$$\delta = \frac{\text{Energy inputs to the system} - \text{Degraded energy ouytputs of the system(dissipation)}}{\text{Energy inputs to the system}}$$

Degraded energy outputs leave the system as garbage, low grade heat, smoke, etc., which damage the environment in terms of pollution. Therefore, it must be kept as low as possible. The numerical value of index, δ, is a measure of the system's acceptability. A value of $\delta = 1$ can be approached by properly conducting any energy management program to avoid dissipation in the system.

1.5 CAUSES OF ENERGY SCARCITY

While the whole world is in the grip of energy scarcity, several countries, including India also, are facing various associated difficulties for its techno-socio-economic development because of energy shortages and many more things. However, they have been further complicated by the energy dependence on the other countries. Energy use scenario, as shown in Table 1.3, indicates that how equality (social and economical) can be achieved, when 30% population is utilizing 70% of energy and 70% population is forced to live with the 30% of the remaining energy.

Following points may be considered as the principal causes of energy scarcity.

1.5.1 Increasing Population

Undoubtedly, only 40–45% population constitutes child producing groups, worldwide population is increasing at an alarming rate. It is extrapolated that by the turn of 21st century, population will increase manifold (Malthusian population model). These populations are unevenly distributed worldwide. Africa shares the largest population growth rate, followed by South Asia and then by Europe.

1.5.2 Increasing Energy Usage or Consumption

The movement of civilization from early man to the present technological man was totally based on energy usage. Energy is constantly used at home, at work, and for leisure period of enjoyment. Energy maintains techno-socio-economic development. Energy provides the society with heat and electricity daily and motive power to industry, transportation, and modern way of life.

1. In homes, for lighting and cooking, domestic appliances, televisions, computers, etc.
2. In industry to power the manufacture of the products.
3. In transport system to power cars, trucks, ships, and aeroplanes for transporting peoples and goods.

An increase in the world population and consequent increase in energy consumption increases energy demands manifolds. World Energy Council has provided the most reliable prediction as

Table 1.3 Energy Use Scenario

% of population	70%	30%
% of energy usage	30%	70%

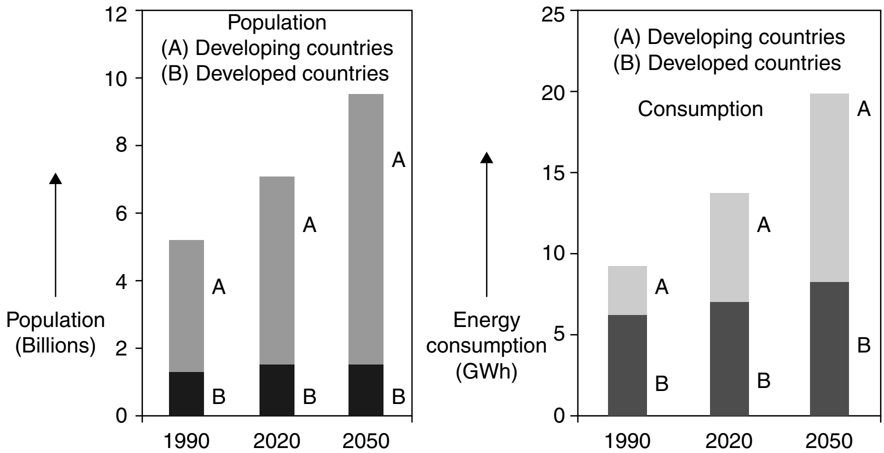


Figure 1.5 Population and energy consumption (Energy council)

shown in Figure 1.5. This indicates that by 2050, the world population will nearly be doubled from the present level and will rise to about 10 billion. Likewise, energy demand is projected to be at least double than the present level (Energy council).

1.5.3 Uneven Distribution of Energy Resources

It is well understood that very few wealthy countries have access to and actually use the largest part of the world's energy and material resources. The generation of environmental and social instability in several area of globe can be discussed in relation to the existence of disparity. Uneven distribution of energy and resource trade among countries is of paramount importance to environmental and political stability. For example, Middle East countries are full of crude oil reserves, but they are forced to involve in conflicts and wars and their energy reserves are forcefully used by wealthy countries. Geographical distribution is the main consideration for an unevenly distribution of fossil fuels (coal, oil, gas, and nuclear). Renewable energy flows are also spread out unevenly. Cloudiness in equatorial regions reduces solar radiation. Whole stretches of the continent have insufficient wind. There are very few sites with the best potential for geothermal, tides, or ocean thermal. In fact, a few densely populated region or area have no significant locally available energy sources at all.

1.5.4 Lacks of Technical Knowhow

Despite the fact that several countries or regions are having energy in abundance, they are not able to fully utilize them due to the lack of knowledge of conversion, transmission, distribution, and utilization. Because of the lack of technical knowledge, resources are mined and processed in resource enriched countries and then refined and used in developed countries. The price of exported resources is normally inadequate to compensate for the depletion of energy reserves and the environmental burden that is generated by resource extraction and primary processing in energy enriched countries. However, resources drive significant economic and environmental benefits in techno-economically developed countries.

applications makes no sense in the context of thermodynamics. For example, when designing a heating system, it makes no sense to produce heat at 100ºC, if the system requires heat at 40ºC. Similarly, producing electricity (and suffering the high losses required to do so) and converting it to heat for space heating is a very inefficient use of energy. For example, converting solar radiation to heat with solar collectors will give about 6 times more energy than converting it to electricity using photovoltaic. The electricity route may be convenient for transport, but it is definitely inefficient. Oil is a very high quality form of energy. It is very concentrated and easy to transport. It took about 85 tons of vegetation to produce one barrel of oil. This means that in the last 100 years, we have consumed oil that is equivalent to 13,000 years of plant growth (or photosynthesis) on the planet. Society has become used at depending on high quality forms of energy to accomplish its everyday tasks, as the planet is enriched with a good supply of them. As these are fast depleting and becoming less abundant, there will be need to replace them with more dispersed ones, like concentrating solar energy to a usable form. Converting dispersed energy into a more concentrated form will always be inefficient, that is, a basic law and technology will not allow anyone to bypass it.

