Solar Energy Project

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1. Introduction – Characteristics of Solar Energy

In the core of the sun, temperatures of 16,000,000 C and pressures of 68×10^9 atm dominate. "Solar energy" is produced in this extreme environment by fusion nuclear reactions (see Figure 1[i], right) in which hydrogens are turned into helium: every 4.032 kg of hydrogen generates 4.003 kg of helium. The difference in mass is converted, then, into energy according to Einstein's equation $E = mc^2$, where E is energy, m is mass, and c is the velocity of light.[ii]

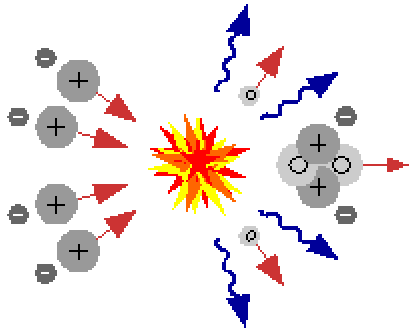


Figure 1: Fusion of hydrogen

The energy, which is mostly produced as high-frequency electromagnetic radiation (gamma rays), is carried to the surface of the sun. Because of the frequent collisions encountered on the way, the composition of solar radiation at the surface of the sun differs: the energy dissipates and the electromagnetic radiation is now mainly visible light and near infrared, with a small admixture of other wavelengths (i.e. gamma rays, radio). [iii]

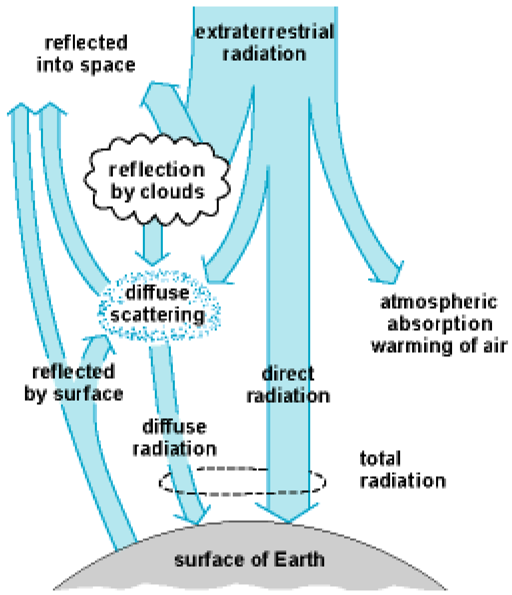


Figure 2: Direct and diffuse radiation

Solar radiation is further modified before reaching Earth's surface by an atmosphere that removes or alters part of the incoming energy by **reflection**, **scattering** and **absorption**. In particular, nearly all ultraviolet radiation and certain wavelengths in the infrared region are removed. Radiation scattered by striking gas molecules, water vapor, or dust particles is known as diffuse radiation. Clouds are a particularly important scattering and reflecting agent, capable of reducing direct radiation by as much as 80% to 90%.The radiation arriving at the ground directly from the sun is called direct radiation – and it is the component that produces the greatest heating effect.[iv v]

But, *what is the true nature of solar radiation?* Historically, light was considered to be only a wave motion composed of a wide spectrum of wavelengths; this, however, left many questions of photosynthesis, photochemical effects, and photoelectric effects unanswered.[vi] Thus, around the 1900s, Max Planck proposed a corpuscular theory radiation that answered such questions not properly answered by wave theory: he proposed that radiation was *emitted in discrete chunks, or photons*; and that the energy of this photon is related to the frequency by the simple formula

$$E = hv$$

where E = energy of each photon
h = Planck's constant, $6.626 \times 10^{-34}\ J \cdot s$
v = frequency, cycles/second

A ramification of Planck's statement and the subsequent quantum theory is that: Because energy is *not* continuous, *only if the molecule can be rearranged to absorb an amount of energy nearly equal to that contained* <u>*in a given photon*</u> *does the photon have a chance of being absorbed by the molecule. Absorption of energy from ultraviolet or visible light is accomplished by displacement of an electron from its resting position in the molecule. In the infrared, the absorption of energy is accomplished by displacement of atoms within the molecule or by rotation of the molecule*.[vii] After this activation of a molecule by a photon of visible or ultraviolet light, the following phenomena may occur:

