

SOLAR ENERGY UTILIZATION

UNIT I - SOLAR RADIATION

What Is Solar Radiation?

Solar radiation is radiant energy emitted by the sun, particularly electromagnetic energy. About half of the radiation is in the visible short-wave part of the electromagnetic spectrum. The other half is mostly in the near-infrared part, with some in the ultraviolet part of the spectrum.

Sun and earth geometry:

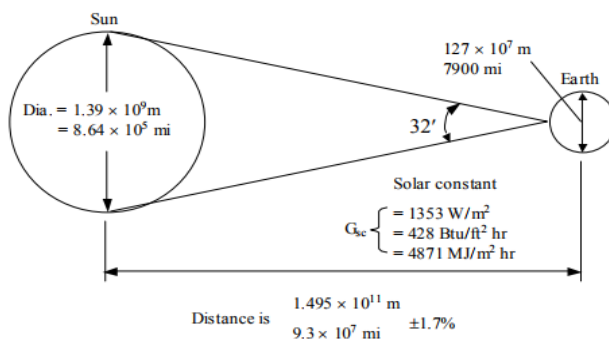
INTRODUCTION

In this module, the geometry of sun-earth positions and sizes and the distance are explained. A Solar constant is defined, commonly taken as 1353 W/m^2 , though there are some variations in the estimates. Further, distinct from the solar constant, solar radiation as received by a plane normal to sun's rays, if there is no attenuation in the atmosphere also is defined. This quantity varies from day to day due to ellipticity of the earth's orbit.

SUN - EARTH SIZE, POSITION

The geometry of the sun-earth relationships is shown schematically in Fig. 3.1. The distance between the sun and earth varies by 1.7 % due to the elliptic orbit of the of the earth around the sun. The mean earth distance is $1.495 \times 10^{11} \text{ m}$. The sun subtends an angle of $32'$ with the earth. The diameter of the sun is $1.39 \times 10^9 \text{ m}$ and that of earth, $1.27 \times 10^7 \text{ m}$.

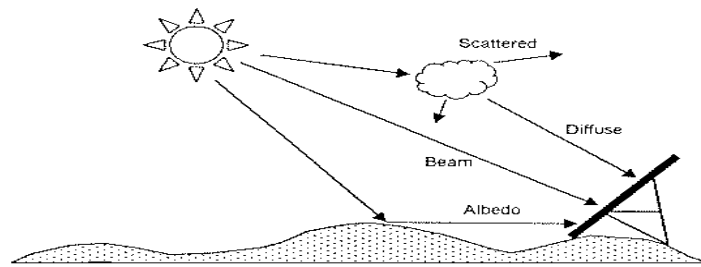
The distance between the earth and the sun determines the intensity of solar radiation that can be received by the earth, notwithstanding the atmospheric attenuation. The elliptic motion (see, Fig. 2.1) of the earth round the sun causes the seasonal variation in the solar radiation as received by the earth. In addition to these geometric or "regular" variations, variation as actually received at any location is due to the position of the location on the earth, day and time during the day and the climatic conditions such as cloudy, bright, or rainy etc.. In this module, attention is focused on the solar radiation intensity, short term and long term (time period) values as received at a location on earth, if the atmosphere is fully transparent, i.e., atmospheric transmittance is equal to unity.



BEAM AND DIFFUSE RADIATION:

BEAM RADIATION: Solar radiation that does not get absorbed or scattered, but reaches the ground directly from the sun. It produces shadow when interrupted by an opaque object.

DIFFUSE RADIATION: Solar radiation received after its direction has been changed by reflection and scattering in the atmosphere.



MEASUREMENT OF SOLAR IRRADIATION:

- The primary instrument used to measure global solar irradiance is the pyranometer, which measures the sun's energy coming from all directions in the hemisphere above the plane of the instrument
- The measurement is of the sum of the direct and the diffuse solar irradiance and is called the global solar irradiance



- The most common pyranometer design uses a thermopile (multiple thermocouples connected in series) attached to a thin blackened absorbing surface shielded from convective loss and insulated against conductive losses
- When placed in the sun, the surface attains a temperature proportional to the amount of radiant energy falling on it. The temperature is measured and converted through accurate calibration into a readout of the global solar irradiance falling on the absorbing surface.
- Example of global (total) irradiance on a horizontal surface for a mostly clear day and a mostly cloudy day in Greenbelt, MD (Thekaekara, 1976): (a) global solar radiation for the day was 27.1 MJ/m² ; (b) global solar radiation for the day was 7.3 MJ/m².

PYRANOMETERS

INTRODUCTION:

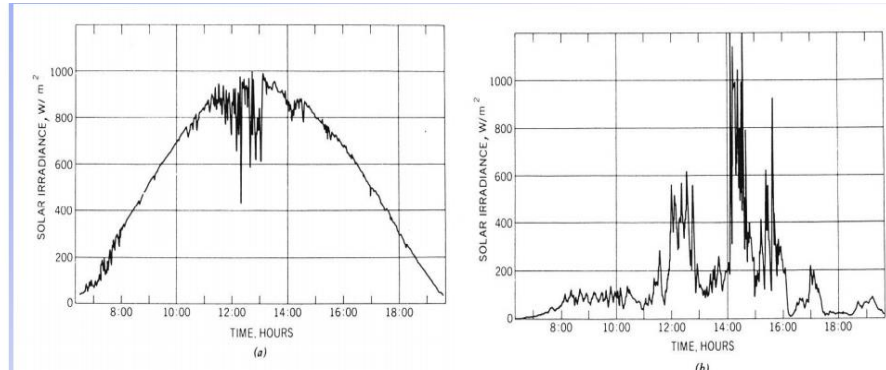
A pyranometer is a type of actinometer that can measure solar irradiance in the desired location and solar radiation flux density. The solar radiation spectrum extends approximately between 300 and 2800 nm. The pyranometer only requires a flat spectral sensitivity to help cover this spectrum.

The World Meteorological Organization has adopted this instrument which is standardized with respect to the ISO 9060 standard. Pyranometers are calibrated based on the World Radiometric Reference, which is maintained by World Radiation Center, Davos, Switzerland.

DESIGN OF PYRANOMETERS:

The following are the two main components of pyranometers:

- Thermopile – A sensor consisting of thermocouples connected in series and provided with a black coating for absorbing all solar radiation. It exhibits a near-perfect cosine response and a flat spectrum that covers 300 to 50000 nm. It is capable of producing a potential that is relative to the temperature gradient.
- Glass dome – This dome restricts the spectral response from 300 to 2800 nm from a field of view of 180 degrees. This hemispherical glass dome also shields the thermopile from wind, rain and convection.
- Occulating disc – It is used for measuring the diffuse radiation and blocking beam radiation from the surface.



WORKING PRINCIPLE:

A pyranometer is operated based on the measurement of temperature difference between a clear surface and a dark surface.

The black coating on the thermopile sensor absorbs the solar radiation, while the clear surface reflects it, and hence less heat is absorbed.

The thermopile is used to measure this temperature difference. The potential difference created in the thermopile owing to the temperature gradient between the two surfaces is used for measuring the amount of solar radiation.

However, the voltage produced by the thermopile can be measured using a potentiometer. Radiation data needs to be integrated by means of an electronic integrator or planimetry.

ADVANTAGES:

The key benefits of pyranometers are listed below:

- Very small temperature coefficient
- Calibrated to ISO standards
- More accurate measurements of performance index and performance ratio
- Longer response time than a photovoltaic cell
- Integrated measurement of the total available short-wave solar energy under all conditions.

APPLICATIONS:

The following are the major applications of pyranometers:

- Predicting insulation requirements for building structures
- Establishment of greenhouse locations
- Designing photovoltaic systems
- Meteorological and climatological studies
- Measurement of solar intensity data.

PYRHELIOMETER:

A pyrheliometer is an instrument for measurement of direct beam solar irradiance. Sunlight enters the instrument through a window and is directed onto a thermopile which converts heat to an electrical signal that can be recorded

Applications:

Typical pyrheliometer measurement applications include scientific meteorological and climate observations, material testing research, and assessment of the efficiency of solar collectors and photovoltaic devices.

Usage:

Pyrheliometers are typically mounted on a solar tracker. As the pyrheliometer only 'sees' the solar disk, it needs to be placed on a device that follows the path of the sun.

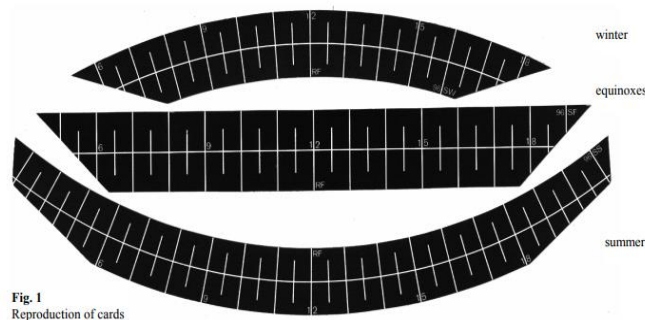


SUNSHINE RECORDER WORKING PRINCIPLE:

Sunshine recorder essentially consists of a glass sphere mounted in a spherical bowl and a metallic groove which holds a record card. Sun's rays are refracted and focused sharply on the record card beneath the glass sphere, leaving burnt marks on the card.

Working principle:

This recorder consists essentially of a glass sphere of 96 mm diameter mounted concentrically in a section of a spherical metal bowl, the diameter of which is such that the sun's rays are focussed sharply on a card held in the grooves, in the bowl. Three overlapping pairs of grooves are provided in the bowl to take up cards suitable for the different seasons of the year.



SOLAR COLLECTORS AND APPLICATIONS:

Solar Collectors:

Solar collectors transform solar radiation into heat and transfer that heat to a medium (water, solar fluid, or air). Then solar heat can be used for heating water, to back up heating systems or for heating swimming pools.