1.9 ENERGY RESOURCES AND CLASSIFICATION

The following sections deals with the classification of promising energy resources of immediate interests.

1.9.1 Primary and Secondary Energy Resources

1. Primary energy resources are derived directly from natural reserve. Examples are chemical fuels, solar, wind, geothermal, nuclear hydropower, etc. They are used either in basic raw energy form or by converting them to usable form (secondary energy).
2. Secondary energy resources are usable forms of energy generated by means of suitable plants to convert the primary energy. Examples are electrical energy, steam power, hot water power, hydrogen energy, etc.

Usable form of energy is cost effective, highly efficient with improved performance, environmentally acceptable and system acceptability index approaching to unity is achievable during conversion, transportation, distribution, and end use. From the abovementioned viewpoints, electrical energy will continue to be dominant and will also be a usable form of energy till the turn of the century.

Primary energy resources may be further sub-classified as follows:

1. *Conventional and non-conventional energy resources*: (a) Conventional energy resources and their technical knowledge are known to mankind to a great extent. They are the energy stored within the earth and the sea. They include both fossil fuels (coal, oil, and gas) and nuclear energy (uranium and thorium) and required human intervention to release the energy from them. These sources have formed over hundreds of millions of years ago and when they are used, there will be no more for future generations. They are also known as finite energy resources. (b) Non-conventional energy resources are also known as infinite energy resources. Their technical knowledge is little known and they need full exploitation and improved technical understanding. However, it may be mentioned that owing to the cost factor and overall performance, one may think of utilizing all these energy resources only

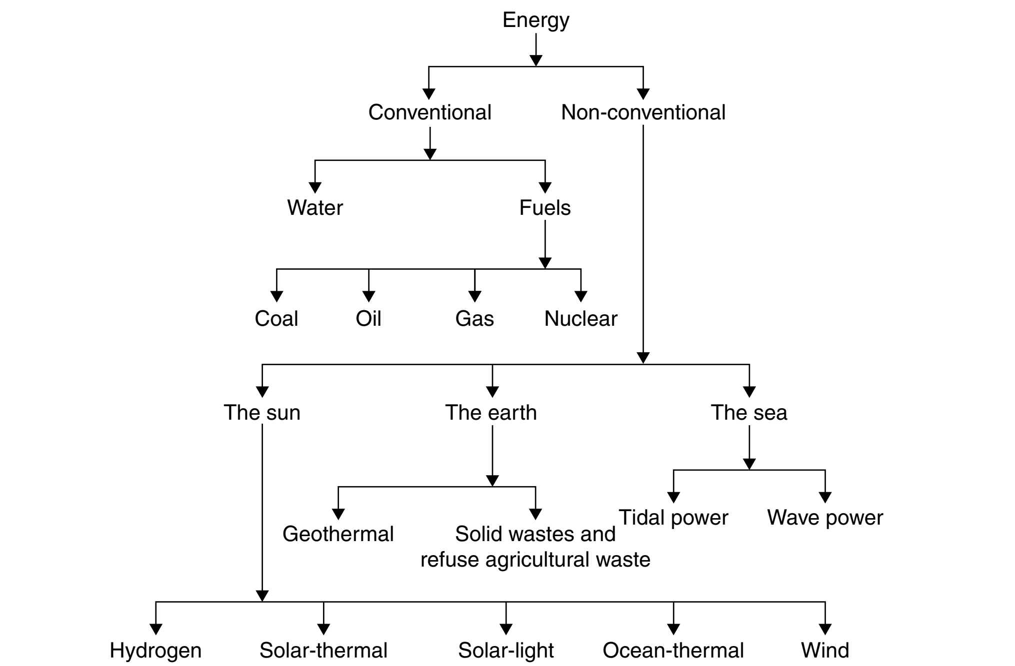
when all the conventional energy resources have been fully exploited and utilized. They are obtained from the energy flowing through the natural environment. It is necessary to note that the energy is passing through the environment as a current or as a flow and whether there is an artificial device there to intercept and harness the power or not. Further, it is important to know the rate at which useful energy can be obtained from these sources.

2. *Renewable and non-renewable energy resources*: (a) Renewable energy resources are continuously restored by nature. Examples are solar, water, wind, etc. (b) Non-renewable energy resources are the reserve that is once accumulated in nature has practically ceased to form under new geological conditions. They are also known as expendable energy. Examples are coal, oil, gas, nuclear, etc. Therefore, energy resources may be represented as shown in Table 1.5.