- *The light activated molecule may transmit its energy to other molecules by collision, increasing the translational energy of the molecules and raising the temperature. This is by far the most common effect produced by sunlight.* **(Thermal applications)**
- The activation may break a chemical bond in the molecule and give chemical decomposition into atoms or groups of atoms.
- *The molecule may be activated to a higher energy level by displacement of an electron within the molecule, and this excited molecule may transfer its energy to a molecule of some other chemical compound with which it collides; and this second molecule may undergo chemical change.* **(Biomass conversion applications)**
- A molecule excited by the absorption of light may fluoresce, giving off light of a different wavelength than the exciting light.
- The activation may have enough energy to drive an electron out of the molecule and produce ionization.[viii] **(Photovoltaic applications)**

These interactions of electromagnetic radiation with other substances are the foundations of utilizing solar energy for all of earth's energy processes such as photosynthesis, wind, etc.

2. Photosynthesis

At the heart of solar biomass conversion is the photosynthetic process. "Photosynthesis" is the name given to the building-block process used by plants (more specifically, the chlorophylls of the plants) to produce organic matter (biomass) with the help of sunlight in the following chemical equation:

$$H_2O + CO_2 + \text{light energy} \xrightarrow[enzymes]{chlorophyll} \{CH_2O\} + O_2$$

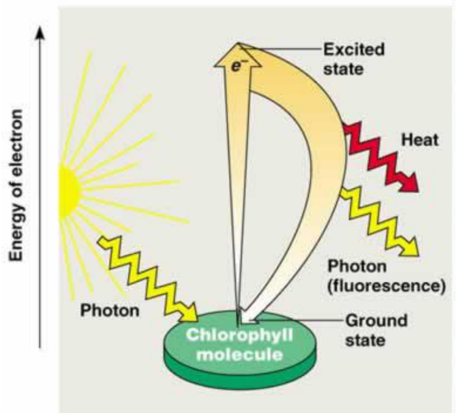
This "biomass resource" (carbohydrate product – most simple sugars have a formula that are some multiple of CH_2O) represents a chemical form of energy which may be used in a variety of ways.[ix]

This manufacture of organic compounds (primarily certain carbohydrates) from inorganic materials by chlorophyll-containing cells *requires* a supply of energy in the form of light, since its products contain much more chemical energy than its raw materials. This is clearly shown by the liberation of energy in the reverse process, the combustion of organic material with oxygen.[x]

The equation for photosynthesis, however, is a deceptively simple summary of a complex process. In fact, photosynthesis is not a single process but two processes with multiple steps. These two stages of photosynthesis are known as the **light reactions** and the **Calvin cycle**.

As a brief summary of the two processes, the light reactions of photosynthesis use solar energy to make ATP (adenosine triphosphate) and NADPH, which function as chemical energy and reducing power, respectively, in the Calvin cycle. The Calvin cycle incorporates CO_2 into organic molecules, which are converted to sugar.[xi] Since this project deals with *solar* energy, the rest of this section will deal with the photosynthetic light reactions.

Photosynthesis begins with the absorption of solar energy (in the form of photons) by molecules such as **chlorophyll a**, **chlorophyll b**, and **carotenoids**. Substances that can absorb visible light are called **pigments**, and are necessary for photosynthesis.



When a molecule (such as chlorophyll molecules in plants) absorbs a photon, one of the molecule's electrons is elevated to an orbital where it has more potential energy. The only photons absorbed are those whose energy is exactly equal to the energy difference between the ground state and an excited state, and this energy difference varies from one kind of atom to another. Thus, a particular only absorbs only photons corresponding to specific wavelengths, which is why each pigment has a unique absorption spectrum.[xii]

Light drives the synthesis of NADPH and ATP by energizing the two photosystems – antenna complexes of pigments and a primary electron acceptor – embedded in the thylakoid membranes of chloroplasts. The key to this energy transformation is a flow of electrons through the photosystems and other molecular components built into the thylakoid membrane. The process is analogous to the cartoon below[xiii]:

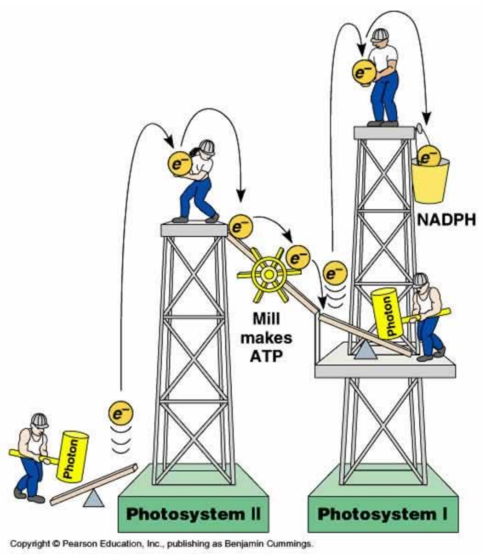


Figure 3: Mechanical analogy to photosynthesis

Photosynthesis is the conversion of light energy into chemical energy – in the form of ATP and NADPH – that can be used for production of long-term chemical energy storage (i.e. carbohydrates, lipids, etc) as well as various cellular processes.

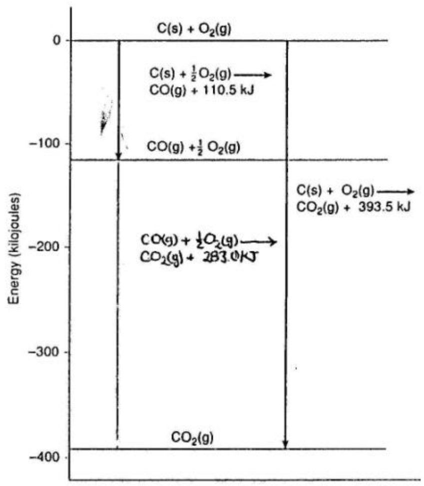
3. Methods of Converting Solar Energy

a) **Biomass**:

- *Formation of fossil fuels*:

  Fossil fuels – coal, oil and natural gas – are “sunshine in the solid, liquid, and gaseous state.”[xiv] When plants die and decay, they are largely transformed into carbon dioxide and water. However, under certain conditions, the glucose and other organic compounds (produced via photosynthesis) that make up the plant only partially decompose; this occurs when such plant life were buried beneath layers of sediment in swamps or the ocean bottom (thus: protected from atmospheric oxygen, and therefore the decomposition process). In Earth’s high-temperature and high-pressure “reactor” other chemical transformations occur culminating into remnants that we call **coal** and **petroleum**. It is important to note that coal and petroleum are single substances but a complex mixture of compounds that occurs in varying grades. Coal, for instance, can be approximated by the formula $C_{135}H_{96}O_9NS$; but coal also typically contains small amounts of silicon, sodium, calcium, aluminum, nickel, copper, zinc, arsenic, lead and mercury.[xv]

- *Combustion*:



  Combustion is the oxidation of substances by molecular oxygen to form carbon dioxide and water. Oxidation of saturated hydrocarbons is the basis for their use as energy sources for heat and power, and releases stored chemical energy as in the potential energy diagram (left).

  Complete combustion produces *only* water and carbon dioxide and releases 393.5kJ/mol CO2 produced. *Incomplete* combustions produce other products, such as CO and a lesser amount of energy.

- *Biogas production*:

  Biogas refers to the methane produced by the fermentation of manure under anaerobic conditions. It provides a convenient way of turning waste into electricity with little pollution.

  Digestion of the manure occurs in a **digestor**, which is strong enough to withstand the buildup of pressure and provides an anaerobic condition for the bacteria inside. Products put into the digestor are composed mainly of carbohydrates with some lipids and proteins.

  The digestion has three main stages: (1) hydrolysis involves breaking down the large macromolecules to sugars, amino acids and fatty acids; (2) acetogenesis, during which bacteria convert sugars into short-chain acids, mainly acetic acid; and (3) methanogensis, carried out by anaerobic bacteria. Here, the acids are converted into methane, which can then be combusted in the presence of dioxygen.

- *Production of ethanol*:

  Ethyl alcohol or *ethanol*, C_2H_5OH, is an alternative fuel formed by the fermentation of carbohydrates such as starches and sugars. Enzymes released by yeast cells catalyze the reaction that is typified by the following equation:

$$C_6H_{12}O_6 \xrightarrow{Enzymes} 2C_2H_5OH + 2CO_2$$

The burning (combustion) of ethyl alcohol in the following reaction releases 1367 kJ per mole of C_2H_5OH.

$$C_2H_5OH + 3O_2 \longrightarrow 2CO_2 + 3H_2O + 1367kJ$$

The energy output corresponds to 29.7kJ/g, which is somewhat lower than the 47.8kJ/g produced by octane, because ethanol is already partially oxidized.

