17

Solar Electrical Energy

17.1. Overview

Solar is the Latin word for sun. The sun is a powerful source of heat and light energy that can be used to heat, cool, and light our homes and businesses. The ability to use solar power for heat was the first discovery. A Swiss scientist, Horace de Saussure, built the first thermal solar collector in 1767, which was later used for heating water and cooking food. The first commercial patent for a solar water heater went to Clarence Kemp of the US in 1891. This system was bought by two California executives and installed in one-third of the homes in Pasadena by 1897. A variety of technologies convert sunlight to usable energy for buildings. The most commonly used solar technologies for homes and businesses are solar water heating, passive solar design for space heating and cooling, and solar photovoltaic for electricity. Businesses and industry also use these technologies to diversify their energy sources, improve efficiency, and save money.

The earth receives an incredible supply of solar energy from the sun. The sun, an average star, is a fusion reactor that has been operating for over 4 billion years, providing enough energy in one minute, sufficient to supply the world's energy demand for one year. It is estimated that in a single course of a day, the sun provides more energy than the present population of the world would consume in 27 years. In fact, the amount of solar radiation striking the earth over a three-day period is equivalent to the energy stored in all fossil energy sources. Solar energy is a free, inexhaustible resource, yet harnessing it is a relatively new idea. As mentioned earlier, solar energy that we receive from the sun is in two basic forms; light and heat. There are two ways of converting these forms into usable electrical energy. The first is by using the photon light energy of the sun to generate electrical energy, known as the photovoltaic process. The second is by harnessing the heat energy of the sun using solar thermal collectors to produce solar hot water steam to produce mechanical work done at the turbine, which in turn drives the generator thus producing electricity. Solar photovoltaic and concentrating solar power technologies are used by developers and utilities to produce electricity on a massive scale for providing electrical power to cities and small towns. In summary, there are a variety of technologies that have been developed to take advantage of solar energy for domestic, commercial and industrial use includes:

1. Solar photovoltaic systems.
2. Solar thermal electrical systems.
3. Solar process for space heating and cooling.

17.2. Solar Electricity

Producing electricity from solar energy was the second discovery after solar heating. In 1839 a French physicist named Edmund Becquerel realized that the sun's energy could produce a photovoltaic effect; photo meaning light and voltaic meaning electrical potential. In the 1880s, selenium photovoltaic (PV) cells were developed that could convert light into electricity with 1-2% efficiency (the efficiency of a solar cell is the percentage of available sunlight converted by the photovoltaic cell into electricity), but how the conversion happened was not understood. Photovoltaic power therefore remained a curiosity for many years, since it was very inefficient at converting sunlight into electricity. It was not until Albert Einstein proposed an explanation for the photoelectric effect in the early 1900s, for which he won a Nobel Prize that people began to understand the related photovoltaic effect. The energy send towards the planet earth from the sun is an almost unimaginable amount, which is estimated to be around 10^{17} Watts. The earth thus receives a huge amount of energy in the form of solar radiation from the sun, which on average is estimated to be about 1700 kWh per square meter per year. The total amount received on the surface of the earth is thus equal to approximately 10^4 times the global energy consumption. In electrical supply terms this can be stated as equivalent to the output of about one hundred million modern fossil fuel or nuclear power stations. The hope for a 'solar revolution' has been floating around for decades; the idea of which is centered on a vision that one day the entire population on the earth will use free electricity from the sun. This is a seductive promise, because on a bright, sunny day, the sunrays give off approximately 1 kW of energy per square meter of the earth surface. If this energy could be collected, we could easily power our homes and offices for free. The power density (the power per unit area normal to its rays) of the sunrays just above the earth atmosphere is known as the solar constant and equals 1366 W/m^2. This is reduced by around 30% as it passes through the atmosphere, giving an insolation (will be discussed later in this section) at the earth surface of about 1000 W/m^2 at sea level on a clear day. This value is the accepted standard for bright and strong sunshine and is widely used for testing and calibrating terrestrial solar cells and systems.

The effectiveness of solar radiations on an object depends on the angle (known as zenith angle) at which it is incident. The distance traveled through the atmosphere by the direct beam depends on this angle of incidence to the atmosphere and the height above sea level of the observer. If the beam is at zenith angle θ_z, the increased mass encountered compared with the normal path is called the air-mass-ratio (or air-mass), denoted by m. The abbreviation AM is also used for air-mass-ratio. AM-0 refers to zero atmosphere, i.e. radiation in outer space; AM-1 refers to $m = 1$, i.e. sun overhead; AM-2 refers to $m = 2$; and so on. The air mass ratio is expressed as:

$$m = \sec\theta_z \qquad 17.1$$

Changes in air-mass-ratio encountered because of change in atmospheric pressure with time and horizontal distance or with change in height of the observer may be considered separately.

Another important quantity is the average power density received over the whole year, known as the annual mean insolation. A best way of estimating it is to realize that, seen from the sun, the earth appears as a disk of radius R with area πR^2. But since the earth is actually spherical with a total surface area $4\pi R^2$, the annual mean insolation just above the atmosphere must be 1366/4 = 341.5 W/m^2. However, it is shared very unequally, being about 430 W/m^2 over the equator, but far less towards the Polar Regions, which are angled well away from the sun. We note that the average insolation at the earth surface is greatly affected by local climatic conditions, ranging from about 300 W/m^2 in the Sahara desert and parts of the Pacific Ocean to less than 80 W/m^2 near the poles. For example London and Berlin, both with mean insolation of about 120 W/m^2, have annual energy totals of about 120 x 8760/1000 = 1051.2 kWh/m^2. Sydney's mean insolation of about 200 W/m^2 is equivalent to 1752 kWh/m^2. Such figures are useful to PV system designers who need to know the total available solar resource. However, it is to be remembered that they are averaged over day and night, summer and winter, and are likely to vary considerably from year to year. It is also interesting to speculate how far global warming, with its interruptions to historical weather patterns, may affect them in the future. The effects and interactions that occur may be summarized as follows:

Reflection: On average, about 30% of the extraterrestrial solar intensity is reflected back into space, so that the reflection coefficient is $\rho_0 = 0.3$. Most of the reflection occurs from clouds, with a small proportion from the earth's surface (especially snow and ice). This reflectance is called the albedo, and varies with atmospheric conditions and angle of incidence. The continuing short wave solar radiation in clear conditions at mid-day has flux density $\approx (1 - \rho_0) \times 1.3\ \text{kW/m}^2 \approx 1\text{kW/m}^2$.

Greenhouse effect: It includes climate change and long wave radiation. If the radius of the earth is R, average albedo from space ρ_0 and the extraterrestrial solar irradiance (the solar constant) is G_0, then the received power P is:

$$P = \pi R^2(1-\rho_0)G_0 \qquad 17.2$$

This is equal to the power radiated from the earth system, of emittance of unity and mean temperature T_e, as observed from space. At thermal equilibrium, since geothermal and tidal energy effects are negligible, therefore:

$$\pi R^2(1-\rho_0)G_0 = 4\pi R^2 \sigma T_e^4$$

Therefore:

$$P = 4\pi R^2 \sigma T_e^4 \qquad 17.3$$

Where σ is Stefan-Boltzmann constant and has a value of $5.67 \times 10^{-8}\ \text{W/m}^2\ {}^0\text{K}^4$. Hence, with $\rho_0 = 0.3$, $Te \approx 250^0\text{K}$, that is; $Te \approx -23^0\text{C}$. Thus, in space, the long wave radiation from the earth has approximately the spectral distribution of a black body at 250^0K. The peak spectral distribution at this temperature occurs at 10μm, and the distribution does not overlap with the solar distribution.

17.3. Solar Cell

Being engineering and science students, you must have probably seen calculators with solar cells; devices that never need batteries and in some cases, and do not even have an off button. As long as there is enough light, they seem to work forever. You may also have seen larger solar panels, perhaps on motorways and highways signs, call boxes, and buoys and even in parking lots to power the lights. Although these larger panels are not as common as solar-powered calculators, they are out there and not that hard to spot if you know where to look. In fact, photovoltaic, which were once used almost exclusively in space, powering satellites electrical systems as far back as 1958; are being used more and more in less exotic ways. The technology continues to pop up in new devices all the time, from sunglasses to electric vehicle charging stations.

The basic building block of a solar photovoltaic system is a solar cell that produces voltage proportional to the intensity of sunlight. The primary material used to convert sunlight to electricity in a solar cell is called a semiconductor. There are two basic types of semiconductors; p-type and n-type. The p-type semiconductor material has an abundance of holes (vacancy created by electron) with a positive electrical charge, while the n-type semiconductor material has an abundance of electrons with a negative electrical charge. When these two semiconductors come into contact with each other, a p-n junction is formed at the interface. At this junction, excess electrons move from the n-type side to the p-type side, resulting in a positive charge along the n-type side and a negative charge along the p-type side. This creates an electric field much like a battery with one side having a positive charge and the other a negative charge. The process through which the device converts sunlight into electricity is called the photoelectric effect. The device is commonly called a photovoltaic or PV cell, the principle of working of which is illustrated in figure 17.1. Sunlight striking a PV cell is either reflected, absorbed, or it passes through. The light that is absorbed in the PV cell transfers energy to the electrons of the atoms of the cell. With the added energy from the absorbed light, the electrons escape from their normal position and become part of the electric current flow through in an external electrical circuit. The typical PV cell produces a small electrical output, usually constructed to produce between 0.5 and 2 Watts.