1.9.2 Oil

Oil companies estimate that the world's proven oil reserves are about 1,050 thousand million barrels (BP 2002). This is equivalent to about $6.4 \times 1,021$ J or 6,400 exajoules. Estimates of reserves are always subject to uncertainty and change. There is a very uneven distribution of oil reserves across the world, with some 71% of proven oil reserves being in the Middle East. The ultimately recoverable and unconventional reserves are very much more difficult to specify. The estimates of additional reserves that will be found and the growth to existing fields will vary widely. However, there is general agreement that crude oil is a finite resource that will run short and may sometime become very expensive in the first half of this century.

Table 1.5 Classification of Energy Resources



1.9.3 Natural Gas

The proven reserves of natural gas are presently some 152 trillion cubic meters (about 5.9 × 1,021 Joules or 5,900 exajoules). This is about the same as the reserves of oil. However, because gas is more difficult to transport and trade, there has not been as much effort is put into finding gas when compared with that of finding oil. There are some prospective regions of the world that have not been fully explored. Technologies for extracting gas constantly improve, thus making it difficult to estimate the sizes of the gas fields. The 2001 world gas consumption rate of 2.5 trillion cubic meters per annum (The World Fact book) has doubled over the last 30 years, while oil consumption has only increased some 30%.

1.9.4 Coal

In 1999, the proved recoverable reserves of coal is around one million tonnes [The World Energy Council estimates]. There is much more coal than any other fossil fuel. This is equivalent to about 3×10^{22} J or 30,000 exajoules; this is enough to sustain present production for more than 200 years. The world's consumption of coal is still rising (at less than 1% a year), but most industrial countries over recent decades have decreased their dependence on coal. The use of coal is limited more by environmental considerations than by the size of the resource. Modern techniques for burning coal using liquefaction and gasification processes can greatly reduce some of the pollutants from coal. However, coal always produces a great deal of carbon dioxide (greenhouse gas). There had been no cost-effective way developed for capturing and sequestering this carbon dioxide, but extensive research programs are underway.

1.9.5 Uranium

The economically accessible reserves of natural uranium were estimated by the World Energy Council in 1999 at three million tonnes. In the 1970s, this was expected to last no more than a few decades, but due to the slower grown than the expected growth in the nuclear industry and increased availability of uranium and the decommissioning of nuclear weapons, this time frame has been extended. There are public reservations about the cost and the safety of nuclear power plants, but they produce almost no CO_2 and the technology is mature.

1.9.6 Hydroelectric Power

At present, hydroelectricity provides the second biggest renewable energy contribution to world energy supply, with an annual output of 2,600 TWh. Information received from energy sources indicates that the world's total technically feasible hydro potential is about 14,400 TWh/yr, out of which just over 8,000 TWh/yr is currently considered to be economically feasible for development.

Hydropower is dependent on rainfall, and climate change could affect this potential. There is also considerable opposition to the building of large dams for social and environmental reasons.

1.10 ENERGY TRANSFER FRAMES

Most of the world's energy resources are from the conversion of the sun's rays to other energy forms after being incident upon the planet. Some of that energy has been preserved as fossil energy; some is directly or indirectly usable; for example, via wind, hydro- or wave power.