	Advantages	**Disadvantages**
Combustion	• Energy converting process is relatively simple: burn fuel. • Mostly *unsaturated* hydrocarbons: can produce more energy in a comparable amount than the other forms.	• Some substances, such as coal, are "dirty." Oxides of sulfur and nitrogen contribute to acid rain. • Nonrenewable resource. • Difficult to obtain (coal); or requires refining process (petroleum).
Biogas Production	• Abundant and renewable. • Can be used to burn waste products. • Combustion of methane ("biogas") is "clean."	• May not be cost effective.
Production of Ethanol	• Can be prepared from almost any plant product (as evidenced by alcoholic beverages) such as corn, wheat, barley, rice, sugar beets, sugar cane, grapes, apples, dandelions, etc.	• Use of agricultural products for production of fuel must depend on supply and demand, surpluses and shortages. • Already partially oxidized, produces less energy than comparable fossil fuels. • Estimated[xvi] that meeting only 10% of current world energy demand with alcohol would require that one-quarter of the world's cropland would have to be removed from food and feed production.

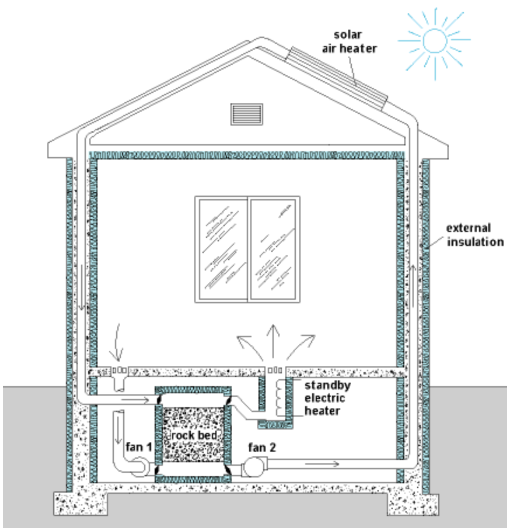
b) Thermal:

Passive solar energy systems[xvii] use the building itself in combination with solar energy as an energy-saving system. In other words, the building is the *collector* for solar energy.

A key principle in using the building as a solar storehouse is that large windows can admit so much solar energy that the building overheats even on winter days. This excess energy is stored by some means for later use to offset the use of conventional fuels against nighttime heat loss. Passive heat storage utilizes the structure of the building itself – its walls, floors, ceiling, and interior partitions. By employing dense materials such as concrete, adobe, brick, and containers of water (which all have large **specific heats**), one can increase the building's ability to absorb and release heat without varying much in room temperature.

In *direct* systems, the Sun's rays enter the building, usually through windows[xviii], and heat the room or space in *direct* sunlight. Excess heat can be vented off or stored in the mass (walls and floor) of the building for later use. The entering solar energy is distributed through a combination of re-radiation from the mass and natural convection of warm air between rooms. *Indirect* heating mechanisms *use one or more rooms as a collector*, which is combined with a storage mass that separates that room from the rest of the building; the energy is reradiated and convected into the building after passing through the storage mass, which can store heat during the day for use at night.

- *Active solar space conditioning systems* use mechanical means to collect, store, and distribute solar energy to heat buildings and water for use. Solar radiation is initially absorbed by a collector (which could be flat-plate, evacuated tube, concentrating, etc) and is converted to heat in a liquid or gas heat-transfer medium. The heat is transported by pumps or fans to the building interior or to storage (often rocks or water).

