REET 2020

Energy Conversion

2 – Solar Energy

Solar Energy

<u>Solar energy</u> is considered a form of renewable or sustainable energy because it will be available as long as the sun continues to shine.

Solar technologies can harness this energy for a variety of uses, including generating electricity and heating water for domestic, commercial, or industrial use.

Solar energy is the considered the cleanest and most abundant renewable energy source available because it is available at all inhabited places on the Earth.

Solar Energy

The energy that we receive from the sun is produced by a nuclear reaction that continuously occurs within the sun's core, a by-product of which is a massive release of energy as hydrogen atoms fuse together to form helium.

The energy radiates outward toward the surface of the Sun and then into the solar system beyond it, a portion of which reaches the Earth in about 8.3 minutes.

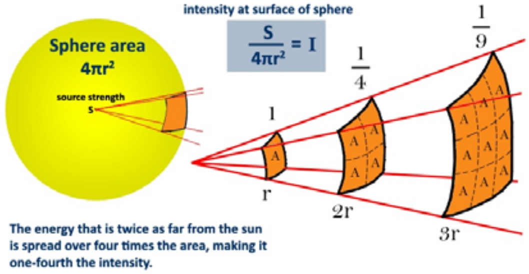
Although the Sun radiates energy at a rate of 3.846×10^{26} J/s, only a small portion actually reaches the Earth.

https://phys.org/news/2015-12-sun-energy.html

Energy Available From the Sun

The Sun radiates energy evenly in all directions.

As the energy travels, it spreads out symmetrically, causing the intensity of the energy to decrease proportionally to the inverse of the distance^2.



http://www.geog.ucsb.edu/ideas/Insolation.html#solardeclination

Solar Energy

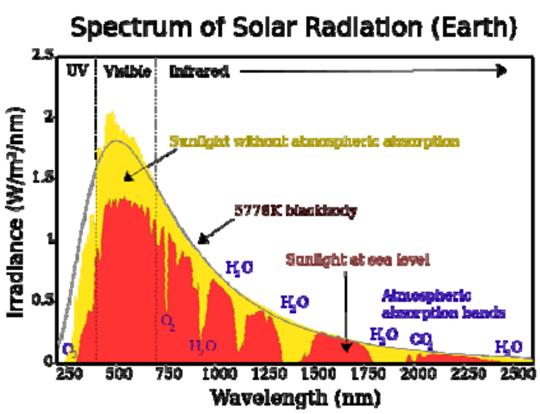
Solar energy reaches the earth in the form of electromagnetic radiation. As humans, we perceive this as “sunlight”.

The energy that reaches the Earth is characterized by its <u>insolation</u>, which is a measure of the solar energy that is incident on a specified area over a set period of time.

Yet, there are a variety of factors that can affect this value, including the position on the Earth (both latitude and altitude), the time of day, the day of the year, and the weather conditions.

Sunlight

The energy from the sun reaches the earth in the form of electromagnetic radiation, the spectrum of which is:



https://en.wikipedia.org/wiki/Sunlight

This spectrum accounts for around 96.3% of the sun’s energy that reaches the Earth, with the remaining 3.7% resulting from shorter and longer wavelengths.

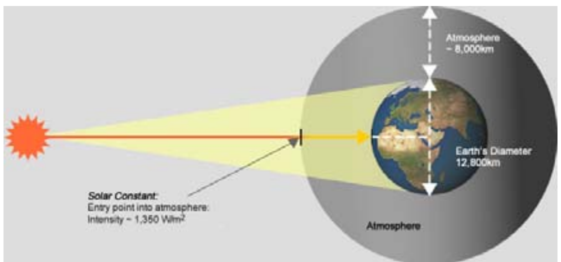
https://www.newport.com/t/introduction-to-solar-radiation

Energy Available From the Sun

When the Sun's energy reaches the Earth's atmosphere, the intensity of the energy is around 1367 W/m^2.

This value is known as the Solar Constant.

Note that this energy value varies by about 6.6% depending on the day of the year and by about 1% due to variations in solar activity.



http://www.geog.ucsb.edu/ideas/Insolation.html#solardeclination

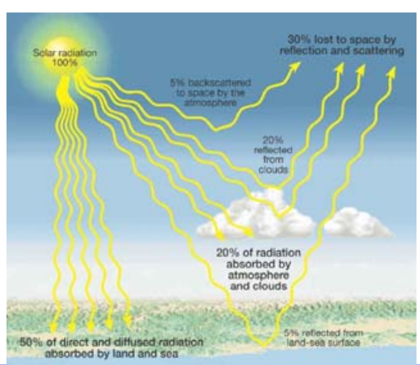
The Solar Constant: 1367 W/m^2 means that a 1 m^2 area at the top of the Earth's atmosphere (in line between the Earth and Sun) receives 1367 J of energy from the Sun each second.

https://www.newport.com/t/introduction-to-solar-radiation

Energy Available From the Sun

But, as the Sun's energy travels through the atmosphere, some of it is absorbed, scattered or reflected.

Water vapor (H_2O), carbon dioxide (CO_2), and ozone (O_3) are some of the primary contributors to absorption of the sun's energy as it travels through the atmosphere.



http://www.geography.hunter.cuny.edu/tbw/wc.notes/2.heating.earth.surface/images/incoming.soler.rad.budget.jpg

Rayleigh scattering and scattering from particulates, including water droplets, changes the spectrum of the radiation that reaches the ground. This is also the mechanism that makes the sky appear to be blue.

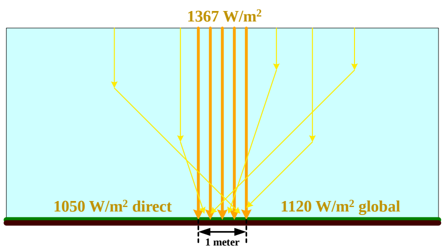
https://www.newport.com/t/introduction-to-solar-radiation

Energy Available From the Sun

The **direct energy** that reaches the ground on a clear day, when the Sun is directly overhead, is around 1050 W/m^2.

Note that the **global energy** that reaches the ground, which includes both direct and indirect energy, is about 1120 W/m^2.

The global energy includes both the energy that arrives in a direct path from the sun and the energy that reaches the surface at a different angles due to being reflected or scattered by the molecules in the atmosphere.

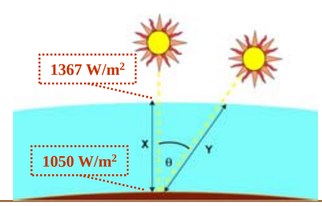


https://www.newport.com/t/introduction-to-solar-radiation

Energy Available From the Sun

The **direct energy** that reaches the ground on a clear day, **when the Sun is directly overhead**, is around 1050 W/m^2.