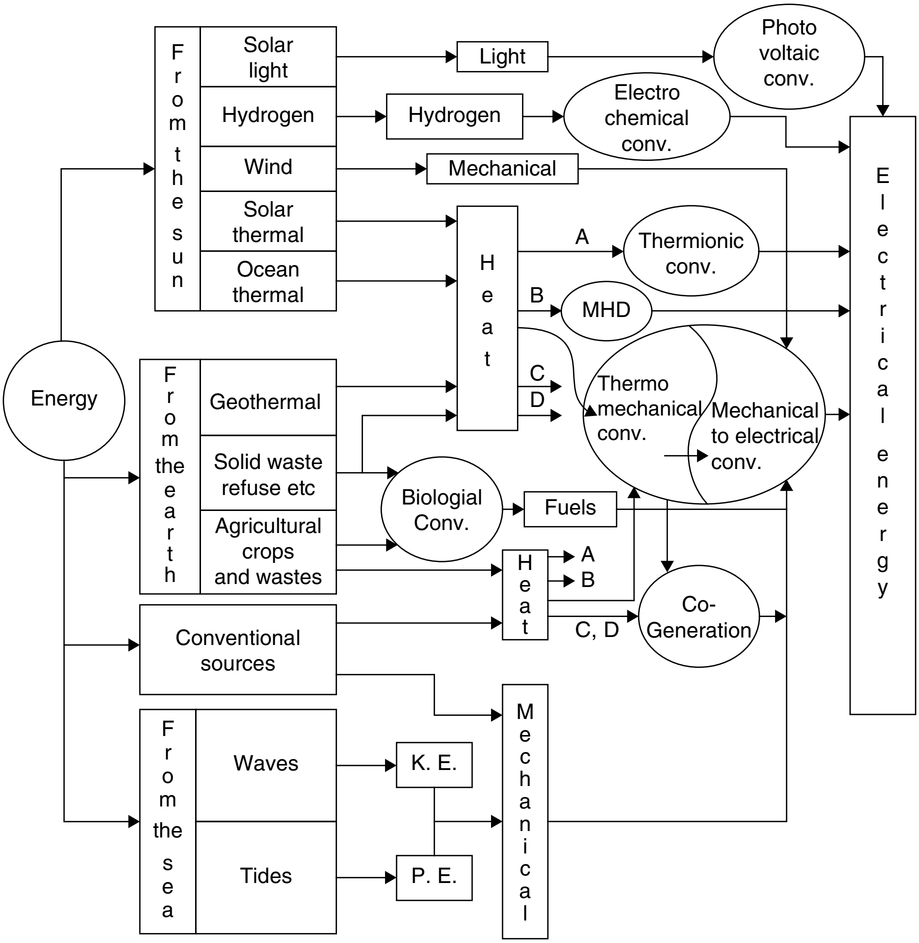


Figure 1.6 Energy transfer frame

In order to have better understanding of the energy conversion storage and related aspects of immediate importance, it is essential to know the promising energy resources and their nature and characteristics in detail, which will lead to the development of economical and feasible energy storage and conversion techniques. Discussions of all these energy resources are beyond the scope of this chapter. However, these resources and the techniques for conversion to usable electrical energy form and intermediary product forms, which are capable of being stored, can be well understood from Figure 1.6. It represents the transformation of basic energy resource to usable form and intermediary products. Following Figure 1.6, a suitable energy conversion and storage schemes can be selected and designed to meet the requirements.

1.11 ENERGY CONVERSION

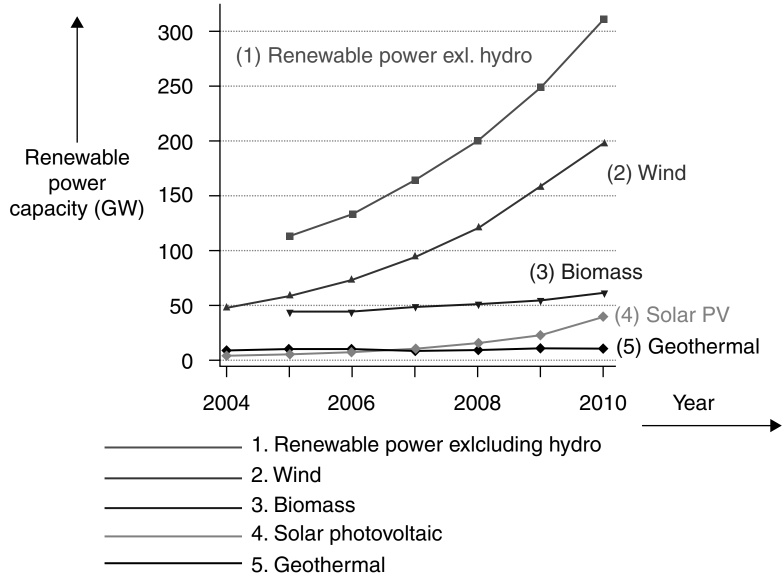
In whatever form the basic energy may be available from various conventional and non-conventional energy reservoirs, the development of techniques and systems for their conversion to usable form,

1.12 RENEWABLE ENERGY

Renewable energy is the energy that comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished). The availability of the renewable energy resources is discussed in the following sections.

1.12.1 Worldwide Renewable Energy Availability

About 16% of global final energy consumption comes from renewable as shown in Figure 1.14, with 10% coming from traditional biomass, which is mainly used for heating, and 3.4% from hydroelectricity.



Source: ren21,UNEP

Figure 1.14 Worldwide renewable power capacity excluding hydro

New renewable energy (small hydro, modern biomass, wind, solar, geothermal, and biofuel) accounted for another 3% and were growing very rapidly. The share of renewable energy in electricity generation is around 19%, with 16% of global electricity coming from hydroelectricity, and 3% from new renewable energy.

Potential for renewable energy is given in Table 1.6.

Table 1.6 Potential for Worldwide Renewable Energy

Energy Resource	Energy Amount
Solar energy	1,600 EJ (444,000 TWh),
Wind power	600 EJ (167,000 TWh)

(*Continued*)

Table 1.6 Continued

Energy Resource	Energy Amount
Geothermal	500 EJ (139,000 TWh),
Biomass	250 EJ (70,000 TWh)
Mini hydropower	50 EJ (14,000 TWh)
Ocean energy	1 EJ (280 TWh)

More than half of the energy has been consumed in the last two decades since the industrial revolution, despite advances in efficiency and sustainability. According to IEA world statistics in four years (2004–2008), the world population increased 5%, annual CO_2 emissions increased 10%, and gross energy production increased 10%.

1.12.2 Renewable Energy in India

It is a sector that is still in its infancy. As of December 2011, India had an installed capacity of about 22.4 GW of renewable technology-based electricity, about 12% of its total. For context, the total installed capacity for electricity in Switzerland was about 18 GW in 2009. Table 1.7 provides the capacity breakdown by various technologies. As of August 2011, India had deployed renewable energy to provide electricity in 8,846 remote villages, installed 4.4 million family biogas plants, 1,800 micro-hydel units, and 4.7 million square meters of solar water heating capacity. India anticipates adding another 3.6 GW of renewable energy installed capacity by December 2012. India plans to add about 30 GW of installed electricity generation capacity by 2017 based on renewable energy program conducted by the central government's Ministry of New and Renewable Energy.

Table 1.7 India Installed Capacity of Renewable Energy Till August 2011

Type	Technology	Installed Capacity (MW)
Grid connected power system	Wind	14989
	Small Hydro	3154
	Biomass	1084
	Bagasse Cogeneration	1799
	Waste to energy	74
	Solar	46
Off-grid, Captive power	Biomass	141
	Biomass non-Bagasse cogeneration	328
	Waste to energy	76
	Solar	73
	Hybrid/Aerogen	01

1.12.3 Solar Energy

The annual amount of energy reaching the surface of the earth as solar radiation is about a billion kWh. An appropriate combination of solar thermal panels and photovoltaic cells could convert this to any desired combination of heat and electricity at an estimated efficiency of about 10%. Thus, the potential amount of energy that could be produced annually is 10^8 kWh; this would mean covering the entire surface of the globe with solar thermal panels and photovoltaic cells.

