength

semiconductor materials have different maximum wavelengths above which photons will not have enough energy to produce electricity. Materials that are well suited for PV cells have band gaps that result in maximum wavelength values just above the range of visible light which optimizes cell efficiency. A smaller band gap would mean more photons with excess energy leading to more heat and

lower efficiency; a larger band gap would mean more of the most plentiful photons would not have enough energy to free electrons, again, decreasing efficiency. The maximum wavelengths for the common PV cell materials are shown in Figure 12.

## 2.2.2 PV materials and panel types

### 2.2.2.1 Crystalline silicon

The first solar PV panels were made from silicon and it is still the most popular material. According to the Department of Energy, 90% of the panels sold in 2011 were made from silicon. It is a good choice as it has an advantageous band gap and is the second most abundant element in the Earth's crust after oxygen. However, it must be 99.99999% pure to make a useful PV cell. There are two basic categories of panels made from crystalized silicon: monocrystalline and polycrystalline.

To create silicon in a single-crystal state, high-purity silicon must first be melted. It is then reformed or solidified into an ingot slowly while in contact with a single crystal "seed" (Fig. 13). The silicon adapts to the pattern of the single-crystal seed as it cools and gradually solidifies. Polycrystalline silicon can be produced in a variety of ways. The most popular commercial methods involve a process in which molten silicon is directly cast into a mold and allowed to solidify into an ingot. This results in material consisting of many smaller crystals, or grains, which makes the semiconductor less efficient, but more cost effective to make. The starting material can be refined lower grade silicon rather than the higher grade semiconductor required for monocrystalline material. Either way, the resulting ingot is sliced into thin wafers, doped with other elements to make n- and p-type semiconductors, treated with a coating to reduce reflection, and finally sandwiched together with electrical contacts to make a functioning cell. Because the underlying material is not a good conductor, contacts must be closely spaced which shades the cell decreasing efficiency. Most of the cost of solar panels is in the fabrication of the solar cells not the raw material.

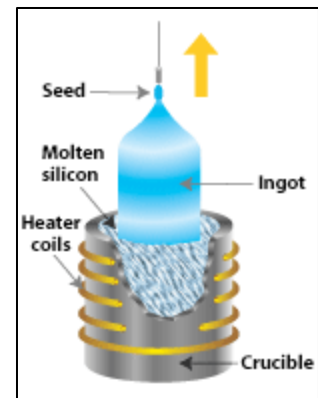


Figure 13. Monocrystalline Silicon Process

Monocrystalline silicon solar cells (Fig. 14) typically have the highest efficiencies (15% to 20%) and are more expensive than polycrystalline cells. Polycrystalline cells have average efficiencies in the

range of 12% to 16% and can be easily identified by their fractured glass appearance (Fig. 15). Monocrystalline cells made up 69% of the crystalline silicon panels manufactured in the U.S. in 2009<sup>6</sup>.

### 2.2.2.2 Amorphous silicon

Silicon can also be used in an amorphous, or non-crystalline, form to make a solar cell. Amorphous solids have no ordered structure like a crystal so there are structural and bonding defects which reduce the material's ability to conduct electrons. However, amorphous silicon absorbs light 40 times more efficiently than crystalline silicon so the resulting solar cell can be extremely thin. It can also be produced at lower temperatures and deposited on inexpensive substrates, like plastic or glass, making it ideal for building integrated PV products such as solar shingles (Fig. 16). Solar cells made with amorphous silicon (a-Si) use much less raw material, are less expensive to fabricate, and can be deposited on flexible substrates giving them many advantages. They also have lower efficiency, averaging about 8%, and experience the Staebler-Wronski effect, which means their electrical output decreases over time when first exposed to sunlight eventually stabilizing at a level up to 20% lower than the initial output. Some manufacturers precondition their panels to minimize this effect. If this is not done, the consumer may have to pay more for electronic components that can handle the larger initial output making the system less cost effective.

### 2.2.2.3 Thin film materials

Other materials, besides silicon, can be used to make PV cells. Several of these fall into a category called *thin film* because of the method used to deposit them, not because of the actual thinness of the resulting PV cell. These materials can be applied in thin layers building up a cell by various processes broadly termed physical vapor deposition. This innovation could potentially be a more economic manufacturing method than the growth and processing of ingots used in the manufacture



Figure 14. Monocrystalline Solar Cell  
(Sunpower Corporation)



Figure 15. Polycrystalline Solar Cell

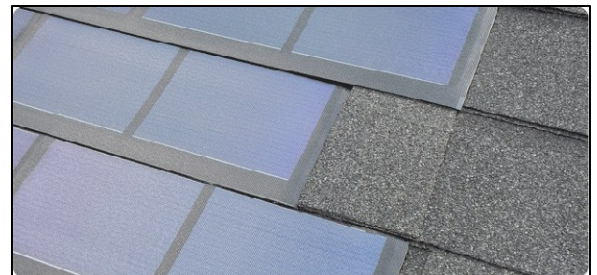


Figure 16. Amorphous Silicon Solar Shingle  
([www.uni-solar.com](http://www.uni-solar.com))

of crystalline silicon PV cells. Thin film materials also generally have higher efficiencies than amorphous silicon. Vapor deposition processes also allow inexpensive and flexible substrates to be used. Moreover, thin film materials usually don't use a metal grid for the top electrical contact, but instead employ a transparent conducting layer like tin oxide. Another advantage of the deposition process is that it can be scaled up easily and allows for the manufacture of a large monolithic module instead of having several cells being wired together to make a module.

Cadmium telluride (CdTe) is the most prominent non-silicon PV semiconductor (Fig. 17) and is used by First Solar, the largest solar PV producer in the world, with panels averaging about 12% efficiency. It has an almost ideal band gap (Fig. 12) which can be modified by alloying it with other elements. Cadmium and tellurium are both rare earth metals and could be subject to relatively large market price fluctuations, especially cadmium which is mostly produced in China and is used in nickel-cadmium batteries.

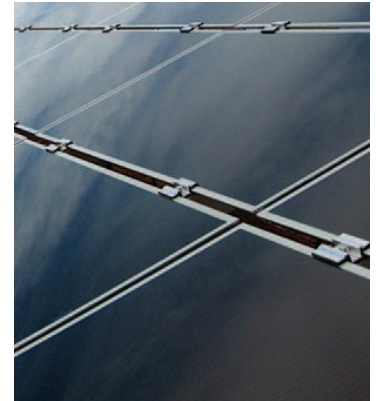


Figure 17. CdTe Based Panel  
(First Solar)

Copper Indium Diselenide (CIS) is another thin film semiconductor that results in panel efficiencies in the 12 to 14% range. CIS can be modified with gallium to produce a



Figure 18. Solyndra Tubular Panel

material with almost any desired band gap (Fig. 12). The modified semiconductor is called Copper Indium Gallium Diselenide (CIGs) and was the basis of the panels made by, the now infamous defunct solar company, Solyndra (Fig. 18). This material has the advantage of not using rare earth metals, but the manufacturing process is more difficult at a large scale than using cadmium telluride which was a major factor in the downfall of Solyndra.

Multi-junction cells are made up of layers of different types of semiconductors each operating at a different band gap. The upper materials produce electricity using the highest energy photons while the lower energy photons pass through to the next material. Each layer is finely tuned to narrow photon energy levels so less energy is turned into heat. This means more electrons can be freed and the cell operates at a lower temperature, also, improving efficiency. Multi-junction cell efficiency

can approach 40%, but is obviously more costly to produce. So far, multi-junction cells have been mostly used in the space program where electricity produced per unit area is the main design driver. Some companies, however, are using this technology to improve the efficiency of amorphous silicon cells.

## 2.2.3 PV system architecture

### 2.2.3.1 Solar cell characteristics

The electrical characteristics of a solar cell may be easier to understand by comparing it to a water tower. The voltage of a cell is the force, or potential, that drives current through a circuit in the same way that the height of a water tower provides the force to drive water through a pipe. The current in an electrical circuit is analogous to the flow rate of water in a pipe, and the power is analogous to the rate at which work could be done by the water pressure in the pipe. Power is an important quantity because it measures a system's ability to do work whether it is turning a water wheel or energizing a light bulb.

The power produced by a solar cell is measured in watts and is equal to the current, measured in amps, multiplied by the voltage, measured in volts. For example, if a solar panel produced a current of 2 amps at a voltage of 12 volts, the power output of that panel would be 24 Watts. An open circuit occurs when the positive and negative leads from a solar cell are not connected to form a circuit. This will result in the highest voltage the cell can produce, called  $V_{oc}$ , but there will be zero current (point E in Fig. 19). A short circuit means the positive and negative leads are connected directly together. This will result in the highest current the cell can produce, called  $I_{sc}$ , but zero voltage (point A in Fig. 19). Since power is equal to the voltage times the current, both of these conditions produce zero power, but are important characteristics of any module as they determine the capacity of wires, fuses, and other electrical equipment that will be required.

The operating voltage of a solar cell is primarily dependent on the electrical resistance of the load for a given amount of solar irradiation falling on

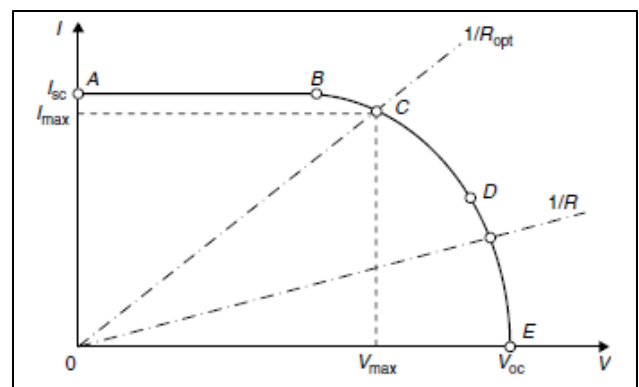


Figure 19. Solar Cell Current(I) vs. Voltage(V)

the panel. In other words, changing the electrical load applied to a solar cell will change the power output of that cell. Using all possible values for the load resistance, a graph of the current versus the voltage, called an I-V curve (fig. 19), can be produced.

Calculating the power for every point of the I-V curve and plotting the result versus the voltage (Fig. 20), it can be seen that there is a voltage that produces the maximum power (point C in Fig. 19 & 20). This is called the maximum power point (MPP), and the load resistance that results in that voltage is the optimal load ( $R_{opt}$ ).

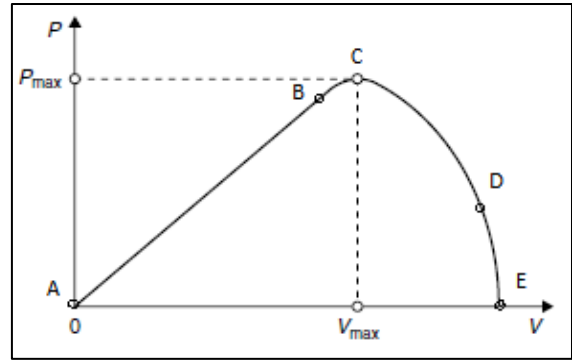


Figure 20. Solar Cell Power(P) vs. Voltage(V)

Modern electrical control devices used in solar PV systems employ a technology called maximum power point tracking (MPPT) to constantly adjust the load resistance the solar panels see to produce the maximum power.

The I-V curve of a solar cell, and the resulting maximum power point, is directly affected by two parameters: sunlight intensity and cell temperature. Cell voltage does not change much at different irradiation levels, but the current output is proportional to the amount of sunlight falling on the cell (Fig. 21a). More sunlight means more photons freeing more electrons. As more sunlight strikes a solar cell, its temperature rises because there are more photons with insufficient energy that is then converted into heat, and more photons with an excess of energy that is also converted into heat.

The increased temperature does not change the number of electrons freed so the current output is largely unaffected, but the voltage is decreased which, in turn, reduces the power output (Fig. 21b). The rate at which the power decreases as the cell temperature increases is a property of the semiconductor material so it varies for different types of cells. A cell with a lower temperature coefficient will produce more energy at peak operating conditions when the cell temperature is highest.

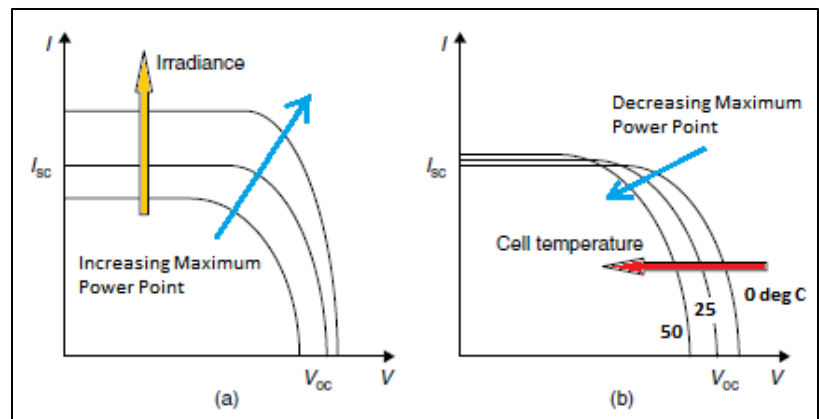


Figure 21. (a) Sunlight and (b) Temperature Effects on Solar Cell Output

The rate at which the power decreases as the cell temperature increases is a property of the semiconductor material so it varies for different types of cells. A cell with a lower temperature coefficient will produce more energy at peak operating conditions when the cell temperature is highest.



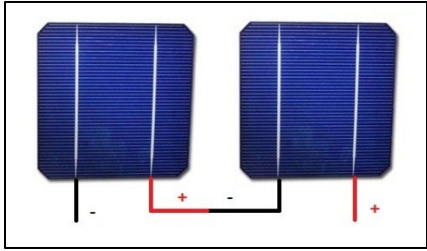


Figure 22. Solar Cells Wired in Series

When two (or more) cells are wired in series the total voltage will be the sum of all the cell voltages, but the current will be the same as a single cell – the cell with the smallest current (Fig. 23a). It is important that cells or modules wired in series be well matched in output for this reason. There can also be to a surprising drop in

performance if one cell in a series string is shaded or malfunctions because all the cells in that string will be reduced to the output of the lower performing cell. This effect can be mitigated with bypass diodes - electrical devices that allow current to flow in only one direction. Bypass diodes allow a low performing cell or series string to be bypassed so it does not affect the output of the rest of the system. Bypass diodes make a panel more expensive so there is a trade-off between increased shade performance and cost. In general, a panel with more bypass diodes will perform better in variable light conditions like cloudy days.

Solar panels, or modules, are composed of multiple cells wired together and solar arrays are composed of multiple modules wired together. There are two basic ways to wire cells or modules together: in series, or in parallel. Wiring cells in series means connecting the positive lead from one cell to the negative lead of

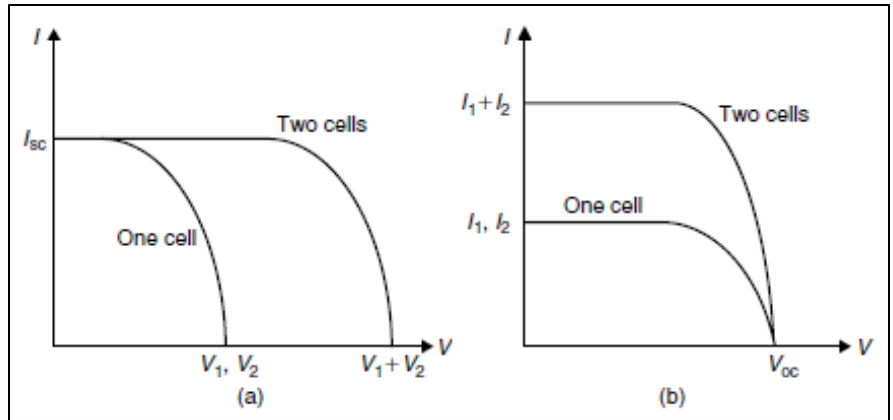


Figure 23. Solar Cell Output when Wired in (a) Series and (b) Parallel

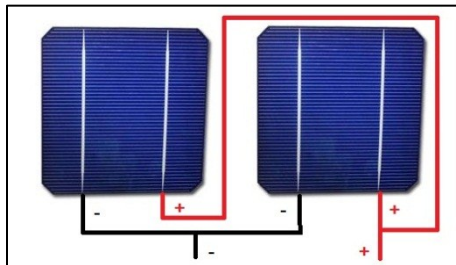


Figure 24. Solar Cells Wired in Parallel

Mismatch or shading of a parallel connected cell or module has no detrimental effect on the other cells in the parallel string, but blocking diodes are sometimes used to prevent current from flowing backwards through a lower performing part of a parallel string.

Wiring cells, or modules, in parallel means the negative leads from all the cells are connected together and all the positive leads are connected together (Fig. 24). This results in the current of each cell being added together to produce the total current while the voltage remains the same as a single cell (Fig.

Cells and modules can be combined in a pattern of series and parallel connected strings (Fig. 25) to produce any desired output voltage and current combination. In the past, modules were typically designed to output a voltage that was a multiple of 12 to make it easier to design systems with batteries. Modern electronic components can easily step system voltages up or down making this unnecessary and most new systems do not use batteries.

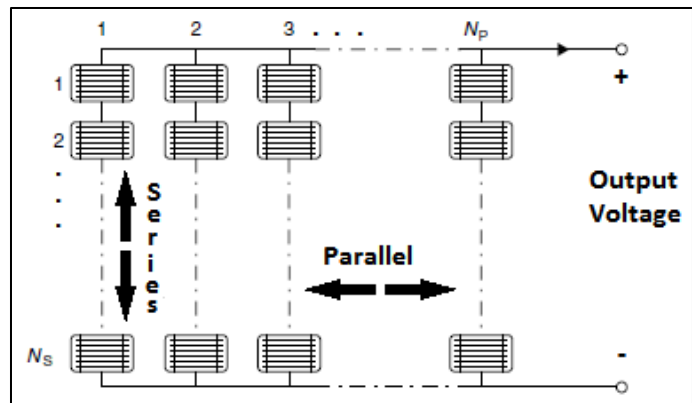


Figure 25. Solar Cells in Series and Parallel Strings

### 2.2.3.2 Grid-tied systems

A solar PV system will generate electricity whenever the sun is shining, but will produce only low levels of electricity in low light conditions and no electricity when it is dark. This generation pattern will usually not coincide with when the electricity is needed so some type of storage system is necessary. One way to do this is to connect the system to the electric utility grid selling electricity to the utility when an excess is being generated and buying electricity when more is needed. This arrangement with a utility company is called net metering.

As of February, 2012, 43 states have a net metering policy requiring electric utilities to purchase consumer produced electricity. There is usually an upper limit on the size of a qualifying system and the rate paid varies by state ranging from a utility's avoided cost to the retail rate. As of this writing in June of 2012, a utility in Minnesota must pay the retail rate for any system not exceeding 40kW in size. For comparison, a 7kW system would generate about 100% of the electricity used annually in the average Minnesota home. Net metering requires a meter that can measure electricity moving in both directions. Many currently installed meters can already do this, but if not, a new meter is usually not a large expense. Net metering policies can change so one should verify rates with the appropriate State or utility representative.

Solar PV panels generate DC, or direct current, electricity which has a positive and negative side like a battery so current only flows in one direction. The electricity supplied by an electric utility is AC, or alternating current, meaning the direction of current flow reverses – 60 times per second (60 Hz) in

the United States. An electrical device, called an inverter, is needed to convert the DC electricity from a solar panel into the AC electricity used by most household appliances and the electric grid. A power inverter used in a solar PV system must be sized to handle the maximum voltage and current that could be produced by that system, and must be able to condition the power so that it matches the quality of the power on the grid. A grid-tied inverter must also have the ability to automatically shut off the power flow to the grid in the event of a power outage. If the utility shuts down power to part of the grid for maintenance or repairs, power lines could be unknowingly energized by a consumer's power generation system posing a safety risk for line workers. A solar PV power inverter should also have maximum power point tracking (MPPT) technology to maximize system performance.

Converting the electricity into AC will reduce the total power generation efficiency. Modern inverters typically advertise a peak efficiency of around 96% although a better estimate of overall efficiency would be around 90%. The normal inverter warranty period is 10 to 15 years, with some stretching to 25 years. Solar PV panels generally have a 25 year warranty, and modern panels can be expected to perform for 50 years or longer under normal conditions. This means the inverter will have to be replaced, perhaps several times, over the lifetime of the system. Inverter replacement costs should be included in any financial analysis.

A few companies offer a micro-inverter that is mounted on the back of each panel (Fig. 26). This eliminates high DC voltages in the system which can be a safety and fire hazard. Converting the electricity to AC at each panel also eliminates any module mismatch and shading concerns associated with panels connected in series or parallel strings. Micro-inverters also allow more flexibility in designing panel arrays because panels do not need to be combined in



Figure 26. Solar Panel with Micro Inverter

fixed proportions to obtain predetermined voltage and current levels. Moreover, asymmetric layouts can be used to accommodate unusual mounting areas or obstructions. Each micro-inverter works on a smaller voltage and current so is less expensive to make, but more of them are needed and when it is time to replace them it may be more difficult depending on the total number of

panels and how accessible they are. Performance data is taken from the inverter so having one on each panel allows each panel to be monitored, and can make troubleshooting easier in the event of a panel failure. While micro inverters offer several advantages, using them in a system will usually cost more initially than using large, centralized inverters.

There are also a few companies incorporating the inverter electronics directly into the PV module making what is called an AC module. These companies have been able to redesign the power inverter electronics so that the whole product can be warranted for 25 years. This represents a significant advance in inverter longevity and decrease in the long term cost of operating a PV system (depending on the cost of the original module). The inverter portion of an AC module is not replaceable, however, so the entire panel needs to be replaced when it fails – probably much earlier than when the solar cells fail.

In summary, a grid-tied PV system consists of solar panels, a power inverter(s), a circuit breaker panel, a two way electric meter, and, of course, the utility electric grid (Fig. 27). The panels generate DC electricity when the sun is shining which is converted to AC electricity by the power inverter. The AC electricity is distributed to the electrical load through the circuit breaker panel. When more electricity is being generated than is being used, excess electricity is directed through the meter and to the electric grid. When not enough electricity is being generated by the panels, additional power is drawn from the grid through the meter and into the circuit breaker panel. The power company keeps track of the net use of electricity and adjusts the electric bill accordingly.