This value decreases if the Sun is at a lower angle due to both the increased path length through the atmosphere and the spreading of the energy across a larger surface area that results from the smaller angle of incidence.



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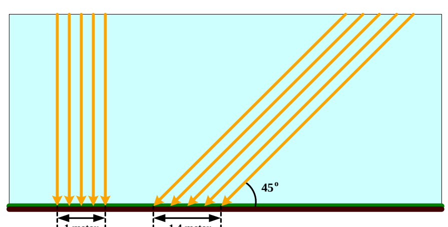
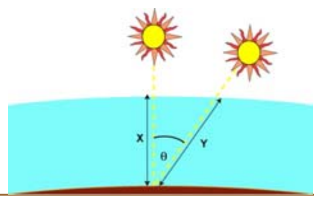


https://www.newport.com/t/introduction-to-solar-radiation

Energy Available From the Sun

The direct energy that reaches the ground on a clear day, when the Sun is directly overhead, is around 1050 W/m^2.

Note that the spreading of energy across a larger surface area that occurs when the Sun is at a lower angle can be compensated for by adjusting the angle of the receiving surface.



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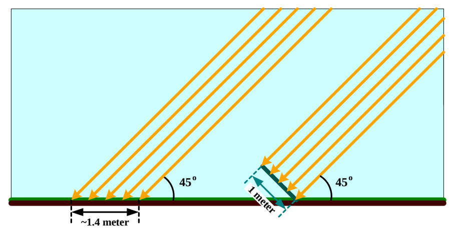
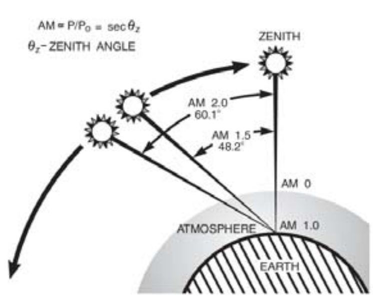


Energy Available From the Sun

The amount of direct energy that reaches the ground is often defined in terms of the air mass that the sun must penetrate based on the position of the sun in the sky.



https://www.newport.com/t/introduction-to-solar-radiation

Solar Condition	Standard	Power Density (Wm^{-2})	
		Total	250 - 2500 nm
WMO		1367	
AM 0	ASTM	1353	1302.6
AM 1	CIE		969.7
AM 1.5 D	ASTM E 891	768.3	756.5
AM 1.5 G	ASTM E 892	963.8	951.5
AM 1.5 G	CEI/IEC 904-3	1000	987.2

WMO – World Metrological Organization
ASTM – American Society for Testing and Materials
CIE – Commission Electrotechnique Internationale
IEC – International Electrotechnical Commission

https://www.newport.com/t/introduction-to-solar-radiation

Uses of Solar Energy

<u>Conversion to Electric Energy</u>

- **Photovoltaics** — direct conversion to electric energy
- **Concentrated Solar Thermal** — indirect conversion
  - — Power Tower
  - — Linear Focus
  - — Point Focus (Parabolic Dish, Fresnel Lens)

<u>Solar Heating</u>

- **Passive Heating** — building interiors
- **Active Heating** — x
- **Solar Cooking** — x

Photovoltaics

<u>Photovoltaics</u> (PV) refers to the direct conversion of light into electricity that occurs within some materials at the atomic level.

A photovoltaic cell, or <u>Solar Cell</u>, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect.

https://en.wikipedia.org/wiki/Solar_cell

Solar Cell Theory

A typical solar cell is composed of two layers of silicon that are doped to form a p-n junction.

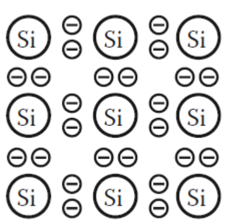
Doping refers to the deliberate introduction of impurities into an extremely pure crystal.

In the case of a solar cell, the silicon is doped with boron atoms to form one of the layers and phosphorous atoms to form the other layer.

https://en.wikipedia.org/wiki/Solar_cell

Solar Cell Theory – Silicon

Silicon atoms, in their base state contain, contain a total of 14 electrons, 4 of which exist in the atom's valence band (highest-energy electron orbital band).



Introduction to Renewable Energy, Vaughn Nelson

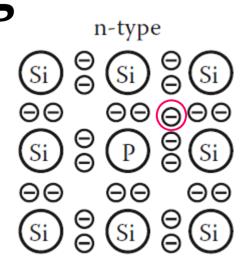
When silicon atoms bond together, they form a lattice structure in which the atoms form four covalent bonds, thus completely filling their valence bands with a total of 8 shared electrons.

The valence shell, M, of a silicon atom, contains only p and d subshells, and thus can hold only 8 electrons at a base energy level.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – doping

When silicon is doped with phosphorous, atoms of which contain 5 electrons in their valence bands, the phosphorous atoms also forms four covalent bonds with their neighbors, but now there is one too many shared valence electrons.



Introduction to Renewable Energy, Vaughn Nelson

The extra phosphorus bonding electrons are only weakly attached to the phosphorus atoms such that, at room temperatures, the thermal energy within the crystal is sufficient to break those bonds, resulting in free electrons that are able to move within the material.

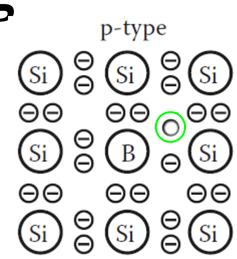
The phosphorous-doped silicon is referred to as an n-type material due to the available free electrons.

In typical solar cell applications, there is about 1 dopant atom for every 5,000,000 silicon atoms.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – doping

When silicon is doped with boron, atoms of which contain only 3 valence electrons, the boron atoms only form three covalent bonds with the adjacent silicon because it is necessary to share two electrons, one from each atom, in order to form a covalent bond.



Introduction to Renewable Energy, Vaughn Nelson

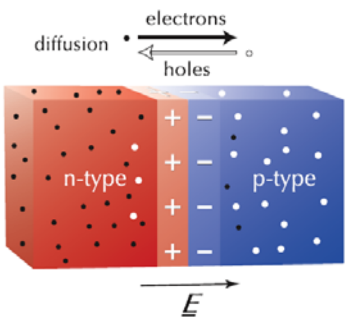
But, at room temperature, there is sufficient thermal energy to push nearby electrons into these vacancies, resulting in a vacancies or "holes" that can move from atom to atom.