Types of collectors

- Stationary
 - Sun tracking
- Applications
- Solar water heating
 - Solar space heating and cooling
 - Refrigeration
 - Industrial process heat
 - Solar thermal power systems

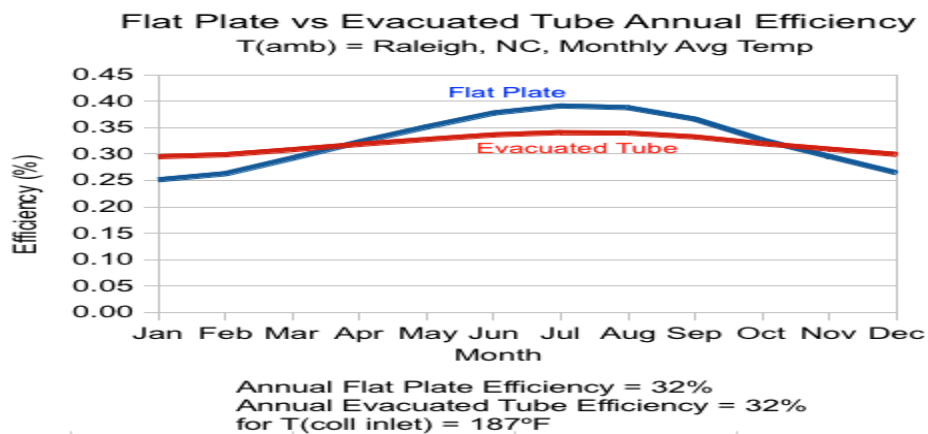
How does a solar collector work?

A solar collector is basically a flat box and are composed of three main parts, a transparent cover, tubes which carry a coolant and an insulated back plate. The solar collector works on the green house effect principle; solar radiation incident upon the transparent surface of the solar collector is transmitted through though this surface. The inside of the solar collector is usually evacuated, the energy contained within the solar collect is basically trapped and thus heats the coolant contained within the tubes. The tubes are usually made from copper, and the backplate is painted black to help absorb solar radiation. The solar collector is usually insulated to avoid heat losses.

UNIT – II SOLAR THERMAL SYSTEMS

FLAT PLATE AND EVACUATED TUBE COLLECTORS:

The evacuated tube manifold is also very well insulated with 3” of rock wool insulation on all sides. Flat plate collectors generally have 1” of insulation on the sides and bottom. Flat plate collectors absorb maximum solar energy only at solar noon.



Solar hot water has come a long way in the last decade, particularly with the introduction of evacuated tube collectors that are rapidly becoming the preferred option over flat plate systems. If you're not sure of the difference between the two in terms of how they work, read our brief [guide to solar hot water systems](#).



The latest is certainly not always the greatest, so which is actually better – a flat plate solar hot water system or one that uses evacuated tube collectors? While evacuated tube technology is more of an investment, the benefits certainly outweigh the cost. Any additional cost may also be offset by solar hot water rebates.

Evacuated tube collector based systems:

- Capture sunlight better as they have a greater surface area exposed to the sun at any time

- Are more efficient in transferring heat – up to 163% demonstrated in Australian conditions!
- Can be used in subzero temperatures
- Are durable and if a tube should be broken, it can be easily and cheaply replaced.
- Provide excellent performance in overcast conditions
- Require a smaller roof area than comparable flat plate collectors
- Do not have the same level of corrosion problems as flat plate collectors.

Domestic hot water and process heat system:

Water heating is a thermodynamic process that uses an energy source to heat water above its initial temperature. Typical domestic uses of hot water include cooking, cleaning, bathing, and space heating. In industry, hot water and water heated to steam have many uses.

Domestically, water is traditionally heated in vessels known as *water heaters, kettles, cauldrons, pots, or coppers*. These metal vessels that heat a batch of water do not produce a continual supply of heated water at a preset temperature. Rarely, hot water occurs naturally, usually from natural hot springs. The temperature varies with the consumption rate, becoming cooler as flow increases.

Appliances that provide a continual supply of hot water are called *water heaters, hot water heaters, hot water tanks, boilers, heat exchangers, geysers, or calorifiers*. These names depend on region, and whether they heat potable or non-potable water, are in domestic or industrial use, and their energy source. In domestic installations, potable water heated for uses other than space heating is also called *domestic hot water (DHW)*.

Fossil fuels (natural gas, liquefied petroleum gas, oil), or solid fuels are commonly used for heating water. These may be consumed directly or may produce electricity that, in turn, heats water. Electricity to heat water may also come from any other electrical source, such as nuclear power or renewable energy. Alternative energy such as solar energy, heat pumps, hot water heat recycling, and geothermal heating can also heat water, often in combination with backup systems powered by fossil fuels or electricity.

Densely populated urban areas of some countries provide district heating of hot water. This is especially the case in Scandinavia and Finland. District heating systems supply energy for water heating and space heating from waste heat from industries, power plants, incinerators, geothermal heating, and central solar heating. Actual heating of tap water is performed in heat exchangers at the consumers' premises. Generally the consumer has no in-building backup system, due to the expected high availability of district heating systems.

Solar Cooker:

A solar cooker is a device which uses the energy of direct sunlight to heat, cook or pasteurise drink. Many solar cookers currently in use are relatively inexpensive, low-tech devices, although some are as powerful or as expensive as traditional stoves, and advanced, large-scale solar cookers can cook for hundreds of people. Because they use no fuel and cost nothing to operate, many nonprofit organizations are promoting their use worldwide in order to help reduce fuel costs (especially where monetary reciprocity is low) and air pollution, and to slow down the deforestation and desertification caused by gathering firewood for cooking. Solar cooking is a form of outdoor cooking and is often used in situations where minimal fuel consumption is important, or the danger of accidental fires is high, and the health and environmental consequences of alternatives are severe.

Principles

1) Concentrating sunlight: A mirrored surface with high specular reflectivity is used to concentrate light from the sun on to a small cooking area. Depending on the geometry of the surface, sunlight can be concentrated by several orders of magnitude producing temperatures high enough to melt salt and smelt metal. For most household solar cooking applications, such high temperatures are not really required. Solar cooking products, thus, are typically designed to achieve temperatures of 150 °F (65 °C) (baking temperatures) to 750 °F (400 °C) (grilling/searing temperatures) on a sunny day.

2) Converting light energy to heat energy: Solar cookers concentrate sunlight onto a receiver such as a cooking pan. The interaction between the light energy and the receiver material converts light to heat.

This conversion is maximized by using materials that conduct and retain heat. Pots and pans used on solar cookers should be matte black in color to maximize the absorption.

3) Trapping heat energy: It is important to reduce convection by isolating the air inside the cooker from the air outside the cooker. Simply using a glass lid on your pot enhances light absorption from the top of the pan and provides a greenhouse effect that improves heat retention and minimizes convection loss. This "glazing" transmits incoming visible sunlight but is opaque to escaping infrared thermal radiation. In resource constrained settings, a high-temperature plastic bag can serve a similar function, trapping air inside and making it possible to reach temperatures on cold and windy days similar to those possible on hot days.

Operation

Different kinds of solar cookers use somewhat different methods of cooking, but most follow the same basic principles.

Food is prepared as if for an oven or stove top. However, because food cooks faster when it is in smaller pieces, food placed inside a solar cooker is usually cut into smaller pieces than it might otherwise be.^[4] For example, potatoes are usually cut into bite-sized pieces rather than roasted whole.^[5] For very simple cooking, such as melting butter or cheese, a lid may not be needed and the food may be placed on an uncovered tray or in a bowl. If several foods are to be cooked separately, then they are placed in different containers.

The container of food is placed inside the solar cooker, which may be elevated on a brick, rock, metal trivet, or other heat sink, and the solar cooker is placed in direct sunlight.^[4] Foods that cook quickly may be added to the solar cooker later. Rice for a mid-day meal might be started early in the morning, with vegetables, cheese, or soup added to the solar cooker in the middle of the morning. Depending on the size of the solar cooker and the number and quantity of cooked foods, a family may use one or more solar cookers.

A solar oven is turned towards the sun and left until the food is cooked. Unlike cooking on a stove or over a fire, which may require more than an hour of constant supervision, food in a solar oven is generally not stirred or turned over, both because it is unnecessary and because opening the solar oven allows the trapped heat to escape and thereby slows the cooking process. If wanted, the solar oven may be checked every one to two hours, to turn the oven to face the sun more precisely and to ensure that shadows from nearby buildings or plants have not blocked the sunlight. If the food is to be left untended for many hours during the day, then the solar oven is often turned to face the point where the sun will be when it is highest in the sky, instead of towards its current position.

The cooking time depends primarily on the equipment being used, the amount of sunlight at the time, and the quantity of food that needs to be cooked. Air temperature, wind, and latitude also affect performance. Food cooks faster in the two hours before and after the local solar noon than it does in either the early morning or the late afternoon. Large quantities of food, and food in large pieces, take longer to cook. As a result, only general figures can be given for cooking time. With a small solar panel cooker, it might be possible to melt butter in 15 minutes, to bake cookies in 2 hours, and to cook rice for four people in 4 hours. With a high performing parabolic solar cooker, you may be able to grill a steak in minutes. However, depending on local conditions and the solar cooker type, these projects could take half as long, or twice as long.

It is difficult to burn food in a solar cooker.^[5] Food that has been cooked even an hour longer than necessary is usually indistinguishable from minimally cooked food. The exception to this rule is some green vegetables, which quickly change from a perfectly cooked bright green to olive drab, while still retaining the desirable texture.

For most foods, such as rice, the typical person would be unable to tell how it was cooked from looking at the final product. There are some differences, however: Bread and cakes brown on their tops instead of on the bottom. Compared to cooking over a fire, the food does not have a smoky flavor.

Solar Dryer:

Solar dryers are devices that use solar energy to dry substances, especially food. There are two general types of solar dryers: Direct and indirect.

Direct

Direct solar dryers expose the substance to be dehydrated to direct sunlight. Historically, food and clothing was dried in the sun by using lines, or laying the items on rocks or on top of tents. In Mongolia cheese and meat are still traditionally dried using the top of the ger (tent) as a solar dryer. In these systems the solar drying is assisted by the movement of the air (wind) that removes the more saturated air away from the items being dried. More recently, complex drying racks and solar tents were constructed as solar dryers.

One modern type of solar dryer has a black absorbing surface which collects the light and converts it to heat; the substance to be dried is placed directly on this surface. These driers may have enclosures, glass covers and/or vents to in order to increase efficiency.

Indirect

In indirect solar dryers, the black surface heats incoming air, rather than directly heating the substance to be dried. This heated air is then passed over the substance to be dried and exits upwards often through a chimney, taking moisture released from the substance with it.^[2] They can be very simple, just a tilted cold frame with black cloth^[8] to an insulated brick building with active ventilation and a back-up heating system.^[9] One of the advantages of the indirect system is that it is easier to protect the food, or other substance, from contamination whether wind-blown or by birds, insects, or animals.^{[2][9]} Also, direct sun can chemically alter some foods making them less appetizing.