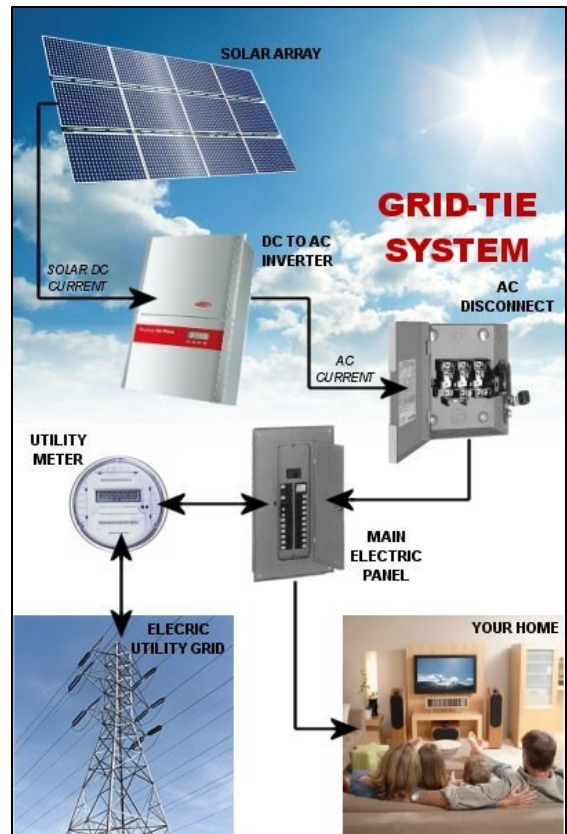


Figure 27. Grid-Tied Solar Power System (MrSolar.com)

### 2.2.3.3 Stand alone systems

Another way to use solar PV is in a stand-alone, or off grid, system (Fig. 28). This collects energy like a grid-tied system, but instead of sending excess energy in the form of AC electricity to the grid, it is stored in batteries as DC electricity. A power inverter is still needed to convert the DC electricity into AC electricity, but an off grid inverter is usually less expensive than a grid-tied inverter because it does not need to have automatic shut down and power conditioning capabilities. However, another device, called a charge controller, is needed to manage the charging and discharging of the battery bank. The charge controller will also include the maximum power point tracking (MPPT) circuitry to keep the panels producing at their highest potential. The battery bank is sized to provide the required power level for a planned length of time without sunlight. A back-up generator may also be included to ensure power is always available even during extended periods without sunlight.

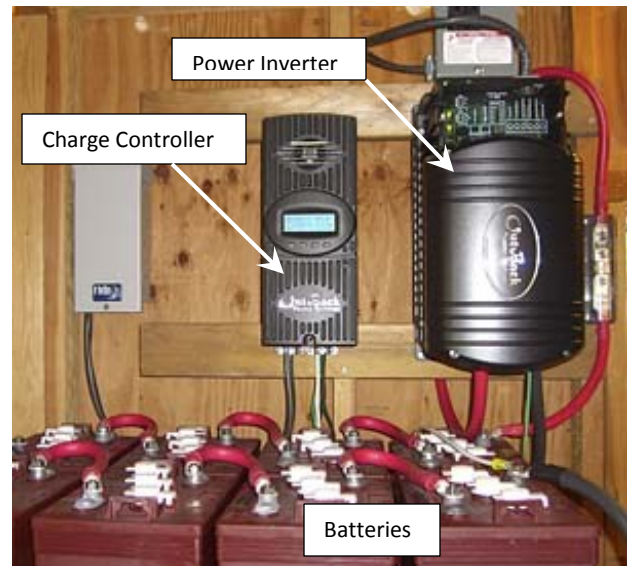


Figure 28. Stand-Alone Solar Power System

A stand-alone system is significantly more expensive than a grid-tied system due to the addition of a charge controller and batteries. Stand-alone systems are typically employed where there is no access to the electrical grid or where such access would be prohibitively expensive. The best way to reduce energy costs when living “off the grid” is through efficiency to minimize the overall size of the energy system. Careful monitoring and matching of electrical supply and demand can result in better energy utilization, but may require some behavioral changes. For instance, it is more efficient to do electrically intensive activities like washing clothes during the day while the sun is shining rather than at night after some efficiency has been lost in the batteries. Even more efficiency can be obtained by using DC appliances which eliminate the inefficiency of the power inverter. The biggest difference between the two types of PV system is in the use of batteries. However, batteries are sometimes used in a grid-tied system if electricity is needed in the event of a utility power outage or if one wants to store power to use during peak demand periods when utility prices might be higher.

### **2.2.3.3.1 Solar batteries**

Batteries are expensive, typically costing as much as the solar panels, and have a 5 to 10 year life span. They also degrade the overall system efficiency since they are only about 80% efficient, and need to be carefully stored and maintained. The type of battery used in a solar PV system is called a deep cycle or solar battery. Deep cycle batteries are needed as they are designed to produce consistent power output while being discharged to a greater extent than a typical battery, like those used in cars. A car battery is designed to provide a large initial power output to start a car, but then is continually charged by the alternator.

The two primary battery parameters are voltage (V) and amp-hours (AH). Batteries can be wired in series and parallel strings, just like solar cells, to provide any desired system voltage. The battery voltage needs to be coordinated with the solar array voltage to ensure proper charging although modern charge controllers can step voltages up and down to make this easier. The amp-hour rating of a battery gives an indication of how much energy it can store. Basically, the rating indicates how many hours the battery can supply 1 amp of current, or how many amps it can supply for 1 hour, or any combination thereof. The amp-hour rating is usually based on the 20 hour discharge rate meaning the battery is completely discharged over a 20 hour period. Discharging a battery more slowly will increase its amp-hour rating so consumers should make sure equivalent discharge rates were used when comparing batteries.

Solar batteries come in two types: flooded and sealed. Flooded batteries use a fluid electrolyte, have ports to access their cells' fluid reservoirs, and require maintenance (adding fluid). Sealed batteries use non-fluid electrolyte contained in inaccessible cells. There's only one flooded type: flooded lead-acid batteries (FLA). Sealed batteries include Absorbed Glass Mat (AGM) batteries and gel cell batteries.

Flooded deep cycle lead-acid batteries (FLA), also called "wet cells", are often the least expensive type of deep cycle battery and can last the longest. They also come in a wide range of sizes. FLA batteries use a sulphuric acid solution which reacts with the lead plates in the cells to produce electricity. When FLA deep cycle batteries are recharged, electrolysis occurs, producing hydrogen and oxygen gases in a normal process called "outgassing". These gases may escape the cells through

the filler/vent caps meaning that the fluid level in the battery goes down. So using FLA batteries means that regular monitoring and maintenance will be required by adding distilled water to each cell as needed. Another concern is the presence and accumulation of hydrogen and oxygen gases which can be dangerous and must be properly vented to the outside air. Because they contain fluid, FLA batteries need to be stored upright and kept from freezing.

One big advantage of sealed deep cycle batteries is that they can be placed in any orientation since the electrolyte is suspended in either an absorbed glass mat (AGM) or in a gel. Sealed deep cycle batteries cost more, as much as twice more, than flooded lead-acid batteries and don't last for as many charging cycles; however, they are the preferred choice for applications requiring frequent battery handling, or where the system needs to be left unattended in a remote location. Like FLA batteries, sealed batteries have vents to allow hydrogen to escape when necessary, though this should not normally occur. Because the batteries are sealed, there is no way to replace the escaped moisture by adding water to the cells; that's why a sealed battery won't last as long as an FLA battery.

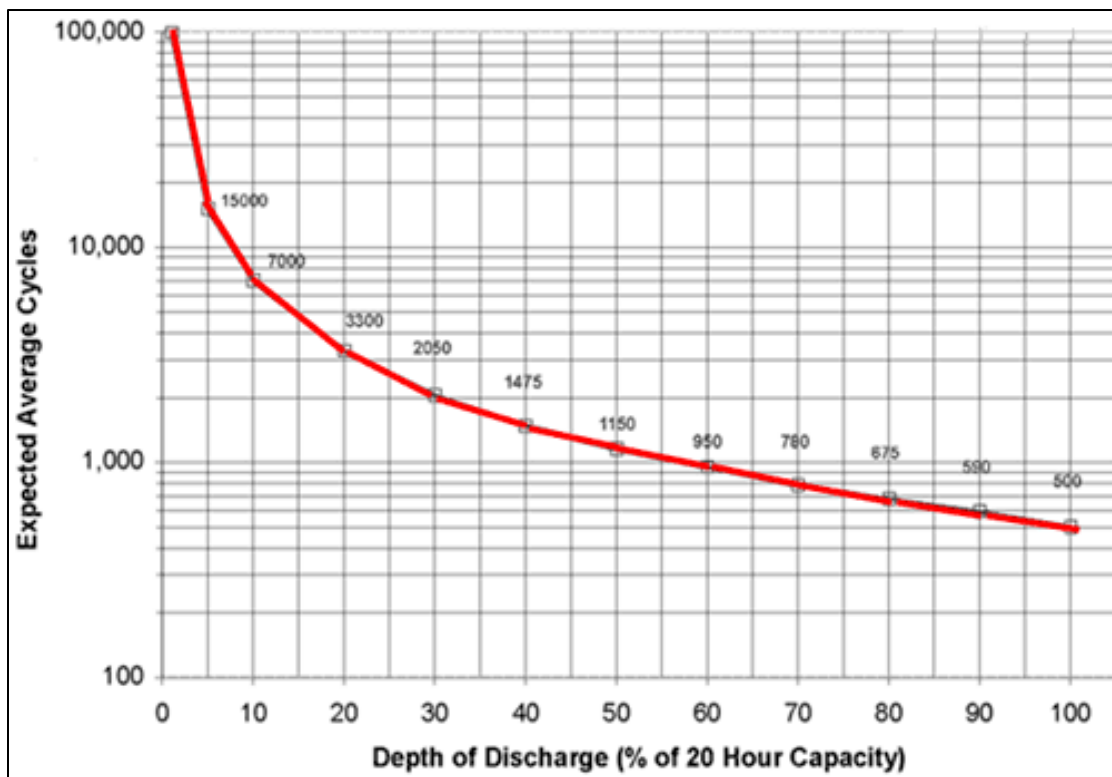


Figure 29. Battery Life versus Depth of Discharge (DOD)

With solar batteries, the primary design decision is how much to let them discharge, called depth of discharge (DOD). Graphing the number of charging cycles a battery will last against the depth of discharge (Fig. 29) shows the more a battery is allowed to discharge, the shorter its expected lifetime. Allowing batteries to discharge more means fewer will have to be purchased, but they will not last as long. Deep cycle batteries are designed to discharge 80% of their capacity, but most system designers will choose a value around 50% as a good trade-off between longevity, cost, and the hassle of replacing batteries. If the battery bank is sized for more than one day without sun, the actual depth of discharge on sunny days will often be less than 20%.

## 2.2.4 Performance and cost considerations

### 2.2.4.1 What's on the label?

The actual performance of any solar PV system will ultimately depend on the available solar resource. For example, a PV system located in the desert of Arizona will produce about 40% more electricity over a year than the same system located in Morris, Minnesota. The following discussion of system performance will assume PV panels are facing south, mounted at an angle equal to the site's latitude, and are not shaded. These are typical assumptions so any significant deviation will decrease system performance and prolong economic payback.

An initial estimate of a system's performance can be made by considering the information included on the solar panel. Every solar panel, or module, has a label on the back that lists the panel's electrical characteristics. While the specific notation may vary, all panels provide the same basic information (Fig. 30). All PV modules are rated under an industry standard called Standard Test Conditions (STC) which specify irradiation at  $1000 \text{ W/m}^2$ , a cell operating temperature of 25 degrees Celsius, and light quality conforming to the standard solar spectrum

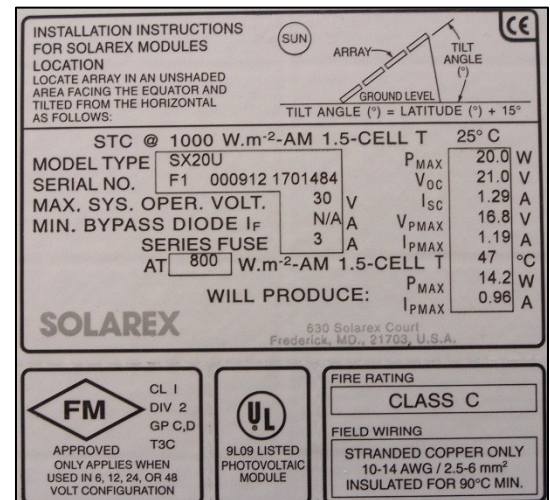


Figure 30. Solar Module Label

designated as AM 1.5 (Fig. 12). Several module output parameters are listed which were measured while the module was subjected to the standard test conditions including  $P_{max}$ , or  $P_{mpp}$ , which is the power output at the maximum power point of the I-V curve. This is also called the name plate power



and is the value used to rate and market solar PV panels. Other output values included are the open circuit voltage (Voc), the short circuit current (Isc), and the voltage and current that occur at the maximum power point. A maximum operating voltage and series fuse rating are listed and should be used to determine the size of the balance of system (BOS) components like an inverter, circuit breakers, and wiring. The label should also indicate the panel is UL listed.

Some panels also list output values for PVUSA test conditions (PTC) which represent more realistic operating conditions. STC conditions model a peak operating condition that is not likely to occur in a real system, especially one installed in Minnesota. PTC conditions were initially required in California and are used to calculate state rebates there. PTC means irradiation at 800 W/m<sup>2</sup>, a cell operating temperature of 47 degrees Celsius, and light quality conforming to the standard solar spectrum designated as AM 1.5. It is possible for a module with a lower STC power rating than a competing module to have a higher PTC power rating if it has a lower temperature coefficient.

#### **2.2.4.2 Example performance calculations**

A simple estimate of the annual production from a solar PV system can be made using the name plate power rating (based on STC), the average solar insolation for the site, and a de-rating factor to account for non-module system losses. The average daily value of solar insolation in Minnesota is 4.5 kWh/m<sup>2</sup>/day which means the sun shines with an irradiation of 1000 W/m<sup>2</sup> for an average of 4.5 hours per day. How this relates to the actual daily variation of solar irradiation throughout the year is depicted in Figure 10. The insolation value is sometimes called, “peak sun hours”, indicating the number of hours per day a solar panel will experience irradiation equivalent to the STC rating. In other words, how many hours per day a module can be expected to produce at its rated power output.

A PV system will suffer losses due to module mismatch, conversion to AC, soiling, wiring, high cell temperature, etc. For Minnesota, 85% has been found to be a good estimate of the de-rating due to these factors for residential scale systems meaning a system will actually produce 85% of its rated power output. The actual module efficiency based on the cell material is not included in this de-rating factor, nor does it need to be, because the name plate power rating will be used to estimate performance. The panel efficiency simply determines the amount of cell area that is needed to get

the rated output. So, two panels rated at 200 Watts will both produce 200 Watts at STC, but the one with lower panel efficiency will be larger in size.

Multiplying the system’s name plate power rating by the insolation and the number of days in a year and the de-rating factor gives an estimate of the total number of kilowatt hours produced in a year. This estimate should be within about 10% of an actual system’s production. Actual production will be higher in the summer and lower in the winter, and total output will change if the average insolation for the year is different than the long term average value of 4.5. Again, shading or non-optimal panel orientation will decrease performance as will module age. Typical module performance will decrease about 0.5% per year<sup>7</sup>, so these estimates assume the system is operating in its first year. This calculation has been done for several system sizes in the following table:

<b>System Size (DC)</b>	<b>Insolation (kWh/m<sup>2</sup>/day)</b>	<b>Days per Year</b>	<b>De-rating Factor</b>	<b>Annual Production (kWh-AC)</b>
1 kW	4.5	365	.85	1396
4 kW	4.5	365	.85	5585
6 kW	4.5	365	.85	8377

Annual savings can be calculated by multiplying the annual production, in kWh, by the cost of electricity. If the cost to install a system is known, a simple payback period can be calculated. Using a single axis tracking system to orient the panels toward the sun throughout the day would increase total production by about 28%, and using a dual axis tracking system so the panels are always pointed at the sun would increase it by about 36%. This analysis could be used to predict the additional savings realized with a tracking system to help determine if the additional cost would be a good investment. Incidentally, according to the Minnesota Department of Commerce, the average Minnesota home uses about 8000 kilowatt hours of electricity per year so a 6kW system would produce all the electricity the average home needed in an average year.

A more detailed performance analysis can be done using a free online tool developed by the National Renewable Energy Lab (NREL) called PVWatts<sup>8</sup>. This tool accesses meteorological data for the desired location and calculates monthly system production based on entered system parameters. It also determines the local electric rate to calculate monthly savings. A detailed

procedure for sizing an off-grid solar PV system from Home Power magazine is available on their website<sup>9</sup>.

In order to stimulate the industry, financial incentives are offered for the installation of solar PV systems. These incentives can be in the form of equipment and installation rebates, grants, and tax incentives from the state and federal governments. Other financial incentives include accelerated depreciation and guaranteed loans. These incentives can have a major impact on the return on investment but tend to frequently change. Check with your utility provider, state energy office, university extension, and USDA Rural Development representatives on the current availability of these incentives. There is a web site (<http://www.dsireusa.org/>) that tracks all incentives on a state by state basis.

### 2.2.4.3 PV costs

Concerns about fossil fuel prices, energy security, and the environment have fueled an exponential growth in the worldwide solar PV industry over the last decade (Fig. 31)<sup>10</sup>. The amount of solar PV installed in the United States is a small part of the world market, but is also growing at an exponential rate. This growth has led to large decreases in the cost of a PV module as companies are able to scale up production and take advantage of economies of scale. Typically, the cost of a PV module is about half the total installed cost of a PV system per Watt. The U.S. Department of Energy (DOE) has a program called the *SunShot Initiative* which is putting millions of dollars into four areas of research (PV cell technology, module manufacturing, electronic components, and

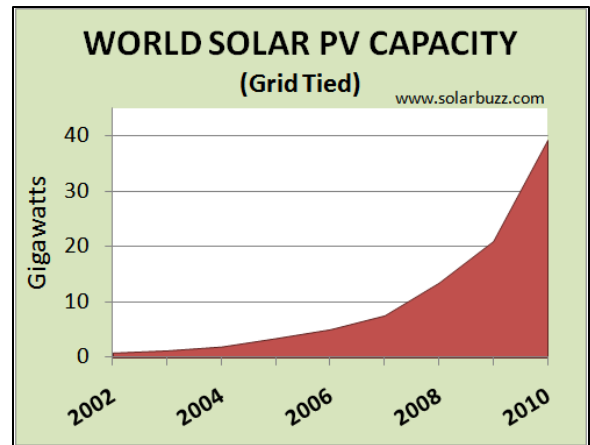


Figure 31. Worldwide Solar PV Installed Capacity

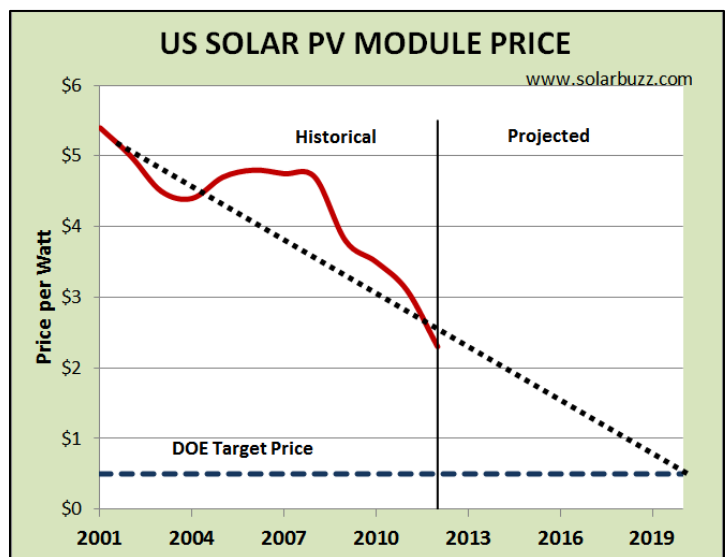


Figure 32. U.S. Module Price Trend

installation/permitting) to get the installed cost of utility-scale, solar PV down to \$1 per Watt by the year 2020<sup>11</sup>. This would produce electricity at about 6 cents per kilowatt hour making solar PV competitive with other forms of energy even without incentives. The cost of a PV module needs to get down to about 50 cents per Watt to reach this goal. Module price in the U.S. has decreased significantly in the past decade and is on track to meet the DOE's goal (Fig. 32). According to the Solar Energy Industries Association (SEIA), the average installed price of a residential solar PV system in late 2011 was between \$6.00 and \$6.50 per Watt<sup>12</sup>.

Solar electricity makes up less than 1% of the electricity generated from renewable sources (including hydroelectric) in the U.S., and a tiny fraction of the electricity generated from all sources (Fig. 33). So, even with the rapid growth of the industry over the last few years, there is still tremendous room for growth which should keep prices trending downwards given a consistent policy environment.

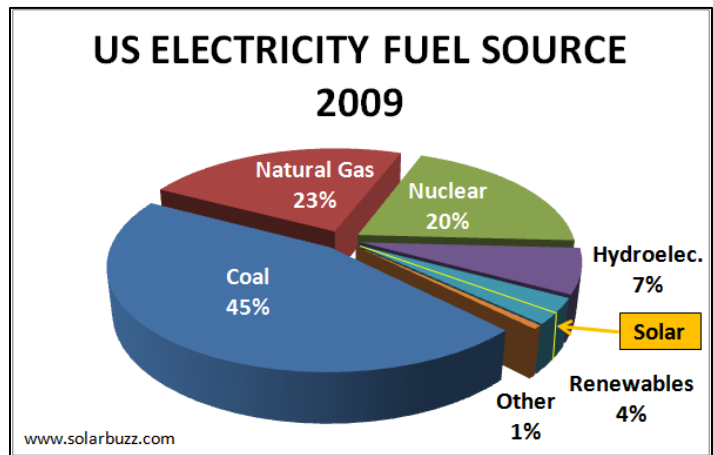


Figure 33. U.S. Electricity Generation by Source

### 2.2.5 Solar PV Consumer guidelines

This section offers a quick reference guide of a few important things to consider when purchasing a solar PV system.

- Nothing will affect the success of a renewable energy project more than an experienced and knowledgeable contractor. NABCEP certified installers have completed a comprehensive certification program for renewable energy installers. The Minnesota branch of the Solar Energy Industry Association maintains a list of certified installers on its web site: <http://mnseia.org/>.
- Be sure to get a thorough on-site evaluation of your planned installation location. The installer should use some type of tool to evaluate shading on the site.
- A report that details the equipment that will be installed as well as the projected performance of the system along with a cost estimate should be provided. The performance assessment should show the monthly output and should come from a computer model of your proposed system – not a general rule of thumb type calculation. An assessment may cost more and involve an energy consultant, but will be worth it in the long run.
- Be sure the contractor has received the proper local, state, and federal permits and approvals for construction as well as proper regulatory approval for interconnection to the grid.
- Search for available incentives from your State, utility, and the federal government. The contractor should be able to provide you with a list of incentives, contacts, and / or the process to obtain the incentives. Consider checking with your tax preparer to determine the value that tax credits and accelerated depreciation bring to the project.
- Based on the expected performance, equipment, and other costs; develop an independent financial model projecting return on investment. When weighing the financial considerations, include realistic maintenance and operations costs plus mileage and labor for a repair technician. Repair and maintenance tend to be undervalued.

Contingency funds should be included in the financial model for both construction and operation. A typical contingency amount would be equal to 10% to 15% of the total project budget.

- Insurance may be available to purchase either as an addition to a home or business policy or as a stand-alone policy for perils such as wind, hail, fire, vandalism, theft, loss of revenue, and liability. In addition to your own personal protection, utilities may require liability insurance coverage as a condition of interconnection to the grid. These costs should be considered in the financial model.
- Be aware of any dangerous locations where high voltage is present and where breakers are located to shut off power in the event of a fire or other emergency. DO NOT ATTEMPT to personally install a system without the proper training and certification.
- You should be able to monitor the system's performance from data already available from the inverter. Data should be tracked and stored over time, preferably on the web. This feature may cost more, but it can identify problems and inefficiencies in a system that might otherwise go unnoticed. Moreover, if there are performance guarantees, you will have no basis to make a claim without monitoring.
- The system should be fully commissioned, meaning the installer verifies all aspects of the system work as planned and meet performance expectations. You should receive manuals for all components and training on how to operate them and identify problems. Also, make sure you know who to call if there are any problems and who will perform routine maintenance.
- Proper and timely maintenance will help insure the optimum performance of the system.
- Finally, learn more about solar PV. Although PV systems are relatively simple and require little maintenance, invariably, they will add complexity to your electrical system. The Clean Energy Resources Team's website is a good place to start: <http://www.cleanenergyresourceteams.org/>. The sources section of this document also lists several good sites for more information.