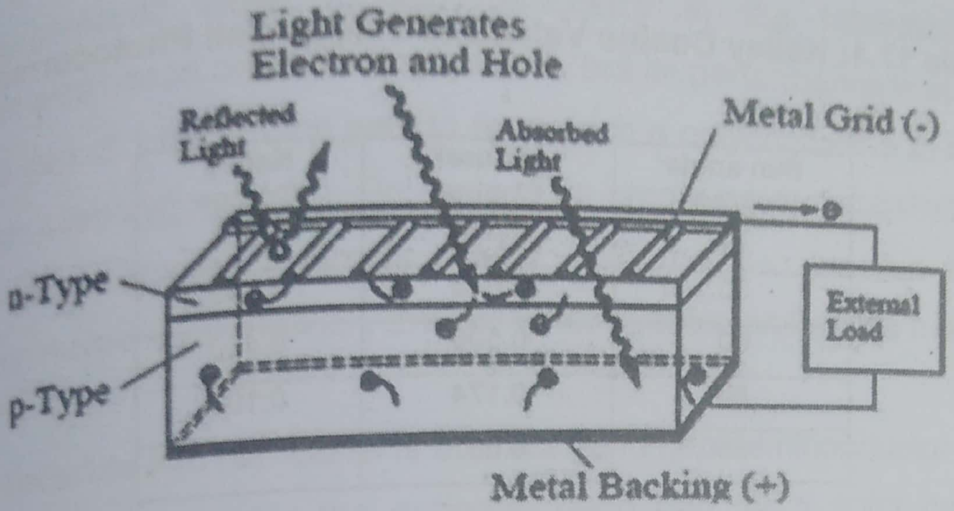

Figure 17.1: A Solar Cell

PV systems produce some electric current any time the sun is shining at any angle, but more power is produced when the sunlight is more intense and strikes the PV modules directly (as when rays of sunlight are perpendicular to the PV modules). While solar thermal systems use heat from the sun to heat water or air, PV does not use the sun heat to make electricity. Instead, electrons freed by the interaction of sunlight with semiconductor materials in PV cells create an electric current. PV modules are much less tolerant of shading than are solar water-heating panels. When siting a PV system, it is most important to minimize any shading of the PV modules. The cell output current is given by:

$$I = I_0 \cos\theta \tag{17.4}$$

Where I_0 is the current with normal sun taken as reference, and θ is the angle of the sun-line measured with respect to the normal and is also called power-angle. This cosine law holds well for sun angles ranging from zero to about 50°. Beyond 50°, the electrical output deviates significantly from the cosine law, and the cell generates no power beyond 85°, although the mathematical cosine law predicts 7.5% power generation. The actual power-angle of the PV cell is called Kelley cosine, the values of which are given in table 17.1.

Table 17.1: Kelley Cosine Values of Silicon Cell Photocurrent

Sun angle (degrees)	Natural Cosine	Kelley Cosine
30	0.866	0.866
50	0.643	0.635
60	0.500	0.450
80	0.174	0.100
85	0.087	0

Photovoltaic (PV) panels convert this natural energy directly into electrical power. These panels contain a semiconductor material, which when illuminated by photons causes an electrical current to flow. As long as there is light, this solar cell will provide a direct current (DC) of electrical power, which can be converted into an alternating current (AC) by using associated electrical system. The physical performance of a solar cell is measured in terms of its conversion efficiency. Currently, commercially available solar cells achieve efficiencies of approximately 15%. Economically, the price of solar electricity as cost per kilowatt-hour is the most important benchmark. PV allows you to produce electricity without noise or air pollution from a clean, renewable resource. PV systems never run out of fuel. These characteristics could make PV technology the global energy source of choice for the 21st century.

17.4. Types of Photovoltaic Cells

The type of photovoltaic cell depends on the type of semiconductor material used The materials that have been developed for use in the thin-film solar cells include amorphous silicon, CdTe and Cu(InGa)Se_2; many more types are under investigation, particularly based on mixed elements of groups III and V of the periodic table like GaAs.

Copper Indium Gallium Selenide, $Cu(InGa)Se_2$: Thin-film cells based on this alloy have achieved close to 20% efficiency in the laboratory. Earlier development was based on excluding gallium, but its performance was limited by its low band gap of 1.0 eV. One way to form such a polycrystalline thin cell is by simultaneous evaporation of Cu, Ga, In and Se onto a neutral substrate such as Mo-coated glass. The alloy film is p-type, with the p–n junction formed by depositing an n-type layer of CdS , ZnO or other suitable and stable material.

Cadmium Telluride (CdTe): CdTe is a direct band gap semiconductor with band gap of 1.5eV, which is near the optimum band gap for a solar cell in AM1 insolation. It can be deposited in thin polycrystalline films by electrode position or other means, and a heterojunction formed with CdS. Efficiencies of 16% have been reported, but performance of CdTe cells is sensitive in ways not yet fully understood to the precise conditions of manufacture, with some cells degrading badly over time, though others do not.

Gallium Arsenide (GaAs): Heterojunctions with $Ga_{1-x}Al_xAs$ can be made commercially. Theoretical target efficiencies for cells are high at about 25%, and GaAs devices have reached practical efficiencies of 16%. The high extinction coefficient necessitates accurate control of layer depths, and surface recombination can be high.

17.5. Modules and Arrays

Generally solar cells come as a very small unit with voltages of few volts and power of few mW. Typically, it is a few square inches in size and produces about one [illegible] devices, they can be obtaining high power, numerous such cells are connected in series and parallel combinations to form modules and arrays on a panel with area of several square feet as illustrated in figure 17.2. Connecting in series increases the voltage output, while connecting in parallel increases the current output. Connecting PV cells in series and parallel strings forms what is called a module. Modules are commonly connected in series and parallel strings to form what is called an array. The solar array is thus a group of several modules electrically connected in series-parallel combinations to generate the required current and voltage. Some manufacturers now produce 'power modules' that can produce 190 Watts or more. A 190 Watt module connected to a load may produce 27 volts at around 7 amps when exposed to full sun conditions. Individual modules produce electric current and voltage that depends upon the specific module. The output of an array can be designed to meet almost any electric requirement, large or small. The electric output wires of the modules are wired together in a combiner box in order to get the voltage and current required by the inverter. The array output can be disconnected by a DC disconnect switch. In order for the system to be disconnected from the grid by utility workers, a utility accessible AC disconnect switch is installed on the inverter output. The inverter may have two connections to the breaker panel.

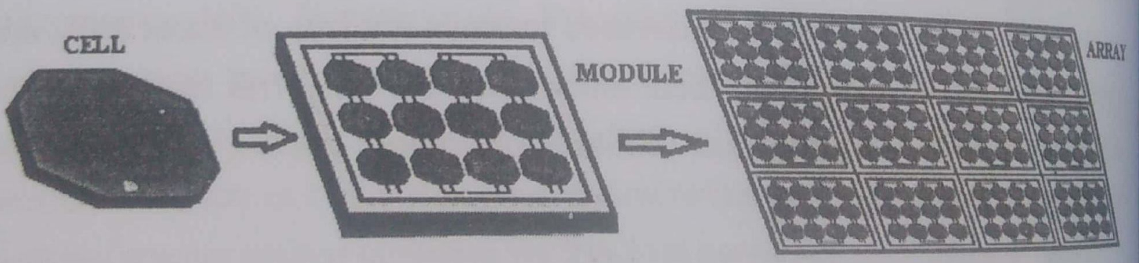

Figure 17.2: Module and Array

Together, modules and array form a solar panel. Photograph of a typical solar panel is shown in figure 17.3. Generally, solar panels do not have the structure needed to withstand wind loading, and so must be mounted on a mounting structure. PV modules are mounted on mounting racks and are attached to a structure or may be mounted on a pole or arranged on the rooftop. Mounting structures are usually made of steel or aluminum and may be attached to the roof of the home in a fashion similar to that for solar water-heating panels. Mounting structures may be fixed mount, may allow the array to be tilted seasonally, or may, on pole mounts, be able to track the sun. Mechanically, modules are designed to withstand golf ball size hail. The panel can be protected by providing a glass sheet, covering the cells to avoid mechanical damage and at the same time allows sunrays to fall on the cells.