Solar Desalination:

Solar desalination is a technique to desalinate water using solar energy. There are two basic methods of achieving desalination using this technique; direct and indirect.

What is meant by solar distillation?

Solar distillation is the use of solar energy to evaporate water and collect its condensate within the same closed system. Unlike other forms of water purification it can turn salt or brackish water into fresh drinking water (i.e. desalination).

Types of solar desalination :

There are two primary means of achieving desalination using solar energy, through a phase change by thermal input, or in a single phase through mechanical separation. Phase change (or multi-phase) can be accomplished by either direct or indirect solar distillation. Single phase is predominantly accomplished by the use of photovoltaic cells to produce electricity to drive pumps although there are experimental methods being researched using solar thermal collection to provide this mechanical energy.

Solar Pond:

UNIT – III - SOLAR POWER PLANT

Principles of solar parabolic concentrators:

Parabolic Trough:

A parabolic trough consists of a linear parabolic reflector that concentrates light onto a receiver positioned along the reflector's focal line. The receiver is a tube positioned directly above the middle of the parabolic mirror and filled with a working fluid. The reflector follows the sun during the daylight hours by tracking along a single axis. A working fluid (e.g. molten salt) is heated to 150–350 °C (302–662 °F) as it flows through the receiver and is then used as a heat source for a power generation system.^[25] Trough systems are the most developed CSP technology. The Solar Energy Generating Systems (SEGS) plants in California, the world's first commercial parabolic trough plants, Acciona's Nevada Solar One near Boulder City, Nevada, and Andasol, Europe's first commercial parabolic trough plant are representative, along with Plataforma Solar de Almería's SSPS-DCS test facilities in Spain.

A parabolic trough is a type of solar thermal collector that is straight in one dimension and curved as a parabola in the other two, lined with a polished metal mirror. The energy of sunlight which enters the mirror parallel to its plane of symmetry is focused along the focal line, where objects are positioned that are intended to be heated. For example, food may be placed at the focal line of a trough, which causes the food to be cooked when the trough is aimed

so the Sun is in its plane of symmetry. Further information on the use of parabolic troughs for cooking can be found in the article about solar cookers.

For other purposes, there is often a tube, frequently a Dewar tube, which runs the length of the trough at its focal line. The mirror is oriented so that sunlight which it reflects is concentrated on the tube, which contains a fluid which is heated to a high temperature by the energy of the sunlight. The hot fluid can be used for many purposes. Often, it is piped to a heat engine, which uses the heat energy to drive machinery or to generate electricity. This solar energy collector is the most common and best known type of parabolic trough. The paragraphs below therefore concentrate on this type.

Design:

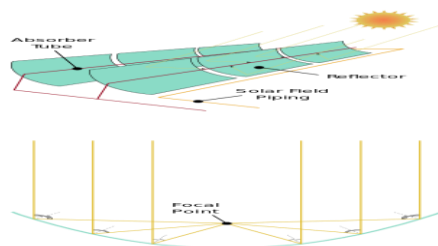
A parabolic trough is made of a number of solar collector modules (SCM) fixed together to move as one solar collector assembly (SCA). A SCM could have a length up to 15 metres (49 ft) or more. About a dozen or more of SCM make each SCA up to 200 metres (660 ft) length. Each SCA is an independently tracking parabolic trough.

A SCM may be made as a single-piece parabolic mirror or assembled with a number of smaller mirrors in parallel rows. Smaller modular mirrors requires smaller machines to build the mirror, reducing cost. Cost is also reduced in case of the need of replacing a damaged mirror, like after an object hit (during bad weather or other causes).

In addition, V-type parabolic troughs exist which are made from 2 mirrors and placed at an angle towards each other.

In 2009, scientists at the National Renewable Energy Laboratory (NREL) and SkyFuel teamed to develop large curved sheets of metal that have the potential to be 30% less expensive than today's best collectors of concentrated solar power by replacing glass-based models with a silverpolymer sheet that has the same performance as the heavy glass mirrors, but at a much lower cost and much lower weight. It also is much easier to deploy and install. The glossy film uses several layers of polymers, with an inner layer of pure silver.^[8]

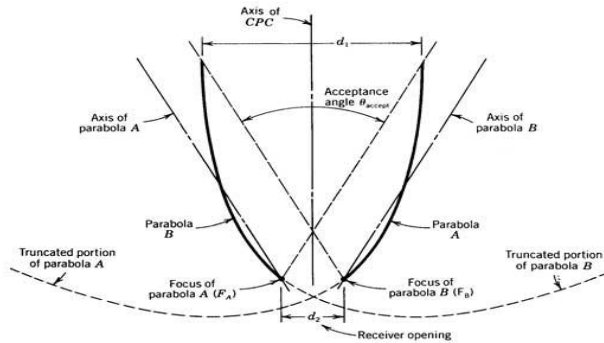
As this renewable source of energy is inconsistent by nature, methods for energy storage have been studied, for instance the single-tank (thermocline) storage technology for large-scale solar thermal power plants. The thermocline tank approach uses a mixture of silica sand and quartzite rock to displace a significant portion of the volume in the tank. Then it is filled with the heat transfer fluid, typically a molten nitrate salt.



A diagram of a parabolic trough solar farm (top), and an end view of how a parabolic collector focuses sunlight onto its focal point.

Compound Parabolic Concentrator:

Compound Parabolic Concentrators (CPCs) are concentrator lenses made from rotated parabolic shapes to create specific acceptance angles through which divergent light is collected. Monica Rainey, Optical Engineer, explains the common features and applications of CPCs.



- 25° and 45° Acceptance Angles
- 2.5mm and 5.0mm Exit Diameters
- Ideal for Concentrating Solar Energy

Compound Parabolic Concentrators (CPCs) are designed to efficiently collect and concentrate distant light sources. With acceptance angle options of 25° and 45°, our CPCs are able to accommodate a variety of light sources and configurations. Compound Parabolic Concentrators are critical components in solar energy collection, wireless communication, biomedical and defense research, or for any applications requiring condensing of a divergent light source. For custom coatings on the entrance and exit faces or for custom sizes and configurations.

CHARACTERISTICS

Concentrating and pipe type solar collector is a new kind of device to collect energy. It consists of compound parabolic concentrator (CPC) which is non-tracing concentrated and vacuum hot-tube collector (receiver). CPC features of non-imaging and low concentration. On the basis of edge-ray principle, CPC can collect incident ray within the specified scope by the ideal concentration ration onto the receiver. The vacuum hot-tube collector converts the solar energy to heat energy, and the medium transfers the heat energy to water.

1. Large collecting scale and high efficiency
2. No water in the vacuum tubes – It means that even the tube breaks up, no water leaks.
3. Pressurized running
4. Arbitrary placement and moderated temperature collector.

Compound Parabolic Concentrators (CPCs) are used to efficiently collect and concentrate light from a distant source.

CPCs are designed using a rotated parabolic shape. The wide end of the CPC collects divergent light which is then reflected in the CPC and concentrated at the narrow output end. CPCs are defined using an acceptance angle which is the angular range in which the CPC can collect light.

Optiforms fabricates hollow CPC's using electroforming technology. The substrate would be Nickel with a specular internal surface. The advantage to this is that the light energy does not need to pass through the surfaces of glass upon entrance and exit.

CPCs are commonly used in solar energy collection, fiber optics, biomedical and defense research, or other applications that require condensing of divergent light sources. These non-imaging components concentrate light rays that are not necessarily parallel nor aligned with the axis of the concentrator.

Optiforms manufactures compound parabolic concentrators to your desired specification.

FRESNEL LENS COLLECTORS:

A **Fresnel lens** a type of compact lens originally developed by French physicist Augustin-Jean Fresnel for lighthouses.

The design allows the construction of lenses of large aperture and short focal length without the mass and volume of material that would be required by a lens of conventional design. A Fresnel

lens can be made much thinner than a comparable conventional lens, in some cases taking the form of a flat sheet. A Fresnel lens can capture more oblique light from a light source, thus allowing the light from a lighthouse equipped with one to be visible over greater distances.

Description:

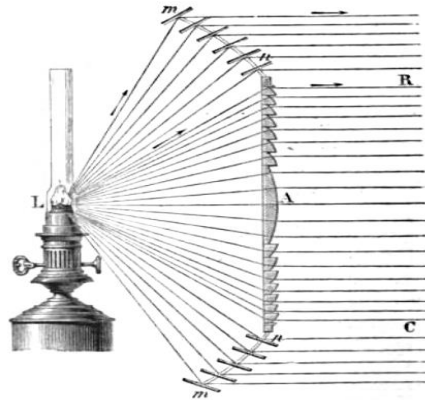
The Fresnel lens reduces the amount of material required compared to a conventional lens by dividing the lens into a set of concentric annular sections. An ideal Fresnel lens would have infinitely many such sections. In each section, the overall thickness is decreased compared to an equivalent simple lens. This effectively divides the continuous surface of a standard lens into a set of surfaces of the same curvature, with stepwise discontinuities between them.

In some lenses, the curved surfaces are replaced with flat surfaces, with a different angle in each section. Such a lens can be regarded as an array of prisms arranged in a circular fashion, with steeper prisms on the edges, and a flat or slightly convex center. In the first (and largest) Fresnel lenses, each section was actually a separate prism. 'Single-piece' Fresnel lenses were later produced, being used for automobile headlamps, brake, parking, and turn signal lenses, and so on. In modern times, computer-controlled milling equipment (CNC) might be used to manufacture more complex lenses.

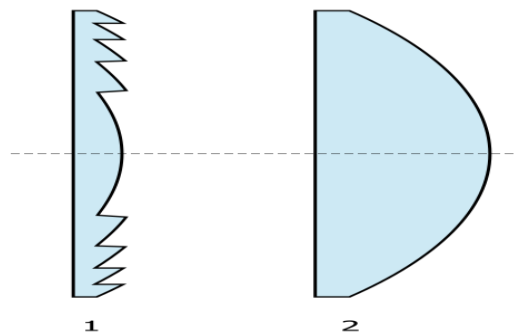
Fresnel lens design allows a substantial reduction in thickness (and thus mass and volume of material), at the expense of reducing the imaging quality of the lens, which is why precise imaging applications such as photography usually still use larger conventional lenses.

Fresnel lenses are usually made of glass or plastic; their size varies from large (old historical lighthouses, meter size) to medium (book-reading aids, OHP viewgraph projectors) to small (TLR/SLR camera screens, micro-optics). In many cases they are very thin and flat, almost flexible, with thicknesses in the 1 to 5 mm (0.039 to 0.197 in) range.