## **2.3 Solar Thermal Energy**

Another way to gather energy from the sun is to collect it as heat. Solar thermal energy is demonstrated by the fact that anything left out in sunlight tends to heat up, and is the reason the Earth is warm enough to support life. Solar thermal energy is collected by any object in the sun, but the efficiency and temperature of that collection can be increased by carefully designing the object. Such an object is called a solar thermal collector.

### **2.3.1 How does it work?**

Solar thermal collectors come in two broad categories: glazed and unglazed. Glazing refers to the use of glass in the collector. Unglazed collectors are typically used to heat swimming pools in warm climates. They consist of channels in a dark colored material, usually plastic, that heat pool water as it is pushed through the channels by the pool pump. These are effective because they do not need to reach very high temperatures relative to the surrounding air. If the temperature of the water in a collector gets much higher than the air temperature, heat will begin transferring to the air and the collector will eventually stagnate. The stagnation temperature of a solar thermal collector is the maximum temperature it can reach. This happens when the amount of heat energy being added to the fluid in the collector is equal to the amount of heat energy lost to the surrounding air.

Glazed collectors greatly increase the stagnation temperature by using glass to enclose a volume of space containing an absorber. The absorber in a collector is the surface that actually heats up by converting sunlight into heat. Heat energy can be transported in three ways: conduction, convection and radiation. Conduction happens when two surfaces at different temperatures contact each other with heat moving from the warmer one to the cooler one. Convection occurs when a fluid (liquid or gas) is circulated greatly increasing the heat transfer. This is why a cold day with wind feels colder than a day without wind, even if the temperature is the same – known as the windchill effect. A very hot surface radiates heat in the form of infrared energy. Heat radiation does not need a transfer medium like air or water, and does not require contact with the hot surface. A campfire feels warm primarily due to the heat radiating from the burning surfaces.

Heat radiating from the absorber in a solar thermal collector is in the form of infrared energy. Glass is effective at raising the operating temperature of glazed collectors because it allows sunlight to pass through, but blocks infrared radiation. There are two basic types of glazed collectors: flat plate collectors and evacuated tubes.

## 2.3.2 Solar thermal collectors

### 2.3.2.1 Flat plate collectors

Flat plate (FP) collectors are essentially a mini greenhouse consisting of an insulated box with an absorber and a glass or plastic cover (Fig. 34). They contain channels for water to flow from the lower part of the collector to the upper part while being heated by the absorber. The channels are attached to the absorber plate which is heated by the sun due to a dark colored coating. The absorber plate and channels are typically made from copper or aluminum. Modern flat plate

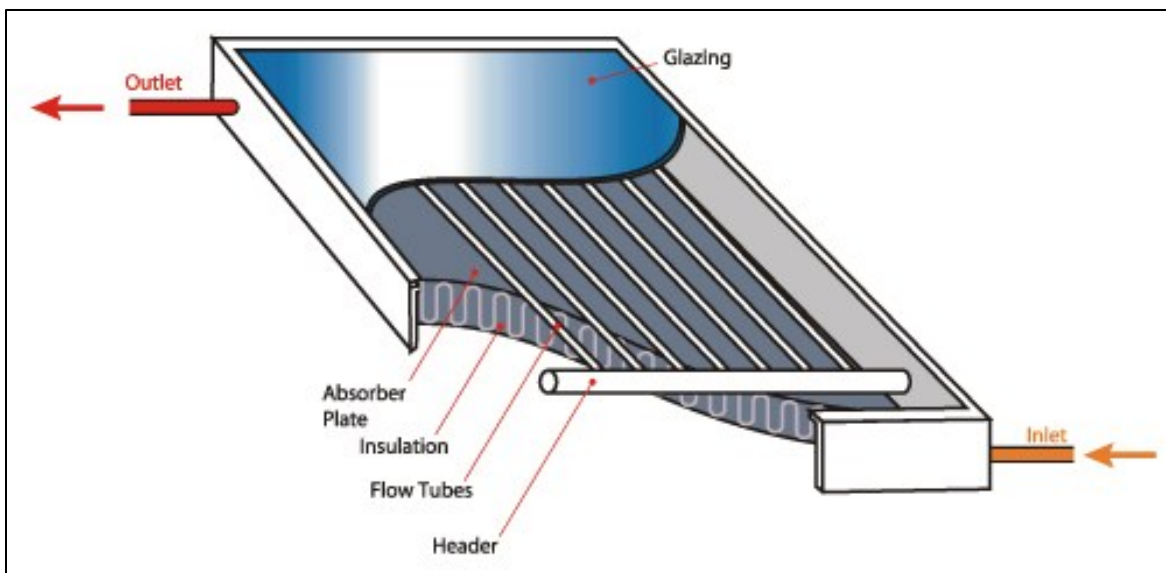


Figure 34. Flat Plate Collector

collectors use special coatings on the glass to reduce relectivity, and on the absorber to increase the collection and retention of heat. The back portion of the collector is filled with insulation to minimize heat loss. This design can also be used to heat air in which case the flow channels are omitted.



Flat plate collectors are simple, robust, and largely unchanged from the earliest designs except for improvements in manufacturing processes. In 1760, Swiss scientist Saussure developed the world's first solar thermal collector which was essentially a hot box that was eventually used as a solar cooker<sup>13</sup>. The first patent on a solar water heater was given to Clarence Kemp in 1891 for the "Climax" solar water heater which consisted of a

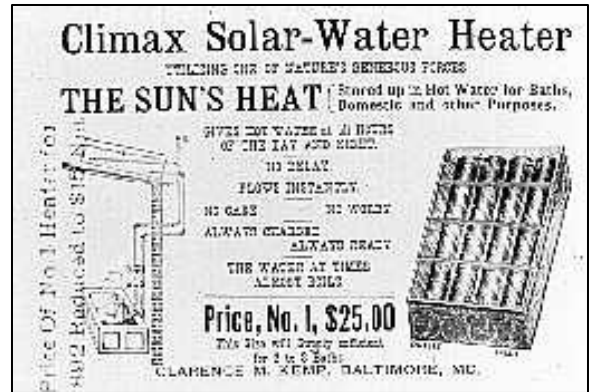


Figure 35. The "Climax" Solar Water Heater

water tank painted black and put inside a glass covered box (Fig. 35)<sup>14</sup>. It sold for \$25 and did quite well with 1600 units in use by 1900. In 1909, a patent was issued to William Bailey for the "Day and Night" collector<sup>15</sup> which separated the storage tank from the collector in essentially the same design that is used today. Bailey sold over 4000 units in California in 10 years until natural gas was discovered in the LA basin in the 20's ending the solar boom. A modified design was in almost half the homes in Florida by 1941 until cheap electricity and utility company rebates on electric water heaters ended that boom.

In summary, the flat plate collector is a well understood, proven, and reliable piece of technology. There are dozens of similar designs available from manufacturers in the U.S. and abroad.

### 2.3.2.2 Evacuated tube collectors

Most evacuated tube (ET) solar thermal collectors consist of two tubes of glass, one inside the other, with all the air evacuated from between the tubes. The inner tube is coated with a selective coating that converts sunlight into heat forming the absorber. The inner tube contains a heat pipe which is a sealed copper tube containing a small amount of fluid that is also under a vacuum (Fig. 36), and some thin fins of aluminum that help transfer heat to the heat pipe. Light passes through

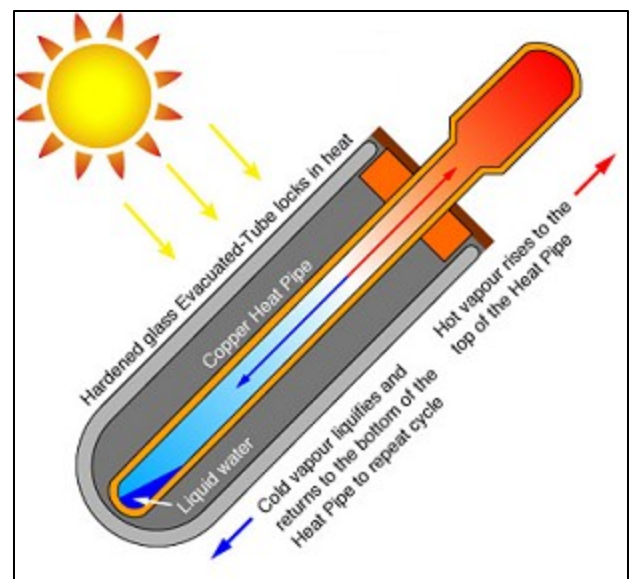


Figure 36. Evacuated Tube Solar Collector (SunMaxx Solar)

the outer glass tube and is converted to heat in the absorber coating. The hot absorber then heats the air and heat pipe inside the inner tube. The vacuum between the two tubes of glass prevents any heat being lost by conduction or convection which gives ET collectors a much higher stagnation temperature than flat plate collectors. They are also much less affected by the outside temperature or wind for the same reason.

The fluid in the heat pipe boils at a relatively low temperature, typically about 85° F, due to the vacuum in the heat pipe. The heated vapor rises to the top of the heat pipe where it is cooled by a water and antifreeze solution which is pumped through a copper header, or manifold, at the top of the collector (Fig. 37). After the vapor transfers its heat to the header, it condenses back into a liquid and runs down the heat pipe to repeat the cycle. The evaporation/condensation cycle allows a lot of energy to be moved quickly which accounts for the rapid response of evacuated tube collectors. The heat pipe design

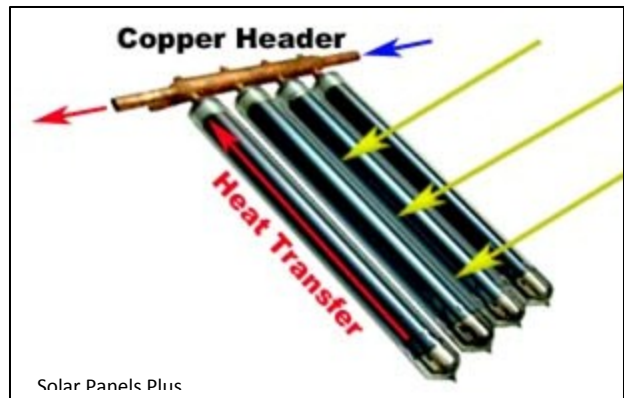


Figure 37. Evacuated Tube Solar Collector with Header

means there is no fluid contact between the liquid being heated in the heat pipe and the water/antifreeze solution in the header collecting heat and transporting it into a building.

Some designs put the absorber coating on a fin of copper that is welded to the heat pipe much like the absorber of a flat plate panel. In this case, the absorber is inside the inner tube of glass instead of on its outer surface. Most evacuated tube collectors use a heat pipe, but there are a few that run a pipe down and back inside the inner tube. In these designs, the same fluid that circulates in the header and building is heated inside the evacuated tubes.

The evacuated tube collector is a relatively new design. It was developed at a university in China in the early 1980's with initial manufacturing starting in 1985. The design began to be copied and broadly distributed in 1998<sup>16</sup>. Most tubes are still made in China and are almost identical across brands since the original equipment and design was simply copied by other manufacturers due to the lack of patent protection in China. The tubes are made from high strength borosilicate glass that is designed to withstand a 1 inch diameter hail stone. The tubes include a barium "getter" at the

bottom of the tube that absorbs gasses to help maintain the vacuum over time. This is silver in color, but turns white instantly if the tube is broken providing a simple visual indication of vacuum status. One advantage of the heat pipe design is that broken tubes can be replaced individually without shutting down any part of the system.

### **2.3.2.3 Comparison of collector types**

Which type of collector will work the best? There are a lot of conflicting opinions on this topic which means there is not a simple answer. The best collector choice will be different for different applications and in different system configurations.

Flat plate collectors are self-contained and require no assembly besides normal plumbing connections. They are simple, have a long track record, and are virtually indestructible. Almost all of the area on the front of a FP collector is absorber area making them very efficient in the use of installation space. There can be a drawback in that larger collectors will be heavy and unwieldy to get onto a roof. They will increase the wind loading on the mounting structure if they are not mounted flush to the surface. Panels mounted at an angle to a roof will probably require an engineering assessment to satisfy local building codes and may increase the installed cost if the roof structure needs to be reinforced.

Evacuated tube collectors require assembly on site which can add to installation costs, but also make it easier to get them on a roof. The tubular shape and space between the tubes makes ET collectors a little less efficient utilizing installation space, but it also allows them to shed wind, greatly reducing any concerns about wind loading on the mounting structure. The fact that FP collectors lose heat to the surrounding air has a positive side effect in that snow and ice are quickly melted off of the collector when the sun comes out. The steeper mounting angles at northern latitudes (typically 45° in Minnesota) helps all collector types shed snow. So far, the experience of the WCROC in Morris, MN, has shown no real difference in snow shedding abilities between FP and ET collectors.

FP collectors are very efficient when the heated fluid temperature is not too much hotter than the outside air temperature, but lose efficiency more rapidly than ET collectors as the difference

between these temperatures increases (Fig. 38)<sup>17</sup>. The efficiency of different types of collectors is usually compared by using an inlet fluid parameter that accounts for the amount of solar irradiation and the difference between the temperature of the heated fluid and the air temperature. Figure 38 shows that the efficiency curves for ET and FP collectors cross meaning that in sunny conditions where the collector fluid temperature is not

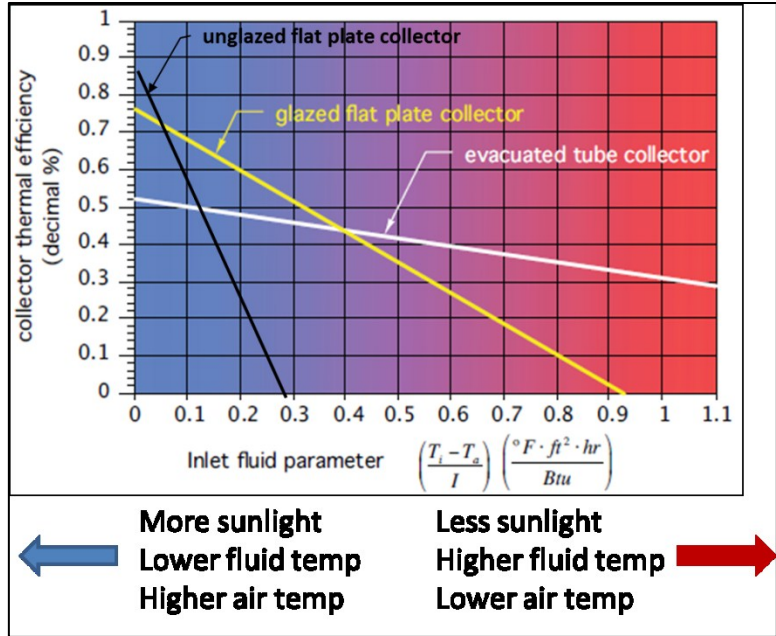


Figure 38. Comparison of Collector Efficiency by Type (Caleffi)

too much higher than the air temperature (left side of the graph), FP collectors are more efficient. At some point when the collector fluid temperature is much higher than the air temperature and/or there is less sunlight (right side of the graph), ET collectors become more efficient. So processes requiring relatively high fluid temperatures like solar air conditioning may not be the best application for flat plate collectors. It should be pointed out that the collector efficiency graphs are based on collector gross area. This makes ET collectors a little less efficient in comparison to FP collectors due to the spaces between the tubes, but this would only be of concern if the installation space for the collectors was limited.

The Solar Rating and Certification Corporation (SRCC) performs testing on all solar thermal collectors using a standard protocol and provides certification that a collector meets acceptable performance standards. A collector typically needs to have SRCC certification to be eligible for federal and state incentive programs. The SRCC determines the daily energy production for each panel it tests for various sunlight conditions and fluid to air temperature differences, and reports the results on its web site (<http://www.solar-rating.org/>).

One way to determine the best collector choice for a particular application would be to determine the daily energy requirements and then determine how many collectors would be needed based on the SRCC rating data. This would account for the operating temperatures needed and the available

solar insolation. The total price could then be determined for different collectors and the most cost effective solution selected unless there are specific site constraints that would dictate the collector type.

Flat plate collectors are the most common solar thermal collectors outside of China, but the market in China is so large that over half the collectors in use world wide are evacuated tube collectors (Fig. 39)<sup>18</sup>. In 2009, China represented almost 80% of the total world market for solar thermal collectors (Fig. 40)<sup>18</sup> meaning it has a large impact on demand and, therefore, collector price. The proportion of ET collectors sold in 2009 closely tracks China's share of the world market (Fig. 41)<sup>18</sup>.

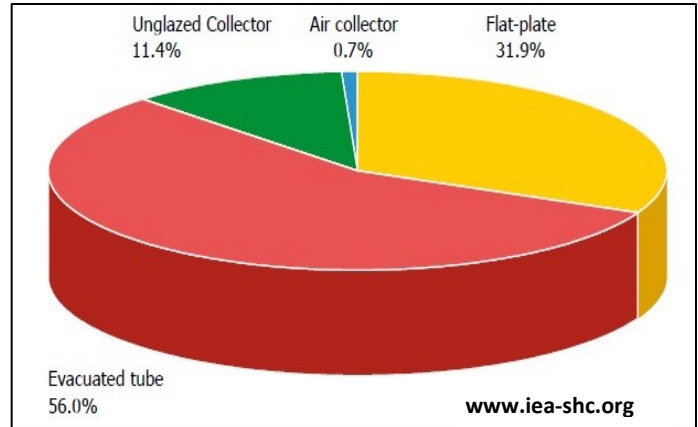


Figure 39. Total World Solar Thermal Collectors in Use as of 2009

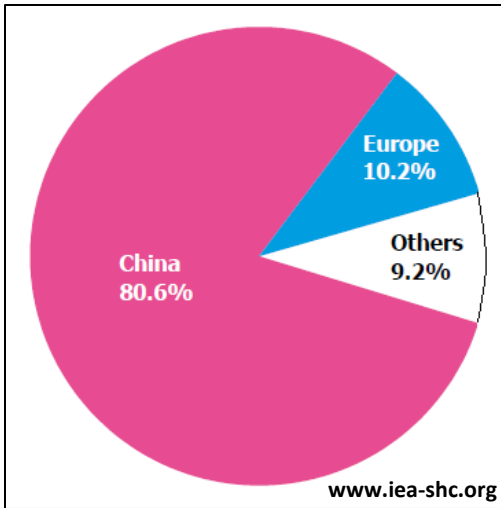


Figure 40. 2009 Total World Solar Thermal Market

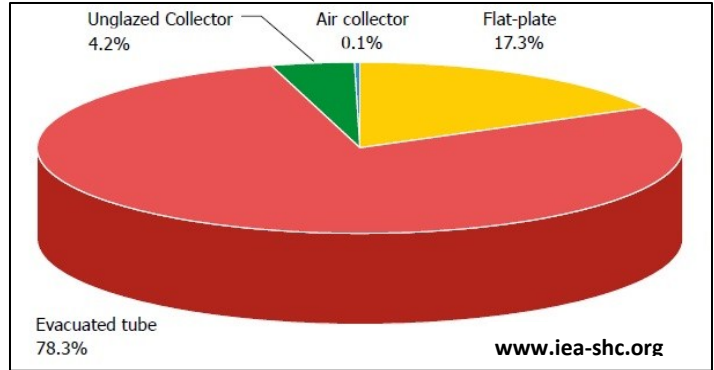


Figure 41. New Solar Thermal Collectors Sold in 2009 Worldwide

All of this suggests that the world market for solar thermal collectors is being largely influenced by the Chinese market, and likely will continue to be for the foreseeable future. The decreasing price of evacuated tube collectors has spurred large gains in market share across most countries in Europe, especially Germany, and the U.S. The market for unglazed collectors, primarily for pool heating, is almost completely in the U.S. and Australia, and solar air heating collectors still represent a relatively small part of the solar thermal market.

### 2.3.3 Solar hot water systems

In the United States, heating water accounts for about 20% of the total energy consumed in residential buildings (Fig. 42)<sup>19</sup>. One of the most cost-effective ways to include renewable technologies into a building is by incorporating solar hot water. A typical residential solar water-heating system reduces the need for conventional water heating by about two-thirds. It minimizes the expense of electricity or fossil fuel to heat the water and reduces the associated environmental impacts. Solar water heating is not a complete replacement for conventional water heaters,

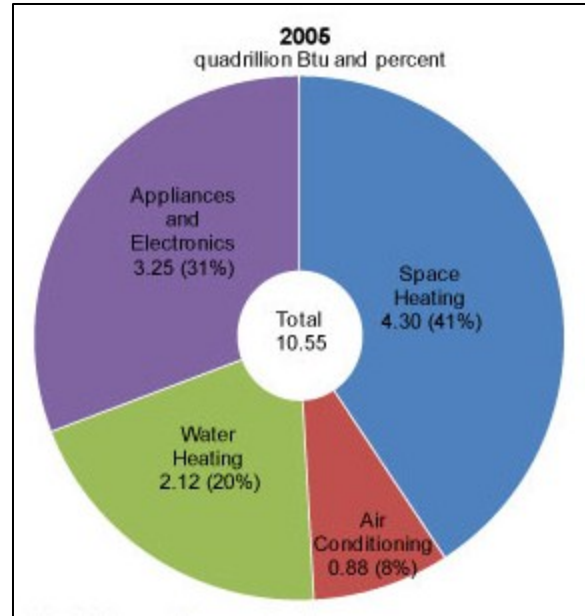


Figure 42. U.S. Residential Energy Use in 2005 (U.S. EIA)

however. Solar fraction is a term used in the solar thermal industry that indicates what percentage of the energy used by a system is provided by solar energy.

#### 2.3.3.1 System Types

Most solar water-heating systems for buildings consist of a solar collector, a storage tank and a control system. One way to classify solar hot water (SHW) systems is by how fluid is moved from the collectors into the storage tank. There are two broad categories: passive and active. Passive systems, sometimes called thermo-syphon systems, use gravity and

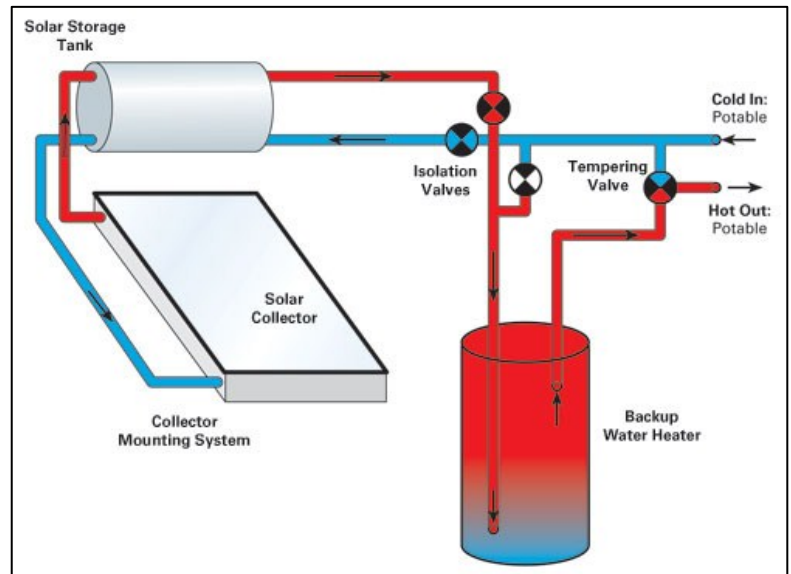


Figure 43. Therm-syphon Solar Hot Water System (HomePower Magazine)

natural convection to circulate water between the collectors and storage tank (Fig. 43). In these systems the storage tank must be mounted higher than the collectors. As water is heated in the collectors it will naturally rise into the tank. Cooler water in the tank will be denser than the heated

water and will sink to the lowest level at the inlet to the collectors creating the necessary circulation. The heated water can be drawn from the tank for use and replaced from the cold water supply. The hot water from the storage tank could be used directly, but it is usually paired with a back-up water heater to ensure a consistent supply. Thermo-syphon systems are simple and inexpensive making them the most common system in temperate climates where they are not hampered by freezing temperatures. In fact, they are the most popular solar hot water choice in the world, but would not work in Minnesota's harsh winter.