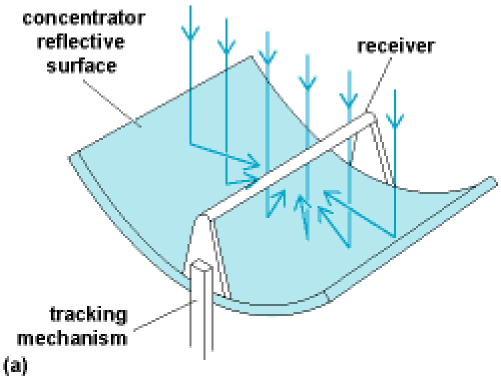


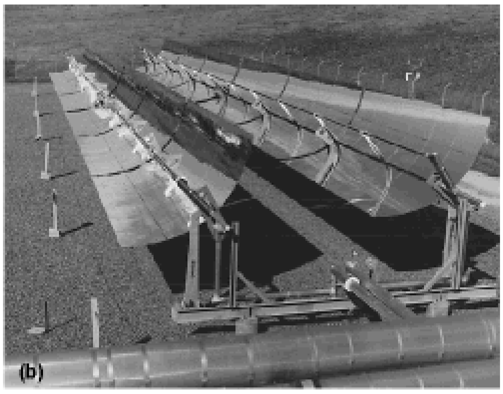
There are different dis/advantages associated with water and air transfer mediums: air cannot freeze or cause corrosion, and leakage is not a serious problem. Water requires relatively small pipes compared to gas pipes. Water tanks can store more than three times as much heat as rocks in a given volume, but rock beds are considerably lower in cost than water tanks. While rocks can tolerate virtually all temperatures, water will boil at 100°C unless its pressure is raised above atmospheric.

c) Electrical:

Solar thermal heat can be converted directly to electricity (photovoltaics), or converted to mechanical then electrical power via an appropriate thermodynamic engine cycle (i.e. conventional steam engine).