Modern Fresnel lenses usually consist of all refractive elements. However many of the lighthouses have both refracting and reflecting elements, as shown in the photographs and diagram. That is, the outer elements are sections of reflectors while the inner elements are sections of refractive lenses. Total internal reflection was often used to avoid the light loss in reflection from a silvered mirror.



A Spherical Fresnel Lens



1: Cross section of a spherical Fresnel lens 2: Cross section of a conventional spherical [plano-convex lens](#) of equivalent power

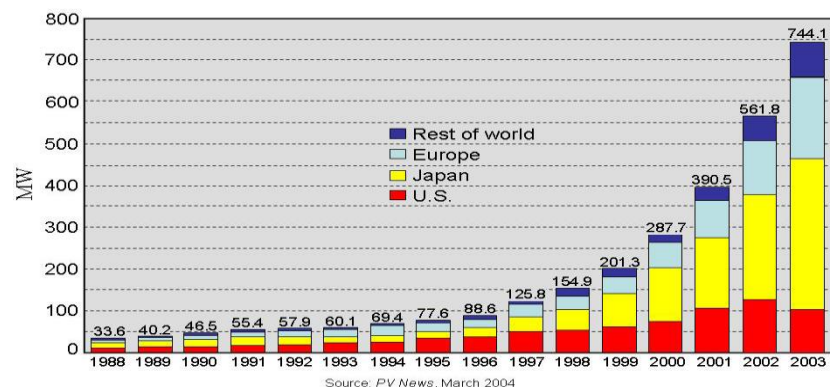
UNIT IV - SOLAR PHOTOVOLTAICS

BASIC RESEARCH CHALLENGES FOR SOLAR PHOTOVOLTAICS

CURRENT STATUS

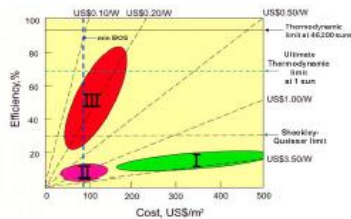
Edmund Becquerel discovered the photovoltaic (PV) effect in 1839, when he observed that a voltage and a current were produced when a silver chloride electrode immersed in an electrolytic solution and connected to a counter metal electrode was illuminated with white light (Becquerel 1839). However, the birth of the modern era of PV solar cells occurred in 1954, when D. Chapin, C. Fuller, and G. Pearson at Bell Labs demonstrated solar cells based on p-n junctions in singlecrystal Si with efficiencies of 5–6% (Chapin, Fuller, and Pearson 1954). This original Si solar cell still works today — single-crystal Si solar cells dominate the commercial PV market.

From the mid 1950s to the early 1970s, PV research and development (R&D) was directed primarily toward space applications and satellite power. Then, in 1973, a greatly increased level of R&D on solar cells was initiated following the oil embargo in that year, which caused widespread concern regarding energy supply. In 1976, the U.S. Department of Energy (DOE), along with its Photovoltaics Program, was created. DOE, as well as many other international organizations, began funding PV R&D at appreciable levels, and a terrestrial solar cell industry quickly evolved. Figure 1 shows a plot of annual PV power production vs. time for the period 1988–2003 (Surek 2005). Total global PV (or solar) cell production increased from less than 10 MWp/yr in 1980 to about 1,200 MWp/yr in 2004; the current total global PV installed capacity is about 3 GWp. The “peak watt” (Wp) rating is the power (in watts) produced by a solar module illuminated under the following standard conditions: 1,000 W/m² intensity, 25°C ambient temperature, and a spectrum that relates to sunlight that has passed through the atmosphere when the sun is at a 42° elevation from the horizon (defined as air mass [or AM] 1.5;



i.e., when the path through the atmosphere is 1.5 times that when the sun is at high noon). Because of day/night and time-of-day variations in insolation and cloud cover, the average electrical power produced by a solar cell over a year is about 20% of its Wp rating. Solar cells have a lifetime of approximately 30 yr. They incur no fuel expenses, but they do involve a capital cost. The cost for the electricity produced by the cell is calculated by amortizing the capital cost over the lifetime of the cell and considering the total electrical output energy produced over the cell lifetime. Higher PV efficiency thus directly impacts the overall electricity cost, because higher-efficiency cells will produce more electrical energy per unit of cell area over the cell lifetime. The cost figure of merit for PV cell modules (\$/Wp) is determined by the ratio of the module cost per unit of area (\$/m²) divided by the maximum amount of electric power delivered per unit of area (module efficiency multiplied by 1,000 W/m², the peak insolation power). In Figure 2, this cost per peak watt (\$/Wp) is indicated by a series of dashed straight lines having different

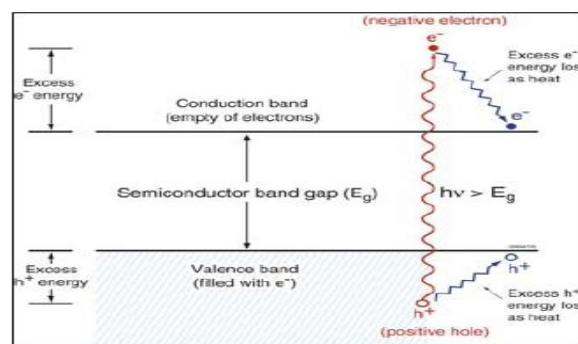
slopes. Any combination of areal cost and efficiency that is on a given dashed line produces the same cost per peak watt indicated by the line labels. Present single-crystalline Si PV cells, with an efficiency of 10% and a cost of \$350/m², thus have a module cost of \$3.50/Wp. The area labeled I in Figure 2 represents the first generation (Generation I) of solar cells and covers the range of module costs and efficiencies for these cells. In addition to module costs, a PV system also has costs associated with the non-photoactive parts of the system. These are called balance of system (BOS) costs, and they are currently in the range of \$250/m² for Generation I cells. Thus, the total cost of present PV systems is about \$6/Wp. Taking into account the cost of capital funds, interest rates, depreciation, system lifetime, and the available annual solar irradiance integrated over the year (i.e., considering the diurnal).



For PV or PEC to provide the full level of C-free energy required for electricity and fuel—solar power cost needs to be < 2 cents/kWh (\$0.40/Wp).
Figure 2 PV power costs (\$/W_p) as function of module efficiency and areal cost (Source: Green 2004)

CONVERSION OF SUNLIGHT INTO ELECTRICITY

Solar power can be converted directly into electrical power in photovoltaic (PV) cells, commonly called solar cells. The sun has a surface temperature of about 6,000°C, and its hot gases at this temperature emit light that has a spectrum ranging from the ultraviolet, through the visible, into the infrared. According to quantum theory, light can behave either as waves or as particles, depending upon the specific interaction of light with matter; this phenomenon is called the wave-particle duality of light. In the particle description, light consists of discrete particle-like packets of energy called photons. Sunlight contains photons with energies that reflect the sun’s surface temperature; in energy units of electron volts (eV), the solar photons range in energy ($h\nu$) from about 3.5 eV (ultraviolet region) to 0.5 eV (infrared region). The energy of the visible region ranges from 3.0 eV (violet) to 1.8 eV (red); the peak power of the sun occurs in the yellow region of the visible region, at about 2.5 eV. At high noon on a cloudless day, the surface of the Earth receives 1,000 watts of solar power per square meter (1 kW/m²). Photovoltaic cells generally consist of a light absorber that will only absorb solar photons above a certain minimum photon energy. This minimum threshold energy is called the “energy gap” or “band gap” (E_g); photons with energies below the band gap pass through the absorber, while photons with energies above the band gap are absorbed. The light absorber in PV cells can be either inorganic semiconductors, organic molecular structures, or a combination of both.



In inorganic semiconductor materials, such as Si, electrons (e^-) have energies that fall within certain energy ranges, called bands. The energy ranges, or bands, have energy gaps between them. The band containing electrons with the highest energies is called the valence band. The next band of possible electron energies is called the conduction band; the lowest electron energy in the conduction band is separated from the highest energy in the valence band by the band gap. When all the electrons in the absorber are in their lowest energy state, they fill up the valence band, and the conduction band is empty of electrons. This is the usual situation in the dark. When photons are absorbed, they transfer their energy to electrons in the filled valence band and promote these electrons to higher energy states in the empty conduction band. There are no energy states between the valence and conduction bands, which is why this separation is called a band gap and why only photons with energies above the band gap can cause the transfer of electrons from the lower-energy-state valence band into the higher-energy-state conduction band. When photons transfer electrons across the band gap, they create negative charges in the conduction band and leave behind positive charges in the valence band; these positive charges are called holes (h^+). Thus, absorbed photons in semiconductors create pairs of negative electrons and positive holes. In a PV cell, the electrons and holes formed upon absorption of light separate and move to opposite sides of the cell structure, where they are collected and pass through wires connected to the cell to produce a current and a voltage — thus generating electrical power. In organic molecular structures, the energy of the photons also must first exceed a certain threshold to be absorbed. This absorption creates an energetic state of the molecular system, called an excited state. These excited molecular states can also generate separated electrons and holes.

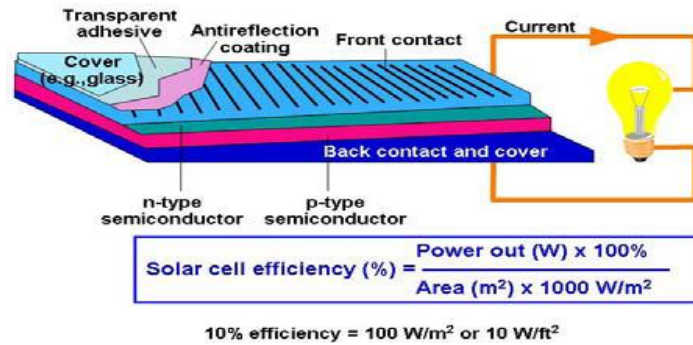
Furthermore, certain organic polymers and other molecular structures can form organic semiconductors that provide the basis for organic PV devices. One difference between inorganic and organic PV cells is that in organic cells, the electrons and holes are initially bound to each other in pairs called excitons; these excitons must be broken apart in order to separate the electrons and holes to generate electricity. In inorganic PV cells, the electrons and holes created by the absorption of light are not bound together and are free to move independently in the semiconductor.