Active systems use a mechanical pump to circulate fluid between the collectors and storage tank allowing longer pipe runs and freeing the tank to be placed wherever it is most convenient, usually inside the building. This removes a heavy load, the storage tank, from the roof structure which may permit a larger tank. Placing the tank inside the building also makes it more thermally efficient in colder climates.

Another way to classify SHW systems is based on the fluid that flows through the collectors. Again, there are two broad categories: direct and indirect. With direct systems, the water being heated in the collectors is the same water that is actually used in the building. Indirect systems employ a heat transfer fluid that circulates between the collectors and storage tank in a closed loop. Heat is transferred to the domestic water supply by some type of heat exchanger (Fig. 44). A pressurized

plumbing system should use an expansion tank. An expansion tank is a sealed tank with a flexible bladder that separates it into two chambers, one in fluid contact with the plumbing loop, and one pressurized with air. As fluid in the loop heats up it will expand which could lead to a catastrophic failure. A properly sized expansion tank gives the fluid a place to go by

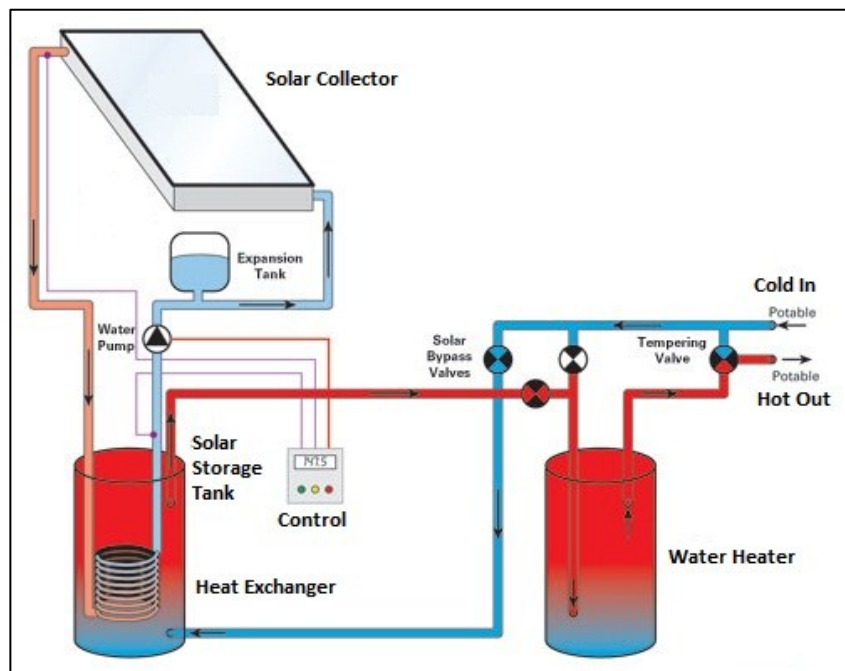


Figure 44. Active, Indirect Solar Hot Water System (HomePower Magazine)

compressing the air behind the bladder.

Active, indirect systems are the most efficient and the most expensive, but are best suited to a Minnesota climate. Preventing fluid from freezing in the collectors at night in winter can be done in two ways. Since indirect systems use a heat transfer fluid, that fluid can contain antifreeze. Propylene glycol is usually mixed with water to obtain a mixture that will not freeze at the lowest expected temperature of the installation site. Propylene glycol is food safe unlike the ethylene glycol used as an antifreeze in automobiles. This prevents poisoning of a building's water supply in the unlikely event of a leak in the heat exchanger. A 50/50 mixture is typically used in Minnesota and freezes at  $-29^{\circ}\text{F}$ .

Another way to prevent freezing is with a drain back system. In this type of system, fluid drains from the collectors into a tank or reservoir anytime the pump is shut off (Fig. 45). A drain back system can operate at atmospheric pressure (open loop) allowing air into the system so the fluid can drain from the collectors. This means there will always be a fresh source of oxygen so iron pumps and fittings should not be used. Water will also evaporate from an open loop system so tanks will include a sight glass to check the level and a means to add water when necessary. A drain back tank can also be pressurized with air (closed loop) to provide the needed air volume for draining the collectors. This may allow iron pumps to be used and generally eliminates the need to add water. Moreover, the expansion tank that would typically be needed in a closed loop plumbing system can be eliminated if the pressurized air volume in the drain back tank is sized correctly.

A two stage pump, or a second pump, is sometimes necessary at start-up if there is a large elevation change

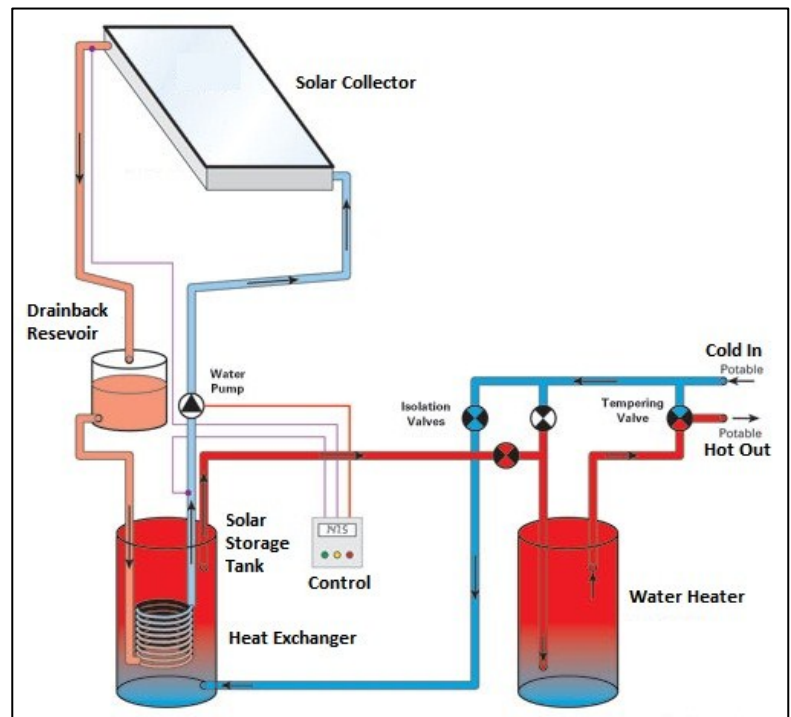


Figure 45. Drain Back Solar Hot Water System (HomePower Magazine)



between the reservoir and collectors. Once the fluid reaches the top of the system, a return syphon will be established that reduces the pumping load. A good drain back pump controller will vary the pump speed of a single pump or shut off a second pump to take advantage of this. The volume needed to accommodate drain back can be included in the storage tank or in a separate smaller tank that can be mounted closer to the collectors reducing the pump load.

Antifreeze is still often used in drain back systems in Minnesota to ensure trouble free operation in winter. Drain back systems have the added advantage that they can be used to prevent overheating by shutting the pump off if the fluid temperature becomes too hot.

### 2.3.3.2 Configuration details

Solar hot water systems are usually set up with one or two tanks. In a one tank system, the tank contains a heat exchanging coil that solar heated fluid circulates through to warm the domestic water in the tank (Fig. 46). It also contains an electric or gas heating element to heat the water if there is not enough solar heat. Sometimes this tank is an existing water heater that has a solar heat exchanging coil added to it. A one tank arrangement has the benefit of being simple and taking up no extra space in the utility room. The drawback is less energy is collected by the solar collectors because the system can only run when the temperature in the collectors is higher than the temperature in the tank. A typical domestic hot water heater is set to about 120°F.

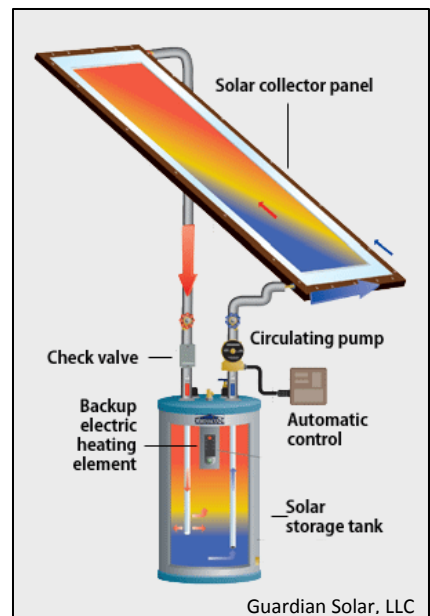


Figure 46. Single Tank System

A two tank configuration can harvest more solar energy because heat can be collected at a lower temperature and used to preheat cold water before it enters the water heater (Fig. 44 & 45). Heat from the solar collectors is stored in the first tank which can be configured as a pressurized system using antifreeze or as a drain back system. A pump is used to circulate the heat transfer fluid whenever the collector temperature is higher than the tank temperature regardless of the final hot water temperature set point. The cold water supply is then routed through a heat exchanger coil in

the first tank before entering the second tank. The first tank can also be filled from the cold water supply with the heat transfer fluid circulated through the heat exchanger coil. The second tank can be a standard water heater or an instant tankless water heater.

The two tank arrangement can significantly increase the solar fraction of a hot water system. For example, if the cold water supply temperature is 60°F and the water heater is set to 120°F, half of the energy needed to heat water could be provided by a storage tank that preheats the supply water to 90°F. In fact, any temperature above the supply temperature will reduce the total energy needed to heat water. This is not possible in a single tank configuration because the circulation pump will only run when the collectors are hotter than the water heater. If the preheat tank temperature is above the water heater set point, then the water heater does not need to add heat to the water and the solar fraction would be 100%.

Any water heating system using solar energy should incorporate an anti-scald, or tempering, valve before the heated water is connected to the building hot water distribution system. An anti-scald valve combines heated water with the cold water supply to ensure a maximum water temperature is not exceeded in the building. Without it, solar heated water poses a potential scalding risk because it can be much hotter than the water heater set point, especially in the summer.

It is also possible to use a boiler as the back up heating element in the water heating tank of a single or two tank system (Fig. 47). In this arrangement the electric or gas back-up heating element is replaced with a heat exchanger coil in the tank. The coil receives heated water from a boiler when a control system senses solar heat is insufficient. This might be desirable when combining space heating and water heating systems or when a water heater needs to be replaced and a high efficiency boiler is already in place.

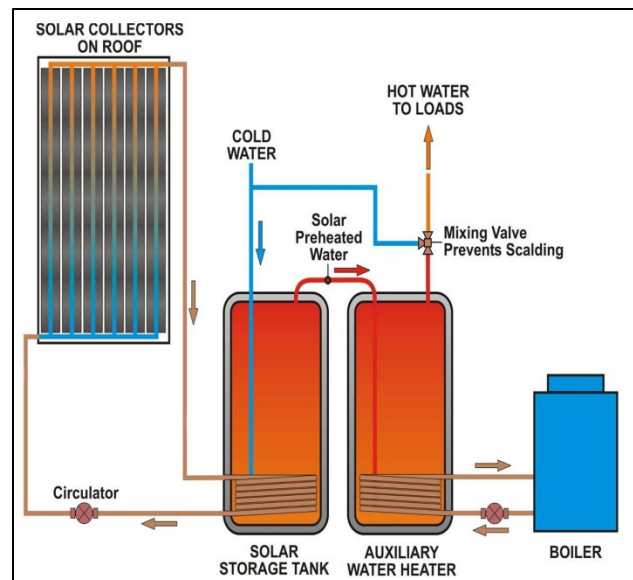


Figure 47. Solar Hot Water System with Boiler Back-up

### 2.3.4 Space heating and cooling

Solar heated air or water can also be used to provide space heating. The simplest way to get solar space heat is to take advantage of passive solar heat gain. This is really nothing more than designing a building to maximize the window area on south facing walls and minimize it on north facing walls. Window overhangs are useful to prevent direct solar gain in summer months when the sun is high in the sky, but still allowing it in winter months when the sun is low.

#### 2.3.4.1 Heating with air collectors

More heat can be gained by using solar thermal air collectors. These are constructed similarly to flat plate water collectors without the copper pipes. They are essentially a large box with a glass front and a dark colored absorber in the back. Air is heated in the collector when sunlight hits the absorber. When the air in the collector is hotter than the air in the room it serves, a fan is turned on to circulate room air through the collector (Fig. 48). Air collectors are typically mounted vertically on south

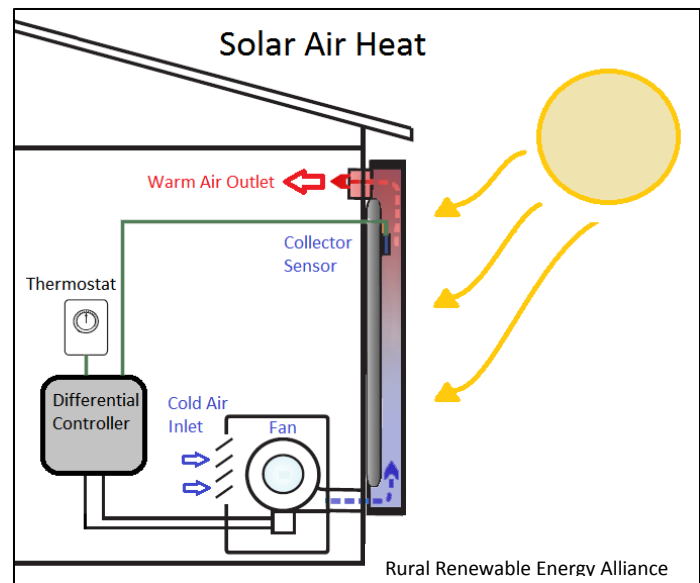


Figure 48. Solar Thermal Air Collector System

facing walls since they are only needed in winter months. They are very economical, easy to install, and can provide a high solar fraction when the sun is out. Obviously, this is a supplemental heat source and not a substitute for a primary heating system.

#### 2.3.4.2 Heating with water collectors

Any space heating system using hot water to provide the heat – called a hydronic heating system - can be readily modified to incorporate solar heated water. A space heating system using forced air can also use solar heated water by inserting a fan coil into the airstream. Hot water circulating

through the coil will heat the air being blown past the coil. This is a little less efficient than with a hydronic system since a water to air heat exchanger is not 100% efficient.

Hydronic systems using radiators in each room require higher temperatures because the surface area of the radiator is small compared to the room volume. Under floor hydronic heating is particularly suited to solar heat because the required water temperature is lower due to the much larger surface area of the “radiator” – the floor. Operating at a lower temperature makes solar collectors more efficient and increases the solar fraction of the system. A system like that shown in Figure 46 can be connected to any number of heating zones with radiators or hydronic loops. The balance of the system would include temperature sensors, valves and a control system that monitors the solar tank temperature and directs solar heated water to the radiators if it is hot enough. If it is not hot enough, the boiler would be fired to heat the water. Heat can be transferred from the solar tank to the heating system by directly circulating the water in the tank through the hydronic system in one big loop, or by maintaining separate loops and using a heat exchanger. Sensors and mixing valves are necessary to prevent water that is too hot from entering hydronic heating loops.

It is also possible to have a large heat storage tank with several heat exchanger coils accepting heat from different sources like a wood burner, solar collectors, and a gas back-up boiler, and delivering heat to various loads like domestic hot water and space heating zones. This requires a more sophisticated system to monitor and control the various sources and loads to provide the most efficient solution. There are numerous possible system architectures that can accommodate almost any need for heated water.

When combining hot water and space heating systems, it is important to find a contractor that understands both types of systems and has access to software that can model these systems to get a better understanding of the interaction between the various components.

Solar thermal systems that include space heating have the largest thermal load in winter months when the amount of solar energy available is lowest, and they will have the smallest thermal load in summer months when solar insolation is highest. This situation can lead to overheating in the summer. One possible remedy is to mount the solar collectors at a steeper angle causing them to

collect more energy in the winter and less in the summer. Collectors are typically mounted at an angle equal to the site's latitude (about 45° in Minnesota) to maximize the total energy collection over the year. Mounting the collectors at 60° will better align with the load pattern of a system providing space heat and hot water.

Moreover, since there is no space heating load in the summer, overheating can become a problem. The problem is somewhat lessened by mounting the collectors at a steeper angle because they will collect less energy in the summer. Lacking a load for summer heat, systems are usually designed to provide a solar fraction of 100% in the summer to prevent overheating. The resulting solar fraction in the winter may be as low as 20% leading to an annual solar fraction of between 50% and 75%. A higher annual solar fraction can be obtained if more energy is collected in the winter, but this can lead to overheating in the summer. The excess summer heat can be accommodated if there is a way to use it or reject it back to the air. A swimming pool provides an ideal way to use the extra heat because it can absorb a lot of heat without getting too hot for swimming. When a pool is not available, heat can be dumped through radiators mounted somewhere outside. Accommodating extra summer heat will raise the solar fraction of the system, but will usually make the system less economical. Another way to use excess heat in the summer is for air conditioning.

#### 2.3.4.3 Solar air conditioning

High air conditioning loads usually coincide with high solar insolation making solar powered air conditioning particularly attractive. It can provide a large summer load to balance the large winter loads experienced by systems that include space heating, thereby, increasing the overall solar fraction. Using solar heated water to produce chilled water for air conditioning may seem counterintuitive, but it is not a new idea.

The first patent on an absorption refrigeration machine was issued in France in 1859 and in the U.S. in 1860 to Ferdinand Carre<sup>20</sup>. The device used ammonia and water and was used in Texas during the civil war when ice supplies from the north were cut off. In 1878, Auguste Mouchout used a solar

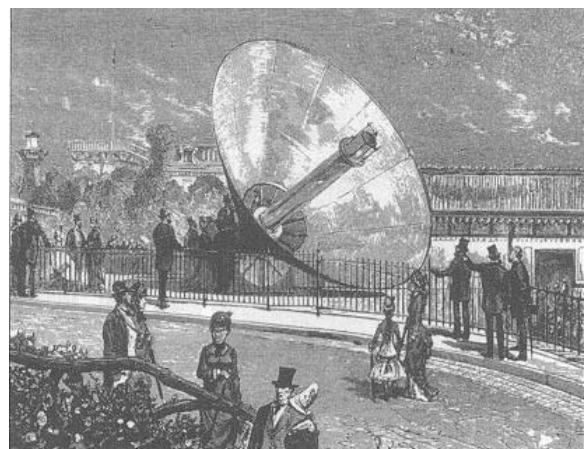


Figure 49. Making Solar Ice in 1878

steam engine and an absorption chiller to make ice at the Universal Exhibition in Paris (Fig. 49)<sup>21</sup>. Even Albert Einstein has a patent for an absorption refrigerator that was later bought by Electrolux. Absorption chillers have been used commercially since the early 20<sup>th</sup> century and continue to be used in things like RV's, refrigeration trucks, and district cooling applications like college campuses.

The basic principle behind solar thermal cooling is the thermo-chemical process of sorption: a liquid or gaseous substance is either attached to a solid, porous material (adsorption) or is taken in by a liquid or solid material (absorption). This process relies on the principle that water molecules bind more efficiently to certain sorbent materials than to other water molecules. If two separate bowls - one containing water and the other containing a sorbent - are put into a closed space, the water will evaporate to get to the sorbent which absorbs or adsorbs the water. If the closed space is in a state of vacuum, the water will start boiling in order to produce vapor at the same speed that it is sorbed. Boiling water requires a lot of energy. If the energy is not supplied from outside the system it will be taken from the water itself, which, as a consequence, gets colder. In essence, the evaporation process transports heat from the water to the sorbent. The temperature difference between the water and the sorbent increases until the sorbent is no longer able to take more water.

A cooling cycle can be created if the chilled water is used to provide air conditioning and the sorbed water is liberated from the sorbent by boiling it out with the heat from a solar heated fluid. The heat transferred to the sorbent also needs to be removed, typically with a wet or dry cooling tower.

A wet cooling tower rejects heat to the environment by spraying warmed water into small droplets



to increase its surface area and drawing air across it with a fan (Fig. 50). As some of the water evaporates, the remaining water cools. The evaporated water needs to be replaced with fresh water. Even a small cooling tower can evaporate hundreds of gallons of water per day so the water must be treated to prevent bacteria growth and the buildup of minerals that could foul heat exchanger surfaces. A dry cooling tower works in a similar manner except the water is kept in a closed loop so it does not evaporate. It is just cooled by moving air similar to an automobile radiator. A dry cooling tower requires less

Figure 50. Wet Cooling Tower

maintenance, but cannot reject as much heat as a wet cooling tower.

Commercial sorption chillers that operate on solar heated water are available in both types: adsorption and absorption. Adsorption chillers typically use water as the refrigerant and a desiccant like silica gel or zeolite as the adsorbent. An adsorption device consists of four main components: the condenser, the evaporator, and two desorbing/adsorbing chambers (Fig. 51). In the first Desorber/Adsorber chamber, the adsorbent is dried out by applying heat

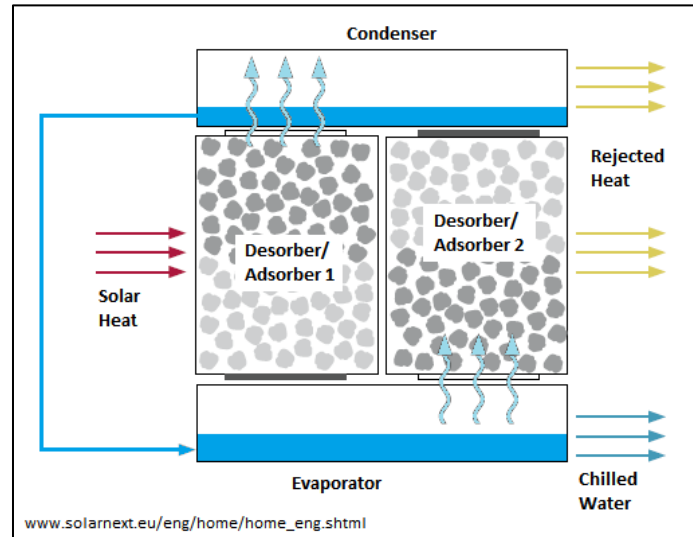


Figure 51. Adsorption Chiller

from solar heated water. Vapor is generated and flows into the condenser. When the material is sufficiently dried out, heat input into the adsorbing chamber is stopped. Water vapor is condensed in the condenser chamber by rejecting excess heat to a cooling tower. The resulting liquid water flows into the evaporator where, under low pressure, it starts to boil due to the attraction of the desiccant in the second adsorbing chamber. This cools the water in the evaporator which is used to provide chilled water for air conditioning. The resulting water vapor is adsorbed in the second adsorbing chamber which produces heat that also has to be removed by the cooling tower. A continuous cooling cycle is created by using two adsorbing/desorbing chambers so that while one chamber is adsorbing water vapor the other one is desorbing water vapor. Valves on the chambers are then reversed, and the chambers work in the opposite direction.