The boron-doped silicon is referred to as an p-type material due to the available mobile holes.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – p-n Junction

When the boron-doped (p) layer of silicon comes into contact with the phosphorous-doped (n) layer of silicon, some of the excess electrons in the n-layer diffuse into the p-layer and recombine to fill the holes at the layer junction.

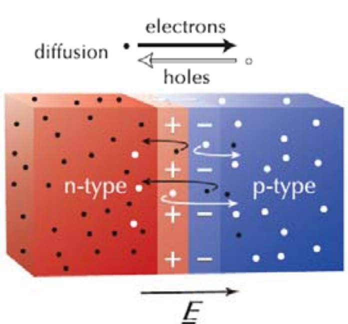


The diffusion of electrons creates an area around the junction, called the <u>depletion zone</u>, the p-type side of which contains negatively charged ions and the n-type side of which contains positively charged ions.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – p-n Junction

The oppositely-charged sides of the depletion region results in an electric field that opposes the diffusion of electrons from the n-region to the p-region, causing some of the electrons and holes to flow back in the opposite direction.

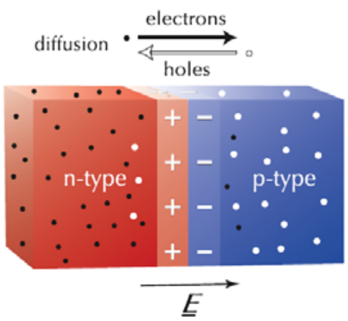


A stable equilibrium is reached when the number of electrons flowing due to diffusion exactly balances the number of electrons flowing back due to the electric field.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – p-n Junction

Within the depletion zone, there are very few mobile electrons and holes. As a result, the depletion region is highly resistive and now behaves as if it were pure crystalline silicon: as a nearly perfect insulator



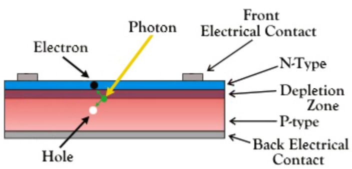
At this point, in the absence of any light, the junction that we have formed is the same as that formed when creating a basic diode.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – Light Interaction

When a photon of light hits a solar cell, one of four things can happen to the photon:

1) Its energy can be absorbed by an electron, exciting the electron into its conduction band, in-turn, generating a free electron-hole pair



The response curve for a typical silicon solar cell peaks at wavelengths around 700nm.

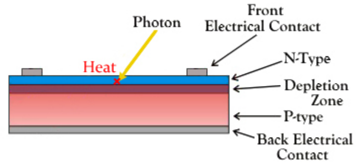
Photons having energy greater than 1.1eV or wavelength less than 1120nm may create electron-hole pairs.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – Light Interaction

When a photon of light hits a solar cell, one of four things can happen to the photon:

2) It can be absorbed as heat by the silicon itself



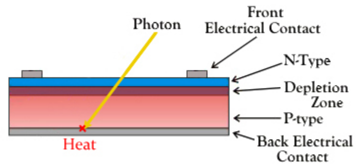
Although electron-hole pairs may still be created, the majority of the energy in higher energy or shorter wavelength photons (<1120nm) will be absorbed as heat by the silicon or the backing material.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – Light Interaction

When a photon of light hits a solar cell, one of four things can happen to the photon:

3) It can pass through the silicon and be absorbed as heat by the backing material



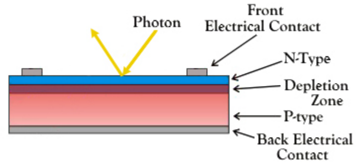
Low energy or longer wavelength photons (>1120nm) will typically pass through the silicon.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – Light Interaction

When a photon of light hits a solar cell, one of four things can happen to the photon:

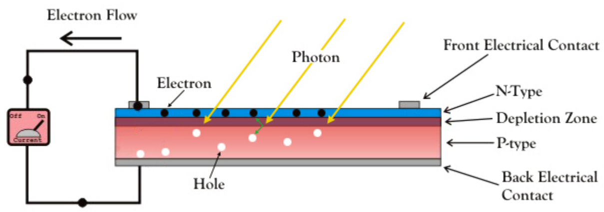
4) It can reflect off the surface



Anti-reflective coatings can be applied to the surface of solar cells to minimize this reflective loss.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – Energy Conversion



Edited from https://www.imagesco.com/articles/photovoltaic/photovoltaic-pg4.html

In a solar cell, the n-type material is kept thin to allow light to pass into the p-n junction.

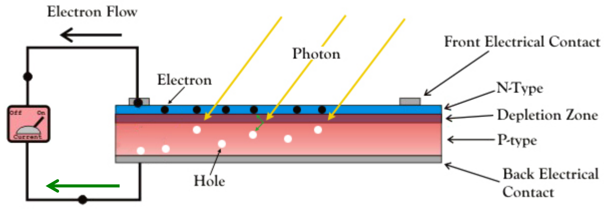
When a photon of light reaches the p-n junction, its energy may be absorbed by an electron on the p-side of the junction, giving the electron the energy required to travel across the depletion zone and into the n-region.

As this continues to occur, a net charge difference is built up across the n-type and p-type materials.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – Energy Conversion

* – current will flow externally from the p-type region to the n-type region



Edited from https://www.imagesco.com/articles/photovoltaic/photovoltaic-pg4.html

Although these electrons in the n-type material are attracted back towards the holes in the p-type material, the depletion zone prevents this internal movement of the electrons.

But, if an external path is provided, then electrons* will flow from the n-type material back to the p-type material in order to recombine with the available holes.

http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Solar Cell Theory – Energy Conversion

Several factors come into play when determining the amount of electric energy that a solar cell is able to produce:

- The amount of solar energy that is incident upon the cell
  - – due to its size, location (latitude), position (angle), time of day…
- The efficiency of the solar cell,
- The operating* temperature,
- The loading* of the solar cell.

* – At higher temperatures, solar cells tend to produce larger currents but at lower voltages that decrease the overall power produced by the cell.

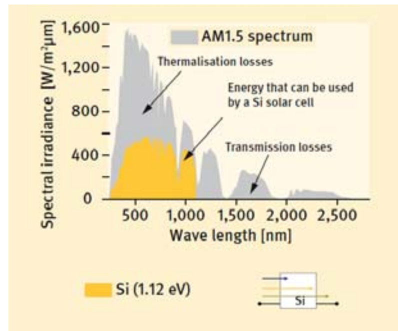
* – If the resistance of the load connected to the solar cell is too small, then the cell will generate a large current but very little voltage. Conversely, if the resistance is too large, the solar cell will produce a large voltage but very little current. Thus, the cell should be loaded such that both the voltage and the current will obtain mid-range values, the multiple of which results in maximum output power.