TYPES OF PHOTOVOLTAIC CELLS

All PV cells depend upon the absorption of light, the subsequent formation and spatial separation of electrons and holes, and the collection of the electrons and holes at different energies (called electrical potential). The efficiency of electron and hole formation, separation, and collection determines the photocurrent, and the energy difference between the electrons and holes in their final state before leaving the cell determines the photovoltage. The product of the photocurrent and photovoltage is the electrical power generated; this product, divided by the incident solar irradiant power, determines the efficiency of converting solar power to electrical power. The output power rating of a solar cell is expressed as the peak power (W_p) generated at high noon on a cloudless day.

PV cells can be divided into three categories: (1) inorganic cells, based on solid-state inorganic semiconductors; (2) organic cells, based on organic semiconductors; and (3) photoelectrochemical (PEC) cells, based on interfaces between semiconductors and molecules. The figure shows the structure of an inorganic solar cell based on a sandwich structure of two types of semiconductor material: one type has mobile free negative electrons (called an n-type semiconductor), and the second type has mobile free positive holes (called a p-type semiconductor). The sandwich, called a p-n junction, allows the photogenerated electrons and holes to be separated and transferred to external wires for electrical power production. PV cells have no moving parts and are silent. (Source: Surek 2005)

A Solar Cell Structure



cycle and cloud cover, which produces an average power over a year that is about 1/5 of the peak power rating), the \$/Wp cost figure of merit can be converted to \$/kWh by the following simple relationship: \$1/Wp ~ \$0.05/kWh. This calculation leads to a present cost for grid-connected PV electricity of about \$0.30/kWh. Areas labeled II and III in Figure 2 present the module costs for Generation II (thin-film PV) and Generation III (advanced future structures) PV cells.

Figure 3 presents the historical progress of the best reported solar cell efficiencies to date (Surek 2005). The efficiencies of commercial (or even the best prototype) modules are only about 50– 65% of the efficiency of the best research cells. The plot includes the various PV technologies of single-crystal Si, thin films, multiple-junction cells, and emerging technologies — such as dyesensitized nanocrystalline TiO₂ cells and cells based on organic compounds.

Over the past decades, improvements have also been made in a second important metric, the manufacturing cost of PV modules. The prices of PV modules have followed a historical trend along a so-called “80% learning curve.” That is, for every doubling of the total cumulative production of PV modules worldwide, the price has dropped by approximately 20%. This trend is illustrated in Figure 4 (Surek 2005). These data are based on annual surveys conducted by PV

PHYSICS OF PHOTOVOLTAIC CELLS

Inorganic PV and electrochemical PV (EPV) cells operate upon the establishment of an electric potential difference between the n- and p-type regions in an inorganic PV cell or between an n- or p-type semiconductor and redox electrolyte, in the case of an EPV cell. This difference creates an electrical diode structure. The current-voltage behavior of such junctions follows the diode equations, in which the current flow in one direction across the junction is constant with voltage, whereas the current flow in the other direction across the junction increases exponentially with the applied voltage. Hence, the dark current density (J_{dark} [amps/cm²]), as a function of the voltage (V) applied to this diode (assuming ideal diode behavior), is:

$$J_{\text{dark}}(V) = J_0(e^{qV/kT} - 1) \quad (1)$$

where J_0 is a constant, q is electronic charge, k is Boltzman’s constant, and T is temperature (K).

If a diode is illuminated, additional charge carriers will be created upon absorption of the light. These carriers will create an additional current flow across the junction, and they must be added to the dark current to obtain the total current in the system. For illumination with light comprising many different wavelengths, the total photo-induced current can be calculated by summing (i.e., integrating) the contributions to the current from excitation at each wavelength. Hence, the short-circuit photocurrent density (J_{sc}) is:

$$J_{\text{sc}} = q \int I_s(E) (QY)(E) dE \quad (2)$$

where I_s = solar photon flux, E = photon energy (inversely proportional to the wavelength of the photon), and QY = quantum yield (electrons collected per incident photon).

The net current density (J) is:

$$J(V) = J_{sc} - J_{dark}(V) = J_{sc} - J_0(e^{qV/kT} - 1) \quad (3a)$$

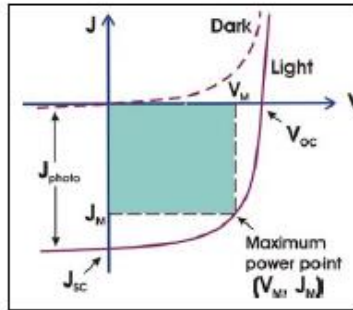
However, ideal diode behavior is seldom seen. This is accounted for by introducing a non-ideality factor, m , into Equation 3a:

$$J(V) = J_{sc} - J_{dark}(V) = J_{sc} - J_0(e^{qV/mkT} - 1) \quad (3b)$$

Because no current flows at open circuit, the open-circuit voltage (V_{oc}) for the ideal device is obtained by setting $J(V) = 0$,

$$V_{oc} = [kT/q] \ln [(J_{sc}/J_0) + 1] \quad (4)$$

A plot of the net photocurrent density (J) vs. voltage is provided in the figure, which shows the current-voltage characteristic of a PV cell.



The conversion efficiency (η) of the PV cell is determined by the maximum rectangle in the figure that can fit within the net photocurrent-voltage characteristic. The maximum power point of the cell, or so-called operating point, is the values of J and V (J_m and V_m) at which the maximum rectangle in the figure meets the J - V curve. This defines a term called the “fill factor” (FF) $FF = J_m V_m / J_{sc} V_{oc}$ (5) that characterizes the “squareness” of the J - V characteristic. The maximum FF value is 1.0; it occurs when $J_m = J_{sc}$ and $V_m = V_{oc}$, but in reality, the diode

equation limits the maximum FF to 0.83. The cell conversion efficiency is the electrical power density ($J_m V_m$) (watts/cm²) divided by the incident solar power density (P_{sun}), multiplied by 100 to obtain a percent value.

$$\eta = J_m V_m / P_{sun} = 100 * J_{sc} V_{oc} FF / P_{sun}$$

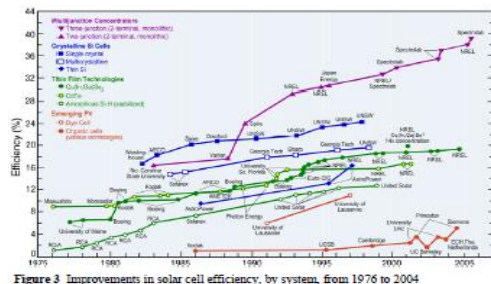


Figure 3 Improvements in solar cell efficiency, by system, from 1976 to 2004

News (PV Energy Systems 2004). The final data point for 2003 corresponds to about \$3.50/Wp and a cumulative PV capacity of 3 GW. An important issue, in terms of future projections, is how this price-reduction trend will continue in the future. As Figure 4 shows, a major reduction in the projected future cost of PV modules depends upon the introduction of thin films, concentrator systems, and new technologies. The third significant metric for PV cells is module reliability. Today, most crystalline Si module manufacturers offer warranties of 25 years, typically guaranteeing that the power output of the module will not decrease by more than 20% over this period. Further details about the current status of solar electricity technologies, costs, and implementation can be found in the Solar Electric Technology Assessment in Appendix 1.

Need for Revolution on Existing Technology Path

Since the 1970s, the PV industry has continually reduced the cost of solar electricity. Over the past three decades, the cost of PV modules has decreased at a rate of 20% for each doubling of module production (see Figure 4). The cost of PV modules per peak watt has declined from about \$70/Wp in 1976 to about \$3.50/Wp in 2003. The BOS cost (support structures, maintenance, land, etc.) for a grid-tied PV system is

Needs of Concentrator Cell Technology. A third strategy would reduce costs by using inexpensive optics to concentrate the light on small-area solar cells. Four recent achievements/developments provide a foundation and momentum:

- (1) An efficiency of 37.9% has been obtained, with possible pathways to higher efficiencies.
- (2) Lattice mismatched III-V solar cells with performance approaching the radiative limit have been demonstrated, implying that such cells may reach efficiencies in the 40–50% range.
- (3) A 1-kW multi-junction concentrator system is now supplying electricity to the grid, paving the way for larger prototypes and manufacturing; and
- (4) In 2004, installations with sizes >100 kW increased to 20 MW, implying that a market appropriate for concentrators may be emerging.

Taken together, these recent developments imply that concentrator cell technology may be poised for rapid growth. Key to this growth is the integration of multiple materials for fabrication of higher-efficiency solar cells.

Inorganic Photovoltaics

As shown in Figure 2, single-crystal Si solar cells, defined as Generation I cells, have module efficiencies of about 10–12% — leading to module costs of about \$3.50/Wp. In order to lower the areal cost, Generation II approaches to PV systems involve the use of semiconductor thin films (amorphous Si, polycrystalline CdTe and CuInSe₂, dye cells, and organic PV cells). However, the system cost will be limited by BOS costs, which means that the Generation II systems cannot have arbitrarily low efficiency even if the module costs are negligible. With low areal costs for both modules and BOS of \$75/m² each, 10% efficiency for Generation II modules (17% cell efficiency) would yield PV costs of \$1.50/Wp (\$0.075/kWh). Thus, unless the module and BOS costs can be reduced well beyond the aggressive target of \$75/m² each, achieving the goal of \$0.40/Wp (\$0.02/kWh) will require efficiency and system costs per unit area that lie in the Generation III area of Figure 2. A critical feature of Generation III PV systems is that their module efficiencies are above 32% — the thermodynamic limit calculated by Shockley and Queisser (1961). In the Shockley- Queisser analysis, a major assumption is that electrons and holes created by absorption of photons with energies above the band gap lose their excess energy (the difference between the photon energy and the semiconductor band gap) as heat through excitation of the lattice vibrations (this is called phonon emission). However, thermodynamic calculations that do not make this assumption show that the thermodynamic efficiency limit can be above 65% if the energetic electrons and holes created by the high-energy photons do not convert the excess energy to heat but produce higher photovoltages or photocurrents (Green 2004; Ross and Nozik 1982; Marti and Luque 2004). Reaching the goals of ultra-high efficiencies and low cost will require basic research to achieve the revolutionary advances indicated in Figure 5. Another way to achieve efficiencies above the Shockley-Queisser limit is to use a series of semiconductor p-n junctions arranged in a tandem configuration (these cells are called multijunction solar cells). Of the approaches proposed to achieve higher efficiency, only multijunction solar cells have been able to actually exceed the performance of conventional singlejunction solar cells. Figure 6 shows the current world-record efficiencies (as a function of the number of junctions) compared with the efficiency limit that is predicted by the thermodynamic analyses. At one sun, the single-junction efficiency is about 75% of the theoretical limit; the multi-junction and concentrator cells show even more opportunity for improvement. The thermodynamic limit for solar-energy conversion is significantly higher still: 66% at one sun and 86% at full solar concentration (46,200 suns).