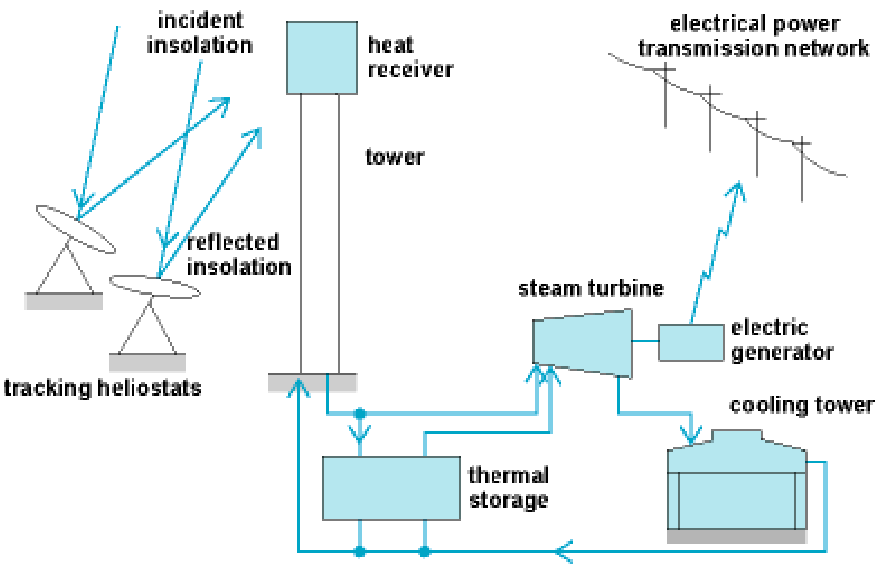
- *Parabolic Troughs*



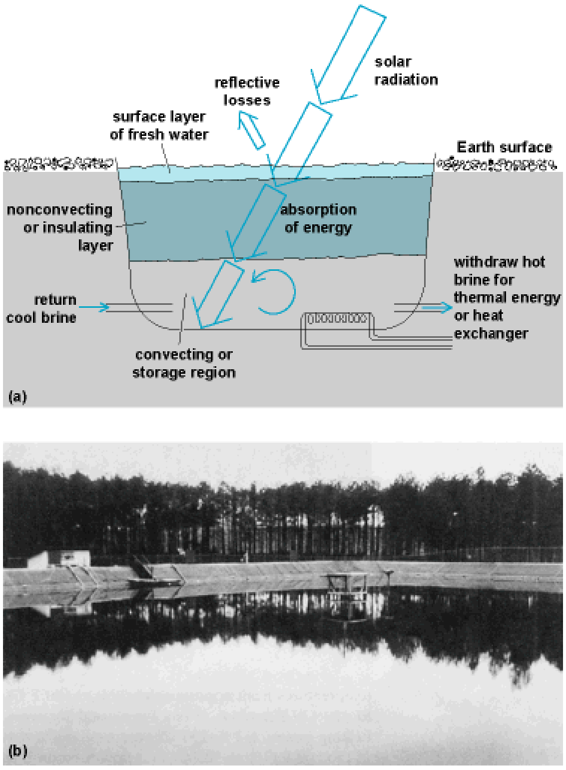


The collector field consists of a large field of single-axis tracking parabolic trough solar collectors. Each solar collector has a linear parabolic-shaped reflector that focuses the sun's direct beam radiation on a **linear receiver** (see Figure to the left) located at the focus of the parabola. The collectors track the sun during the day to ensure that the sun is continuously focused on the linear receiver. A heat transfer fluid (HTF) is heated as it circulates through the receiver and returns to a series of heat exchangers in the power block where the fluid is used to generate high-pressure superheated steam. The superheated steam is then fed to a conventional reheat steam turbine/generator to produce electricity. The spent steam is returned to the heat exchangers via pumps to be transformed back into steam. After passing through the steam turbine side of the process and the cooling tower, the cooled HTF is recirculated through the solar field.[xix]

Below is a schematic of a typical central receiver/parabolic trough collector for power generation using conventional steam technology.



- *Salt-Gradient Ponds*:

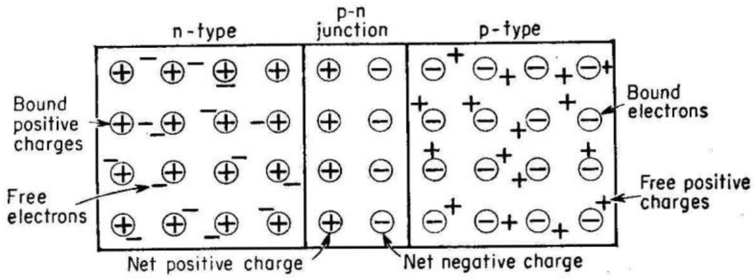


In a salt-gradient pond, a thin layer of fresh or low-salinity water covers a deeper layer of water in which a salinity gradient is created (that is, salt concentration increases with depth). The bottom later is usually at or near salt saturation. Sunlight passing through the water is reabsorbed and heats the bottom layer. Water in the gradient zone can't rise because the water above it contains less salt and therefore is less dense. Similarly, the cool water can't sink because the water below it has a higher salt content and is denser. Hot water in the storage zone is piped to a boiler where it is heated further to produce steam, which drives a turbine. The heat is thus trapped and stored at the bottom and can be extracted for use. An **organic Rankine cycle**[xx] can be used to convert this trapped heat into electricity.

- *Photovoltaic Cells*:

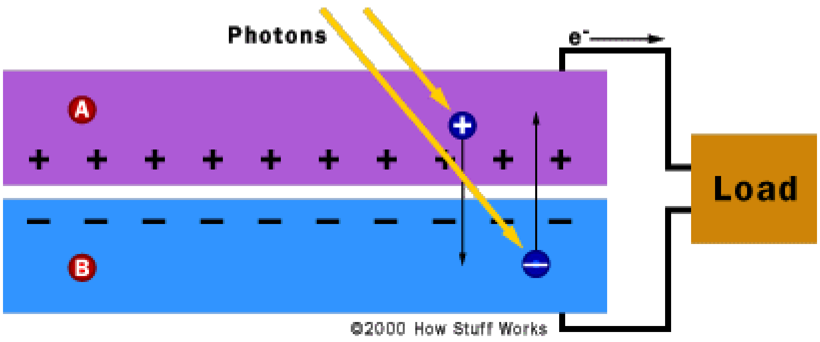
Photovoltaic systems convert light energy directly to electrical energy. In these devices, the energy of the absorbed light is transferred to a semiconductor (often silicon), elevating an electron from a lower energy orbital to a higher energy orbital where they are free to move about. With the use of an external electric field, those free electrons can be induced to move in one direction, producing a usable electric current.

A **solar cell** is composed of silicon parts with impurities ("doped"): the **n-type** (negative) silicon contains phosphorous atoms which bind in tetrahedral fashion with silicon atoms. Because of phosphorous' additional electron, however, (five as opposed to four) this new amalgam has electrons that are not localized in a bond and has an overall negative charge. The fifth electron is held very loosely by the plus charge of the nucleus, but it easily wanders off to be a conducting electron without even absorbing a photon.[xxi] The **p-type** (positive) silicon, on the other hand, is doped with boron atoms, whose three valence electrons produce "holes," a bond associated with a crystal structure that is unoccupied; recall that boron is now bonded in a tetrahedral fashion. To sum up, with a phosphorous-doped silicon, there are fixed positive charges and free electrons, whereas with boron-doped silicon, there are bound electrons and free holes (See diagram[xxii] below).