Solar heating and photovoltaic are potentially a very large source of energy in the forms, and the technology to use them already exists. Still, it has to be worked out how to integrate them with other technologies, and they need storage to be used effectively. Therefore, the contribution from this source must remain substantial, but uncertain at this stage.

The solar thermal power industry is growing rapidly with 1.2 GW under construction as of April 2009 and another 13.9 GW announced globally through 2014. Spain is the epicentre of solar thermal power development with 22 projects for 1,037 MW under construction, all of which are projected to come online by the end of 2010. In the United States, 5,600 MW of solar thermal power projects have been announced. In developing countries, three World Bank projects for integrated solar thermal or combined cycle gas turbine power plants in Egypt, Mexico, and Morocco have been approved.

Solar photovoltaic cells convert sunlight into electricity and photovoltaic production has been increasing by an average of more than 20% each year since 2002, making it a fast-growing energy technology. At the end of 2010, cumulative global photovoltaic (PV) installations surpassed 40 GW and PV power stations are popular in Germany and Spain.

Many solar photovoltaic power stations have been built, mainly in Europe.[9] As of December 2011, the largest photovoltaic (PV) power plants in the world are the Golmud Solar Park (China, 200 MW), Sarnia Photovoltaic Power Plant (Canada, 97 MW), Montalto di Castro Photovoltaic Power Station (Italy, 84.2 MW), Finsterwalde Solar Park (Germany, 80.7 MW), and Okhotnykovo Solar Park (Ukraine, 80 MW).

1.12.4 Wind Power

Wind energy is the kinetic energy of air in motion. Wind turbines extract the kinetic energy present in the wind, and convert it to rotary shaft motion. The shaft motion transmits power to generators by gearboxes, belts and pulleys, roller chains, or by hydraulic transmissions. The power in the wind is proportional to the cube of the wind velocity.

Let us assume

V is the wind speed (m/sec); ρ is the air density (approximately1.2 kg/m^2 at sea level); S is the cross-sectional area of air flow m^2; m is the mass of the wind passing per unit time through rotor area; t is the time period of wind flow (s).

Therefore, SVt is the volume of air passing through S (which is considered perpendicular to the direction of the wind) and

$$m = \rho SVt \tag{1.11}$$

Total wind energy flowing through an imaginary area A during the time t is

$$E = ½mV^2 = ½(SVt)V^2 = ½(St)V^3 \tag{1.12}$$

2.2 LAYER OF THE SUN

The sun can be divided into following six layers as shown in Figure 2.2:

1. Core
2. Radiative zone
3. Convection zone
4. Photosphere
5. Chromosphere
6. Corona

2.2.1 Core

The innermost layer of the sun is called the core. With a density of 160 g/cm^3, which is 10 times that of lead, the core might be expected to be solid. However, the core's temperature of 1,50,00,000°C keeps it in a gaseous state.

In the core, *fusion reactions* produce energy in the form of gamma rays and neutrinos. Gamma rays are photons with high energy and high frequency. The gamma rays are absorbed and re-emitted by many atoms on their journey from the envelope to the outside of the sun. When gamma rays leave atoms, their average energy is reduced. However, the first law of thermodynamics (which states that energy can neither be created nor be destroyed) plays an important role and the number of photons increases. Each high-energy gamma ray that leaves the solar envelope will eventually become one thousand low-energy photons.

The neutrinos are extremely nonreactive. Several experiments are being performed to measure the neutrino output from the sun. Chemicals containing elements with which neutrinos react are put in large pools in mines, and the neutrinos' passages through the pools can be measured by the rare changes they cause in the nuclei in the pools. For example, perchloroethane contains some isotopes of chlorine with 37 particles in the nucleus (17 protons and 20 neutrons).

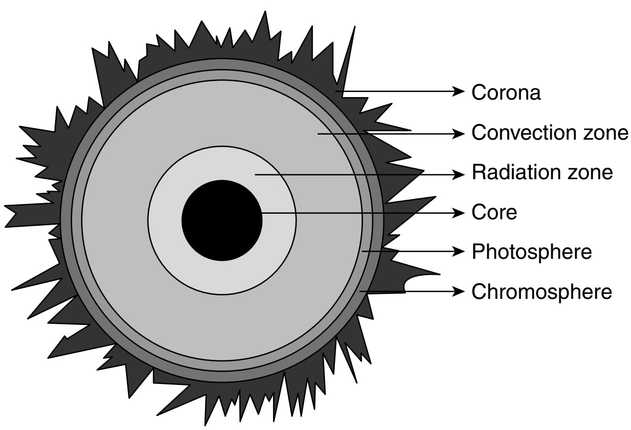


Figure 2.2 Interior of the sun

These Cl-37 molecules can take in neutrinos and become radioactive Ar-37 (18 protons and 19 neutrons). From the amount of argon present, the number of neutrinos can be calculated.

2.2.2 Solar Envelope

Outside of the core is the radiative envelope, which is surrounded by a convective envelope. The temperature is 4 million kelvin (7 million degrees F). The density of the solar envelope is much less than that of the core. The core contains 40% of the sun's mass in 10% of the volume, whereas the solar envelope has 60% of the mass in 90% of the volume. The solar envelope puts pressure on the core and maintains the core's temperature. The hotter a gas is, the more transparent it is.