Organic Photovoltaics

Solid-state PV cells based on carbonaceous (organic) matter were first discovered 20 years ago (Tang 1986). Early work on organic photovoltaics using molecular-based systems demonstrated the concept; however energy conversion efficiencies were low. Considerable excitement in this area was generated by a report published in the mid-1990s of 2.9%-efficient cells based on conducting organic polymers mixed with derivatives of C₆₀ (fullerene) (Yu et al. 1995). During the past decade, refinements in the chemical

components of the cells, improvements in cell physics, and device engineering have led to individual demonstration cells that operate at greater than 5% solar-to-electrical-power conversion efficiency. The opportunities and potential payoff here are significant: low-cost, lightweight, large-area, flexible, high-efficiency solar cells. The materials are basically like those used in video display technology, and they offer the possibility of very significant cost reduction, as well as flexibility in installation, form factor, etc.

The basic principle of operation in an organic PV cell is that illumination of a mixture of electron-rich (donor) and electron-poor (acceptor) species leads to separation of (+) and (-) charge carriers. Collection of these carriers at electrodes produces an electrical current that can do work on a load in an external circuit. Although the basic principles behind the operation of organic PV cells and conventional p-n junction cells are similar, the details of key events, such as charge carrier generation and charge transport, are very different in the organic cells. Consequently, the basic understanding of the physics and chemistry of organic PV systems lags behind that of conventional p-n junction devices. The molecules and materials from which these devices are made vary considerably, with polymers, organic molecules, inorganic molecules, quantum dots, and other nanostructures all contributing equally to the field. The large array of options provides ample scope for researchers to develop novel solutions for improving device performance. Despite the promise of photovoltaics based on organics, significant challenges must be overcome to develop molecular structures and cells that operate efficiently and are stable for long-term operation under one-sun solar conditions. Four key areas that need to be explored are outlined below.

Photon Energy Management in Organic and Hybrid Photovoltaic Devices. Current state-of-the-art organic and hybrid PV cells produce a photovoltage that is considerably less than is feasible on the basis of thermodynamic principles. Solving this problem should lead directly to a threefold increase in overall cell efficiency. Although recent investigations have shed some light on the reasons for the low photovoltage, researchers lack a clear understanding of the factors that control this parameter. Basic science investigations are needed to correlate the chemical and physical properties of the active layers with their performance in operating PV devices. Sustained work in this area could have a substantial payoff in improved cell efficiency. *Organic and Hybrid Photovoltaic Layers and Cell Architectures.* Organic-inorganic hybrid layers will provide opportunities for the use of different building blocks in the fabrication of PV cells, allowing researchers to combine the best properties of organic and inorganic structures. The fabrication methods developed could allow the assembly of high-efficiency tandem device structures to extract energy from the different wavelengths of sunlight, thereby leading to a substantial improvement in solar-to-electrical energy conversion. More complex fabrication techniques may also allow the integration of photonic structures to allow wavelength shifting and optical field concentration, which would also lead to substantial increases in cell efficiencies. The light-absorbing and semiconducting properties of quantum structures (e.g., nanoparticles, nanorods, and more complex structures), combined with the range of properties accessible with organic semiconducting polymers, afford new active layers for PV cells that could enhance efficiency. Fabrication methods, such as novel vapor deposition techniques, and solution processing methods, such as layer-by-layer deposition, could allow construction of layers and structures with precise control over the three-dimensional architecture of the active components.

Chemical Discovery and Synthesis. Improved molecular, polymer, and nanocrystal building blocks are needed to address such issues as (1) light harvesting across the visible and nearinfrared spectrum, (2) electron donor and acceptor properties, (3) electronic (semiconducting) properties, (4) charge transport in the solid state, and (5) nonlinear optical properties. While many materials are already available, systematic chemical discovery and synthesis are needed to broaden the scope of materials and to allow the development of improved synthetic methods to lower costs and improve purity.

Properties of Organic and Hybrid Photovoltaic Structures. Many basic science questions need to be addressed to better understand the fundamental steps involved in energy conversion in organic and hybrid systems. First, the morphology of the solid-state PV film needs to be defined, then researchers need to develop an understanding of the relationship between the morphology and the structure of the building blocks, the nature of the substrate, and the deposition method used to fabricate the film. Physical methods are needed to elucidate the thermodynamics and dynamics of the fundamental steps of light absorption and exciton generation, charge carrier generation, and charge carrier diffusion to the collector

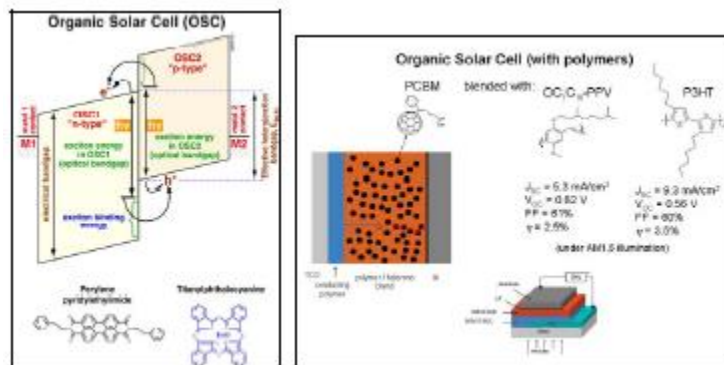
electrodes. To obtain cells that are durable enough for long-term use, photostability and photochemical degradation pathways need to be improved. Achieving the long-term objective of an organic PV solar cell with a power conversion efficiency that approaches 50% will require solar cells that can extract more of the photon energy available within the solar spectrum. This can be achieved through one of two methods:

- (1) A device architecture designed to match individual solar photons, such as the tandem solar cell (see Figure 8);
- (2) Up-conversion or down-conversion of the solar photons to match an existing single-junction PV design (see Figure 9).

While the first method requires specific design characteristics of the PV structures to have absorption profiles that match the solar spectrum, combined with balanced charge-carrier transport properties, the second requires control of the material to efficiently shift the photon frequencies. An intrinsic feature of the organic solar cell is the diversity of interfaces; either between dissimilar organic materials acting as the photo conversion layer; with the contact electrodes, where transparency and good ohmic contact are essential; or between multiple layers in a tandem design, where carrier annihilation must be facilitated. These features provide additional challenges that can be met through molecular design and an understanding of electronic interactions at an interface.

ORGANIC PV CELLS

Organic solar cells also operate with junctions, but the n-type and p-type semiconductors are organic compounds, and the interfacial junction between the n- and p-type regions does not produce an electric field and serves a different purpose than the inorganic p-n junctions. Furthermore, when electrons and holes are produced upon light absorption in organic solar cells, the negative electrons and positive holes become bound to one another through strong attractive electrical forces and form coupled electron-hole pairs, which have been labeled excitons. These excitons have no net electrical charge and cannot carry current — they must be broken apart, or dissociated, in order to produce the free electrons and holes required in the cell to produce electrical power. This is the function of the junction between the n- and p-type organic compounds — when the excitons diffuse to this region of the cell, they split apart and produce the required free electrons and holes. Also, organic solar cells have electrical contacts with different electronic properties. The organic components of the n- and p-type regions of the organic solar cells can be either molecular semiconductors (like an n-type perylene and a p-type phthalocyanine) or semiconducting polymers (like a p-type polyphenylvinylidene or polythiophene and an n-type fullerene). The figures show the PV cell with both types of organic components and their corresponding chemical structures.



light energy directly into fuel eliminates the need for external wires and a separate electrolyzer. The PEC approach to solar energy conversion has achieved high efficiencies for both electrical power (>15%) and hydrogen generation (>10%). However, photoelectrode lifetime and cost issues have restricted commercialization efforts to date (Memming 2001; Bard et al. 2002; Nozik and Memming 1996). The electric field formed by the junction at the semiconductor-electrolyte interface plays a large role in efficiently separating the electron-hole pairs created by light absorption. When electrons or holes cross the interface between the semiconductor and the electrolyte, they can drive chemical oxidation or reduction half-reactions at the semiconductor surface to produce either fuels (e.g., hydrogen, reduced

carbon, ammonia) or, in a regenerative photovoltaic configuration, DC electrical power. In the latter case, termed an electrochemical photovoltaic (EPV) cell, the oxidation and reduction half-reactions at the two cell electrodes are the inverse of one another, thus producing no net change in the electrolyte. In the former case, the oxidation and reduction half-reactions at the two electrodes are different, and their sum produces a net chemical change in the electrolyte (e.g., decomposition of water into H₂ and O₂).

One critical property of the photoactive material in either a PV or a PEC system is the minority carrier diffusion length (i.e., the distance that electrons or holes created upon light absorption can travel in the structure before they recombine to produce heat). If the minority carrier diffusion length is too short, photogenerated carriers cannot reach the interface to drive the desired reactions and produce output power in the form of electricity or fuels. This is the basic limitation of cheap absorbers: because they have a large concentration of impurities and defects, and therefore have a short minority carrier diffusion length, they generally produce PV cells with low efficiencies. However, the development of nanoscale materials has rescaled the diffusion length requirements, because the minority carrier diffusion length need only be comparable to the dimensions of the sub-units of the nanostructured device (typically a few tens of nanometers).