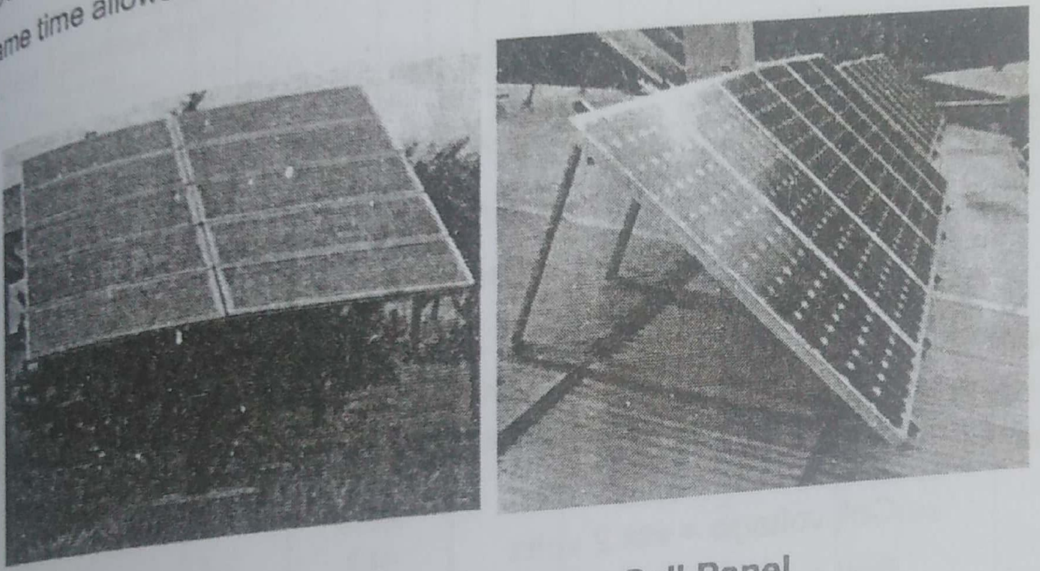

Figure 17.3: Typical Solar Cell Panel

It must be remembered that a suitable size of array of solar panel must be formed from modules. A large array may get partially shadowed due to a structure interfering with the sun-line. If a cell in a long-series string gets completely shadowed, it will lose the photo-voltage, but still must carry the string current by virtue of its being in series with the other fully operating cells. Without internally generated voltage, it cannot produce power. Instead, it acts as a load, producing local I^2R loss and heat. The remaining cells in the string must work at higher voltage to make up the loss of the shadowed cell voltage. The current loss is not proportional to the shadowed area, and may go unnoticed for mild shadow on a small area. The commonly used method to eliminate the loss of string due to shadow effect is to subdivide the circuit length in several segments with bypass diodes (Figure 17.4). The diode across the shadowed segment bypasses only that segment of the string. This causes a proportionate loss of the string voltage and current, without losing the whole string power. Some modem PV modules come with such internally embedded bypass diodes.

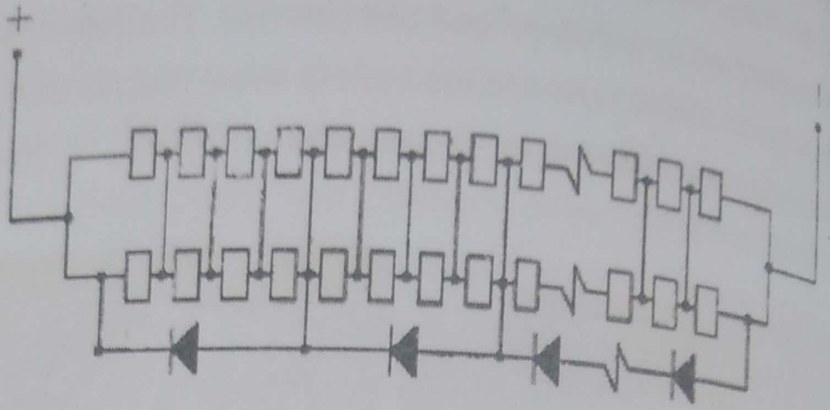

Figure 17.4: Modules with By-Pass Diodes

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Example 17.1: Form module and array for obtaining 2 kW at a voltage of 100 volts for a solar PV system. The cells available have a power of 1.8 Watts at 2 volts.

Given that:

Cell voltage = v = 2 volts

Cell power = p = 1.8 Watts

The current that should be available from the whole PV system is:

$$I=\frac{P}{V}=\frac{2000}{100}=20\text{A}$$

In order to obtain a voltage of 100V, the cells must be connected in series. Thus the number of cells to be connected in series is:

$$=\frac{100}{2}=50\text{ cells}$$

This arrangement will give a current of:

$$i=\frac{p}{v}=\frac{1.8}{2}=0.9\text{A}$$

In order to obtain 20A as required, the number of group of series cells will be:

$$=\frac{20}{0.9}=22.2$$

Thus a figure of 23 seems to be just right. The number of cells required will be: 23 x 50 = **1150**. Thus by arranging 12 parallel arrangements of 50 series cells, a module can be formed. By forming an array of 2 such modules, 2.16 kW of power can be obtained, which seems appropriate to account for losses.

Example 17.2: A manufacturer provides solar modules rated at 95 Watts, 12 volts and 5.5 amperes. Calculate:

(a) The maximum current that can be made available by forming solar panels of 24 volts using 4 identical modules.

(b) Maximum current by forming solar panel of 24 volts using 3 identical modules.

Part (a): To form 24 volts from 4 identical modules as given in the question, two, 12 volts modules are connected in series to obtain 24 volts. Connecting two such series formed modules in parallel will result in 24 volts and 11 amperes. The schematic arrangement is shown in figure 17.5(a).

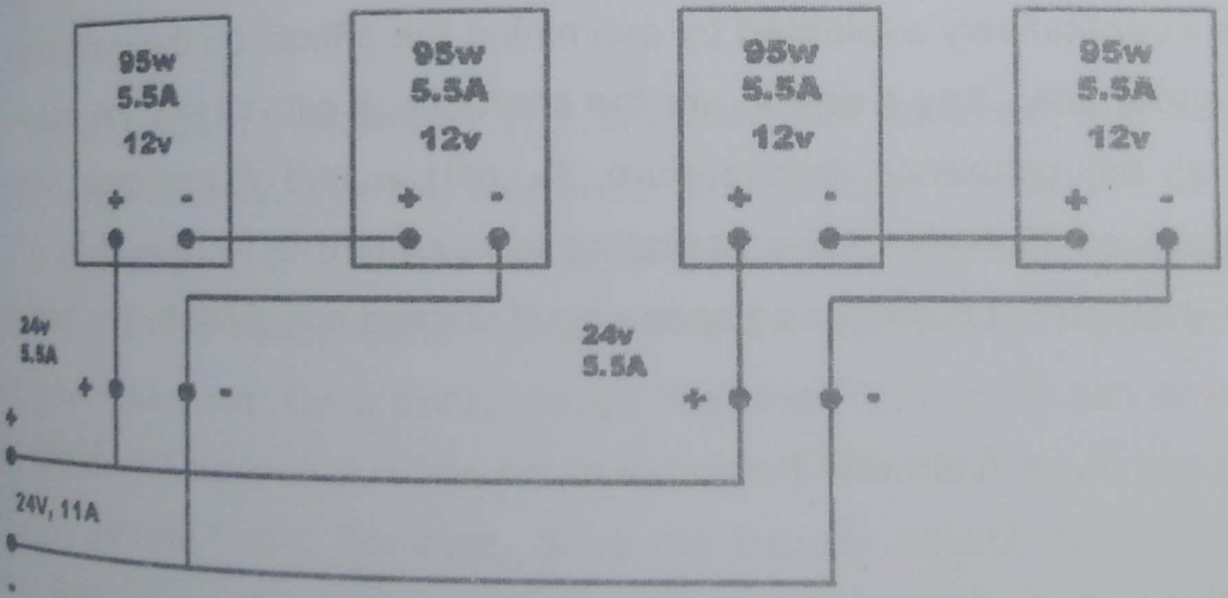

Figure 17.5(a)

Part (b): Two identical modules

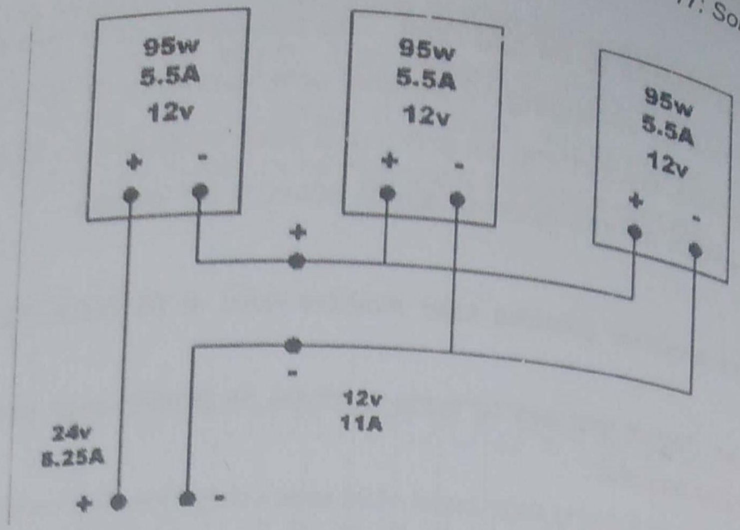

Figure 17.5(b)