Solar Cell Efficiency

Single-layer solar cells typically operate with an efficiency that ranges from 7% to 17%.

The low efficiency is primarily due to two factors:

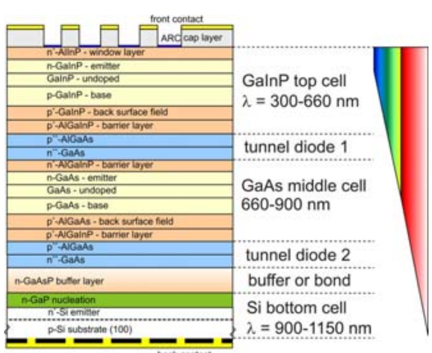
- Wavelengths longer than 1120nm will not excite free electrons
- Although wavelengths less than 1120nm can excite free electrons, the majority of the energy present in photons whose wavelengths are much shorter than 1120nm is still absorbed as heat.

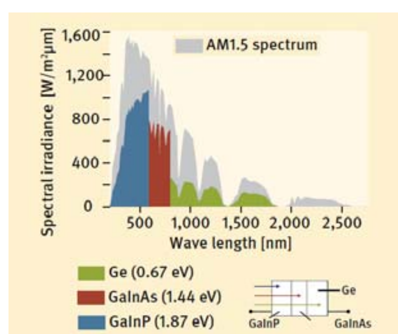


https://www.ise.fraunhofer.de/en/research-projects/mehrsi.html

Solar Cell Efficiency

Higher efficiencies have been reached by multi-junction cells in which the various layers are chosen based on their ability to convert different wavelengths of light into electricity.

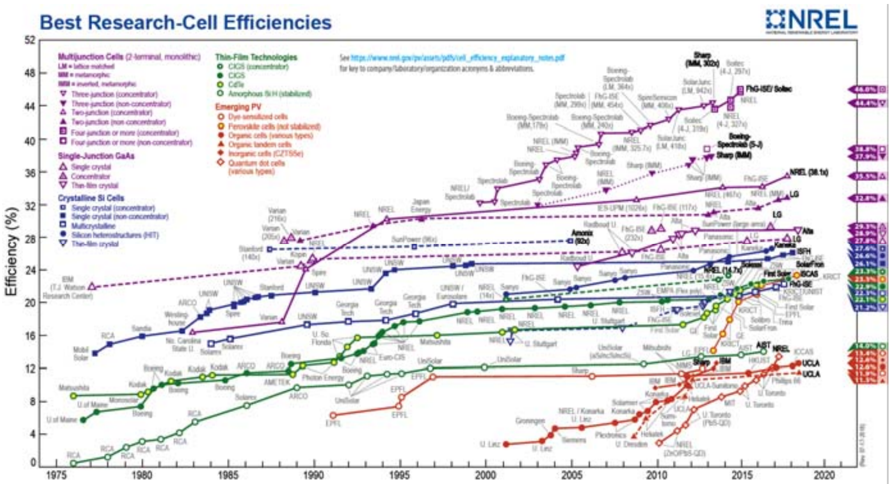




https://www.ise.fraunhofer.de/en/research-projects/mehrsi.html

https://www.ise.fraunhofer.de/content/dam/ise/en/documents/information-material/Photovoltaics/ProjektInfo_0214_engl_internetx.pdf

Solar Cell Efficiency



https://www.nrel.gov/pv/assets/pdfs/pv-efficiencies-07-17-2018.pdf

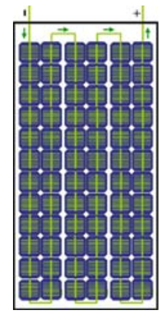
Photovoltaic Systems

<u>Photovoltaic Systems</u> are systems that are designed to convert solar energy into electricity by means of the photovoltaic effect and to condition that electricity for:

- **Use by directly-connected Electric Loads (DC or AC)**
- **Delivery into the utility's Electric Power Grid (AC)**
- **Temporary Storage**

The design of these systems can vary greatly based on a variety of factors including the specific end-use of the electricity.

Solar Arrays



When exposed to light, a single solar cell develops a relatively small voltage and is capable of producing only a small amount of current (and power) due to its small surface area.

When larger voltages and power levels are required, multiple cells can be connected together, either:

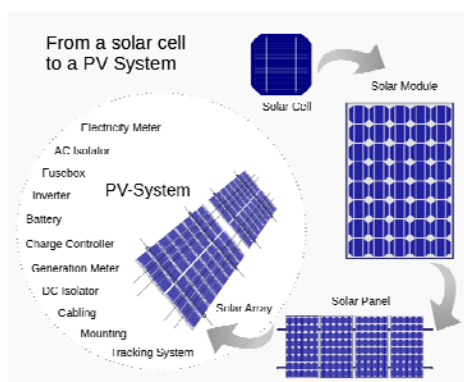
- In <u>series</u> to increase the overall voltage magnitude, or
- In <u>parallel</u> to increase the maximum current capability.

Note that batteries are often connected together in either a series or a parallel configuration for the same reason. For example, two AA (1.5V) batteries connected in series will develop a total of 3V, and those same two AA's, each of which may be capable of supplying 800mA, can supply a total of 1600mA when connected in parallel.

Solar Arrays

Thus, in a practical PV System, multiple cells are connected together to form solar modules, which are then combined to form the solar panels that, in-turn, are integrated into large solar arrays.

The size (surface area) of the solar array determines the theoretical maximum amount of solar energy that can be collected from the Sun and converted into electricity.



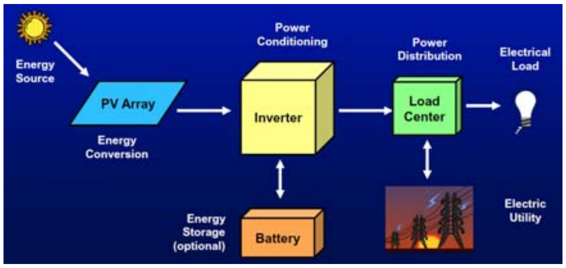
But, in addition to the solar array, many other devices are required in order to create a PV system.

https://en.wikipedia.org/wiki/Solar_cell

Photovoltaic Systems

Although solar cells form the heart of any PV system, there are many additional components that perform key tasks with respect to the system's overall operation, including:

- **Mounting Structures**
- **Power Condition Devices (Charge Controllers, Inverters, etc.)**
- **Storage Devices**



https://ecgllp.com/files/6814/0200/1304/4-System-Components-and-Configurations.pdf

Mounting Structures

Fixed <u>mounting structures</u> tilt the PV array at a fixed angle, based on the local latitude and the structure's orientation, in order to maximize the amount of insolation.

https://s3.amazonaws.com/hoth.bizango/images/147472/ground_mount_2_home.jpg

Modules in the northern hemisphere are typically pointed due south and inclined at an angle equal to the local latitude.