Some commercial absorption chillers use water as a refrigerant and a hygroscopic, nontoxic salt as the absorbent while other systems use ammonia as the refrigerant and water as the absorbent. Most solar powered absorption chillers use a solution of lithium bromide and water, under a vacuum, as the working fluid. Water is the refrigerant and lithium bromide is the absorbent. An absorption chiller also consists of four chambers: a generator, condenser, evaporator, and absorber (Fig. 52).

A pump forces dilute lithium bromide solution into the generator where it boils vigorously under a vacuum. After separation, water vapor flows to the condenser and concentrated solution flows to the absorber.

In the condenser, the water vapor is condensed on the surface of the cooling coil producing latent heat in the coil which is removed by cooling water and rejected to a cooling tower. Liquid water accumulates in the condenser and then passes through an orifice into the evaporator.

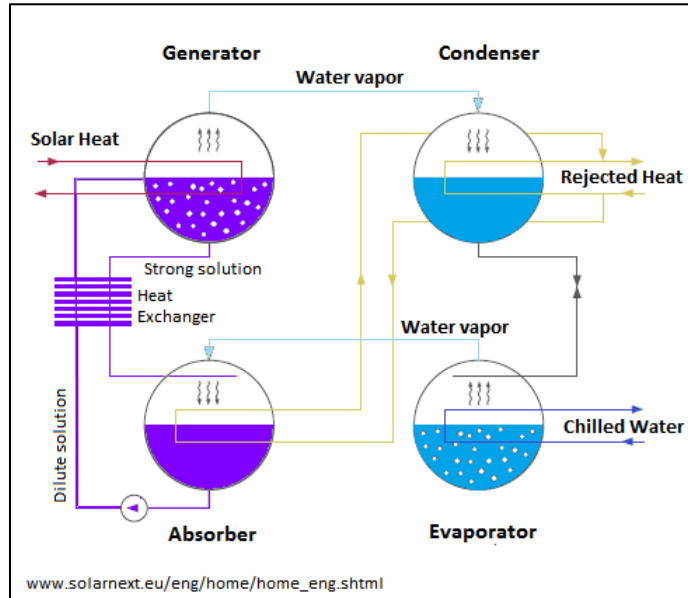


Figure 52. Absorption Chiller

In the evaporator, the water is exposed to a substantially deeper vacuum than in the condenser. As water flows over the surface of the evaporator coil, it boils and removes heat from the water circulating in the coil which lowers its temperature. The resulting water vapor is absorbed by the concentrated lithium bromide solution in the absorber chamber, and the chilled water in the evaporator coil is circulated to fan coils in the building providing air conditioning. The absorption process creates heat which must also be removed by cooling water and rejected to a cooling tower. The resulting dilute solution is preheated in a heat exchanger before returning to the generator where the cycle is repeated.

Solar air conditioning is rare in the U.S., but has been investigated in Europe and Asia for more than a decade. There are still only around 1500 installations worldwide so it is a very small market which means prices are relatively high. The sorption chilling process is not as thermodynamically efficient as the more common vapor compression process using a mechanical compressor, especially at the residential scale. However, the main source of fuel – solar energy – is free so it can be economical depending on the cost of the associated equipment. Research is being conducted to find better sorbents and to make the whole process more efficient. As the benefit of adding air conditioning to a solar thermal system becomes more prevalent, equipment prices can be expected to decrease as has been the case for other parts of the solar industry.



### 2.3.5 Performance and cost considerations

Predicting the performance and resulting cost savings from a solar thermal system is much more difficult than with a solar PV system. The SRCC does extensive testing on every solar thermal collector under various insolation conditions and at different fluid temperatures. The total daily energy output for each of the various test configurations is summarized in a table. While this is a great deal of information, in an actual system the storage volume, thermal load, collector performance, and insolation levels are all interdependent and vary throughout the day and year. So, SRCC data can provide an estimate of collector performance for a particular operating condition, but this will only be a snapshot in time.

#### 2.3.5.1 What’s in an SRCC report?

The SRCC report includes four categories of information including general information about the product and manufacturer, a table of performance data for various test conditions, physical data about the collector and materials, and technical information that can be used to produce the collector’s efficiency graph.

Figure 53 shows the top portion of the SRCC report with the general product information about the Solar Skies model SS-32 flat plate collector that will be used to illustrate how to read the report.


<p><b>SOLAR COLLECTOR CERTIFICATION AND RATING</b></p>  <p>SRCC OG-100</p>	<p><b>CERTIFIED SOLAR COLLECTOR</b></p> <p>SUPPLIER: <b>Solar Skies Mfg, LLC</b> 106 Donovan Drive Alexandria, MN 56308 USA</p> <p>MODEL: Solar Skies SS-32</p> <p>COLLECTOR TYPE: Glazed Flat-Plate</p> <p>CERTIFICATION#: 2007039E</p> <p>Original Certification Date: 04-OCT-07</p>
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Figure 53. SRCC Report – Top Portion

Figure 54 shows the tabular portion that details the collector performance for various test conditions. There are actually two tables. The left one uses metric units while the right one presents the same data in English units. The leftmost column is labeled “category” and refers to the

difference between the temperature of the fluid entering the collector ( $T_i$ ) and the ambient temperature ( $T_a$ ). There are five categories based on typical temperature differences that might

COLLECTOR THERMAL PERFORMANCE RATING							
Kilowatt-hours Per Panel Per Day				Thousands of BTU Per Panel Per Day			
CATEGORY ( $T_i-T_a$ )	CLEAR DAY (6.3 kWh / m <sup>2</sup> .day)	MILDLY CLOUDY (4.7 kWh / m <sup>2</sup> .day)	CLOUDY DAY (3.1 kWh / m <sup>2</sup> .day)	CATEGORY ( $T_i-T_a$ )	CLEAR DAY (2000 Btu / ft <sup>2</sup> .day)	MILDLY CLOUDY (1500 Btu / ft <sup>2</sup> .day)	CLOUDY DAY (1000 Btu / ft <sup>2</sup> .day)
A (-5 °C)	12.2	9.2	6.3	A (-9 °F)	41.7	31.5	21.3
B (5 °C)	11.1	8.1	5.1	B (9 °F)	37.9	27.7	17.5
C (20 °C)	9.3	6.4	3.5	C (36 °F)	31.7	21.8	11.9
D (50 °C)	5.6	3.0	0.7	D (90 °F)	19.0	10.1	2.2
E (80 °C)	2.2	0.3	0.0	E (144 °F)	7.4	1.1	0.0

A- Pool Heating (Warm Climate) B- Pool Heating (Cool Climate) C- Water Heating (Warm Climate) D- Water Heating (Cool Climate) E- Air Conditioning

Figure 54. SRCC Report – Performance Data

occur for various applications. The applications are identified below the tables. Category “A” is identified as pool heating in a warm climate and is associated with a temperature difference of -9°F. For example, this would correspond to a situation where pool water was entering the collector at 80°F and the outdoor temperature was 89°F. Clearly this could also occur in a cool climate during the summer. In other words, the category descriptions only give a general idea of what kind of applications might use the associated temperature difference. Category “D” is for water heating in a cool climate with a temperature difference of 90°F. This would apply to a situation where water was entering the collector at 100°F while the outdoor temperature was 10°F. However, this would also apply to a system using an absorption chiller for air conditioning where the collector fluid is at 180°F when the outdoor temperature is 90°F. Category “E”, labeled as air conditioning, would only apply to chiller technologies using higher temperatures that would require special collectors with reflectors or lenses that are not typically effective in a Minnesota climate. Notice that the collector output is 5 to 6 times higher for categories A and B then for category E. This illustrates the importance of matching the collector performance to the system application.

The three other columns in each table list the total daily energy output for the collector under different insolation conditions. Outputs are listed for each of the temperature difference categories. In order to calculate the total daily collector output values listed in the tables, SRCC procedures include an empirical method to distribute the total insolation into a certain irradiation level for each hour of a day. This gives a more accurate estimate of daily energy output than simply assuming a

constant irradiation level. The insolation levels are labeled clear day, mildly cloudy, and cloudy day. This is a little misleading since it actually has nothing to do with clouds.

SRCC testing specifications require the solar irradiation during testing to be no more than 20% diffuse<sup>22</sup>. In other words, the quality of the irradiation is always like a sunny day and the insolation levels really refer to how much energy is received over the course of a day. For example, the insolation level labeled cloudy day would correspond to a sunny day in late October or early February in Minnesota. This means some collector differences, like the fact that evacuated tube collectors perform a little better than flat plate collectors in cloudy conditions, will not show up in the tabulated results.

Also note that any collector can be made to operate at almost any temperature difference (up to the collector’s stagnation temperature) by slowing the flow rate of fluid through the collector. This is not done during SRCC testing so any deviation in flow rate from the tested value will produce an energy output that does not correspond to the tabulated results. However, lowering the flow rate will directly lower the energy output for a given temperature difference. Lowering the flow rate in an actual system during cloudy weather may allow some energy to be collected when none might be available otherwise. For this reason, it is desirable to have a pump controller that can vary pump speed based on fluid temperature or irradiation levels.

Figure 55 shows the physical data portion of the SRCC report. It lists the materials used in all the main collector components along with overall dimensions. The collector gross area is listed along with the absorber area. The gross area is based on the largest dimensions and indicates how much

COLLECTOR SPECIFICATIONS			
<b>Gross Area:</b>	2.965 m <sup>2</sup>	31.91 ft <sup>2</sup>	<b>Net Aperture Area:</b> 2.78 m <sup>2</sup> 29.93 ft <sup>2</sup>
<b>Dry Weight:</b>	51.2 kg	113. lb	<b>Fluid Capacity:</b> 4.9 liter 1.3 gal
<b>Test Pressure:</b>	1103. KPa	160. psig	
COLLECTOR MATERIALS		Pressure Drop	
<b>Frame:</b>	Anodized Aluminum		
<b>Cover (Outer):</b>	Low Iron Tempered Glass		
<b>Cover (Inner):</b>	None		
<b>Absorber Material:</b>	Tube - Copper / Plate - Copper	<b>Insulation Side:</b>	Polyisocyanurate
<b>Absorber Coating:</b>	Selective Coating	<b>Insulation Back:</b>	Polyisocyanurate

Figure 55. SRCC Report – Physical Data

mounting area will be needed. The absorber area measures the actual area that converts sunlight into heat. Most performance calculations are based on gross area which is certainly important if the installation space is limited.

The technical information needed to construct the collector’s efficiency curve is also included in the SRCC report (Fig. 56). This information can also be used to calculate the collector’s efficiency, and energy output, for any combination of fluid temperature, air temperature, and solar irradiation. The

TECHNICAL INFORMATION					
Efficiency Equation [NOTE: Based on gross area and (P)=Ti-Ta]				Y INTERCEPT	SLOPE
SI Units:	$\eta = 0.691$	$-3.39600 (P)/I$	$-0.01968 (P)^2/I$	0.706	$-4.910 \text{ W/m}^2 \cdot ^\circ\text{C}$
IP Units:	$\eta = 0.691$	$-0.59821 (P)/I$	$-0.00193 (P)^2/I$	0.706	$-0.865 \text{ Btu/hr.ft}^2 \cdot ^\circ\text{F}$
Incident Angle Modifier [(S)=1/cos $\theta$ - 1, 0°< $\theta$ <=60°]				Test Fluid:	Water
K $\tau\alpha$ = 1	$-0.194 (S)$	$-0.006 (S)^2$	Test Flow Rate:	20.1 ml/s.m <sup>2</sup>	0.0296 gpm/ft <sup>2</sup>
K $\tau\alpha$ = 1	$-0.20 (S)$	Linear Fit			
REMARKS:					
May, 2012 Certification must be renewed annually, For current status contact: SOLAR RATING & CERTIFICATION CORPORATION 400 High Point Drive, Suite 400 ♦ Cocoa, Florida 32926 ♦ (321) 213-6037 ♦ Fax (321) 821-0910					

Figure 56. SRCC Report – Technical Data

coefficients used to construct the efficiency graph are listed under the heading “Y Intercept” and “Slope” for both metric (SI) and English (IP) units. The equation is:

$$\text{Efficiency} = (\text{Y Intercept}) + (\text{Slope}) * (T_i - T_a)/I$$

Where:  $T_i$  = The fluid inlet temperature, °C or °F

$T_a$  = The air temperature, °C or °F

$I$  = The solar irradiation, W/m<sup>2</sup> or Btu/hr/ft<sup>2</sup>

So, for this collector, in IP units, the efficiency =  $.706 - .865 * (T_i - T_a)/I$ . The actual energy output for a given time interval can be found by multiplying the efficiency by the gross area and the insolation received in that time interval. For example, if the fluid to air temperature difference is 36°F and the irradiation is 221 Btu/hr/ft<sup>2</sup> (700 W/m<sup>2</sup>), then the efficiency is:

$$.706 - (.865 * 36 / 221) = .565 \text{ (56.5\%)}$$

The collector gross area is 31.91 ft<sup>2</sup> and the insolation received in one hour would be 221 Btu, so the total energy collected in that hour would be:

$$.565 * 31.91 * 221 = \mathbf{3,985 \text{ Btu or } 3.985 \text{ thousand Btu (kBtu)}}$$

The values listed in the SRCC table are the total for a whole day after adding up the energy collected each hour with a different irradiation level each hour. The table results are in thousands of Btu's. In SRCC testing the entering fluid temperature is held constant, but in a real system this would vary continuously making accurate predictions very difficult.

The additional information listed under the heading "Efficiency Equation" is for a more accurate efficiency calculation that accounts for temperature related losses. This is the data that is usually used in computer simulations of thermal systems. The incidence angle modifier is used to account for the fact that a collector is typically less efficient when the incoming sunlight is not perpendicular to the collector. The incident angle modifier is multiplied by the efficiency to calculate the actual efficiency as the sun moves across the sky from morning to evening. In the equation, 0° is when sunlight is perpendicular to the collector and an angle of up to 60° can be used for early morning and late evening hours. This effect is already included in the tabular results of the SRCC report, but should be accounted for when making new performance calculations.

The last bit of information on the report is the test fluid and flow rate. As mentioned above, any deviation from the test values will change collector performance. If multiple collectors are used, the flow rate should be chosen so that the flow rate through each collector is equal to the test rate. So if five collectors are plumbed together in series, the system flow rate should be five times the flow rate for one collector. It is generally not recommended to put more than five collectors in series because the fluid temperature will be increasing across each collector, and, as explained above, the collector efficiency drops as the entering fluid temperature rises.

### **2.3.5.2 Solar water heating performance**

As a general rule, a solar hot water system should be designed to provide close to 100% of the summer hot water load resulting in 50% to 75% of the annual hot water load being met. Increased

cloud cover and reduced solar insolation can result in a solar contribution of as little as 10% in the winter.

According to the SRCC, average residential hot water usage requires 41,045 Btu per day which is equivalent to about 12 kWh per day. Knowing a system's solar fraction (the portion of the hot water heating load provided by solar energy) allows the estimation of savings in operating costs.

$$\text{Annual Savings (gas)} = 365 \times (.41045 / 0.6^*) \times \text{Solar Fraction} \times \text{Fuel Cost (therm)}$$

$$\text{Annual Savings (elec.)} = 365 \times (12.03 / 0.9^*) \times \text{Solar Fraction} \times \text{Fuel Cost (kWh)}$$

\*SRCC standard Energy Factor for auxiliary water heater ([www.solar-rating.org](http://www.solar-rating.org))

The energy factor in the equations accounts for the inefficiency of converting the existing water heater's fuel source into hot water. A gas water heater is only 60% efficient due to the heat lost up the flue. Electric water heaters are more efficient because the heating elements are immersed in the water, but still usually result in a higher annual cost to heat water due to the higher cost of electricity on a per Btu basis.

If the solar fraction was 100%, the total savings per year would be about \$150 to \$250 per year (\$0.66 to \$1 per therm) when replacing a gas water heater and about \$400 to \$500 per year (\$0.08 to \$0.10 per kWh) when replacing an electric water heater. The average installed cost of a solar water heating system is between \$5,000 and \$8,000 in the U.S. so the payback period is significant especially considering the solar fraction will be less than 100%. The bottom line is that in most scenarios federal, state, and local incentives are still necessary to make solar hot water financially attractive, but higher hot water usage and replacing more costly existing water heaters will result in faster payback.

### 2.3.5.3 Solar water heating and space heating performance

Adding space heating loads to a solar hot water system will generally result in a lower overall solar fraction. The increased load allows more solar energy to be used, but this load peaks in the winter when solar resources are at a minimum. Modeling a solar thermal system that includes both water heating and space heating requires computer simulation. One such method, called f-Chart analysis,

was used to model an average home located in Syracuse, New York<sup>23</sup>. Syracuse is at about the same latitude as central Minnesota, but gets 10% to 15% less annual solar insolation. The results illustrate an often misunderstood aspect of systems combining water and space heating, namely, doubling the system size will not double the solar fraction.

Thermal loads modeled include a heating load of 35,000 Btu/hr with an outdoor temperature of 0°F and an indoor temperature of 70°F, and a water heating load of 60 gallons per day. Two system sizes were modeled. The first assumed 128 ft<sup>2</sup> of flat plate collector area with a 256 gallon storage tank. The second system used twice as much collector area and storage tank volume. The program predicts the resulting solar fraction of each system

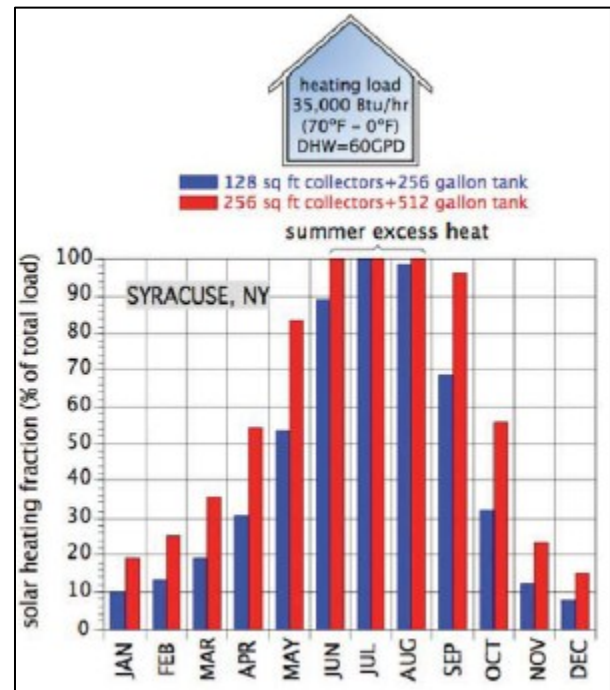


Figure 57. f-Chart Analysis Results (Caleffi idronics)

for each month of the year (Fig. 57). It can be seen that doubling the system size almost doubles the solar fraction in winter months, but produces excess heat in the summer months. The overall solar fraction went from 24% for the smaller system to 37% for the larger system.

Again, more solar energy is used in a combined system, but the solar fraction is less than for just a solar water heating system due to the large winter space heating load that cannot be met with solar. Also, due to excess summer heat, increasing the collection capacity of a system may not be more economical than a smaller system unless a summer heat load, like a swimming pool or chiller, is available. Thermal storage, especially the ability to store heat in the summer and have it available in the winter, could also make solar thermal systems more economical. Currently, chillers and storage solutions are still relatively expensive, but ongoing research could produce a breakthrough that would make these systems more attractive.

The same f-chart analysis was also done with the model house located in Colorado Springs, Colorado, where it is still cold in the winter, but quite a bit sunnier. The overall solar fraction for the same two systems becomes 35% and 55%, respectively. Assuming a larger house in Colorado Springs

with larger space (100,000 Btu/hr) and water (100 gal/day) heating loads, the same systems produce solar fractions of 15% and 27%. This analysis highlights the interdependence of system variables and the impossibility of making a simple calculation of system performance that will work in different applications.

There is a free Microsoft Excel based tool called RETScreen that was developed with support from the Canadian government. The tool includes a comprehensive insolation and weather database as well as all the available SRCC data on thermal collectors. The tool can be downloaded from: <http://www.etscreen.net/ang/home.php>. The web site also includes extensive training materials for the tool. It can model a wide variety of renewable energy and energy efficiency applications which makes it a powerful tool, but also makes it more complicated to use.



### 2.3.6 Solar thermal Consumer guidelines

This section is intended to offer a quick reference guide of a few important things to consider when purchasing a solar thermal energy system.

- Nothing will affect the success of a renewable energy project more than an experienced and knowledgeable contractor. NABCEP certified installers have completed a comprehensive certification program for renewable energy installers. The Minnesota branch of the Solar Energy Industry Association maintains a list of certified installers on its web site: <http://mnseia.org/>.
- Be sure to get a thorough on-site evaluation of your planned installation location. The installer should use some type of tool to evaluate shading on the site.
- A report that details the equipment that will be installed as well as the projected performance of the system along with a cost estimate should be provided. The performance assessment should show the monthly output and should come from a computer model of your proposed system – not a general rule of thumb type calculation. An assessment may cost more and involve an energy consultant, but will be worth it in the long run.
- Be sure the contractor has received the proper local, state, and federal permits and approvals for construction.
- Search for available incentives from your State, utility, and the federal government. The contractor should be able to provide you with a list of incentives, contacts, and / or the process to obtain the incentives. Consider checking with your tax preparer to determine the value that tax credits and accelerated depreciation bring to the project.
- Based on the expected performance, equipment, and other costs; develop an independent financial model projecting return on investment. When weighing the financial considerations, include realistic maintenance and operations costs plus mileage and labor for a repair technician. Repair and maintenance tend to be undervalued. Contingency funds should be included in the financial model for both construction and

operation. A typical contingency amount would be equal to 10% to 15% of the total project budget.

- Insurance may be available to purchase either as an addition to a home or business policy or as a stand-alone policy for perils such as wind, hail, fire, vandalism, theft, loss of revenue, and liability. These costs should be considered in the financial model.
- There should be a heat management strategy for overheating situations and a freeze prevention strategy for cold weather.
- Invest in monitoring equipment. Extra temperature sensors and flow meters will cost more, but they can identify problems and inefficiencies in a system that might otherwise go unnoticed. Data should be tracked and stored over time. Moreover, if there are performance guarantees, you will have no basis to make a claim without monitoring.
- The system should be fully commissioned, meaning the installer verifies all aspects of the system work as planned and meet performance expectations. You should receive manuals for all components and training on how to operate them and identify problems. Systems containing antifreeze will need to be checked annually and the antifreeze will need to be replaced periodically (about every 5 yrs). Make sure the system can be readily drained, filled and any trapped air removed. Also, make sure you know who to call if there are any problems and who will perform routine maintenance.
- Proper and timely maintenance will help insure the optimum performance of the system.
- DO NOT ATTEMPT to personally install a system without the proper training and certification.
- Finally, learn more about solar thermal energy. Invariably, solar thermal systems will be more complicated than the systems they replace and may require additional oversight. The Clean Energy Resources Team's website is a good place to start for more information: <http://www.cleanenergyresourceteams.org/>. The sources section of this document also lists several good sites.