17.6. Effect of Temperature

With increasing temperature, the short-circuit current of the cell increases, whereas the open-circuit voltage decreases. The effect of temperature on the power is quantitatively evaluated by examining the effects on the current and the voltage separately. Say I_0 and V_0 are the short-circuit current and the open-circuit voltage at the reference temperature T_0, and α and β are their respective temperature coefficients. If the operating temperature is increased by ΔT, then the new short-circuit current and open-circuit voltage are given by the following:

$$I_{SC} = I_0(1+\alpha\Delta T) \qquad 17.5$$

$$V_{OC} = V_0(1-\beta\Delta T) \qquad 17.6$$

Since the operating current and the voltage change approximately in the same proportion as the short-circuit current and open-circuit voltage, respectively, the new power is as follows:

$$P = V_{OC} I_{SC} \qquad 17.7$$

Substituting I_{SC} and V_{OC} from equations 17.5 and 17.6 respectively in equation 17.7, we obtain:

$$P=[V_0(1-\beta\Delta T)]\times[I_0(1+\beta\Delta T)]$$

This can be simplified in the following expression by ignoring a small term and that: $P_0=V_0I_0$, we obtain:

$$P=P_0[1+(\alpha-\beta)\Delta T)] \qquad 17.8$$

The values of α and β for a single crystal silicon cell is 500μm per ^{0}C and 5000μm per ^{0}C respectively at 25^{0}C, so that equation 17.8, withese values of α and β will take the form:

$$P=P_0[1-0.0045\Delta T)] \qquad 17.9$$

The expression in equation 17.9 indicates that for every 1°C rise in the operating temperature above the reference temperature, the silicon cell power output decreases by 0.45%. Since the increase in the current is much less than the decrease in the voltage, the net effect is the decrease in power at high operating temperatures. On a partly cloudy day, the PV module can produce up to 80% of their full sun power. Even on an extremely overcast day, it can produce about 30% power. Snow, however, does not usually collect on the modules, because they are angled to catch the sun. If snow does collect, it quickly slides down.

Example 17.3: Determine the theoretical decrease in output power at 37^{0}C from a silicon cells PV module with design power of 1.2 kW.

Given that:

P_0 = 1.2kW

T_0 = 25^{0}C

$T = 37^0C$

Since the values of α and β for a single crystal silicon cell is 500μm per ^{0}C and 5000μm per ^{0}C, so that using equation 17.8:

$$P = P_0[1 - 0.0045\Delta T)]$$

$$\Delta T = (T - T_0) = 37 - 25 = 12^0 C$$

Therefore: $P = 1.2 \times [1 - 0.0045 \times 12)] =$ **1.13 kW**

17.7. Components of a Photovoltaic System

A general schematic diagram of a PV system is shown in figure 17.6 showing the major components. The system can provide power to DC loads through converters (not shown) and AC loads through inverter, which also acts a battery charger, operated through a changeover or transfer switch. During day time, with plenty of sun shine, the batteries are charged directly through charge controller and during night time batteries are charged from utility supply system.

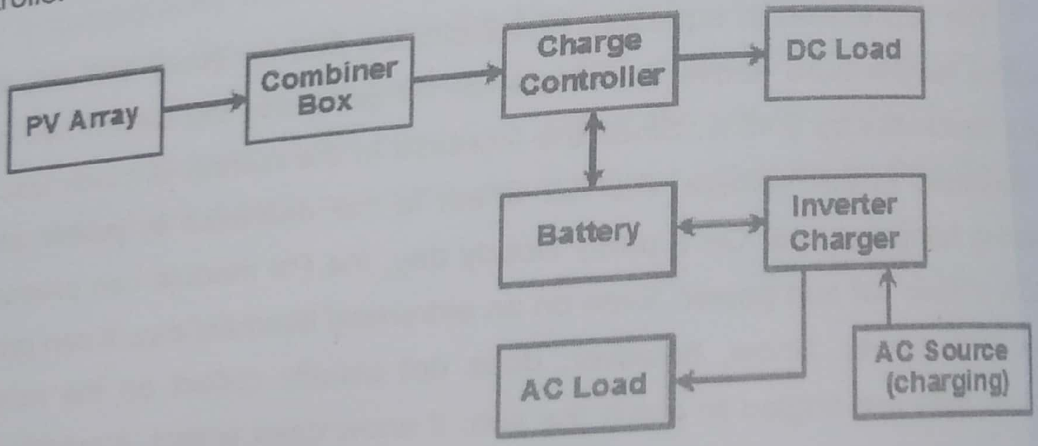

Figure 17.6: PV System

Solar Panels: Electrical energy with the sun starts at the solar panels. Solar panels are typically mounted in a location where plenty of sunshine can be captured; for example on a rooftop or open space with almost no chance of any shadow. Solar panels are composed of modules and arrays of photovoltaic (or

PV) cells, which convert sunlight into direct current (DC). Panels produce electricity with no moving parts and last a very long time. Solar panels can also be integrated into other structures such as carports, parking shade structures, fixed ground mounts, and trackers.

Combiner Box: Combiner box is another major component of a PV system as shown in figure 17.7. Modules are commonly connected into an electrical string to produce the desired voltage and amperage. The resulting wires from each string are routed to the combiner box. In this box all the strings are combined into one electrical output. A typical combiner box has ten strings of modules are fed through fuses to produce a single output. Some standard combiner boxes also contains a surge arrester for overvoltage and surge protection.

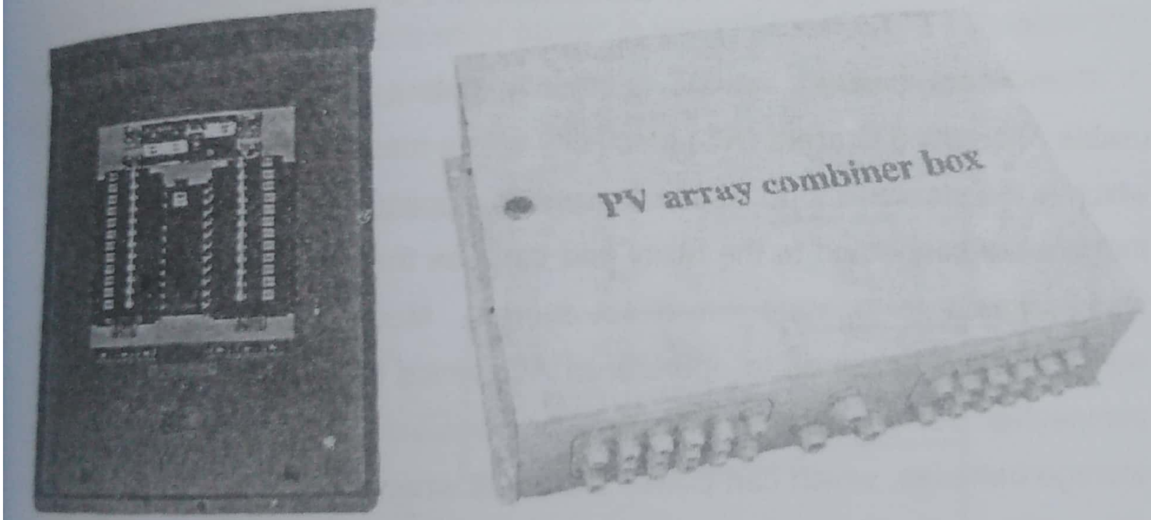

Figure 17.7: Combiner Box

Inverter: PV cells, modules, and arrays produce Direct Current (DC), which is not suitable for most appliances. In combiner box all the strings are combined into one electrical output, which is fed to the inverter as shown in the schematic of figure 17.8.

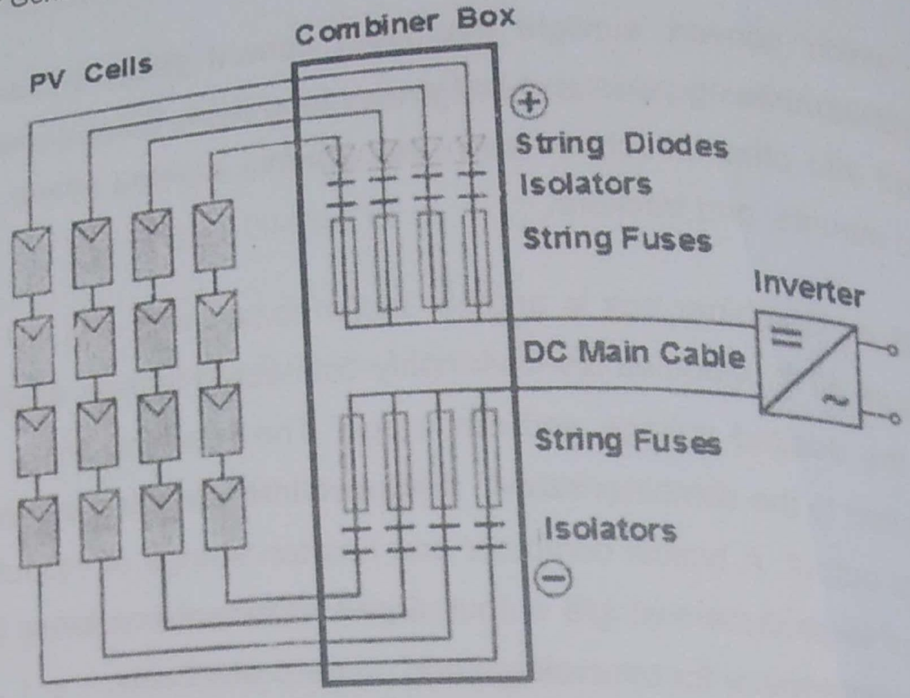

Figure 17.8: Schematic of PV System

Inverters convert the DC electricity output from the solar panels into usable Alternating Current (AC) electricity with a standard frequency and voltage, which is the standard form of power used by appliances. However, electric loads that are not connected to the utility grid can use the PV-generated power if they are designed to operate on direct current. Most domestic appliances and equipment are designed to operate on AC, which is generated by electric utility companies. Using a charge controller, PV-generated power can charge a bank of storage batteries, which can power DC loads when the sun is not shining on the array. The type of inverter will, however, depend on the type of system, which is typically determined by the type of modules and the size of the system. In stand-alone or grid-connected PV system installations, inverters that are commonly used do not need the utilities voltage and frequency reference to produce AC with electrical characteristics much like utility-generated AC. Inverters that are connected to the utility grid produce AC that is identical to the power produced by the utility. These inverters sense the utility's generated voltage and waveform characteristics and produce AC of the same form.