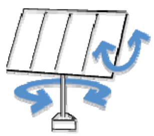
https://www.energy.gov/eere/solar/articles/solar-photovoltaic-system-design-basics

Mounting Structures

https://i1.wp.com/ontario-solar-installers.ca/wp-content/uploads/2017/05/Solar-tracker.jpg

To increase a system's overall efficiency, <u>tracking mechanisms</u> can be added to the mounting structure that automatically align panels to follow the sun across the sky.

<u>One-axis trackers</u> are typically designed to track the sun from east to west.



http://www.solar-tracking.com/images/Dual_Axis_Tracking.png

<u>Two-axis trackers</u> allow for modules to remain pointed directly at the sun throughout the day.

https://www.energy.gov/eere/solar/articles/solar-photovoltaic-system-design-basics

Inverters

<u>Inverters</u> convert the direct current (DC) electricity generated by solar photovoltaic modules into alternating current (AC) electricity, which is used for local transmission of electricity as well as for grid connection.

https://www.cleanenergyreviews.info/blog/2014/5/4/how-solar-works

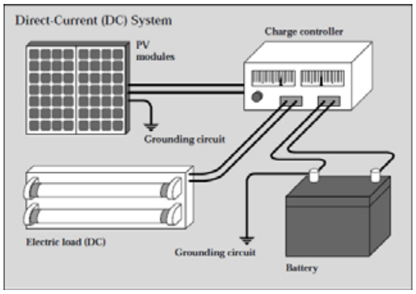
PV systems either have one inverter that converts the electricity generated by all of the modules, or micro-inverters that are attached to each individual module.

Micro-inverters allows for independent operation of each panel, which is useful if some modules might be shaded.

https://www.energy.gov/eere/solar/articles/solar-photovoltaic-system-design-basics

Charge Controllers

<u>Charge Controllers</u> regulate battery charging by limiting the charging current from PV arrays in order to protect the battery from overcharging.



https://www.nrel.gov/docs/legosti/fy97/6981.pdf

Charge controllers may also contain a load controller that regulates battery discharge current by disconnecting electrical loads in order to prevent battery overdischarge.

https://ecgllp.com/files/6814/0200/1304/4-System-Components-and-Configurations.pdf

Storage

<u>Batteries</u> allow for the storage of solar photovoltaic energy, so we can use it to power our homes at night or when weather elements keep sunlight from reaching PV panels.

Not only can they be used in homes, batteries are playing an increasingly important role for utilities.

https://www.solarpowerworldonline.com/wp-content/uploads/2018/05/NX_Flow.jpg

http://www.lowtechmagazine.com/2015/05/sustainability-off-grid-solar-power.html

https://www.energy.gov/eere/solar/articles/solar-photovoltaic-system-design-basics

Photovoltaic Systems

Photovoltaic systems generally fall into two different classes:

- **Grid-Connected Systems**
- **Stand-Alone (Off-Grid) Systems**

Grid-connected systems are those that are connected to the utility's AC power grid.

Off-grid systems are those that produce electricity for loads that are not connected to the AC power grid.

Lookup Reference from PPT

Grid-Connected Systems

A grid-connected system is connected to a larger independent grid (typically the public electricity grid) and feeds energy directly into the grid.

Photovoltaic systems are generally categorized into three distinct market segments:

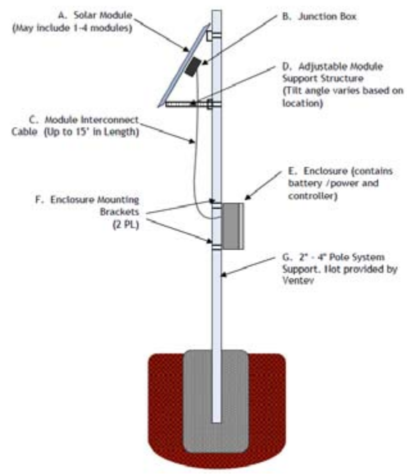
- **residential rooftop**
  - **– typically in the 5-10kW range**
- **commercial rooftop**
  - **– typically on a MW scale**
- **ground-mount utility-scale**
  - **– typically on a MW scale**

https://en.wikipedia.org/wiki/Photovoltaic_system

Stand-Alone Systems

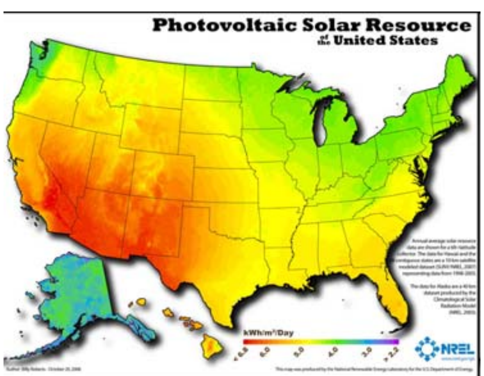
Stand-alone systems are often utilized in areas where utility grid power is not available.

They often contain batteries that store the energy produced by the array in order for use by the loads during times of no solar activity.



Solar Power Systems – Ventev Innovations

PV Solar Power Plants



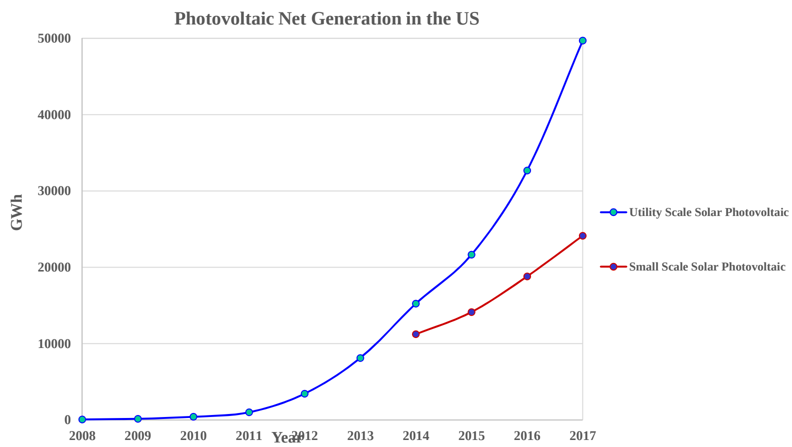
Large scale PV arrays are best suited for areas in which there is a large average insolation.