### **3. Geothermal Heat Pumps**

Geothermal energy refers to heat collected from the Earth. Heat is produced inside the Earth due to extreme pressures resulting from gravitational forces and the slow decay of radioactive materials. Geothermal energy can be collected as steam or hot water and used to heat buildings or generate electricity in one of three ways. Hot water can be collected directly from hot springs or reservoirs located near the surface and used in individual buildings or district heating systems. Another option is to collect very hot water or steam (300°F to 700°F) to drive a turbine and generate electricity in a geothermal power plant. Such plants are only practical where the super-heated water is available within one or two miles of the Earth's surface. Neither of these methods is available in Minnesota or practical on a small scale. The third method involves using the Earth as a heat source or heat sink to heat and cool a building with the aid of a heat pump. In other words, heat is either collected from the ground and moved to a building, or collected in the building and moved to the ground.

All areas of the United States have nearly constant shallow-ground temperatures, which are suitable for geothermal heat pumps. The upper 10 feet of the Earth maintains a nearly constant temperature between 50° and 60°F. Like a cave, this ground temperature is warmer than the air above it in the winter and cooler than the air in the summer. Geothermal heat pumps take advantage of this resource to heat and cool buildings by pulling heat from the ground during the winter and dumping it in the ground during the summer. A large body of water that is deep enough to avoid freezing can be used instead of the ground as the heat source/sink.

#### **3.1 How Does It Work?**

Geothermal heat pump systems are usually referred to as ground source heat pumps (GSHP) to avoid confusion with the other forms of geothermal energy. Ground source heat pumps consist of three parts: a ground heat exchanger, a heat pump unit, and an air or water delivery system in the space to be conditioned. The heat exchanger is basically a system of pipes which is buried in the ground near the building, called a loop. Water circulates through the pipes to absorb or relinquish heat within the ground.

If two objects with different temperatures are in contact with each other, heat will naturally flow from the higher temperature object to the lower temperature one. In order for a GSHP system to function, some means is necessary to raise the temperature of the heat naturally residing in the ground to a level sufficient for it to be delivered to the home as useful heat (typically 100+°F). Work must be done to accomplish this which is why the device is called a heat pump. The pump consists of a compressor, condenser, and refrigerant using a vapor compression cycle.

In reality, a heat pump is nothing more than a refrigeration unit (Fig. 58). Any refrigeration device (air conditioner, refrigerator, etc.) moves heat from a space to keep it cool and discharges that heat at a higher temperature to the room or the outside air. The only difference between a heat pump and a refrigeration unit is that heat pumps are generally reversible and can provide either heating or cooling to the space.

One of the most important characteristics of heat pumps is that the energy efficiency of the unit is directly related to the temperature difference between the heat source and the heat sink. The larger the temperature difference, the greater the power input required by the heat pump. Ground source heat pumps are more efficient than air-source heat pumps because they operate over a smaller temperature difference. An air-source heat pump (ASHP)

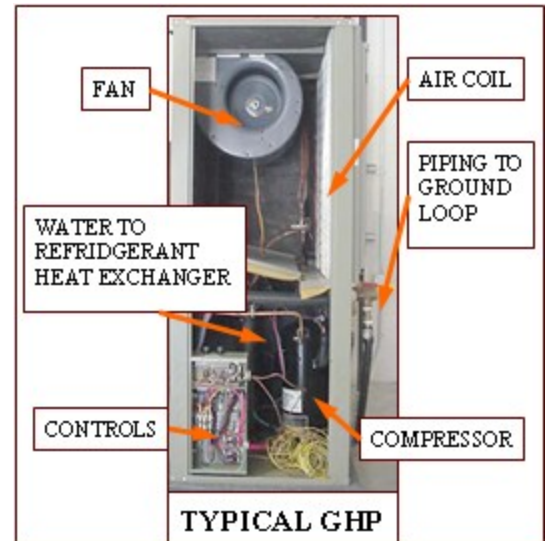


Figure 58. Ground Source Heat Pump Components

must remove heat from cold outside air in the winter and deliver heat to hot outside air in the summer. In contrast, a GSHP retrieves heat from relatively warm soil (or groundwater) in the winter and delivers heat to the same relatively cool soil (or groundwater) in the summer.

As a result, a GSHP is always pumping the heat over a smaller temperature difference than an air-source heat pump regardless of the season. This leads to higher efficiency and lower energy use. GSHP systems also improve humidity control and can maintain about 50% relative indoor humidity making them very effective in humid areas. They also provide excellent "zone" space conditioning allowing different parts of your home to be heated or cooled to different temperatures. A GSHP can

also be equipped with a device called a "desuperheater" which can function as a home's water heater.

### 3.2 GSHP Loop Configurations

There are four basic types of ground loop systems. Three of these—horizontal, vertical, and pond/lake—are closed-loop systems. The fourth type of system is an open-loop option. Which one of these will work best depends on the climate, soil conditions, available land, and local installation costs at the site. All of these approaches can be used for residential and commercial building applications.

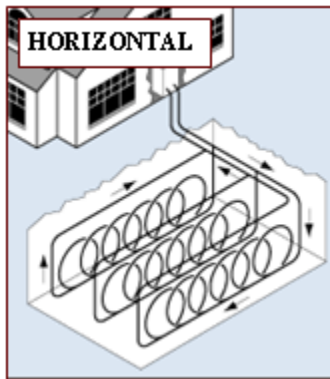


Figure 59. Horizontal Loop  
(US Department of Energy)

The horizontal type of installation (Fig. 59) is generally most cost-effective for residential installations, particularly for new construction where sufficient land is available. It requires trenches below the frost line and at least four feet deep. The most common layouts either use two pipes, one buried about two feet below the other, or two pipes placed side-by-side about two feet apart. The Slinky™ method of looping pipe allows more pipe in a shorter trench, which cuts down on installation costs and makes horizontal installation possible in areas where there would not be room otherwise.

Large commercial buildings and schools often use vertical systems (Fig. 60) because the land area required for horizontal loops would be prohibitive. Vertical loops are also used where the soil is too shallow for trenching or existing landscaping needs to be protected. For a vertical system, approximately four inch diameter holes are drilled about 20 feet apart and 100 to 400 feet deep. Two pipes are inserted into each hole connected at the bottom with a U-shaped bend to form a loop. The vertical loops are connected together with horizontal pipe to form a manifold which is then connected to a heat pump in the building.

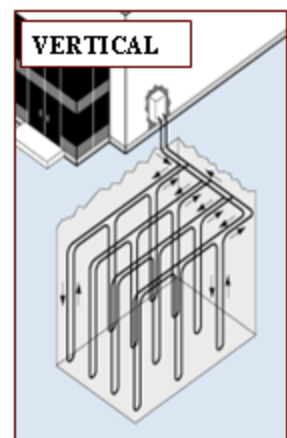


Figure 60. Vertical Loop  
(US Department of energy)

The ground heat exchanger loop can be placed at the bottom of a lake or pond instead of being buried (Fig.61). This may be the lowest cost option if the site has an adequate water body. A supply line pipe is run underground from the building to the water and coiled into circles at least eight feet under the surface to prevent freezing. The coils should only be placed in a water source that meets minimum volume, depth, and quality criteria as determined by a licensed contractor. Depending on the water body, environmental impacts may need to be addressed in the event of a leak since closed loop systems usually contain an anti-freeze mixed with water.

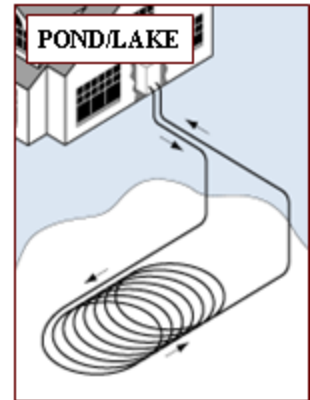


Figure 61. Pond/Lake Loop  
(US Department of energy)

It is also possible to use well or surface water as the heat exchange fluid that circulates directly through the GSHP system in an open loop (Fig. 62). Once water has circulated through the system, it returns to the ground through the well, a recharge well, or surface discharge. This option is obviously practical only where there is an adequate supply of relatively clean water and all local codes and regulations regarding groundwater discharge are met. This is not a common configuration and also may require an environmental impact assessment.

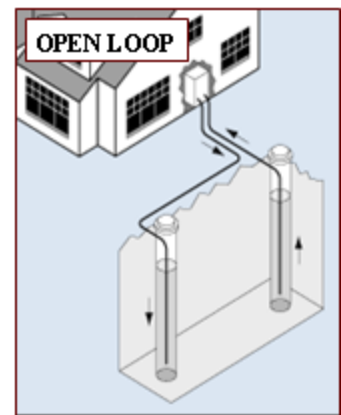


Figure 62. Open Loop  
(US Department of Energy)

### 3.3 System Performance

The heating efficiency of ground source and air source heat pumps is indicated by a dimensionless number called the Coefficient Of Performance (COP). The COP of a device indicates how many units of heat are provided for each unit of energy input. The cooling efficiency is determined by the Energy Efficiency Ratio (EER), which is the ratio of the heat removed (in Btu per hour) to the electricity required (in watts) to run the unit. The ENERGY STAR® label requires a heating COP of 2.8 or greater and an EER of 13 or greater. The COP and EER ratios are calculated for specific operating conditions which do not reflect the extremes of temperature and humidity experienced in Minnesota. The Heating Seasonal Performance Factor (HSPF) and Seasonal Energy Efficiency Ratio (SEER) are averaged over a typical season of use which makes them a better estimate of likely performance. In all cases, a higher number indicates a more efficient unit.

The COP of a heat pump is typically advertised to be between 3 and 5. This means about 4 units of heat are delivered for each unit of electricity consumed. Actual performance in a Minnesota winter will result in a COP closer to 2 or 2.5. A COP greater than 1 is possible because a heat pump is just moving heat from one place to another. A heating system using combustion cannot produce more heat than is in the fuel that it consumes so the maximum COP of such a unit would be 1.

Air source heat pumps work in the same way that a ground source heat pump does except heat is exchanged with outside air instead of the Earth. ASHPs are much less expensive to install since there is no excavation required for a ground loop heat exchanger, but do not perform well in temperature extremes. The performance of ASHP systems starts to decrease as the outdoor temperature drops below about 40°F. Performance falls by about 40% at temperatures around 15°F and heating becomes impractical at temperatures around 0°F unless the unit has been specifically designed for cold temperatures which sacrifices air conditioning performance. An ASHP often includes an electric element to provide supplemental heat for colder outdoor temperatures. An electric element will extend the lower operational range of an ASHP, but this is no more efficient than any other electric element based heating system and is probably more costly to operate than a combustion based heating system. Manufacturers of ASHPs include electrical elements in their units to make them functional over a greater temperature range when there is no other system to provide heating or cooling for a building. A back-up heating system is advisable in cold climates like Minnesota. ASHP systems do not control humidity as well as GSHP systems when outdoor conditions are hot and humid.

Although initially more expensive to install than conventional systems, ground source heat pumps are generally less expensive to operate and maintain. Typical annual energy savings range from 30% to 60% depending on factors such as climate, soil conditions, the system features you choose and available financing and incentives.

### 3.4 Geothermal Heat Pump Consumer guidelines

This section is intended to offer a quick reference guide of a few important things to consider when purchasing a geothermal energy system.

- Nothing will affect the success of a renewable energy project more than an experienced and knowledgeable contractor. The International Ground Source Heat Pump Association (IGSHPA) provides accreditation for installers and designers that have completed a training program and passed a certification exam. Accredited installers and designers can be found at: <http://www.igshpa.okstate.edu/directory/directory.asp>
- Be sure to get a thorough on-site evaluation of your planned installation location. The installer should assess the soil at the proposed site.
- A report that details the equipment that will be installed as well as the projected performance of the system along with a cost estimate should be provided.
- Be sure the contractor has received the proper local, state, and federal permits and approvals for construction.
- Search for available incentives from your State, utility, and the federal government. The contractor should be able to provide you with a list of incentives, contacts, and / or the process to obtain the incentives. Consider checking with your tax preparer to determine the value that tax credits and accelerated depreciation bring to the project.
- Based on the expected performance, equipment, and other costs; develop an independent financial model projecting return on investment. When weighing the financial considerations, include realistic maintenance and operations costs plus mileage and labor for a repair technician. Repair and maintenance tend to be undervalued. Contingency funds should be included in the financial model for both construction and operation. A typical contingency amount would be equal to 10% to 15% of the total project budget.



- Insurance may be available to purchase either as an addition to a home or business policy or as a stand-alone policy for perils such as wind, hail, fire, vandalism, theft, loss of revenue, and liability. These costs should be considered in the financial model.
- The system should be fully commissioned, meaning the installer verifies all aspects of the system work as planned and meet performance expectations. You should receive manuals for all components and training on how to operate them and identify problems. Systems containing antifreeze will need to be checked annually and the antifreeze will need to be replaced periodically (about every 5 yrs). Make sure the system can be readily drained, filled and any trapped air removed. Also, make sure you know who to call if there are any problems and who will perform routine maintenance.
- Proper and timely maintenance will help insure the optimum performance of the system. Air filters need to be replaced regularly. Dirty filters can have a greater impact on the performance of a geothermal heat pump system than they do on a typical forced air furnace.
- DO NOT ATTEMPT to personally install a system without the proper training and certification.
- Finally, learn more about geothermal energy. Invariably, geothermal systems will be more complicated than the systems they replace. The Clean Energy Resources Team's website is a good place to start for more information:  
<http://www.cleanenergyresourceteams.org/>. The sources section of this document also lists several good sites.

#### **4. Small-Scale Wind**

Wind energy is actually a form of solar energy since wind results primarily from the uneven heating of the atmosphere by the sun. Irregularities in the Earth's surface and the rotation of the Earth also contribute to wind production. Wind power refers to the process of converting the kinetic energy of wind into mechanical energy. The mechanical energy can be used to pump water, grind grain or turn a generator shaft to produce electricity. For a discussion of energy, power, and the associated measurement units see Appendix A.

People have been harnessing wind energy since the first sail boats sailed on the Nile River in about 5000 B.C.E. The first windmills were used for pumping water in China and grinding grain in the Middle East from about 200 B.C.E. Wind technology spread around the world in various forms and was refined by the Dutch to drain lakes and swamps in the Rhine River valley. Settlers eventually brought the technology to the New World in the late 19<sup>th</sup> century. The first wind turbine adapted to generate electricity appeared as early as 1890 in Denmark. In 2011, Denmark produced 28% of its electricity supply with wind turbines and plans to produce 50% of its electricity from wind power by 2050. Utility-scale wind turbines with power ratings in megawatts (MW) are used to produce that much electricity. They are mounted on tall towers (70 meters or more) and often grouped together in "wind farms" requiring large tracts of land on favorable wind sites.

Wind turbines rated at less than 100 kilowatts (kW) in size are generally considered small-scale. Small-scale wind turbines are suitable for siting at an individual residence or farm site and can offset some or all of the electricity used at the site.

##### **4.1 The Wind Resource**

Unlike solar and geothermal resources, wind is very site specific. The amount of energy that can be harvested from the wind depends heavily on the local geography and weather patterns, nearby obstructions like buildings and trees, and the tower height of the wind turbine. The typical small-scale wind turbine is mounted on a tower that ideally puts the hub about 100 ft. (30m) off the ground. The average speed of the wind in Minnesota at a 30 meter height (Fig. 63) has been modeled and mapped by the National Renewable Energy Lab (NREL).

# Minnesota - Annual Average Wind Speed at 30 m

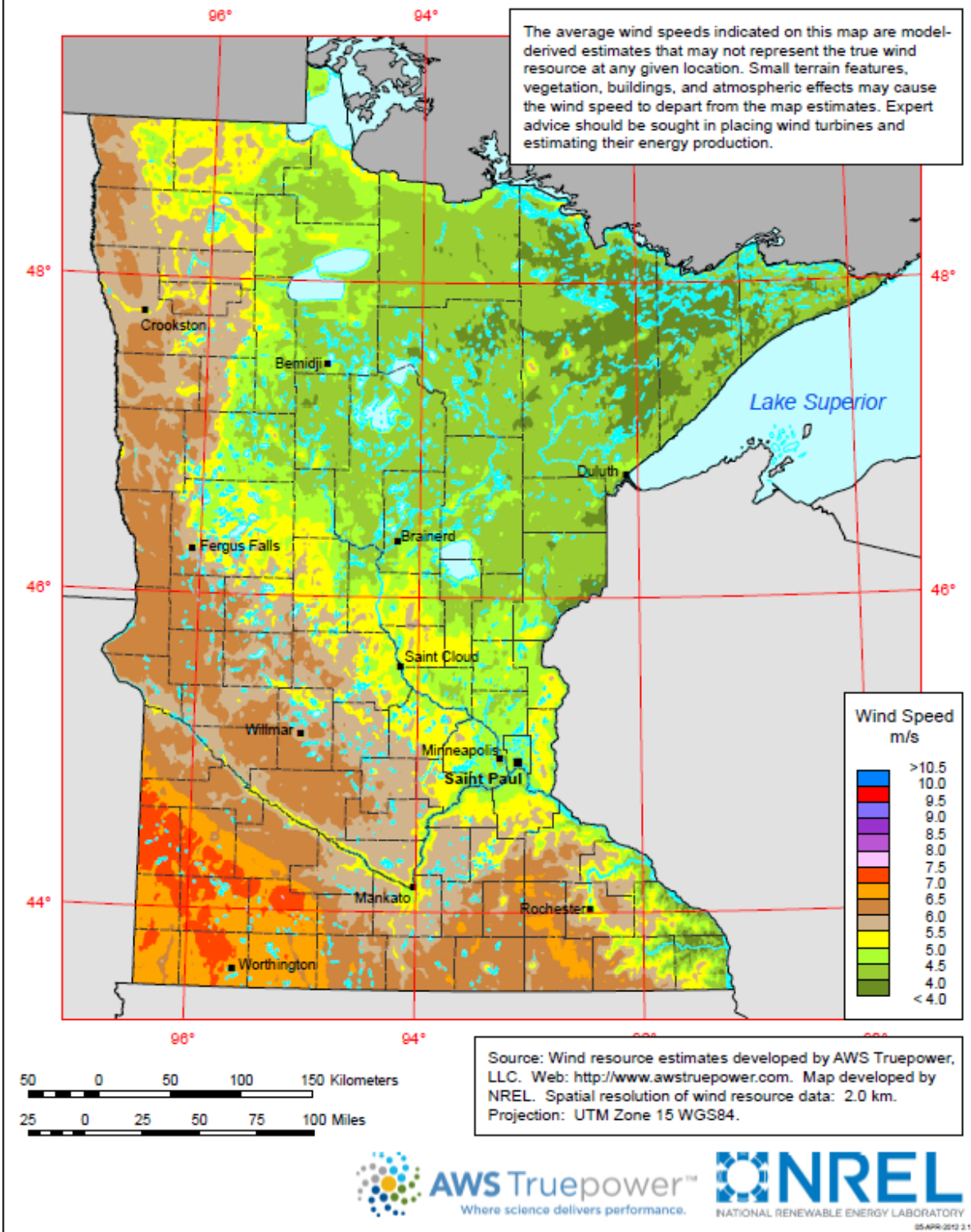


Figure 63. MN Wind Resources

One of the first steps to developing a wind energy project is to assess the area's wind resources and estimate the available energy. Correct estimation of the energy available in the wind can make or break the economics of a project. The average annual wind speed can be used to make general estimates of a turbine's annual energy production, but direct monitoring by a wind resource measurement system at a proposed site will provide the most accurate data. If direct monitoring is done, it should be done for at least one full year. Direct monitoring of the wind resource may be cost prohibitive for a small scale system. A good overall guide on this subject is the *Wind Resource Assessment Handbook* (<http://www.nrel.gov/docs/legosti/fy97/22223.pdf>) produced by NREL.

The wind power equation shows wind power is most affected by the wind speed:

$$\text{Wind Power} = \frac{1}{2} \times \text{Air Density} \times \text{Swept Area} \times \text{Velocity}^3$$

The wind speed is taken to the third power so doubling the wind speed will result in eight times more power. This is why even small increases in the average wind speed can lead to significantly more power production. The average wind speed increases with height so an incrementally taller tower may be worth the extra investment due to the increased power available. The swept area is determined by the length of the turbine blade and air density is determined by altitude above sea level and air temperature. So, at a given site, the most power is produced with the longest blade and tallest tower. This will be the most expensive option as well, so a careful analysis is needed to determine the most economical solution.

Wind turbines collect energy from the wind by slowing it down. To harvest all the energy available in the wind, the wind speed would need to be reduced to zero by the turbine. This is impossible. As a turbine removes more energy from the wind, more wind tends to flow around the turbine. The amount of energy that can be extracted depends on turbine and blade design and varies with the wind speed. The maximum energy extraction of any turbine is 59% which is called the Betz limit<sup>24</sup>. The coefficient of power ( $C_p$ ) is the ratio of the electrical power produced by a turbine to the total power available in the wind. This is analogous to the efficiency of a solar PV panel. The actual electrical power of a turbine is calculated by multiplying the wind power by the turbine's coefficient of power, which varies between .25 and .45 for most wind turbines.

## 4.2 How Does It Work?

A small-scale wind electric system generally consists of a rotor, comprised of any number of individual blades, a generator or alternator mounted on a frame, a tail, a tower, and the “balance of system” electronic components (Fig. 64). The blades are shaped like airfoils to generate a lift force which turns the rotor. Through the spinning blades, the rotor captures kinetic energy from the wind and converts it into rotary motion to drive the generator. The tail is designed to keep the rotor pointed into the wind and is sometimes spring loaded to prevent erratic movements. Some systems use an anemometer to sense the wind direction and a yaw motor to mechanically orient the rotor into the wind. Most modern turbines have two or three blades made of a composite material like fiberglass.

Turbines may generate DC or AC electricity. In either case, the electricity must be conditioned to be fed onto the local utility grid or used to charge batteries. Wind electric systems can be configured as grid tied or stand-alone systems in the same way as solar PV systems. Refer to sections 2.2.3.2 and 2.2.3.3 for a discussion of the particulars of both alternatives.

Since wind speeds increase with height, a tower is used to get the turbine as high as possible. Air turbulence is created by obstructions to the wind like buildings, trees, and hills. Air turbulence decreases the performance and longevity of a wind turbine and is another reason to mount a turbine on a tower as high as possible. A general rule of thumb is to have the bottom of the rotor blades at least 30 feet above any obstacle within 300 feet of the tower.