The liquid contact in PEC systems is ideally suited for nanostructured devices, guaranteeing complete filling of the gaps within the porous structures. The goal is to improve the efficiency of such systems by a factor of 2–3, while ensuring stability and robust performance for periods of years in sunlight under maximum load conditions. Another key advantage of PEC cells is that they naturally offer the opportunity to integrate the energy conversion and storage functions. Photoelectrochemical cells have been shown to directly split water into H₂ and O₂, thereby providing a basis for the renewable, clean production of hydrogen from sunlight. The materials can be cheap polycrystalline forms, because of the relaxed requirements on the minority carrier diffusion length. However, the known materials, which are robust in water splitting, are not responsive to a wide portion of the solar radiation spectrum; they work best in the ultraviolet (UV) — yielding relatively low efficiencies at the surface of the Earth. Finding new photoelectrodes, either individually or in combination, that can allow the efficient, integrated conversion of sunlight to chemical fuels is one of the primary aims of solar energy conversion research. The goal is to identify PEC systems that display the same efficiency and stability for visible-light-induced water splitting as those demonstrated for near-UV-light-induced water splitting. Closing this gap will lead to the development of cheap and efficient systems that, in an integrated fashion, could produce chemical fuels (e.g., hydrogen) directly from sunlight and therefore directly address, not only the conversion, but also the storage issues, associated with solar energy conversion schemes. These examples illustrate the central role played by nanostructured systems in the renaissance of PEC systems, which are poised to make an important contribution to solar energy conversion and storage. Additional basic scientific research will support the development of improvements in the existing nanostructured cell and photoelectrolysis approaches and will also support the discovery of disruptive technologies that can dramatically accelerate progress toward high-efficiency solar photon conversion technologies at low cost.

UNIT V - SOLAR-CONSCIOUS BUILDINGS

ORIENTATION AND DESIGN OF BUILDINGS:

Orientation is simply what compass direction the building faces. Does it face directly south? 80° east-northeast?

Along with massing, orientation can be the most important step in providing a building with passive thermal and visual comfort. Orientation should be decided together with massing early in the design process, as neither can be truly optimized without the other.

Orientation is measured by the azimuth angle of a surface relative to true north. Successful orientation rotates the building to minimize energy loads and maximize free energy from the sun and wind. Successful orientation can also take advantage of other site conditions, such as rainwater harvesting driven by prevailing winds. It can even help the building contribute to the health and vitality of the

surrounding social, and economic communities, by orienting courtyards or other social spaces to connect to street life.

ORIENTATION FOR VISUAL COMFORT:

As with massing for visual comfort, buildings should usually be oriented east-west rather than north-south. This orientation lets you consistently harness daylight and control glare along the long faces of the building. It also lets you minimize glare from the rising or setting sun.

If the building has cutouts to maximize daylighting, the orientations of these cutouts should also be chosen to maximize north and south walls. With good building massing, such cutouts can also act as their own shading to prevent glare.

Orientation for Thermal Comfort: Solar Heat Gain

Different faces of the building get very different amounts of heat from the sun. As with massing, orientation for thermal comfort is similar to orientation for daylighting, with some exceptions:

- First, the amount of sunlight that is optimal for daylighting is often not optimal for solar heat gain.
- Second, since the sun's heat does not come from all directions like the sun's light can, walls facing away from the sun's path get no heat gain, even though they can still get large amounts of diffuse light.
- Third, the sun's heat can be stored by thermal mass, which the sun's light cannot. This can be useful for west-facing walls to store heat for the night.

With BIM, you can quantify the amount of incident solar radiation that strikes each face of your building, and visualize it by overlaying an analysis grid on the building model.

To optimize your design, you can choose to analyze the solar radiation on a single day (like the summer solstice) or over multiple days (like the entire year). To understand the maximum loads you'll have to design for, you'll want to look at the peak solar radiation. To get a sense for how much total solar energy is available for direct-gain passive solar heating, you'll want to estimate the cumulative solar radiation on the building's face.

To do detailed design for glazing and façade, it's important to understand the patterns of solar radiation that affect the building. The following image shows solar incident radiation throughout the day and throughout the year on the five exposed faces of a cube-shaped building. The vertical axis shows times of day while the horizontal axis shows times of year, and the color shows the amount of incident heat.

This graph shows how thermal heat gain on the east and west sides of buildings change rapidly as the sun moves through the day, while northern and southern exposures are more consistent.

Thus, buildings that are longer than they are wide should usually be oriented east-west rather than north-south. This orientation lets you consistently harness thermal gain, or consistently avoid it, along the long face of the building. It also lets you minimize the area that's subject to faster energy swings from the rising or setting sun. Solar heat gain on the east side can be acceptable or even useful, because it happens in the morning after the cooler night; but solar heat gain on the west side is rarely desirable at the end of an already warm day.

PASSIVE SOLAR BUILDING DESIGN:

In passive solar building design, windows, walls, and floors are made to collect, store, and distribute solar energy in the form of heat in the winter and reject solar heat in the summer. This is called passive solar design because, unlike active solar heating systems, it does not involve the use of mechanical and electrical devices. The key to design a passive solar building is to best take advantage of the local climate performing an accurate site analysis. Elements to be considered include window placement and size, and glazing type, thermal insulation, thermal mass, and shading.^[2] Passive solar design techniques can be applied most easily to new buildings, but existing buildings can be adapted or "retrofitted".

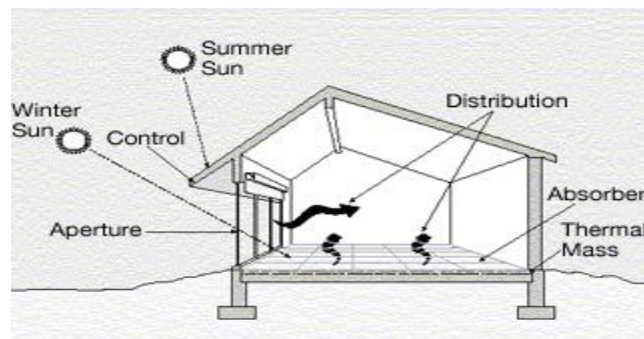
Passive energy gain:

Passive solar technologies use sunlight without active mechanical systems (as contrasted to active solar). Such technologies convert sunlight into usable heat (in water, air, and thermal mass), cause air-movement for ventilating, or future use, with little use of other energy sources. A common example is a solarium on the equator-side of a building. Passive cooling is the use of the same design principles to reduce summer cooling requirements.

Some passive systems use a small amount of conventional energy to control dampers, shutters, night insulation, and other devices that enhance solar energy collection, storage, and use, and reduce undesirable heat transfer.

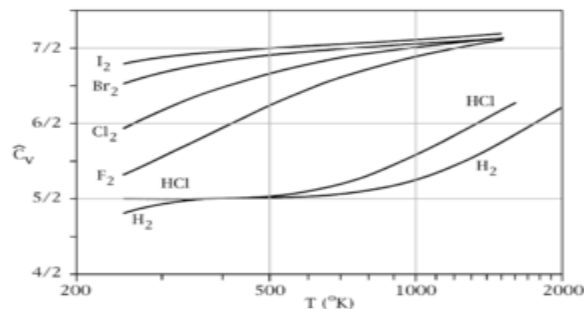
Passive solar technologies include direct and indirect solar gain for space heating, solar water heating systems based on the thermosiphon, use of thermal mass and phase-change materials for slowing indoor air temperature swings, solar cookers, the solar chimney for enhancing natural ventilation, and earth sheltering.

More widely, passive solar technologies include the solar furnace, but this typically requires some external energy for aligning their concentrating mirrors or receivers, and historically have not proven to be practical or cost effective for widespread use. 'Low-grade' energy needs, such as space and water heating, have proven over time to be better applications for passive use of solar energy.



THERMAL CAPACITY:

Heat capacity or thermal capacity is a measurable physical quantity equal to the ratio of the heat added to (or removed from) an object to the resulting temperature change. Specific heat is the amount of heat needed to raise the temperature of one kilogram of mass by 1 kelvin.



Heat capacity is an extensive property of matter, meaning that it is proportional to the size of the system. When expressing the same phenomenon as an intensive property, the heat capacity is divided by the amount of substance, mass, or volume, thus the quantity is independent of the size or extent of the sample. The molar heat capacity is the heat capacity per unit amount (SI unit: mole) of a pure substance, and the specific heat capacity, often called simply specific heat, is the heat capacity per unit mass of a material. Nonetheless some authors use the term specific heat to refer to the ratio of the specific heat capacity of a substance at any given temperature to the specific heat capacity of another substance at a

reference temperature, much in the fashion of specific gravity. In some engineering contexts, the volumetric heat capacity is used.

Temperature reflects the average randomized kinetic energy of constituent particles of matter (i.e., atoms or molecules) relative to the centre of mass of the system, while heat is the transfer of energy across a system boundary into the body other than by work or matter transfer. Translation, rotation, and vibration of atoms represent the degrees of freedom of motion which classically contribute to the heat capacity of gases, while only vibrations are needed to describe the heat capacities of most solids as shown by the Dulong–Petit law. Other contributions can come from magnetic and electronic degrees of freedom in solids, but these rarely make substantial contributions.

INSULATION:

. **Insulation** may refer to:

- Thermal insulation, materials used to reduce the rate of heat transfer
- Building insulation, thermal insulation added to buildings for comfort and energy efficiency
- Insulated glazing, a thermally insulating window construction
- Insulator (electricity), the use of material to resist the electric current and magnetism
- Soundproofing, also known as acoustic insulation, any means of reducing the intensity of sound

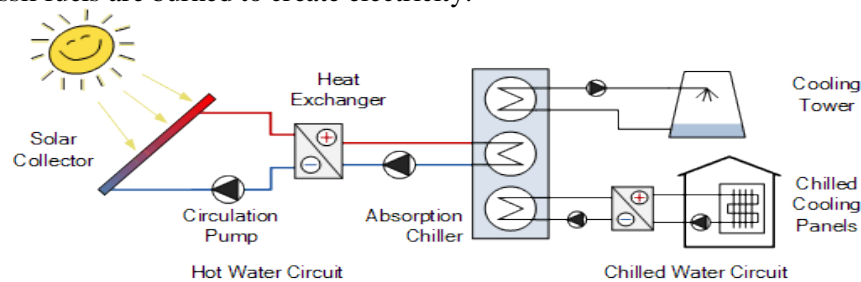
SOLAR COOLING:

What is solar cooling?

Solar air conditioning refers to any air conditioning (cooling) system that uses solar power. This can be done through passive solar, solar thermal energy conversion and photovoltaic conversion (sunlight to electricity).

How Does Solar Cooling Work?

Concentrating solar collectors use mirrors to focus the sun's energy on a tube containing fluid. The mirrors follow the sun, heating the fluid to very high temperatures. Absorption chillers operate by using this solar-heated fluid, rather than fossil fuels or electricity, to drive the refrigeration process. Using solar energy with absorption chillers reduces site-generated greenhouse gases as well as the emissions created when fossil fuels are burned to create electricity.



There are multiple alternatives to compressor-based chillers that can reduce energy consumption, with less noise and vibration. Solar thermal energy can be used to efficiently cool in the summer, and also heat domestic water and buildings in the winter. Single, double or triple iterative absorption cooling cycles are used in different solar thermal cooling system designs. The more cycles, the more efficient these systems are.