The solar envelope is cooler and more opaque than the core. It becomes less efficient for energy to move by radiation, and as a result, heat energy starts to build up at the outside of the radioactive zone. The energy begins to move by convection in huge cells of circulating gas with several hundred kilometres in diameter. Convection cells nearer to the outside are smaller than the inner cells. The top of each cell is called a granule. These granules, when observed through a telescope, look like tiny specks of light. Variations in the velocity of particles in granules cause slight wavelength changes in the spectra emitted by the sun.

2.2.3 Photosphere

The photosphere is the zone from which the sunlight is both seen and emitted. The photosphere is a comparatively thin layer of low-pressure gasses surrounding the envelope. It is only a few hundred kilometres thick with a temperature of 6,000°C. The composition, temperature, and pressure of the photosphere are revealed by the spectrum of sunlight. When analysing the solar spectrum, William Ramsey discovered helium in 1896 and found that features of the gas did not belong to any gas known on earth. Hence, the newly discovered gas was named as helium in honour of Helios, the mythological Greek god of the sun.

2.2.4 Chromospheres

During an eclipse, a red circle can sometimes be seen outside the sun. This circle is called the chromospheres. Its red colouring is caused by the abundance of hydrogen. From the centre of the sun to the chromospheres, the temperature decreases proportionally as the distance from the core increases. The chromospheres' temperature, however, is 7,000 K, which is hotter than that of the photosphere. Temperatures continue to increase through the corona.

2.2.5 Corona

The outermost layer of the sun is called the corona or the crown. The corona is very thin and faint and is, therefore, very difficult to observe from the earth. Typically, we can observe the corona during a total solar eclipse or by using a coronagraph telescope, which simulates an eclipse by covering the bright solar disk. This outer layer is very dim—a million times dimmer than the photosphere and oddly enough, it is the hottest. At 10^6 K, it would seem that the heat would be unbearable for us, but remember in Physics, heat is a measure of molecular energy, that is, the movement of molecules within a space. Because the Corona extends several million kilometres into space, there is a lot of room for molecules to move. It is this movement that forms the source of the solar winds. The high temperature of the corona can force ions to move as fast as a million kilometres per hour.

Table 2.1 Characteristics of the Sun

Present Age	**4.5×10^9 years**	**Life Expectancy**	**10×10^9 years**
		Distance to Earth	
Mean	1.496×10^{11} m = 1.000 AU	variation	1.016735–0.98329 AU
Diameter (photosphere)	1.39×10^9 m	Angular diameter (from earth):	9.6×10^{-3} radians
Variation	±1.7%	Volume (photosphere):	1.41×10^{27} m^3
		Composition	
Hydrogen	73.46%	Helium	24.85%
Oxygen	0.77%	Carbon	0.29%
Iron	0.16%	Nitrogen, silicon, magnesium, sulphur, etc.	<0.1%
		Density	
Mean	14.1 kg/m^3	Centre	1,600 kg/m^3
		Solar Radiation	
Entire sun	3.83×10^{26} W	unit area of surface	6.33×10^7 W/m^2
At 1 AU (i.e., the solar constant)	1,367 W/m^2		
		Temperature	
Centre	1,50,00,000 K	Surface (photosphere)	6,050 K
Chromospheres	4,300–50,000 K	Corona	8,00,000–30,00,000 K
		Rotation	
Solar equator	26.8 days	30º latitude	28.3 days
60º latitude	30.8 days	75º latitude	31.8 days
Energy resource	$4\,H \rightarrow He + 2\,e^{-1} + 2\,\upsilon + \gamma$	Rate of mass loss:	4.1×10^9 kg/s

Source: Abridged from Eddy (1979); www.powerfromthesun.net/Book/chapter02/chapter02.html

2.3 EARTH-SUN ANGLES AND THEIR RELATIONSHIPS

In order to understand how to collect energy from the sun, one must first be able to predict the location of the sun relative to the collection device.

2.3.1 Hour Angle (ω)

The hour angle is the angular distance between the meridian of the observer and the meridian whose plane contains the sun.

To describe the earth's rotation about its polar axis, the concept of the hour angle (ω) is used. As shown in Figure 2.3, the hour angle is zero at solar noon (when the sun reaches its highest point in the sky). At this time, the sun is said to be 'due south' (or 'due north', in the Southern Hemisphere) since the meridian plane of the observer contains the sun. The hour angle increases by 15° every hour. An expression to calculate the hour angle from solar time is,

$$\omega = 15 \times (t_s - 12); \text{ (in degrees)} \tag{2.1}$$

Where, t_s is the solar time in hours.

Hour angle (ω) can be calculated simply as follows:

Since the earth makes one revolution on its axis in 24 h, then 15 minutes will be equal to 15/60 = 1/4 min

Therefore,

$$\omega = 1/4 \times t_m; \text{ (in degrees)} \tag{2.2}$$

Where, t_m is the time in minutes after local solar noon. ω will be +ve if solar time is after solar noon. However, ω will be –ve if solar time is before solar noon as shown in Figure 2.4.

Example 2.1

Calculate hour angle when it is 3 h after solar noon.