Smaller plants may be located in less desirable locations if there is a need to help satisfy the region's peak energy needs.

Until recently, micro-scale systems were only cost effective in areas where other power sources were not readily available. But, as solar cells costs decrease, the global viability of micro-scale systems continues to increase.

https://en.wikipedia.org/wiki/Solar_cell

Solar Power in the US



https://www.solarinsure.com/largest-solar-power-plants

Large PV Solar Power Plants in the US

Solar Star Power Plant – 579MW – California

This solar power plant uses 1.7 million solar panels made by SunPower and spreads over 13 square kilometers (3,200 acres).

https://albaenergy.com/biggest-solar-power-plants-in-america/

Large PV Solar Power Plants in the US

Solar Energy Generating Systems (SEGS) – 354MW – California

The overall plant, which consists of nine plants constructed at three separate locations, is the oldest solar power plant in the world.

https://en.wikipedia.org/wiki/Solar_Energy_Generating_Systems

Large PV Solar Power Plants

Tengger Desert Solar Park – 1500MW – China

The 1547MW solar power was installed in Zhongwei, Ningxia is the world's largest solar array by far.

https://www.solarinsure.com/largest-solar-power-plants

Large Solar Power Plants

Kamuthi Solar Power Project – 648MW – India

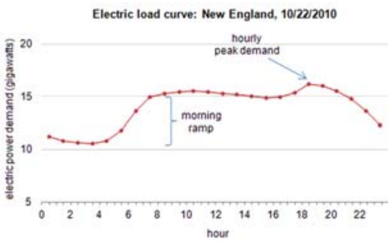
The facility in Kamuthi, Tamil Nadu, has a capacity of 648 megawatts and covers an area of 10 km^2.

https://www.solarinsure.com/largest-solar-power-plants

Solar Power Limitation

One limitation to concentrating solar power systems is that they can only collect the solar energy during daylight hours, the amount of which rises and drops off quickly at sunrise and sunset respectively.

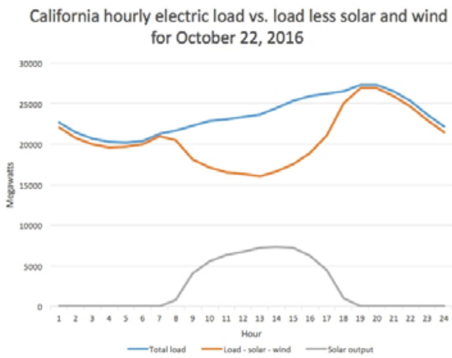
Although the electric power demand tends to rise quickly in the morning, it typically peaks during the early evening hours before it drops back to a minimum after midnight.



https://www.greentechmedia.com/articles/read/introducing-the-shark-curve

Solar Power Limitation

The timing imbalance between peak demand and solar energy production can result in power system stability issues.



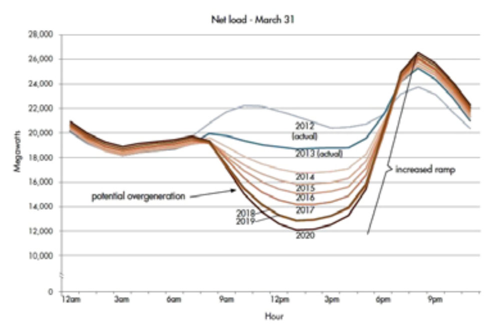
In locations where a substantial amount of solar electric capacity has been installed, the amount of power that must be generated from sources other than solar displays a drop-off after sunrise and a rapid increase around sunset that peaks in the mid-evening hours.

https://en.wikipedia.org/wiki/Duck_curve

Solar Power Limitation

To help combat this problem, many solar power plants temporarily store some of the energy they produce, allowing them to continue producing electricity after the sun sets.

Even short term storage can help by smoothing out the rapid change in generation required at sunset when a grid includes large amounts of solar capacity.



https://en.wikipedia.org/wiki/Duck_curve

Concentrating Solar Power

<u>Concentrating Solar Power</u> (CSP) systems capture and convert sunlight into the heat energy required to drive conventional thermoelectric generators.

CSP systems offer a carbon-free, renewable alternative to the power generated by fossil fuels.

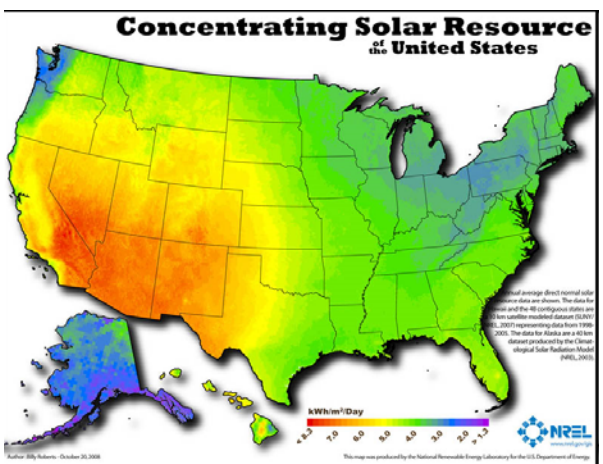
In general, CSP systems utilize:

- Mirrors reflect and concentrate sunlight
- Receivers convert the solar energy into heat energy
- Generators to convert the heat energy into electricity

https://science.howstuffworks.com/environmental/green-tech/energy-production/solar-thermal-power.htm

Concentrating Solar Power

Annual Average Direct Normal Solar Data



https://www.nrel.gov/

Concentrating Solar Power

The three main types of concentrating solar power systems are:

- **Linear Concentrator Systems**
- **Power Tower Systems**
- **Parabolic Dish / Engine Systems**

https://science.howstuffworks.com/environmental/green-tech/energy-production/solar-thermal-power1.htm

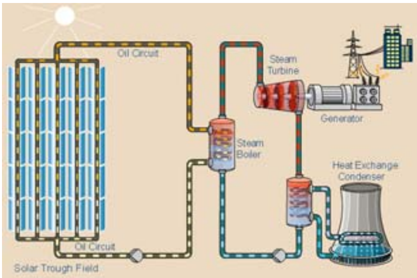
http://solareis.anl.gov/guide/photos/index.cfm

http://solareis.anl.gov/images/photos/Dish08728.jpg

Linear Concentrator Systems

<u>Linear Concentrator Systems</u> utilize parabolic troughs, long rectangular, parabolic-shaped mirrors, to focus the Sun's energy onto receivers (tubes) that run the length of the troughs, in-turn heating oil or some other heat transfer fluid (HTF) that flows through the tubes.