Charge Controller: Figure 17.9 is the simple diagram of charge controller used with the PV system. The most basic function of a controller is to prevent battery overcharging. If batteries are allowed to routinely overcharge, their life expectancy will be dramatically reduced. A controller will sense the battery voltage, and reduce or stop the charging current when the voltage gets high enough. This is especially important with sealed batteries where battery fluid that is lost during overcharging cannot be replaced. PV controllers can open the circuit when the batteries are full without any harm to the modules. Most PV controllers simply open or restrict the circuit between the battery and PV array when the voltage rises to a set point. Then, as the battery absorbs the excess electrons and voltage begins dropping, the controller will turn back on. PV controller also prevents reverse current flow at night. Reverse current flow is the tiny amount of electricity that can flow backwards through PV modules at night, discharging the battery, but the loss of power is insignificant. Only with larger PV systems is this significant but and almost all charge controllers deal with it automatically.

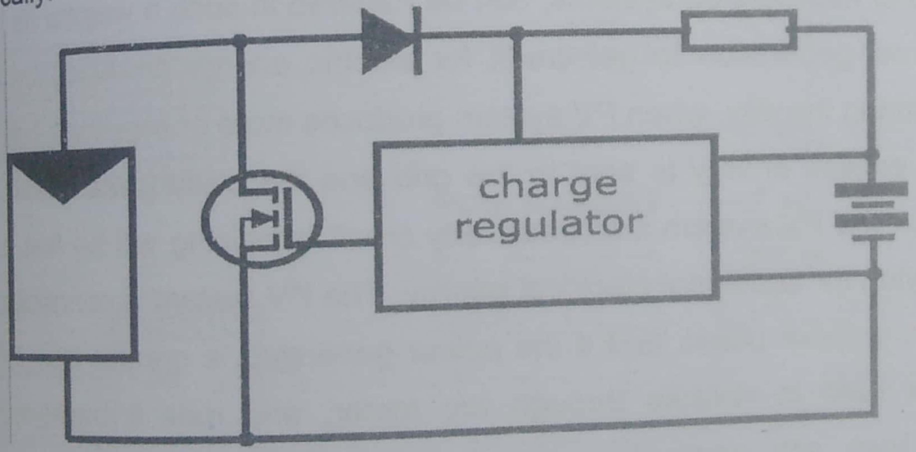

Figure 17.9: Charge Controller

The only exception to controller need is when the charging source is very small and the battery is very large in comparison. If a PV module produces 1.5% of the battery's ampere-hour capacity or less, then no charge control is needed. Controllers are rated by how much amperage they can handle. It is generally required that controllers should be capable of withstanding 25% over-current for a limited time. This allows the controller to survive the occasional edge-of-cloud effect, when sunlight increases dramatically. Exceeding the current rating for a controller can destroy it. The use of a controller with higher current capacity than the generating will allow for future expansion, and is not expensive.

Solar Meter: The solar meter measures only how much electricity the PV system produces.

AC Disconnect: This enables electricians to disconnect the premises electrical system from the solar electricity system. By switching the AC disconnect off, workers can safely perform system maintenance. In many cases, the DC disconnect switch also contains a ground fault interrupter for the PV array.

Electric Panel: AC electricity from your inverter is passed onto the electric service panel where it is routed to power various electric loads.

Net Meter: PV systems interconnected to the utility are called grid-connected or net-métered systems; can be metered in such a way so as to allow the customer-generation to get credit for electric energy produced by the PV system. During the day, when PV system produces more energy than that can be used, the excess energy is sent to the grid and the utility gives credit. As the demand on the PV system increases, any credit remaining will be first used up before paying for additional electrical energy. The PV system is connected at the customer's breaker panel, and if the power generated is greater than the load, the power runs in reverse through the meter, and runs it backwards. Net metering laws are generally in place in developed countries in order to encourage renewable energy generation. The net-metered customer is to be reimbursed (by the electric distribution company) at the full retail rate for each kilowatt-hour produced by the customer during a billing period and at the end of the billing period, the customer will be compensated if they generated more than they used during the period. In other words, the electric utility meter in the premises can backup whenever the PV system produces more electricity than is being consumed and if at the end of the billing period the PV installed premises still has generated more than it consumed, the distribution company will pay for the excess.

17.8. Utility Grid and Stand-Alone Systems

PV systems that have excess energy can be connected to the utility grid are called utility grid or grid-tied system or hybrid system. If the PV system is connected to the power grid, storage can be provided by the local utility company. The excess energy generated by the customer can be sold to the utility, may be for a price below that charged by the utility to the customer. The price differential would pay for storage and distribution. As mentioned earlier, a dual metering system, called a net metering system can be used: one meter measures the outgoing power from the customer to the utility, and the other the power from the utility to the customer. Figure 17.10 shows a schematic of grid-tied system.

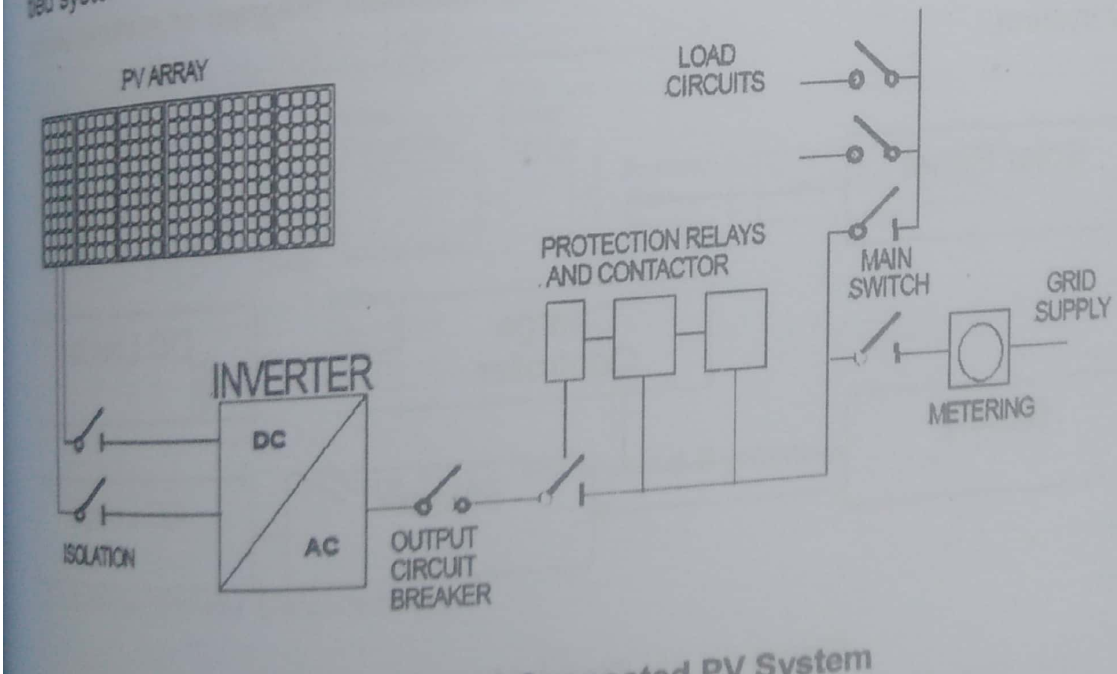

Figure 17.10: Grid Connected PV System

Grid-tied solar photovoltaic systems interface seamlessly with the utility grid, which allows the utility grid to serve as the back-up power for the premises, rather than storing excess electricity in batteries. During the day, the PV system will first power any electrical loads in the premises, before sending any excess generation back to the utility grid. At night, however, the system will draw from the utility grid, essentially using the electrical grid as a giant storage battery. In some cases, the average energy generated may well exceed the needs of the building. The excess power is generated only on sunny days and not on rainy days and at night. Consequently, adequate storage facilities must be available, especially in case of residences, where demand during the day may be small, while at night requirements are higher. As the cost of solar cells becomes progressively less, such utility grid-tied system will become much more common, thus forming building-integrated photovoltaic (BIPV) systems. The land area of the building, the structure on which to mount the solar collectors (roof and external walls), the very roof, and the connection to the grid are all investments made even if no BIPV is used and thus should not be charged to the BIPV cost even though they must be included in the cost of centrally generated PV systems. PV systems that are not connected to the utility grid are called stand-alone or remote systems. Figure 17.11 is a schematic diagram of a stand-alone PV system.