When the n-type and p-type silicon are put together, the flow of excess electrons from the n-type to the p-type occurs and results in a **p-n junction** that creates an electric field.[xxiii] *The electric field allows electrons to move from the p-type to the n-type but not visa versa.*

When a photon hits the solar cell at a region close enough to the electric field, the field will send the electron to the N side and cause a hole in the P side; this causes a disruption of electrical neutrality, and with an external current path, electrons will flow through the path to their original side to unite with the hole caused by the photon (see diagram below). *The electron flow provides the current, and the cell's electric field causes a voltage. With both current and voltage, power is generated, which is the product of the two.*[xxiv]



	Advantages	Disadvantages
Parabolic Troughs	• Manufacturing simplicity. • Use of standard equipment and improvements. (modularity) • No pollution.	• Operation can be dangerous: exposing eyes or skin to the concentrated sunlight can result in blindness or burns. • Large plants are required. • Not very cost-effective.
Salt Gradient Ponds	• Can be built easily and at a relatively low cost over large areas. • Can't pollute the air, and coupled with desalting units, they can be used to purify water.	• Lower efficiency. • Receives less radiation than flat-plate collectors since it cannot be tilted. • Can't be installed on rooftops.
Photovoltaic Cells	• Modular design: can be used to provide power for applications ranging from the milliwatts to megawatts. • Can be used in locations where traditional electric	• Expensive, particularly due to the price of semi-conductive materials. • Must be constructed manually.

	power is unavailable or too expensive (for instance, satellites, remote cabins, etc.)	

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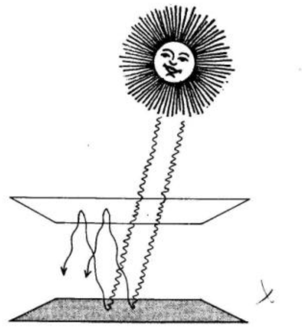
[i] http://www.opencourse.info/astronomy/introduction/12.sun_interior/
[ii] Howell and Bereny 21.
[iii] Ibid 21.
[iv] Howell and Bereny 27.
[v] San Martin. "Solar Energy."
[vi] Chapin 154.
[vii] Daniels 302.
[viii] Ibid 3030.
[ix] Howell and Bereny 13.
[x] Govindjee, et al., "Photosynthesis."
[xi] Campbell. There is no page number here because I used the e-book version.
[xii] Campbell.
[xiii] Campbell.
[xiv] "There's No Fuel Like An Old Fuel" Packet obtained in class.
[xv] "There's No Fuel Like An Old Fuel."
[xvi] Bernard Gilland. "Population, Economic Growth and Energy Demand" in Population and Development Review, Volume 14, Number 2, June 1988, pp. 223-244.
[xvii] It is noted that passive solar systems is often dismissed as being "merely good architecture." This, to some degree, summarizes my own feelings on the topic.



[xviii] Figure 3-3. Solar radiation penetrates window glass and warms surfaces below; thermal radiation, which has longer wavelengths, is kept inside. Windows are the most important element to be utilized for capturing solar energy. The solar heat gain through an area of window glass can be more than 40 times the gain through the same area of conventional wall or roof. It allows sunlight to freely pass, but insulates heat – the longer wavelengths of thermal radiation – inside the building. (Howell and Bereny 71)

[xix] http://www.eere.energy.gov/consumerinfo/pdfs/solar_trough.pdf

[xx] Organic Rankine Cycle: "A thermodynamic cycle used as an ideal standard for the comparative performance of heat-engine and heat-pump installations operating with a condensable vapor as the working fluid." See http://www.accessscience.com/server-java/Arknoid/science/AS/Encyclopedia/5/57/Est_573000_frameset.html?qq=&q=rankine|cycle|cycling|cycles|cycled|rankin for more information.

[xxi] Chapin 158.

[xxii] Ibid 160.

[xxiii] Recall that the excess electrons in n-type silicon were balanced by an additional proton (in the phosphorous) and that the electron deficiency in p-type silicon was balanced by a deficiency of a proton (in boron).

[xxiv] http://science.howstuffworks.com/solar-cell1.htm