The hot oil then passes through a heat exchanger in order to boil water, in-turn producing steam, the pressure from which drives a conventional steam-turbine generator that produces electricity.

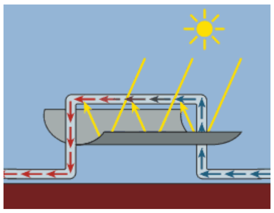


https://www.mtholyoke.edu/~wang30y/csp/PTPP.html

https://www.eia.gov/kids/energy.php?page=solar_home

Linear Concentrator Systems

The parabolic reflectors are typically aligned north-south and have the ability to pivot east-west in order to follow the sun as it moves across the sky throughout the day.



https://www.mtholyoke.edu/~wang30y/csp/PTPP.html

Because of its parabolic shape, a trough can focus the sunlight from 30 times to 100 times its normal intensity on the receiver pipe, located along the focal line of the trough, achieving operating temperatures higher than 750°F (400°C).

https://science.howstuffworks.com/environmental/green-tech/energy-production/solar-thermal-power.htm

Linear Concentrator Systems

Mojave Solar Project (California)
Electricity Generating Capacity – 250 Megawatts

http://www.graywolfindustrial.com/project/mojave-solar-project-mirror-project/

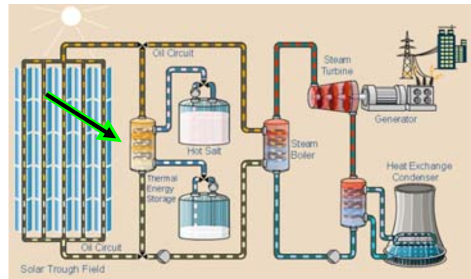
https://en.wikipedia.org/wiki/Mojave_Solar_Project

Consisting of two, independently-operable, solar fields, the system's array of parabolic troughs are constructed from 22,500 solar modules.

Energy Storage

Concentrating solar power systems often utilize a second heat exchanger to transfer heat between the HFT and molten salt.

During daylight, some of the heat is transferred to the molten salt which is stored in large vessels.



At night, the thermal energy stored in the molten salt is transferred back to the HFT, allowing the system to continue producing electric energy even during the absence of sunlight.

https://maarky.com/products/solar-power-plant-heat-exchangers/

Energy Storage

The 150 MW Andasol Solar Power Station, located in Spain, that uses tanks of molten salt to store solar energy.

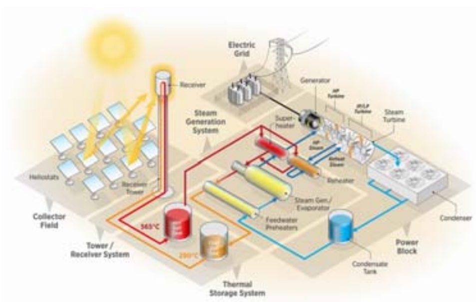
Tanks sized to power a 100-megawatt turbine for four hours would have to be about 30 feet tall and 80 feet in diameter.

The storage of heat is more efficient and cost-effective than the storage of electricity in batteries.

https://en.wikipedia.org/wiki/Solar_thermal_energy

Power Towers

Solar <u>Power Tower</u> systems utilize a large field of flat mirrors, called heliostats, that track the Sun in order to reflect and concentrate sunlight onto a receiver on the top of a tower.



https://green-power.no/services

Similar to linear concentrator systems, the collected solar energy heats a fluid flowing through the receiver tubes, which is then used to boil water in a conventional steam-turbine generator system.

https://www.eia.gov/kids/energy.php?page=solar_home

Power Towers

When focused on a tower, the sunlight can be concentrated as much as 1,500 times, resulting in temperatures that can range from 500°C to 1500°C.

https://climatekids.nasa.gov/concentrating-solar/

The advantage of this design above the parabolic trough design is the higher temperature. Thermal energy at higher temperatures can be converted to electricity more efficiently and can be more cheaply stored for later use.

https://www.eia.gov/kids/energy.php?page=solar_home

Power Towers

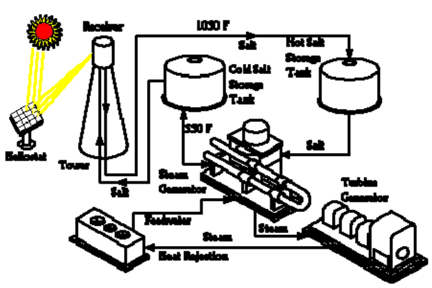
SolarReserves Crescent Dunes CSP Project (Nevada)
Electricity Generating Capacity – 110 Megawatts

The project includes 10,347 heliostats and is the largest power tower system with direct thermal energy storage.

https://www.nrel.gov/csp/

The Future of Power Towers?

The U.S. Department of Energy, along with several electric utilities, built and operated the first demonstration solar power tower near Barstow, California, in the 1980s and 90s.



http://lisas.de/projects/alt_energy/sol_thermal/powertower.html

Despite their initial promise, as of the end of 2014 in California, the state had 10 gigawatts of installed solar capacity, less than four percent of which was produced by power towers.

https://www.kcet.org/redefine/are-solar-power-towers-doomed-in-california

The Future of Power Towers?

Solar power towers have two main technological competitors; photovoltaic cells and parabolic trough solar thermal.

In California, PV panels have become the dominant method in which turn sunlight is turned into electrical power because:

- **The materials and installation costs of PV has gotten a lot cheaper over the last decade**
- **Once installed, PV is less expensive to operate than almost any other form of power generation, renewable or otherwise**
- **PV is modular; you can increase the capacity of a PV plant by installing additional solar panels**
- **Power Towers present a hazard to birds/wildlife.**

https://www.kcet.org/redefine/are-solar-power-towers-doomed-in-california

Parabolic Dish / Engine Systems

Parabolic Dish / Engine systems utilize a mirrored dish that focuses the sunlight onto a thermal receiver, which absorbs and collects the heat and transfers it to an engine generator.

Solar dish/engine systems have tracking modules so they can always point straight at the Sun and concentrate its energy at the focal point of the dish.