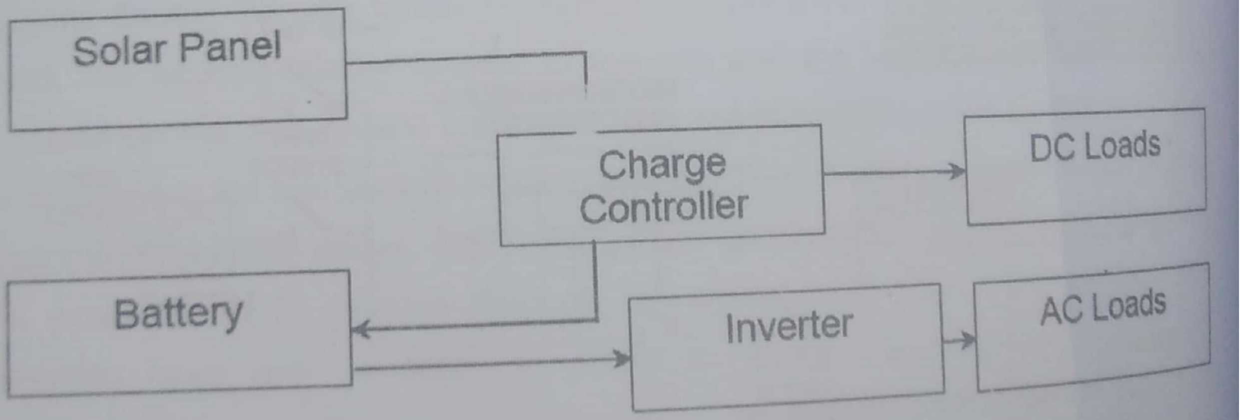

Figure 17.11: Stand-Alone PV System

Stand-alone PV systems are sized large enough to meet all the electric needs of the building, house or a small farm, rather than just a portion as is common in grid-connected systems. To reduce the size and cost of these systems, the owner must wisely use electrical energy. In remote areas where existing utility lines are a considerable distance away, PV is often the least expensive way to provide electricity to a building. If the building is off-grid, as some rural properties are; that is, if it has to be entirely self-sufficient, expensive batteries or some other storage scheme is required. A remote solar electric system can be less expensive than the distribution line extension and transformer installation.

Off-grid systems have the same components as grid-connected systems, except that they do not need a grid-tie inverter, and they do need storage batteries. Also, off-grid systems may have additional components such as an auxiliary generator, or even a wind turbine forming a hybrid system as shown in the schematic of figure 17.12. A utility-tied inverter must be used synchronize the customer-generated electricity with the grid.

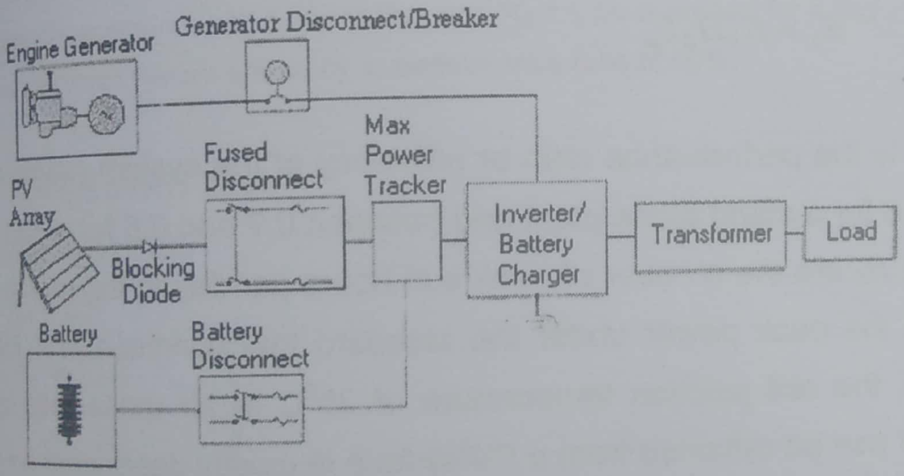

Figure 17.12: PV Hybrid System

17.10. Solar Power Calculations

The first task of the designer of solar photovoltaic system is to work out the size of the PV array in accordance with the peak power demand of electricity it has to satisfy. The sun energy available per day is not the same throughout the year since the amount of sunlight falling on the array is bound to be seasonal.

Therefore it is important to introduce the concept of peak sun hours for estimating an array's annual output. This involves compressing the total radiation (direct plus diffuse) received throughout the year into an equivalent duration of standard 'bright sunshine' (1 kW/m^2). The same concept may be used for daily radiations. For example, if an inclined array receives an average insolation of 3 kWh/m^2 per day in April, this is considered equivalent to 3 peak sun hours; so an array rated at (say) 2 kW peak is predicted to yield 3 × 2 = 6 kWh/day. Although it is an approximation that tends to be over-optimistic for arrays receiving a high proportion of diffuse radiation, it offers a very straightforward way to estimate array output in a particular location.

Knowing the average insolation at a particular location, it is simple to estimate the total energy received over the course of a year (1 year = 8760 hours). The yearly delivery of sun energy E_S in kWh per year is given as:

$$E_S = K_S H_S P_m \tag{17.10}$$

Where K_S is the performance ratio or efficiency of the system (which is between 0.5 and 0.6 for a stand alone plant and between 0.7 and 0.8 for a grid connected plant) and H_S are the number of peak sun hours per day in the month of interest and P_m is the peak power under the standard test condition of 1 kW/m^2 solar irradiation, the cell junction temperature of 25^{0}C at air mass ratio of 1.5. The power that can be obtained from a PV system is mostly dependent on the overall efficiency of the entire system, which is the product of the efficiencies of all the components. For PV modules and arrays, the efficiency is generally considered as 85% or 0.85. This is because the power output is less than the rated value in standard 'bright sunshine' (1 kW/m^2), which is due to factors such as raised cell operating temperatures, dust or dirt accumulation on the modules, and cell aging. In addition, modules are not generally operated at or close to their maximum power capability, unless a controller with solar tracking system is used. The batteries or battery bank's efficiency is also generally considered to be 80-85%.

This is because of the charge retrieved from the battery bank is substantially less than input charge. The efficiency of inverter is generally considered as 90%. This, however, is a typical figure for a high quality inverter, bearing in mind that it must sometimes work at low output power levels. Other components, such as, charge controller, blocking diodes, and cables together is considered to be about 80-85% due to small amount of losses. The product of all these figures is 60-65%. If solar tracking is used and that the system is DC only (no inverter) the system efficiency may approach or go beyond 70%. But in practice it is hard to predict how components will behave in variable sunlight and ambient temperatures, or how the system will actually be used, so the above figures should be treated with caution. In view of all these uncertainties, plus the vagaries of the weather, over-sizing a PV array by a reasonable amount of 20% seems reasonable and is often recommended.

Example 17.4: Calculate the rated peak power of PV array to be used for a stand-alone PV system for a residential apartment with 5.5 kWh/day and $H_S = 6.5$h averaged for a day throughout the year. Assume an overall system efficiency or performance ratio of 60%.

Given that:

$$E_S = 5.5 \text{ kWh / day}$$

$$H_S = 6.5 \text{ hours}$$

$$K_S = 0.6$$

Using:

$$E_S = K_S H_S P_m$$

Or

$$P_m = \frac{E_S}{K_S H_S} = \frac{5.5}{0.6 \times 6.5} = \mathbf{1.41\ kW}$$

17.11. Battery Sizing

The sizing and selection of batteries in solar energy system is an important task. Batteries are rated according to voltage and the number of ampere-hours (Ah). The biggest decision is how many hours of battery storage are required. Too few, and a spell of unusually dull or wet weather may cause a serious loss of electricity supply. Too many, and the battery bank becomes unnecessarily large and expensive. A reasonable size of battery or the number of batteries in a bank is necessary, which depends on the energy requirements. For example a 12V, 120Ah battery will have energy rating E_R of theoretically of 12 x 120 = 1440 Wh (1.44 kWh). Ideally, a 12V, 120 Ah storage battery can provide a power to a 100-Watts bulb for 1440 / 100 = 14.4 hours. One day of usable battery storage for energy consumption in example 17.4 will be: $\left(\frac{5.5\times1000}{12}\right) = 458.3$ Ah.