There are two basic types of towers: self-supporting (free standing) and guyed. Most home wind power systems use a guyed tower as they are the least expensive and easiest to install. Guyed towers require more installation area since the guy radius must be one-half to three-quarters of the tower height. Tilt-down towers have a hinge mechanism at their base which allows them to be

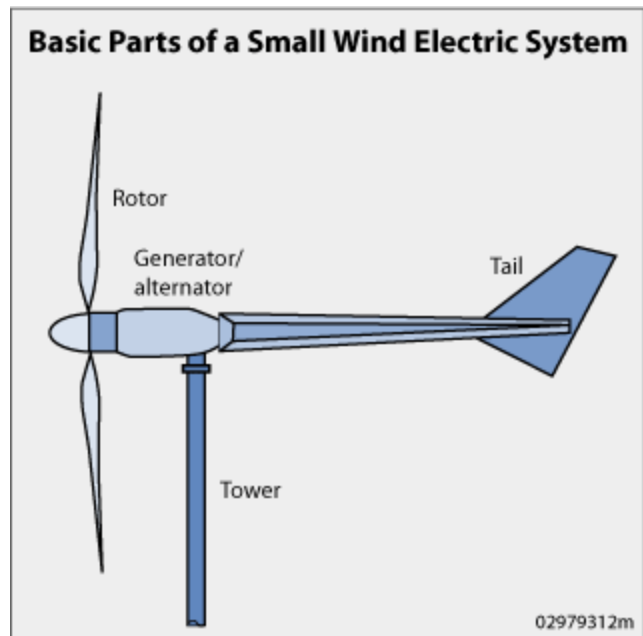


Figure 64. Small-Scale Wind Turbine Parts

raised and lowered through a winching action. Although tilt-down towers are more expensive, they offer an easy way to perform maintenance on smaller turbines – usually 5kW or less. They also offer a way to protect the turbine in the event of severe weather.

Mounting turbines on roof tops is not recommended. All turbines transmit vibrations to the structure on which they are mounted. Wind turbine vibration can lead to structural problems with the building and the rooftop can create turbulence affecting the turbine's performance and service life.

Wind turbines of the type depicted in Figure 63 are classified as horizontal access wind turbines (HAWT) because the rotating shaft is mounted horizontally. There are also vertical access wind turbines (VAWT) which have the rotating shaft mounted vertically (Fig. 65). There are several advantages to this configuration, namely, VAWTs do not need to be pointed into the wind, the generator/gearbox can be mounted on or near the ground, and they take up much less space than a HAWT. Vertical access wind turbines are, therefore, better suited to urban environments where a HAWT may not be possible.

There are some disadvantages as well. The rotor of a VAWT can stall in gusty conditions, there is generally less experience with the design, and the configuration introduces bending loads into the rotor shaft. Bending loads reduce the life of shaft bearings which can lead to higher maintenance costs. VAWT systems have not enjoyed as much success in the small wind market due, in part, to past issues with longevity.



Figure 65. Vertical Access Wind Turbine (VAWT)  
([www.diamondwindsolutions.com](http://www.diamondwindsolutions.com))

### 4.3 Performance and Cost Considerations

Wind turbine manufacturers provide a power rating for their products based on a particular wind speed. The speed typically used is between 24 mph (10.5 m/s) and 36 mph (16 m/s) which is much higher than the average wind speed at a typical site. So, while the wind power calculation provides

insight into important design considerations, a more useful measure of wind turbine performance is annual energy output in kilowatt-hours per year (kWh/yr). The predicted annual energy output of a turbine is the best measure of how well a proposed design will meet the power needs at a specific site. Calculation of the annual energy output of a turbine at a particular site involves the complex interaction of a turbine's power curve and the frequency distribution of the wind at the proposed tower height. A turbine power curve

shows how much power the turbine will produce at different wind speeds (Fig. 66). It includes the cut-in speed below which the turbine does not produce any electricity, and the maximum speed at which the turbine can safely operate.

There are three general zones of operation for a wind turbine. Zone I is

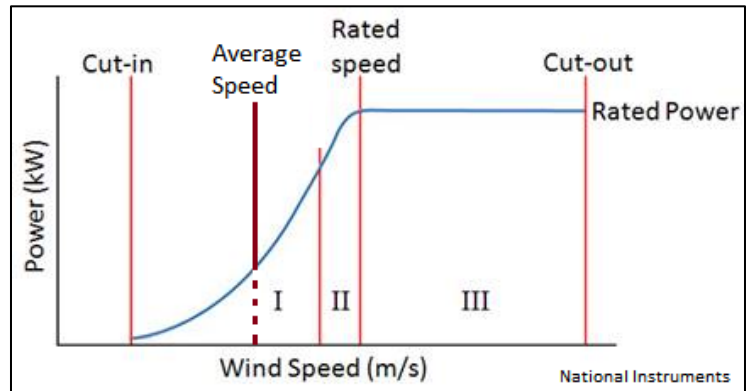


Figure 66. Ideal Wind Turbine Power Curve

the low speed realm where the turbine is operating at maximum efficiency, but generating power below its rated output. Zone III is the area where the wind speed is above the rated power speed. In this zone the turbine is most inefficient because it is shedding wind as the speed increases to avoid exceeding the turbine's rated output. Zone II is the transitional area where the wind speed is approaching the rated speed.

A wind frequency distribution chart shows the number of hours the wind will blow at each speed during an average year. The distribution changes with height so it is important to have this information at the proposed tower height. A wind installation contractor, energy analyst or turbine manufacturer should be consulted for an accurate estimate of the annual energy output.

A preliminary estimate of the performance of a particular wind turbine can be made with the following formula:

$$\text{AEO} = 0.01328 \times D^2 \times V^3$$

Where: AEO = Annual energy output, kWh/yr  
D = Rotor diameter, feet

V = Annual average wind speed, mph

For example, the Jacobs model 31-20 wind turbine is rated for 20kW at a wind speed of 26 mph (11.6 m/s) and has a rotor diameter of 31 feet. If this turbine were to be installed in Morris at a tower height of 30 meters, the average wind speed would be 13.4 mph (6 m/s). Using the annual energy output equation:

$$\text{AEO} = 0.01328 \times (31)^2 \times (13.4)^3 = 30,707 \text{ kWh}$$

This works out to about 2560 kWh per month. The annual energy output can be used with the local utility rates and the cost to install the system to estimate a payback period. The cost to install a small-scale wind turbine is heavily influenced by the turbine type and size, the tower height, and the site accessibility so it is best to get an estimate from an experienced contractor.

Much more information can be found on the National Renewable Energy Lab (NREL) website: <http://www.nrel.gov>. NREL has produced a small wind informational pamphlet for Minnesota which is available at [http://www.windpoweringamerica.gov/pdfs/small\\_wind/small\\_wind\\_mn.pdf](http://www.windpoweringamerica.gov/pdfs/small_wind/small_wind_mn.pdf). There are also efforts being led by NREL to establish national testing standards for small-scale wind turbines similar to the certification testing done for solar thermal panels. Some models have already been tested and results are available on the web site of the Small Wind Certification Council (SWCC), <http://www.smallwindcertification.org/>.



#### 4.4 Small-scale wind Consumer guidelines

This section is intended to offer a quick reference guide of a few important things to consider when purchasing a small-scale wind energy system.

- Nothing will affect the success of a renewable energy project more than an experienced and knowledgeable contractor. NABCEP certified installers have completed a comprehensive certification program for renewable energy installers <http://www.nabcep.org/>.
- Be sure to get a thorough on-site evaluation of your planned installation location. The installer should use some type of tool to evaluate the wind resources and potential obstacles on the proposed site.
- A report that details the equipment that will be installed as well as the projected performance of the system along with a cost estimate should be provided. The performance assessment should show the monthly output and should come from a computer model of your proposed system – not a general rule of thumb type calculation. An assessment may cost more and involve an energy consultant, but will be worth it in the long run.
- Be sure the contractor has received the proper local, state, and federal permits and approvals for construction as well as proper regulatory approval for interconnection to the grid.
- Search for available incentives from your State, utility, and the federal government. The contractor should be able to provide you with a list of incentives, contacts, and / or the process to obtain the incentives. Consider checking with your tax preparer to determine the value that tax credits and accelerated depreciation bring to the project.
- Based on the expected performance, equipment, and other costs; develop an independent financial model projecting return on investment. When weighing the financial considerations, include realistic maintenance and operations costs plus mileage and labor for a repair technician. Repair and maintenance tend to be undervalued.

Contingency funds should be included in the financial model for both construction and operation. A typical contingency amount would be equal to 10% to 15% of the total project budget.

- Insurance may be available to purchase either as an addition to a home or business policy or as a stand-alone policy for perils such as wind, hail, fire, vandalism, theft, loss of revenue, and liability. These costs should be considered in the financial model.
- Invest in monitoring equipment. Extra sensors will cost more, but they can identify problems and inefficiencies in a system that might otherwise go unnoticed. Data should be tracked and stored over time. Moreover, if there are performance guarantees, you will have no basis to make a claim without monitoring.
- The system should be fully commissioned, meaning the installer verifies all aspects of the system work as planned and meet performance expectations. You should receive manuals for all components and training on how to operate them and identify problems. Also, make sure you know who to call if there are any problems and who will perform routine maintenance.
- Proper and timely maintenance will help insure the optimum performance of the system.
- DO NOT ATTEMPT to personally install a system without the proper training and certification.
- Finally, learn more about small wind. Invariably, wind energy systems will be more complicated than the systems they replace. The Clean Energy Resources Team's website is a good place to start for more information:  
<http://www.cleanenergyresourceteams.org/>. The sources section of this document also lists several good sites.

## **APPENDIX A - Energy and Power Units**

Energy is the ability to do work like lifting a weight or moving a car. Energy comes in many different forms: heat, light, electricity, chemical, nuclear, gravitational, etc. Everything contains energy, but different substances have different amounts of energy per unit of mass or volume which is called energy density. All useful work is done by converting one form of energy into another form, like changing the chemical energy in a piece of wood into heat and light to make a campfire.

There are many different units that can be used to measure energy, but the most basic comes from the definition of work – force times distance. So, lifting a 10 pound block 5 feet requires 50 foot pounds (ft-lbs) of energy. In the metric system the units of work are Newton meters (N-m). These energy units are not typically used when referring to thermal energy. The most common unit of energy used in the U.S. system is the British Thermal Unit (Btu), and in the metric system, it is the Joule (J). The Btu is a small unit of energy; about equal to the amount of energy released from burning one wooden kitchen match. Technically, it is defined as the amount of energy required to raise the temperature of one pound of water by one degree Fahrenheit. The Joule is even smaller.

Energy, however, is not the most important quantity. The most important quantity is power. Power is the rate at which work can be done and is quantified by dividing a unit of energy by a unit of time. In equation form:

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

Again, all work is done by converting one form of energy into another. The rate at which that can be done, or power, is what determines the utility of an energy source. For example, a large water tower is a huge source of potential energy, but if it can only be accessed through a drinking straw sized pipe, it will not be very useful because the available power will be relatively small.

In the U.S., power is usually measured in horsepower (hp) or Btu per hour (Btu/h). The unit of horsepower was originally developed to compare the work done by draft horses to steam engines and is approximately equal to the amount of work that one horse can do in an hour. It is interesting to note that 100 years ago a farmer might work his fields with 2 or 4 “horsepower” while today, the average car has about 150 horsepower and the average SUV has about 250 horsepower.

In the metric system, power is measured in joules per second (J/s) where one joule per second is defined as one watt (W). Watts are also used in the U.S. when referring to electrical power and energy. To use the watt to measure energy, the power unit must be multiplied by a unit of time which leads to the watt-hour (Wh), or more often, the kilowatt-hour (kWh).

The following table compares energy units in the U.S. and metric systems with several common variations.

U.S. Customary Energy Units	Metric System (SI) Energy Units
1 Btu	= 1055 joules (J) = .293 watt-hours (Wh) = 778 foot-pounds (ft-lbs)
1 kBtu (or MBtu) = 1000 Btu	1 kilojoule (kJ) = 1000 joules (J)
1 therm = 100,000 Btu	1 megajoule (MJ) = 1 million joules (J)
1 MMBtu = 1 million Btu	1 watt-hour (Wh) = 3600 joules (J)
1 quad = 1 quadrillion Btu	1 kilowatt-hour (kWh) = 3.6 megajoules (MJ)

The energy densities of several common fuels and electricity are listed in the following table:

Source	Unit	Energy
Coal (ave.)	Pound	9,812 Btu
Crude Oil	Gallon	138,095 Btu
Gasoline (reg.)	Gallon	114,100 Btu
Diesel	Gallon	139,000 Btu
Ethanol (E100)	Gallon	76,100 Btu
Ethanol (E85)	Gallon	81,800 Btu
Liquid Natural Gas	Gallon	75,000 Btu
Propane	Gallon	84,300 Btu
Wood	Pound	≈8,000 Btu
Electricity	Kilowatt-hour	3,412 Btu

There is more energy in a gallon of diesel fuel than in a gallon of gasoline so a diesel fueled car should get better gas mileage than the same car fueled by gasoline since gas mileage is a measure of work done per gallon. Likewise, gasoline contains more energy than ethanol so a gasoline powered car should get better mileage than one run on ethanol. In general, fossil fuels have the advantage of being relatively energy dense so a lot of work can be done with reasonable quantities of fuel. The chemical energy in fossil fuels can also be converted to other forms of energy at a high rate (power) giving them another useful advantage. The following table provides a comparison of power units:

Power Units	Equivalent Units
1 Btu/h	= .293 W
1 horsepower (hp)	= 2,544 Btu/h = 746 W
1 ton of heating or cooling	= 12,000 Btu/h = 3.5 kW = 4.7 hp
1 kilowatt (kW)	= 3,412 Btu/h = 1.34 hp
1 MBH or kBtu/h	= 1000 Btu/h = 293 W

### The effect of power on cost

Consider the cost to cool a small building that requires 12,000 Btu (3.5 kWh) of heat energy to be removed. If this must be done in 1 hour, an air conditioner having a power rating of one ton (12,000 Btu/h, 3.5 kW or 4.7 hp) would be required. If the heat energy could be removed over 10 hours, only 1200 Btu/h (.35 kW or .47 hp) of power would be needed. The total amount of energy used, and the associated cost, would be the same in both cases, but the initial cost of the more powerful air conditioner would be much higher. In other words, power is related to the initial capital costs and energy is related to the ongoing operating costs of an energy system.

Electric utilities charge customers for the amount of energy they use (kWh) per month. Large users may also pay a demand charge based on the maximum power (kW) they use during any 15 minute interval during the month. The utility charges for demand power in addition to energy usage to offset their investment costs in the generating equipment and distribution network to handle peak power loads. Utilities often charge more for electricity during peak demand times like hot summer days when lots of air conditioners are running, again, due to the larger power requirements on the system.

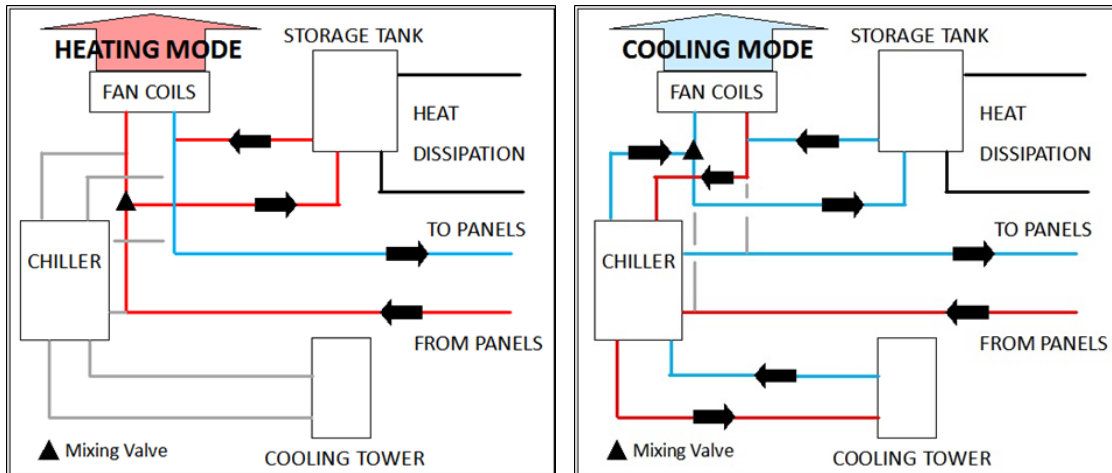
One way renewable energy sources, especially solar, can help everyone is by providing electricity at peak times to lessen the overall power demand. A large amount of solar PV on the electric grid has been demonstrated in Germany to lead to lower electricity rates for everyone by diminishing the need to use more expensive peaking power plants<sup>25</sup>.

## **APPENDIX B – Solar Energy Performance Data**

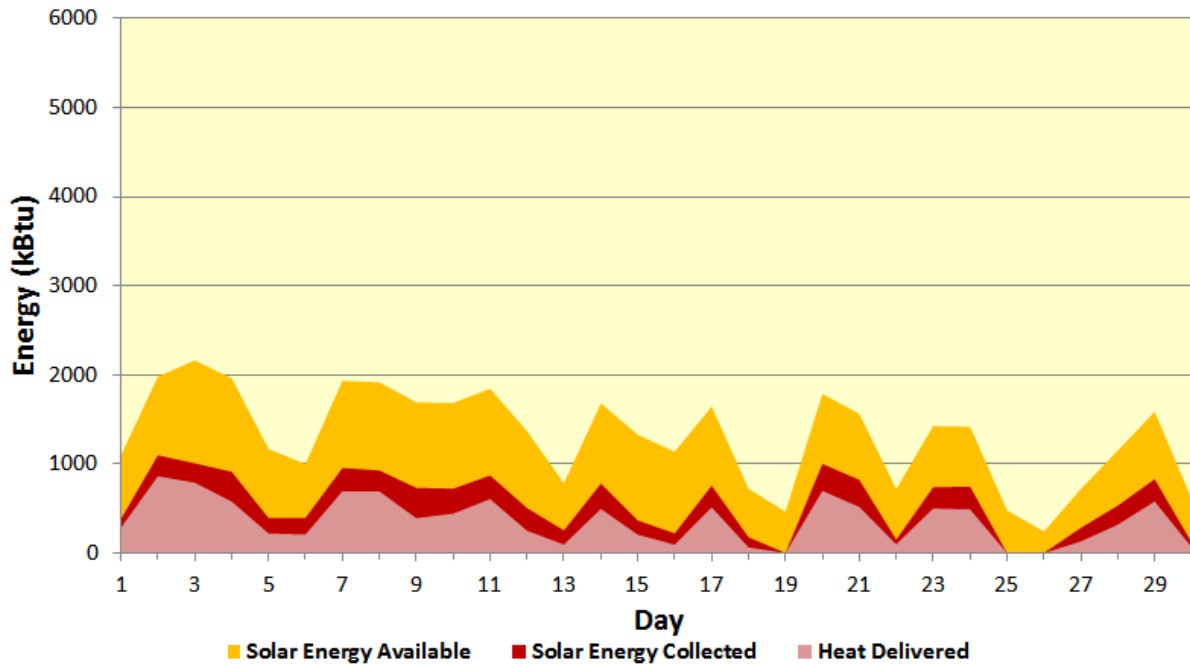
### **Evacuated tube heating and air conditioning system:**

A large evacuated tube solar thermal system was installed at the WCROC office building in 2010 and was commissioned in October of 2011. Key system details and performance results are as follows:

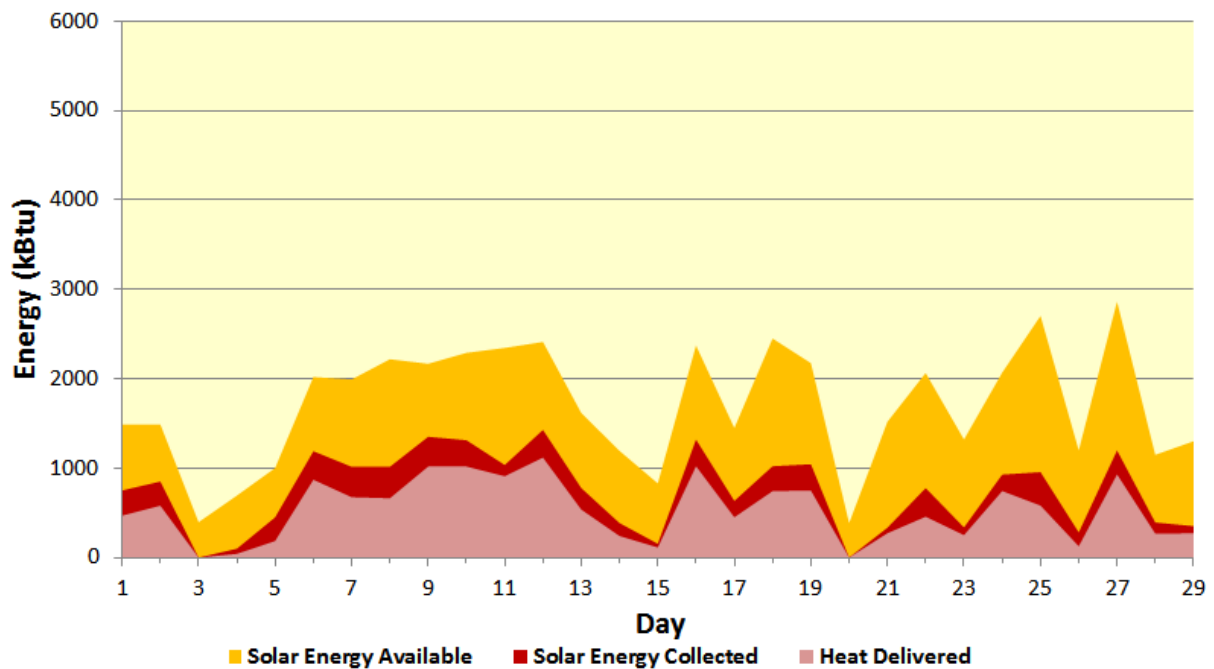
- Conditioned space is 4700 ft<sup>2</sup> (434 m<sup>2</sup>)
- About 2100 ft<sup>2</sup> (200 m<sup>2</sup>) of evacuated tube collector area (40 Solar Panels Plus, SPP-30 panels)
- Yazaki WFC-SC10 absorption chiller, water as refrigerant, lithium bromide as absorbent
- Heat transfer fluid is 50/50 mix of water and food grade propylene glycol
- System volume is 600 gallons (2270 liters) including 300 gallons (1135 liters) of storage
- Collectors are mounted at 45° facing due south



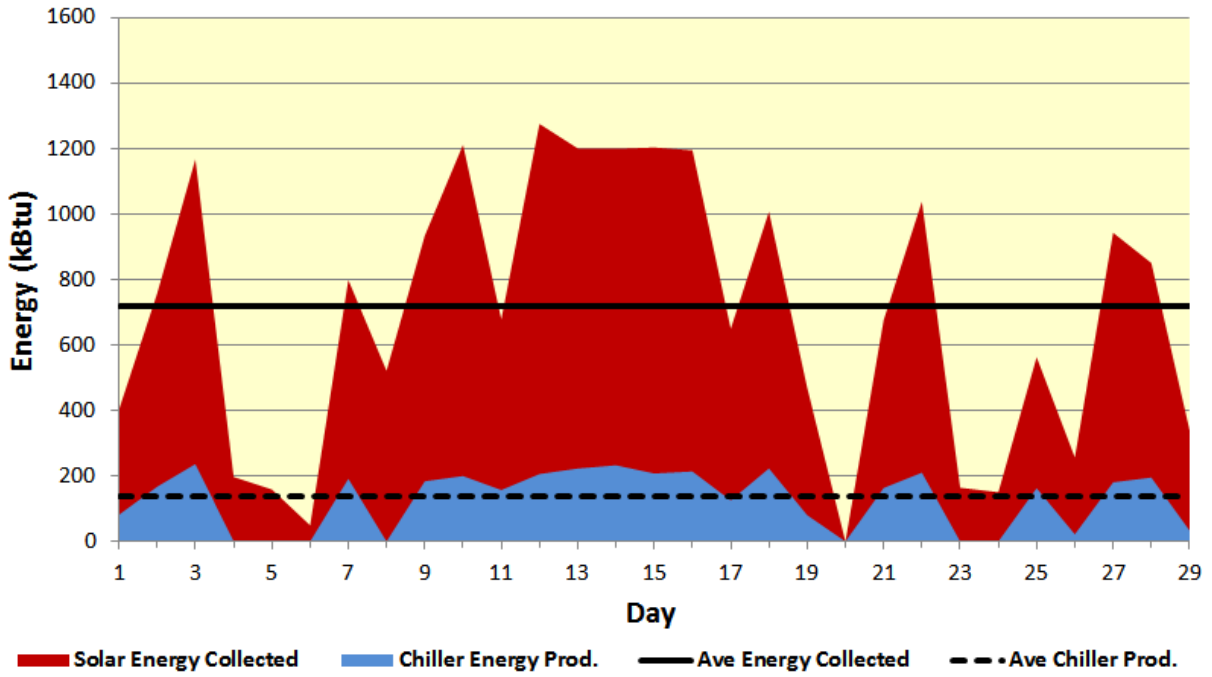
## Evacuated Tube Heating Performance Nov 2011