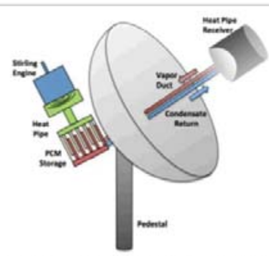
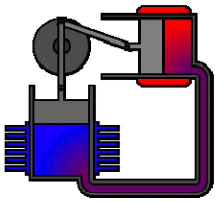


Figure 19: New concept in Dish Stirling technology.

https://www.omicsonline.org/articles-images/innovative-energy-Dish-Stirling-5-149-g019.png

https://www.eia.gov/kids/energy.php?page=solar_home

Parabolic Dish / Engine Systems



http://stirling-engine-en.blogspot.com/2013/07/how-stirling-engines-work.html

The most common type of heat engine used in dish / engine systems is the Stirling engine.

In these systems, a Stirling engine coverts heat to mechanical energy by compressing working fluid when cold and allowing the heated fluid to expand outward in a piston.

A generator then converts this mechanical energy to electricity.

http://stirling-engine-en.blogspot.com/2013/07/solar-dish-stirling-power-plant.html

https://energyeducation.ca/encyclopedia/Solar_thermal_power_plant

Parabolic Dish / Engine Systems

Stirling engine parabolic dish have the highest efficiency of all solar technologies.

In 2015, Rispasso Energy, a Swedish firm, tested a Stirling / dish system in the Kalahari Desert in South Africa that showed 34% efficiency.

Additionally, the U.S. Army commissioned a 1.5 MW system at the Tooele Army Depot in Utah with 429 Stirling engine solar dishes in 2016.

https://galvanizeit.org/project-gallery/stirling-solar-array-tooele-army-depot

https://www.eia.gov/energyexplained/?page=solar_thermal_power_plants

Passive Solar Heating

Passive solar heating systems make use of the building components to collect, store, and distribute solar heat gains in order to reduce the demand for space heating.

A passive solar system does not require the use of mechanical equipment because the heat flow is by natural means, such as radiation, convection, and conductance, and the thermal storage is in the structure itself

https://www.wbdg.org/resources/passive-solar-heating

Passive Solar Heating

Direct-Gain Solar System – the indoor space acts as a solar collector, heat absorber, and distribution system.

Indirect-Gain Solar System – the thermal mass (concrete, masonry, or water) is located directly behind the south-facing glass and in front of the heated indoor space and so there is no direct heating.

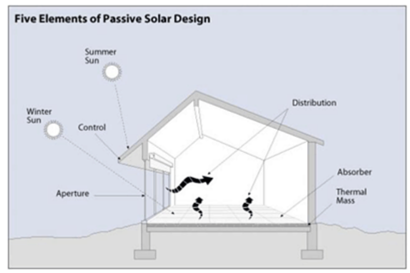
Isolated Passive Solar System – the components are isolated from the indoor area of the building, such as a solar room or solarium.

https://en.wikipedia.org/wiki/Passive_solar_building_design

Passive Solar Heating

A direct-gain, passive solar heating system is made up of the following key components, all of which must work together for the design to be successful:

- **Aperture (Collector)**
- **Absorber**
- **Thermal Mass**
- **Distribution**
- **Control**



https://www.wbdg.org/resources/passive-solar-heating

Passive Solar Heating

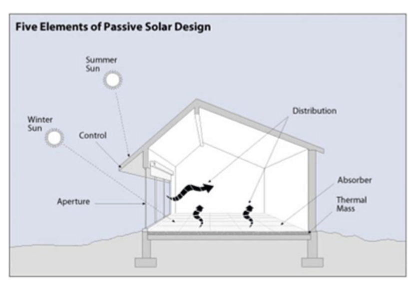
Aperture – a large glass area through which sunlight enters the building

Absorber – darkened surface that sits in the direct path of sunlight and absorbs the sunlight as heat

Thermal Mass – the materials that store the heat produced by sunlight

Distribution – the method by which solar heat circulates from the collection and storage points to different areas of the building

Control – the elements used to control heating of a passive solar system (overhangs, blinds, dampers)



https://www.wbdg.org/resources/passive-solar-heating

Passive Solar Heating

Modest levels of passive solar heating (sun-tempering) can reduce building auxiliary heating requirements from 5-25% at little or no incremental first cost.

Zion's Visitor Center showing thermal storage wall and clerestory windows

More aggressive passive solar heated buildings can reduce heating energy use by 25-75% compared to a typical structure while remaining cost-effective on a life-cycle basis.

WBDG WHOLE BUILDING DESIGN GUIDE a program of the National Institute of Building Sciences

https://www.wbdg.org/resources/passive-solar-heating

Solar Cookers

Solar Cookers utilize the energy from the Sun to heat, cook or pasteurize food and drink.

Solar cookers provide a simple solution for the hundreds of millions of people around the Earth that have limited or little-to-no access to electricity, gas, charcoal, firewood or other sources of energy that can be used for cooking.

Solar cookers are best suited for:

- Climates in which it is dry and sunny at least six months a year,
- Locations within 40° (N or S) of the equator
- Use between 10am and 2pm

Introduction to Renewable Energy, Vaughn Nelson

Solar Cooking

3.2+ million solar cookers used across the world... meaning:

- 11.5+ million people directly impacted by solar cooking
- 3 - 9 million tons reduced CO_2 emissions in one year
- 16- 45 million tons reduced CO_2 emissions over the cookers' lifespans
- Equivalent to planting 376 - 1,058 million trees
- $256 million - $1,305 million estimated savings from reduced CO_2 emissions

SCI SOLAR COOKERS INTERNATIONAL
https://www.solarcookers.org/

Types of Solar Cookers

__Box__ – reach moderate to high temperatures and can accommodate multiple pots.

Added surfaces can reflect sunlight into the box cooker to increase the temperature.

__Panel__ – utilizes panels that to radiation onto the cooking pot.

Simple panel cookers can be built in an hour at very little cost.

SCI SOLAR COOKERS INTERNATIONAL
https://www.solarcookers.org/

Types of Solar Cookers

Concentrator – utilize parabolic or other curved surfaces to focus the sunlight to a single point.

Concentrators reach higher temperatures, which means they cook faster; however, they require frequent adjustment and supervision.

SCI SOLAR COOKERS INTERNATIONAL
https://www.solarcookers.org/

Solar Cooking

For more information on solar cooking, view:

https://www.solarcookers.org/

http://solarcooking.org/plans/

http://solarcooking.wikia.com/wiki/Category:Solar_cooker_plans#Selected_designs

SCI SOLAR COOKERS INTERNATIONAL
https://www.solarcookers.org/