But in practice it depends on the type of application; a small home is by no means a crucial case and many 'professional' systems demand far higher reliability to avoid risking serious inconvenience, economic penalties, or even danger to life. In such cases the amount of battery storage may have to be raised greatly, perhaps to a few days. When the number of days of storage N has been decided, the capacity E_B of the battery bank can be calculated:

$$E_B = \frac{NE_S}{\eta_B \eta_{inv}} \qquad 17.10$$

Where (as before) E_S is the daily electrical energy requirement, η_B is the efficiency of the battery bank, and η_{Inv} is the efficiency of the inverter, assuming an AC supply is required. Note that the usable capacity of the battery bank is less than its nominal, rated, capacity because complete discharge must be avoided. The number of batteries n required can be calculated by dividing the total energy requirement by the energy rating E_R of the battery, given as:

$$n = \frac{NE_S}{E_R} \qquad 17.11$$

Example 17.5: Determine the size of storage batteries required for 2 days in example 17.4. Assume that the standard batteries available are 120 Ah, 12 volts and efficiency of battery and that of inverter are 80% and 90% respectively. The inverter is rated for voltage of 48 volts DC.

Given that:

Battery efficiency: $\eta_B = 80\%$ or 0.80

Inverter efficiency: η_{inv} = 90% or 0.90

Days of storage required: N = 2 days

In example 17.4 the energy requirements per day is 5.5 kWh. For 2 days of storage, battery discharge up to 80% of nominal capacity, and an inverter efficiency of 90%. Hence using oquation 17.10:

$$E_B = \frac{NE_S}{\eta_B \eta_{inv}}$$

$$E_B = \frac{NE_S}{\eta_B \eta_{inv}} = \frac{2 \times 5.5}{0.8 \times 0.9} = 15.27 \text{ or } 15.3 \text{ kWh}$$

The available batteries are rated as 12 volts and 120 Ah, therefore the energy rating of the battery is:

$$E_R = 12 \times 120 = \mathbf{1.44\ kWh}$$

As with the PV array, it may be sensible to oversize the battery bank or to treat it as modular with the option of upgrading it later. To summarize, the stand-alone system considered in the example 17.5 should be able to supply the desired amount of electrical energy, PV array rated at 1.41 kW with a battery bank of capacity 15.3 kWh. If the batteries are connected to give 48V DC, which is quite common for a system of this size, then the required charge capacity is:

$$\frac{15300}{48} = 318.75 \text{ Ah}$$

Since the inverter is rated at 48 volts, a battery bank consisting of modules and array has to be formed. Thus to form a battery bank, 4 batteries will be connected in series to give 48 volts, forming a module. Connecting 3 similar modules in parallel will form an array, which completes the battery bank. Thus in this case **12 batteries of 12 volts and 120 Ah** will be required, forming a reasonable over sized arrangement, with a capacity of 17.28 kWh, giving 120 x 3 = 360 Ah of storage.

17.12. Benefits of PV Systems

Solar photovoltaic systems provide power for communications satellites, water pumps, and the lights, appliances, and machines in homes and workplaces. For convenient and energy saving, many traffic lights on the roads are now powered by PV cells so that the traffic lights can work in the event of power outages. As a form of energy supply, photovoltaic panels offer a broad range of advantages:

1. The fuel source is essentially infinite.
2. PV produces energy without greenhouse gas emissions.
3. PV modules are a reliable technology as they have no moving parts and the average lifetime for a module is often in excess of 25 years.
4. The materials used in PV modules and cells can be recycled at end-of-life.
5. Photovoltaic energy is sustainable, even in the strict meaning; the energy-pay-back of a module is between 1.5 and 3 years. After this period, the module has produced more energy than had been used for its production.

17.13. Environment and Land Use

The main environmental credentials of PV are established beyond doubt; its important contribution to reducing carbon emissions; cleanliness and silence in operation; lack of spent fuel or waste; and general public acceptability in terms of visual impact. But there are further environmental considerations as PV accelerates into multi-gigawatt annual production; the question is; can our planet earth provide the necessary quantities of raw materials, and is there enough land available for hundreds of millions of PV modules. It is generally estimated that an area of land 140 × 140 km, or 20,000 km^2, roughly three times the size of London or Paris, would be sufficient to accommodate about 1000 GW of PV modules. It seems that by 2020, or soon after, we may be approaching this huge total, some

50 times greater than the existing global installed capacity, assuming PV continues its present remarkable progress. A question arises as to where would the land actually come from. If 20000 km^2 sounds like a large chunk of land, consider some even larger ones: the Sahara Desert is about 850 times bigger; the Australian Outback about 200 times; and the state of Arizona about 15 times. In the USA, cities and towns cover some 700,000 km^2 and in many countries wide tracts of land are set aside for military uses, airports, highways, fuel pipelines, and so on. In short, if the world's PV is sensibly spread around among the world's nations, the landscapes seen by the vast majority of people will be virtually unchanged from those they enjoy today. Of course this is far from the whole story, because PV can be installed on buildings. There are vast numbers of existing homes, offices, public buildings, factories, warehouses, airports, parking lots and railway stations with suitable roofs and façades, and we may be sure the that tomorrow's architects will be even more aware of the possibilities. BIPV will undoubtedly provide a major part of PV's future space requirements, leaving deserts and other unproductive land to supply most of the balance. Sunshine is everywhere, high and low, city and country, and at fairly predictable levels. There is absolutely no need for PV to dominate with unsightly and unwelcome 'blots on the landscape'.

17.14. Solar Thermal Energy System

One of the most promising renewable energy sources of electricity for the future is solar thermal electric power plants. It is important to understand that solar thermal energy is not the same as solar power or solar photovoltaic energy as photovoltaic system converts the suns light directly into electricity. However, solar thermal energy can be used to concentrate the rays from the sun creating heat, which is then used to produce steam, which turns a generator to provide electricity. Solar thermal energy refers to a technology that uses the sun energy to heat water or other types of heat transfer fluids for a variety of residential, industrial and other applications with swimming pool heating, hot water heating and space heating currently being the major applications of solar thermal energy. Solar thermal electric power plants generally use concentrated sunlight obtained through various mirror configurations to focus the sun energy to produce high-temperature heat. The heat energy is then transferred to a fluid or gas, which is used in a typical power plant cycle to convert the heat energy to mechanical energy and then to electrical energy. The two major parts of a solar thermal electric power plant are the component that collects the solar energy and converts it to heat and the component that then converts the heat energy into electrical energy. One of the major benefits of solar thermal energy is that it involves a thermal intermediary, so fossil fuels can easily be integrated into the system as an alternative source of fuel if the sun is not providing enough energy unlike photovoltaic solar panels. In some cases the heat produce by the solar energy can go into thermal storage for periods of low to no sunlight, further reducing the average cost of the electricity produced.

The first test of a large-scale thermal solar power tower plant was in the California Mojave desert, constructed in 1981. The project produced 10 MW of electricity using 1818 mirrors, concentrating solar radiation onto a tower, which used high-temperature heat transfer fluid to carry the energy to a boiler on the ground, where the steam was used to spin a series of turbines. Water was used as an energy storage medium. The system was redesigned in 1995 and renamed “Solar 2”, which used molten salt as an energy storage medium. In this type of system, molten salt at 290°C is pumped from a cold storage tank through the receiver where it is heated to about 565°C. The two major parts of a solar thermal electric power plant are the component that collects the solar energy and converts it to heat and the component then converts heat energy into electricity.

17.15. Solar Thermal Collector

Solar thermal energy systems typically incorporate a roof or pole mounted solar energy collector commonly called a ‘solar thermal collector’ which receives sunlight and changes it into usable heat producing pollution-free heat source. The solar energy collector or solar collector is a parabolic trough type of dish. Parabolic trough power plants use concentrated sunlight, in place of fossil fuels. They provide the thermal energy required to drive conventional power plants. These plants use a large field of parabolic trough collectors which track the sun during the day and concentrate the solar radiation on a receiver tube located at the focus of the parabolic shaped mirrors. A parabolic trough is constructed as a long parabolic mirror that is usually coated silver or polished aluminum. It has a Dewar tube down its length at the focal point of the mirror. Sunlight is reflected from the mirrors and is concentrated on the Dewar tube. Figure 17.13 is an illustration of how the sunlight hits and is reflected from the parabolic trough. The receiver of a trough concentrator (Dewar tube) is typically a metal absorber surrounded by a glass tube. The absorber is coated with a selective surface that has a high absorptance for incoming light in the visible range, and a low emittance in the infrared wavelength. The glass insulates the pipe from the effects of the wind and thus greatly reduces heat losses due to convection and conduction. Glass is also a radiation barrier to infrared light so it reduces heat loss due to radiation. Heat transfer fluid (usually oil) runs through the tube to absorb the concentrated sunlight. The heat transfer fluid is then used to heat steam in a standard turbine generator system.