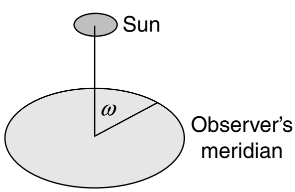
Solution Solar time = 12 + 3 = 15:00

Therefore, hour angle (w) = 15 × (t_s – 12) = 15 × (15 – 12) = 45°

Example 2.2

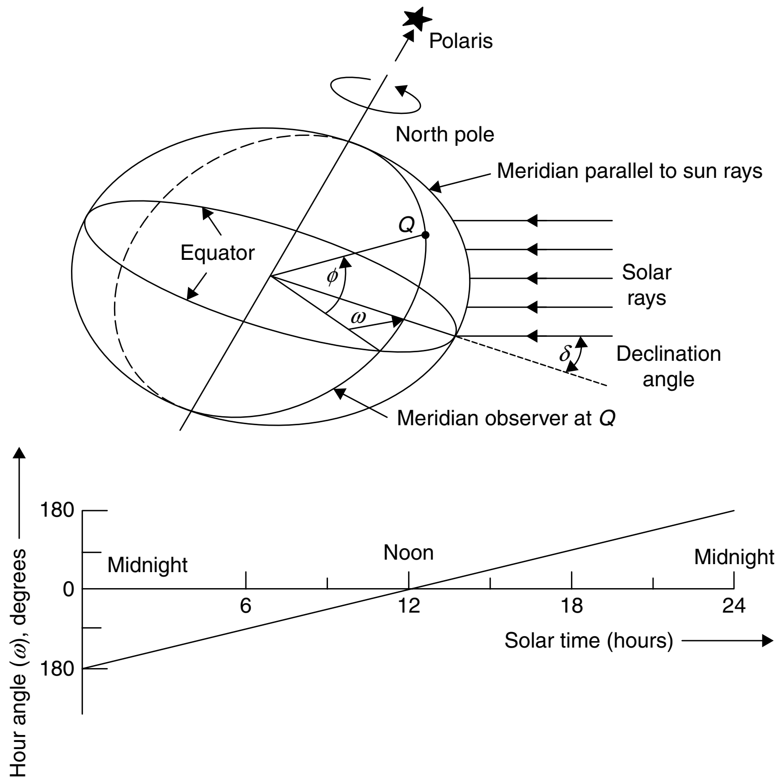
Calculate hour angle when it is 2 h 20 min before solar noon.

Solution Solar time = –1/4 × (t_m) = –1/4 × 140 = –35°



Source: http://www.brighton-webs.co.uk/energy/solar_earth_sun.aspx

Figure 2.3 Hour angle (ω)



Source: www.powerfromthesun.net/Book/chapter03/chapter03.html

Figure 2.4 Variation of hour angle (ω) 24 h

2.3.2 Equation of Time

This is the difference between the local apparent solar time and the local mean solar time. The actual equation of time (EOT), which is mathematically defined as apparent solar time minus mean solar time, varies slightly from year to year due to variations in the earth's eccentricity and obliquity and in the time of the solstices and equinoxes. However, for a century, either side of the year 2000, it may be approximated (to an accuracy of better than 1%) by the formula:

$$\text{EOT} = 9.87 \times \sin(2\text{B}) - 7.67 \sin(\text{B} + 78.7°);\ \text{(in minutes)} \tag{2.3}$$

This can further be simplified as

$$\text{EOT} = 9.87 \sin 2\text{B} - 7.53 \cos \text{B} - 1.5 \sin \text{B} \tag{2.3a}$$

Where,

$$\text{B} = 360\,(n - 81)/365;\ \text{(in degrees)} \tag{2.4}$$

Another formula equation for EOT can be approximated as

$$\text{EOT} = 9.8 \times \sin(2\text{A}) + 7.6 \times \sin(\text{A} - 0.2) \tag{2.3b}$$

Where,

$$A = K \times (n + 10) + 0.033 \times \sin [K (n - 2)]$$
$$K = 2\pi/365$$

n is the total number of days of the year (e.g., $n = 1$ on Jan 1 and $n = 33$ on Feb 2)

Important to remember: During leap year, February month will have 29 days.

The level of accuracy required in determining the EOT will depend on whether the designer is doing system performance or developing tracking equations. An approximation for calculating the EOT in minutes is given by Woolf (1968) and is accurate to within about 30 s during daylight hours.

$$\text{EOT} = 0.258 \times \cos(\alpha_d) - 7.416 \times \sin(\alpha_d) - 3.648 \times \cos(2\alpha_d) - 9.228 \times \sin(2\alpha_d); \quad \text{(in minutes)}, \qquad (2.5)$$

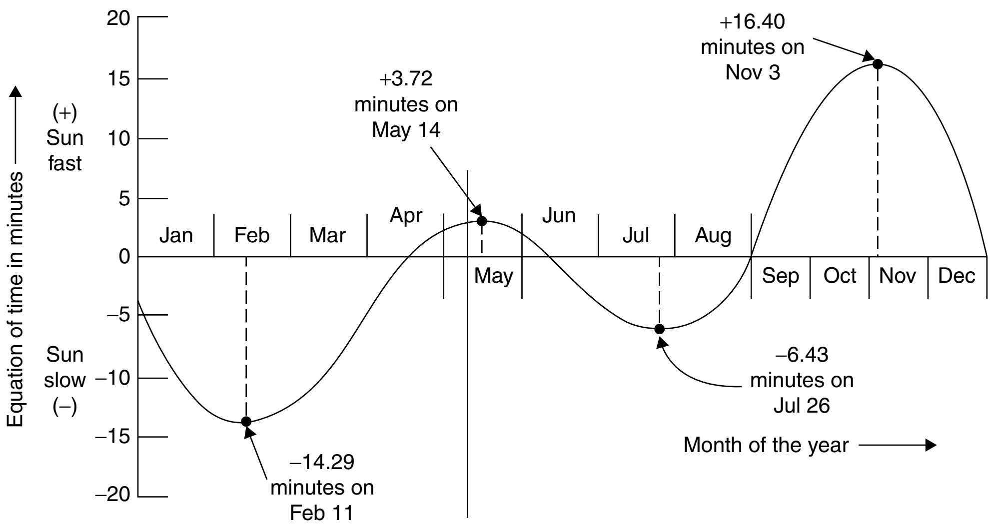
Where the angle (α_d) is defined as a function of n.