SOLAR COOLING REFRIGERATION:

What is solar refrigeration?

The solar refrigerator is the refrigeration system that runs on the solar energy. They don't use domestic power supply, rather use power produced by the solar panels.

A solar-powered refrigerator is a refrigerator which runs on energy directly provided by sun, and may include photovoltaic or solar thermal energy.

Solar-powered refrigerators are able to keep perishable goods such as meat and dairy cool in hot climates, and are used to keep much needed vaccines at their appropriate temperature to avoid spoilage.

Solar-powered refrigerators are typically used in off-the-grid locations where utility provided AC power is not available.

Technology and Use

Solar powered refrigerators are characterized by thick insulation and the use of a DC (not AC) compressor. Traditionally solar-powered refrigerators and vaccine coolers use a combination of solar panels and lead batteries to store energy for cloudy days and at night in the absence of sunlight to keep their contents cool. These fridges are expensive and require heavy lead-acid batteries which tend to deteriorate, especially in hot climates, or are misused for other purposes. In addition, the batteries require maintenance must be replaced approximately every three years, and must be disposed of as hazardous wastes possibly resulting in lead pollution. These problems and the resulting higher costs have been an obstacle for the use of solar powered refrigerators in developing areas.

In the mid-1990s NASA JSC began work on a solar powered refrigerator that used phase change material rather than battery to store "thermal energy" rather than "chemical energy." The resulting technology has been commercialized and is being used for storing food products and vaccines.

Solar-powered refrigerators and other solar appliances are commonly used by individuals living off-the-grid. They provide a means for keeping food safe and preserved while avoiding a connection to utility-provided power. Solar refrigerators are also used in cottages and camps as an alternative to absorption refrigerators, as they can be safely left running year-round. Other uses include being used to keep medical supplies at proper temperatures in remote locations, and being used to temporarily store game at hunting camps.

SOLAR AIR CONDITIONING:

Solar air conditioning refers to any air conditioning (cooling) system that uses solar power.

This can be done through passive solar, solar thermal energy conversion and photovoltaic conversion (sunlight to electricity). The U.S. Energy Independence and Security Act of 2007^[1] created 2008 through 2012 funding for a new solar air conditioning research and development program, which should develop and demonstrate multiple new technology innovations and mass production economies of scale. Solar air conditioning might play an increasing role in zero-energy and energy-plus buildings design

Photovoltaic (PV) solar cooling

Photovoltaics can provide the power for any type of electrically powered cooling be it conventional compressor-based or adsorption/absorption-based, though the most common implementation is with compressors. For small residential and small commercial cooling (less than 5 MWh/a) PV-powered cooling has been the most frequently implemented solar cooling technology. The reason for this is debated, but commonly suggested reasons include incentive structuring, lack of residential-sized equipment for other solar-cooling technologies, the advent of more efficient electrical coolers, or ease of installation compared to other solar-cooling technologies (like radiant cooling).

Since PV cooling's cost effectiveness depends largely on the cooling equipment and given the poor efficiencies in electrical cooling methods until recently it has not been cost effective without subsidies. Using more efficient electrical cooling methods and allowing longer payback schedules is changing that scenario.

For example, a 100,000 BTU U.S. Energy Star rated^[note 1] air conditioner with a high seasonal energy efficiency ratio (SEER) of 14 requires around 7 kW of electric power for full cooling output on a hot day. This would require over a 20 kW solar photovoltaic electricity generation system with storage.

A solar-tracking 7 kW photovoltaic system would probably have an installed price well over \$20,000 USD (with PV equipment prices currently falling at roughly 17% per year). Infrastructure, wiring, mounting, and NEC code costs may add up to an additional cost; for instance a 3120 watt solar panel grid tie system has a panel cost of \$0.99/watt peak, but still costs ~\$2.2/watt hour peak. Other systems of different capacity cost even more, let alone battery backup systems, which cost even more.

A more efficient air conditioning system would require a smaller, less-expensive photovoltaic system. A high-quality geothermal heat pump installation can have a SEER in the range of 20 (\pm). A 100,000 BTU SEER 20 air conditioner would require less than 5 kW while operating.

SPACE HEATING:

A space heater is a device for heating an enclosed area. Space heating is generally employed to warm a small space, and is usually held in contrast with central heating, which warms many connected spaces at once.

What is solar space heating system?

Solar space heating systems are an effective and excellent way to reduce costly energy bills during your heating season. A solar space heater works alongside your current heating system to use the sun's energy to reduce your consumption of oil, propane, or other fossil fuels.

Definition of space heating

Heating of spaces especially for human comfort by any means (such as fuel, electricity, or solar radiation) with the heater either within the space or external to it.

How does space heating work?

Gas space heaters work by passing cold air over a heat exchanger, which is warmed by gas combustion. The warmed air is then pushed through a vent into the room.

A thermostat is installed inside the heater. This senses the air temperature inside the room and sends a signal to the heater to turn on or off, or turn up or down.

Unlike unflued gas heaters, which increase the level of pollutants in the home, Braemar space heaters are flued, so exhaust gases are expelled outside. With unflued heating doors or windows must be kept open to expel polluted air, but with Braemar's flued heaters you can keep doors and windows closed and eliminate cold draughts.

sensible and latent heat energy storage in buildings

Latent heat

Latent heat is energy released or absorbed, by a body or a thermodynamic system, during a constant-temperature process.

The term was introduced around 1762 by British chemist Joseph Black. It is derived from the Latin *latere* (*to lie hidden*). Black used the term in the context of calorimetry where a heat transfer caused a volume change while the thermodynamic system's temperature was constant.

In contrast to latent heat, sensible heat involves an energy transfer that results in a temperature change of the system.

Usage

The terms "sensible heat" and "latent heat" are specific forms of energy; they are two properties of a material or in a thermodynamic system. "Sensible heat" is a body's internal energy that may be "sensed" or felt. "Latent heat" is internal energy concerning the phase (solid / liquid / gas) of a material and does not affect the temperature.

Both sensible and latent heats are observed in many processes of transport of energy in nature. Changes of Latent heat is associated with the change of phase of atmospheric

water, vaporization and condensation, whereas sensible heat is energy that reflects the temperature of the atmosphere or ocean, or ice.

The original usage of the term, as introduced by Black, was applied to systems that were intentionally held at constant temperature. Such usage referred to *latent heat of expansion* and several other related latent heats. These latent heats are defined independently of the conceptual framework of thermodynamics.

When a body is heated at constant temperature by thermal radiation in a microwave field for example, it may expand by an amount described by its *latent heat with respect to volume* or *latent heat of expansion*, or increase its pressure by an amount described by its *latent heat with respect to pressure*. Latent heat is energy released or absorbed, by a body or a thermodynamic system, during a constant-temperature process. Two common forms of latent heat are latent heat of fusion (melting) and latent heat of vaporization (boiling). These names describe the direction of energy flow when changing from one phase to the next: from solid to liquid, and liquid to gas.

In both cases the change is endothermic, meaning that the system absorbs energy. For example, when water evaporates, energy is required for the water molecules to overcome the forces of attraction between them, the transition from water to vapor requires an input of energy.

If the vapor then condenses to a liquid on a surface, then the vapor's latent energy absorbed during evaporation is released as the liquid's sensible heat onto the surface.

The large value of the enthalpy of condensation of water vapor is the reason that steam is a far more effective heating medium than boiling water, and is more hazardous.

Specific latent heat

A *specific* latent heat (L) expresses the amount of energy in the form of heat (Q) required to completely effect a phase change of a unit of mass (m), usually 1kg, of a substance as an intensive property:

Intensive properties are material characteristics and are not dependent on the size or extent of the sample. Commonly quoted and tabulated in the literature are the specific latent heat of fusion and the specific latent heat of vaporization for many substances.

From this definition, the latent heat for a given mass of a substance is calculated by

where:

Q is the amount of energy released or absorbed during the change of phase of the substance (in kJ or in BTU),

m is the mass of the substance (in kg or in lb), and

L is the specific latent heat for a particular substance (kJ kg^{-1} or in BTU lb^{-1}), either L_f for fusion, or L_v for vaporization.

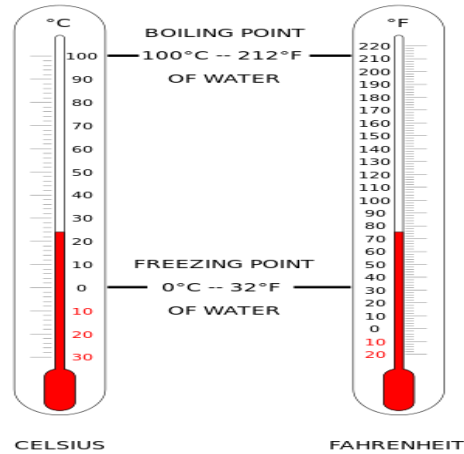
Sensible heat

Sensible heat is heat exchanged by a body or thermodynamic system in which the exchange of heat changes the temperature of the body or system, and some macroscopic variables of the body or system, but leaves unchanged certain other macroscopic variables of the body or system, such as volume or pressure

Usage

The term is used in contrast to a latent heat, which is the amount of heat exchanged that is hidden, meaning it occurs without change of temperature. For example, during a phase change such as the melting of ice, the temperature of the system containing the ice and the liquid is constant until all ice has melted. The terms latent and sensible are correlative. That means that they are defined as a pair, depending on which other macroscopic variables are held constant during the process.

The sensible heat of a thermodynamic process may be calculated as the product of the body's mass (m) with its specific heat capacity(c) and the change in temperature.



Sensible heat and *latent heat* are not special forms of energy. Rather, they describe exchanges of heat under conditions specified in terms of their effect on a material or a thermodynamic system.

In the writings of the early scientists who provided the foundations of thermodynamics, sensible heat had a clear meaning in calorimetry. James Prescott Joule characterized it in 1847 as an energy that was indicated by the thermometer.^[5]

Both sensible and latent heats are observed in many processes while transporting energy in nature. Latent heat is associated with changes of state, measured at constant temperature, especially the phase changes of atmospheric water vapor, mostly vaporization and condensation, whereas sensible heat directly affects the temperature of the atmosphere.

In meteorology, the term 'sensible heat flux' means the conductive heat flux from the Earth's surface to the atmosphere.^[6] It is an important component of Earth's surface energy budget. Sensible heat flux is commonly measured with the eddy covariance method.