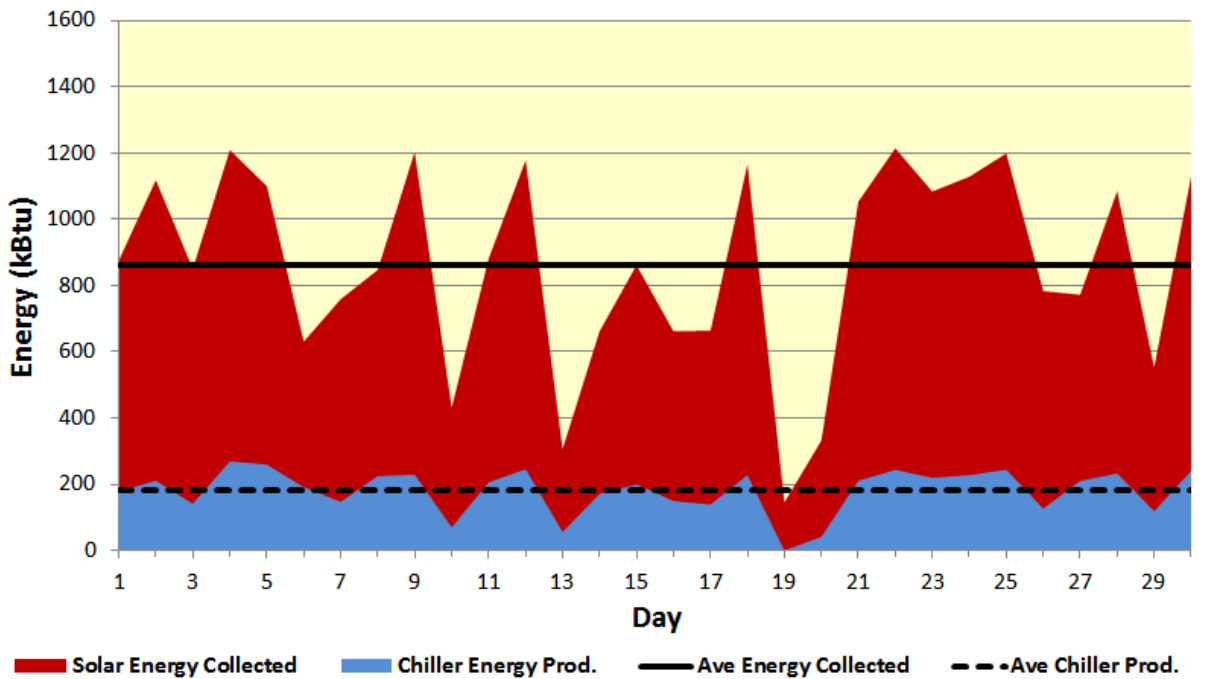
## Evacuated Tube Heating Performance Feb 2012



## Evacuated Tube & Chiller Performance May 2012



## Evacuated Tube & Chiller Performance June 2012

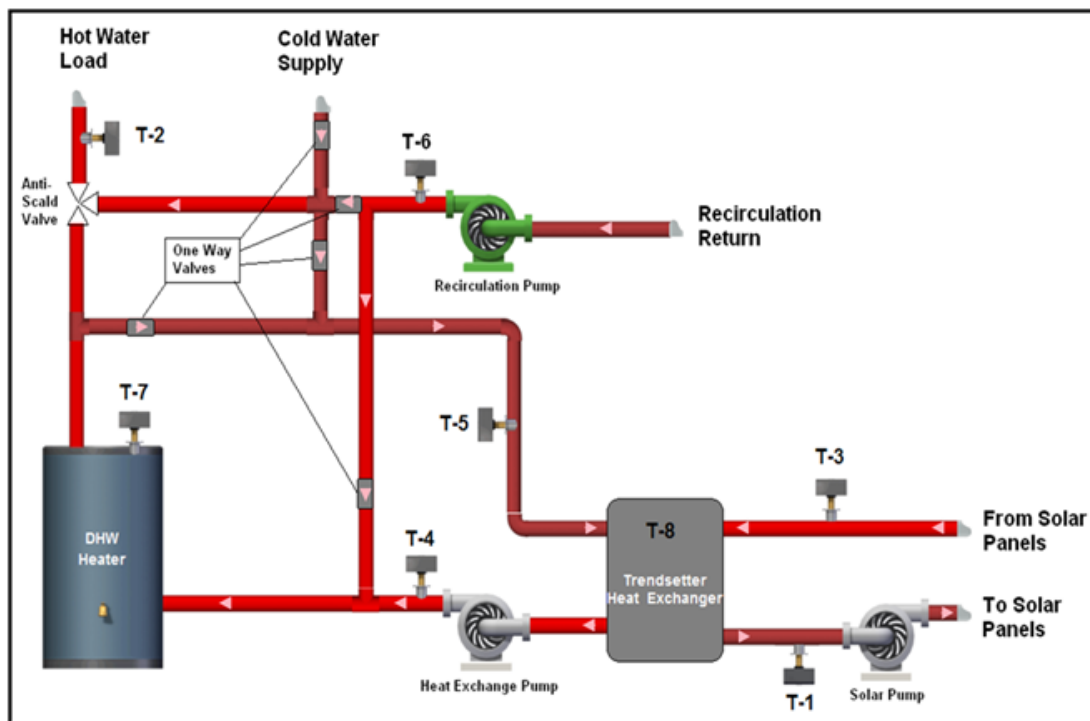


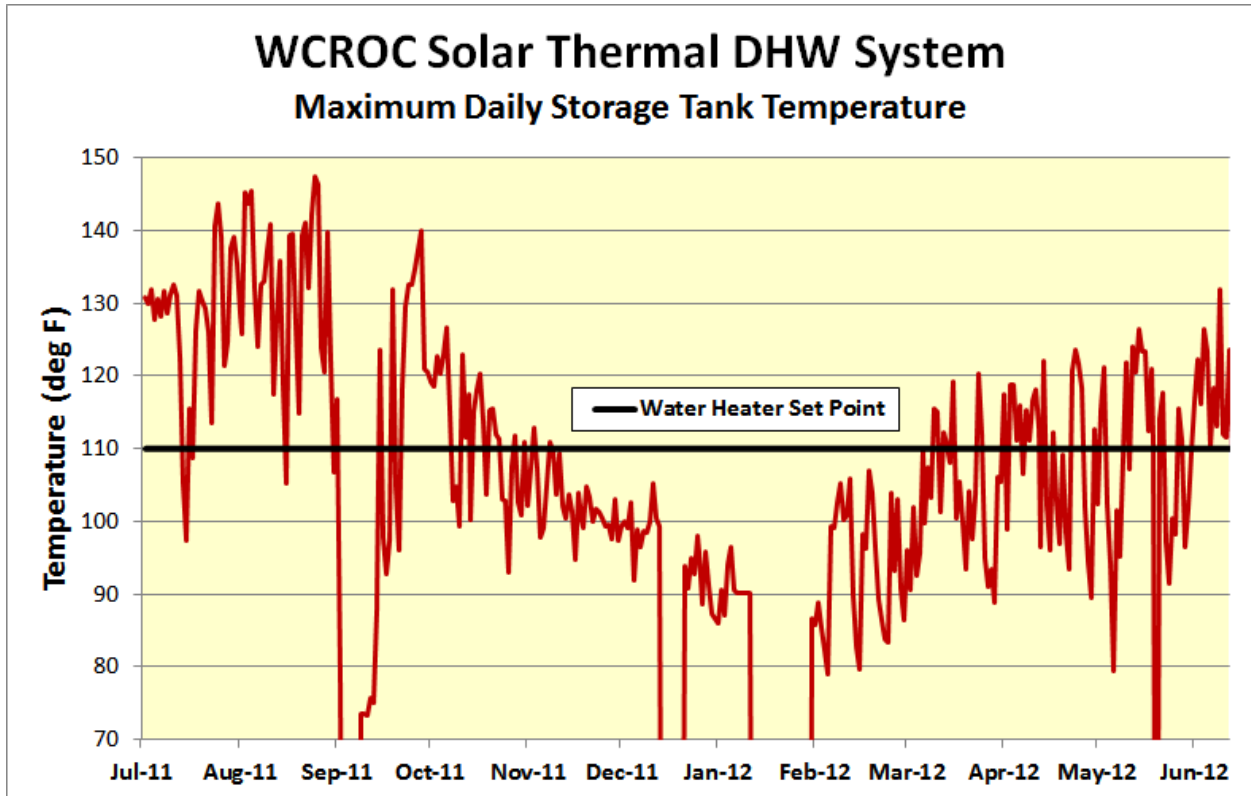


### Flat plate solar hot water system:

A flat plate solar thermal system was installed at the WCROC office building in 2010 and was commissioned in early 2011. Key system details and performance results are as follows:

- 64 ft<sup>2</sup> (6 m<sup>2</sup>) of flat plate collector area provided by Solar Skies, model SS-32
- Trendsetter TS-100 thermal tank, 105 gallon capacity
- The back-up water heater is a 40 gallon Marathon electric unit, model MR40245B
- Heat transfer fluid is a 50/50 mix of water and propylene glycol
- Collectors are mounted at 45° facing about 10° east of true south



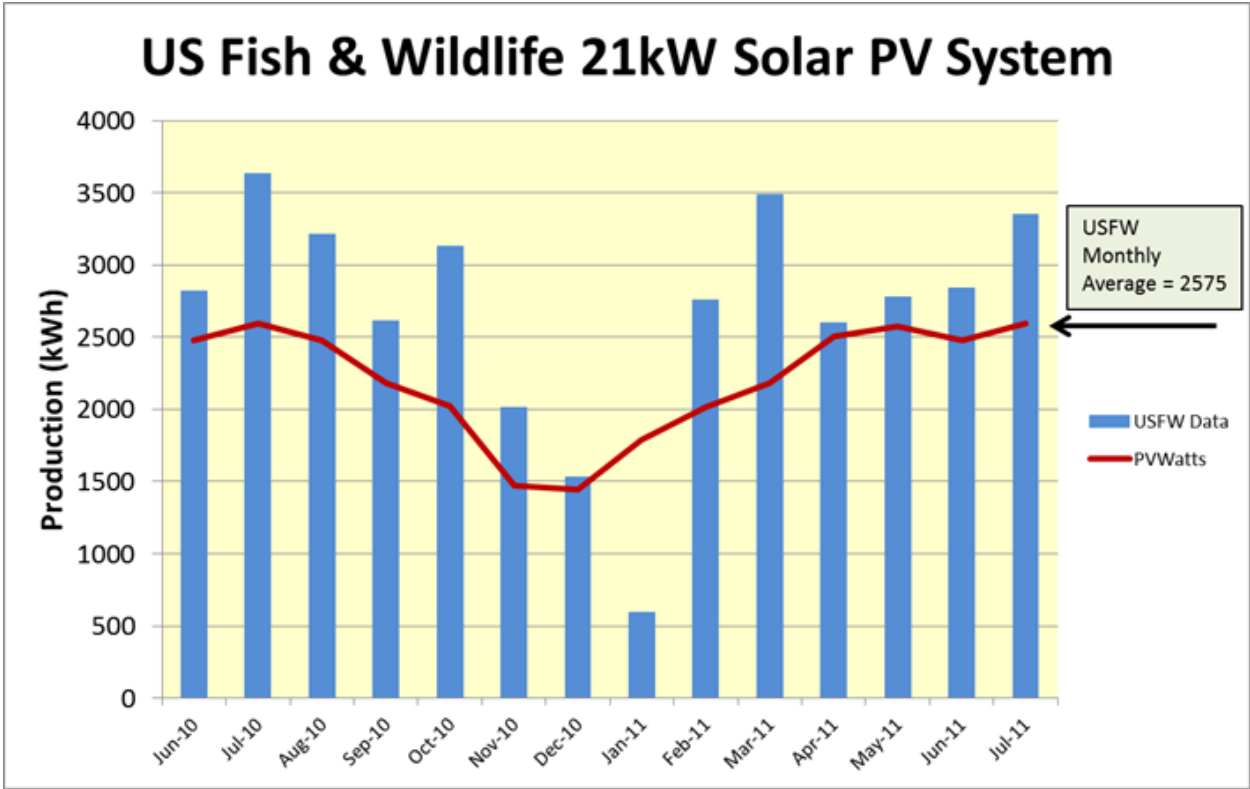


**US Fish and Wildlife solar PV system:**

The Morris office of the US Fish and Wildlife service (USFW) installed a 21.6 kW solar PV system in the summer of 2010. The system is a fixed array and was designed to provide all the electricity for the visitor’s center. Key system details and performance results are as follows:

- Rated total power is 21.6 kW , 96 modules at 225 W each (4 arrays)
- Modules provided by Solon Corp., model Blue 220/01, eff. = 13.7%
- 240 V, 21 Amp true sine wave inverter with peak power tracking
- Inverter provided by SMA America Inc., model Sunny Boy 5000US
- Mounted at 45° facing due south

The USFW provided access to the electrical production data recorded by the electric meters installed with the panels. Data was tracked from June of 2010 to July of 2011 and compared to the predicted results from the National Renewable Energy Labs (NREL) web-based model called PVWatts. The USFW system’s average monthly output is 2575 kWh. The annual production from the system was 30,900 kWh which is about 20% more than the predicted value of 25,741 kWh.



### **UMM Pole Mounted solar PV systems:**

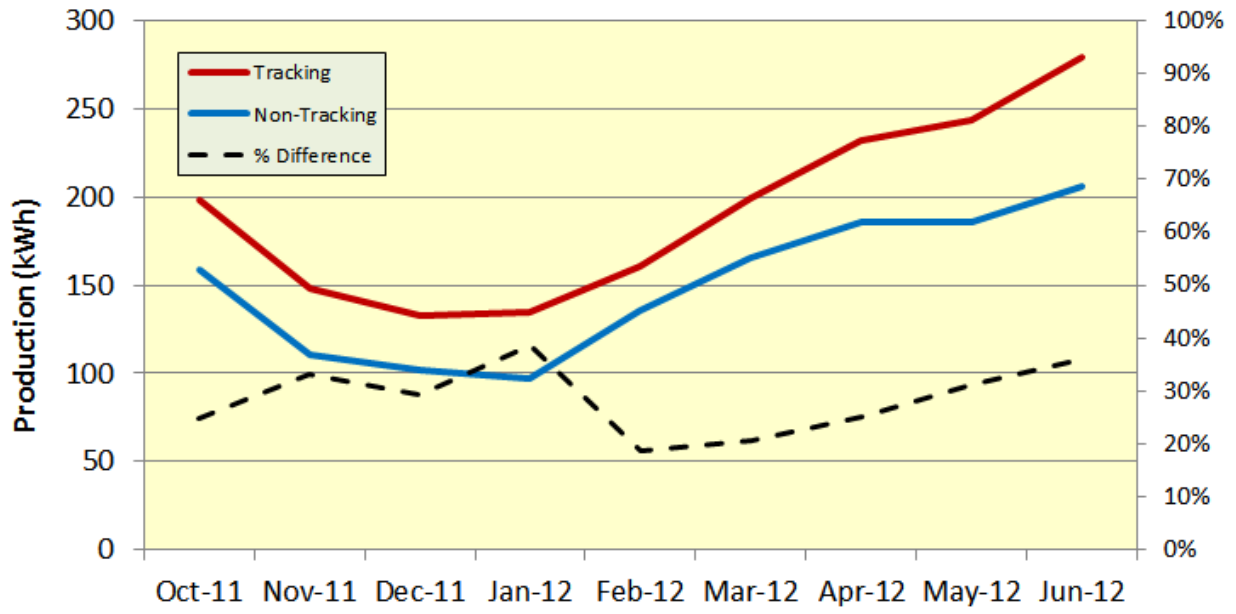
The University of Minnesota Morris campus installed two 1.32 kW, pole mounted solar PV arrays. One is fixed and one utilizes two-axis tracking to follow the sun during the day and throughout the year. Both systems use microinverters which convert DC electricity into AC electricity at each panel instead of first combining the DC electricity from all the panels before converting it with a large centralized inverter. Key system details and performance results are as follows:

- Each array uses 6 Schott 220W panels, eff. = 14.5%
- One Enphase microinverter per panel
- Fixed array mounted at 45° facing due south

Data was collected from October of 2011 to June of 2012 for both arrays. The array with two-axis tracking produced about 30% more electricity than the fixed array on average. The difference is greater in summer months than in winter months. The value of the extra electricity produced by a tracking array could be compared with the cost of the tracking equipment to determine if tracking is a good investment based on the array size.



# UMM Pole Mounted PV Systems 1.32 kW per Array



## Sources

- <sup>1</sup> [http://www.eia.gov/forecasts/aeo/er/early\\_production.cfm](http://www.eia.gov/forecasts/aeo/er/early_production.cfm)
- <sup>2</sup> <http://www.asrc.cestm.albany.edu/perez/Kit/pdf/a-fundamental-look-at%20the-planetary-energy-reserves.pdf>
- <sup>3</sup> <http://www.eia.gov/forecasts/ieo/>
- <sup>4</sup> [http://www1.solmetric.com/cgi/insolation\\_lookup/lookup.cgi](http://www1.solmetric.com/cgi/insolation_lookup/lookup.cgi)
- <sup>5</sup> [http://www.state.mn.us/mn/externalDocs/Commerce/MN\\_Solar\\_Map\\_110802025502\\_solarmap5.pdf](http://www.state.mn.us/mn/externalDocs/Commerce/MN_Solar_Map_110802025502_solarmap5.pdf)
- <sup>6</sup> <http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb1008>
- <sup>7</sup> Jordan, D.C.; Smith, R.M.; Osterwald, C.R.; Gelak, E.; Kurtz, S.R. (2010). "[Outdoor PV Degradation Comparison](#)", "35th IEEE Photovoltaic Specialists Conference (PVSC '10), 20-25 June 2010, Honolulu, Hawaii. NREL/CP-520-47704.
- <sup>8</sup> <http://www.nrel.gov/rredc/pvwatts/grid.html>
- <sup>9</sup> [http://homepower.com/article/?file=HP136\\_pg78\\_Munro](http://homepower.com/article/?file=HP136_pg78_Munro)
- <sup>10</sup> <http://www.solarbuzz.com/facts-and-figures/markets-growth/market-growth>
- <sup>11</sup> <http://www1.eere.energy.gov/solar/sunshot/index.html>
- <sup>12</sup> <http://www.seia.org/galleries/pdf/SMI-YIR-2010-ES.pdf>
- <sup>13</sup> <http://solarcooking.org/saussure.htm>
- <sup>14</sup> [http://www.californiasolarcenter.org/history\\_solarthermal.html](http://www.californiasolarcenter.org/history_solarthermal.html)
- <sup>15</sup> [http://www.californiasolarcenter.org/history\\_solarthermal.html](http://www.californiasolarcenter.org/history_solarthermal.html)
- <sup>16</sup> [http://www.navitron.org.uk/download\\_data.php?catid=6&did=73](http://www.navitron.org.uk/download_data.php?catid=6&did=73)
- <sup>17</sup> [http://www.caleffi.us/caleffi/en\\_US/Site/Technical\\_library/Idraulica\\_magazine/args/detail/~Details~Magazines~magazine\\_detail\\_0000082/type/magazine/index.sdo](http://www.caleffi.us/caleffi/en_US/Site/Technical_library/Idraulica_magazine/args/detail/~Details~Magazines~magazine_detail_0000082/type/magazine/index.sdo)
- <sup>18</sup> <http://www.iea-shc.org/about/annualreports.aspx>
- <sup>19</sup> <http://www.eia.gov/consumption/residential/reports/electronics.cfm>
- <sup>20</sup> <http://www.tshaonline.org/handbook/online/articles/dqr01>
- <sup>21</sup> Gordon, Jeffrey, *Solar energy*, International Solar Energy Society, p.598 ISBN 978-1-902916-23-1
- <sup>22</sup> [http://www.solar-rating.org/certification/ogdocuments/OG100\\_document.pdf](http://www.solar-rating.org/certification/ogdocuments/OG100_document.pdf)
- <sup>23</sup> [http://www.caleffi.us/caleffi/en\\_US/Site/Technical\\_library/Idraulica\\_magazine/args/detail/~Details~Magazines~magazine\\_detail\\_0000082/type/magazine/index.sdo](http://www.caleffi.us/caleffi/en_US/Site/Technical_library/Idraulica_magazine/args/detail/~Details~Magazines~magazine_detail_0000082/type/magazine/index.sdo)
- <sup>24</sup> [http://en.wikipedia.org/wiki/Betz'\\_law](http://en.wikipedia.org/wiki/Betz'_law)
- <sup>25</sup> K "http://www.ilsr.org/lots-solar-power-reduce-increase-electricity-prices/" <http://www.ilsr.org/lots-solar-power-reduce-increase-electricity-prices/>

### Other helpful sites

General energy sites:

- <http://www.dsireusa.org/> for incentive information
- <http://www.nrel.gov/> National Renewable Energy Labs
- <http://energy.gov/> US Department of Energy
- <http://mn.gov/commerce/energy/> MN Energy Office
- <http://mnrenewables.org/> MN Renewable Energy Society
- <http://www.eere.energy.gov/basics/> US DOE Energy Efficiency & Renewable Energy
- <http://renewables.morris.umn.edu/> WCROC Renewable Energy
- [Cleanenergyresourceteams.org](http://Cleanenergyresourceteams.org) Clean Energy Resource Teams
- <http://www.nabcep.org/> North American Board of Certified Energy Practitioners

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Solar sites:

<http://www.solar-rating.org/> Solar Rating & Certification Corporation  
<http://www.californiasolarcenter.org/index.html> California Solar Center  
<http://solar.gwu.edu/index.html> George Washington University Solar Institute  
<http://www.ases.org/> American Solar Energy Society

Geothermal heat pump sites:

<http://www.igshpa.okstate.edu/index.htm> International Ground Source Heat Pump Association  
<http://www.geothermalgenius.org/> Non-profit geothermal information and advocacy

Small-scale wind sites:

<http://awea.org/> American Wind Energy Association  
<http://www.smallwindcertification.org/> Small Wind Certification Council