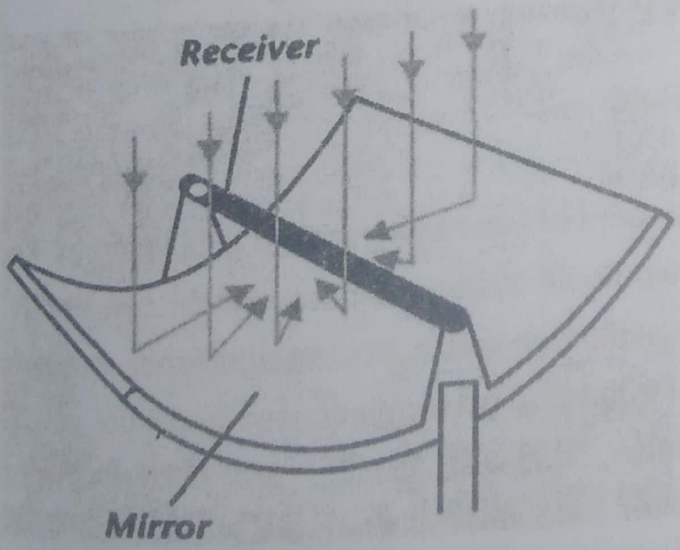

Figure 17.13: A Parabolic Solar Collector

The intensity of the sun can be multiplied by a concentration ratio of 30 to 80. To achieve such concentration, a trough tracks the sun in one axis continually throughout the day. To maximize the sunlight incident on the absorber, the reflectance of the parabolic reflector must be as high as possible. This is why aluminum or silver reflectors are used. Silver has the higher reflectance, but is harder to protect against the corrosive effects of the outdoor environment. It is also important to keep the reflectors clean since dirt will degrade the reflectance of light from the parabola.

Most solar thermal systems use mirrors to focus sunlight, generating temperatures high enough to produce steam to drive a turbine. One of the advantages of the solar thermal approach, versus conventional photovoltaics that convert sunlight directly into electricity, is that heat can be stored cheaply and used when needed to generate electricity. In all solar thermal plants, some heat is stored in the fluids circulating through the system. This evens out any short fluctuations in sunlight and allows the plant to generate electricity for some time even after the sunset. But adding storage systems would allow the plant to compensate for longer cloudy periods and generate power well into, or even throughout, the night. Such long-term storage could be needed if solar is to provide a large share of the total power supply. Certain regular maintenance is needed on the mirrors, collectors and turbines. For instance, the receivers and mirrors need to be periodically washed and cleaned.

17.16. Working Fluid

The vast amount of heat transfer fluid circulating in the solar field already represents a considerable storage capacity which can bridge short term cloudy phases. Molten salt storage tanks provide additional power even when the sun sets. In Spain, solar thermal power plant uses a mixture of 25000 tons of sodium and potassium nitrate heated to 384°C (723°F). This allows the power plant to operate for well over 6 hours after the sunset. The Spanish national carrier has given this kind of power plant system the same reliability rating as power plants using fossil fuels. The output of solar thermal power plants is thus available continuously.

17.16. Components and Working of Solar Thermal Electric System

The three most commonly used solar thermal electric power plant designs are the parabolic trough design, the power tower design, and the parabolic dish/engine system. After the array of mirrors focuses the sunlight, the concentrated sunlight then heats up the working fluid to temperatures of around 750^{0}C within the receiver. This fluid is pumped to the central generating unit. It passes through several downstream heat exchangers and, as in conventional thermal power plants, generates the steam that is required to drive the turbine generator to produce electricity. The heated high temperature working fluid is then used in either a Stirling or Brayton thermodynamic cycle to produce mechanical power via rotational kinetic energy and then to electricity by an electric generator for utility use. An example of a Brayton cycle used to produce electricity for a parabolic dish power plant is shown in figure 17.14.

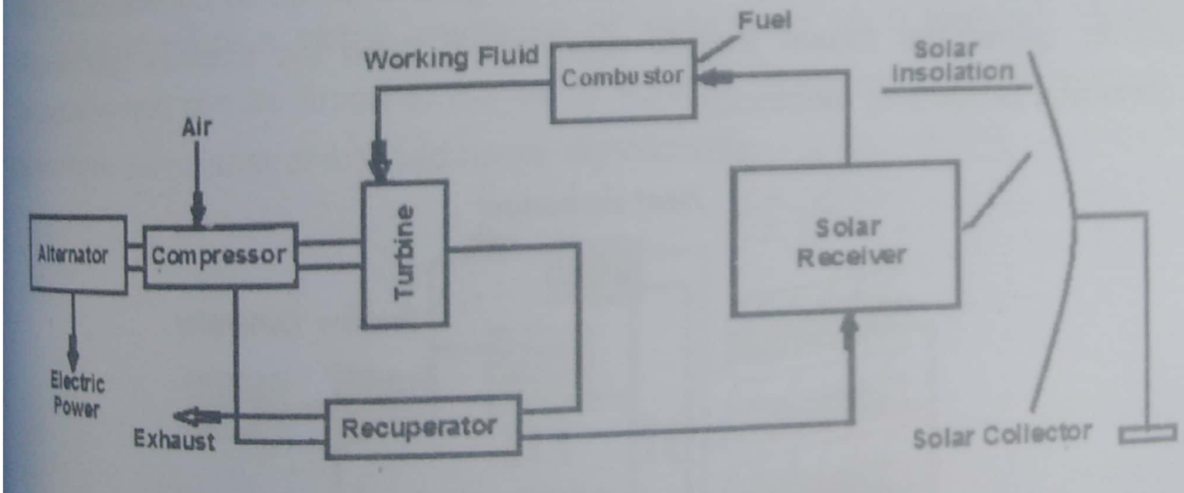

Figure 17.14: Schematic of Solar Thermal Brayton Cycle Plant

In Brayton cycle the concentrated sunlight focused on the solar fluid heats up the compressed working fluid of the cycle, air, replacing altogether or lowering the amount of fuel needed to heat up the air in the combustion chamber for power generation. As with all Brayton cycles, the hot compressed air is then expanded through a turbine to produce rotational kinetic energy, which is converted to electricity using the alternator. A recuperator is also utilized to capture waste heat from the turbine to preheat the compressed air making the cycle more efficient. A Stirling cycle would generate mechanical power in a similar way by using the heat from the concentrated sunlight to move pistons to produce rotational kinetic energy like an internal combustion engine in an automobile. The rotation of the engine's crankshaft could be used to drive an electrical generator and produce electricity. Currently, Stirling engines are more commonly used than Brayton cycles in dish/engine systems, but analysis performed on the dish/Brayton applications predicts possible potential thermal to electric efficiencies of over 30%.

Another type of solar thermal plant works on a Rankine cycle of the conventional thermal power plant, the schematic diagram of which is shown in figure 17.15. A heat transfer fluid passes through the receiver and is heated to high temperature. This fluid is pumped to the central generating unit. It passes through several downstream heat exchangers and, as in conventional power plants, generates steam that is required to drive the turbines that drives a generator producing electricity.

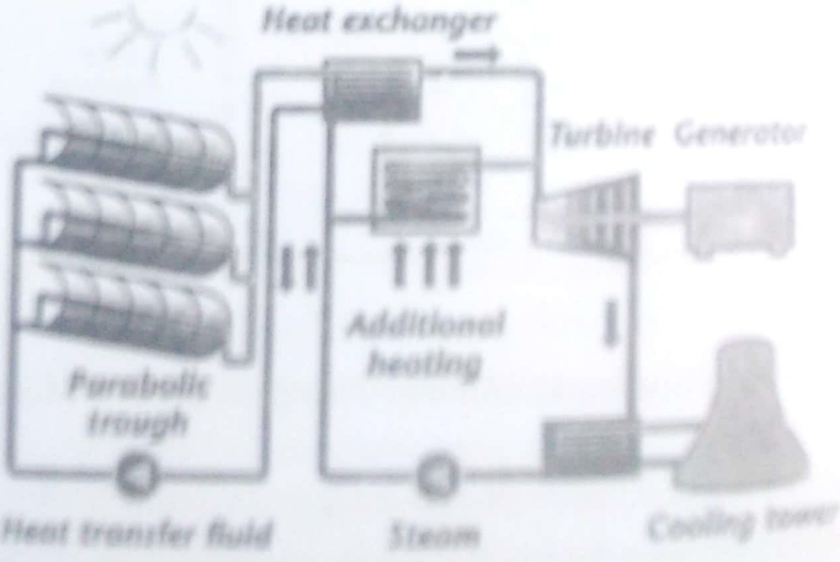

Figure 17.15: Schematic of Solar Thermal Rankine Cycle Plant

17.17. Future of Solar Thermal System

The potential for solar thermal power plants is enormous: for instance, it is estimated that about 1% of the area of the Sahara Desert covered with solar thermal power plants would theoretically be sufficient to meet the entire global demand of electrical energy. Therefore, solar thermal power systems will hopefully play an important role in the global future electricity supply. The largest cost involved in solar thermal power plants is the initial capital cost to build the plant rather than operating costs. Solar thermal power plants have the added advantage over photovoltaic electric generation in that it is possible to generate electricity even during unfavorable weather and at night using heat storage systems. The vast amount of heat transfer fluid circulating in the solar field already represents a considerable storage capacity which can bridge short term cloudy phases.

However, due to the poor part-load behaviour of solar thermal power, such power plants should be installed in regions with a minimum of around 2000 full-load hours. This is the case in regions with a direct normal irradiance of more than 2000 kWh/m^2 or a global irradiance of more than 1800 kWh/m^2. These irradiance values can be found in the earth sunbelt; however, thermal storage can increase the number of full-load hours significantly.