$$\alpha_d = 360 \times (n - 1)/365.242; \text{ (in degrees)} \qquad (2.6)$$

n = the number of days counted from January 1

2.3.3 Declination Angle (δ)

The declination angle (δ) of the sun is the angle between the rays of the sun and the plane of the earth's equator. The earth's axial tilt (called the obliquity of the ecliptic by astronomers) is the angle between the earth's axis and a line perpendicular to the earth's orbit. The earth's axial tilt changes gradually over thousands of years, but its current value is about $\varepsilon = 23°26'$. Because this



Source: www.powerfromthesun.net/Book/chapter03/chapter03.html

Figure 2.5 Equation of time

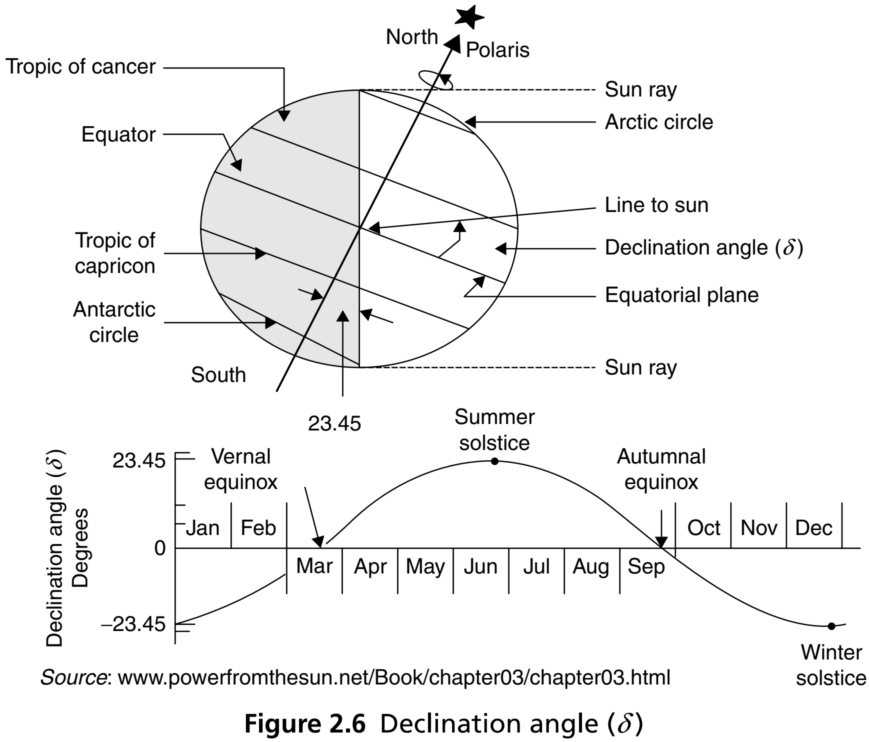
axial tilt is nearly constant, the solar declination angle (δ) varies with the seasons, and its period is one year. At the solstices, the angle between the rays of the sun and the plane of the earth's equator reaches its maximum value of 23°26'. Therefore, δ = +23°26' at the northern summer solstice and δ = −23°26' at the southern summer solstice.

At the moment of each equinox, the centre of the sun appears to pass through the celestial equator, and the declination angle (δ) is 0°.

The plane that includes the earth's equator is called equatorial plane. If a line is drawn between the centre of the earth and the sun, then the angle between this line and the earth's equatorial plane is called the declination angle (δ), as depicted in Figure 2.6.

At the time of year when the northern part of the earth's rotational axis is inclined towards the sun, the earth's equatorial plane is inclined 23.45° to the earth–sun line. At this time (about June 21), it is observed that the noon time sun is at its highest point in the sky and the declination angle (δ) = +23.45°. This condition is known as the summer solstice, and it marks the beginning of summer in the Northern Hemisphere.

As the earth continues its yearly orbit about the sun, a point is reached about 3 months later where a line from the earth to the sun lies on the equatorial plane. At this point, an observer on the equator would observe that the sun was directly overhead at noon time. This condition is called an equinox since anywhere on the earth, the time during which the sun is visible (daytime) is exactly 12 h and the time when it is not visible (night time) is 12 h. There are two such conditions during a year: the autumnal equinox on about September 23, which marks the start of the fall and the vernal equinox on about March 22, which marks the beginning of spring.



Source: www.powerfromthesun.net/Book/chapter03/chapter03.html

Figure 2.6 Declination angle (δ)

At the equinoxes, the declination angle (δ) is zero. The earth is shown in the summer solstice position when $\delta = +23.45°$.

Note the definition of the tropics as the intersection of the earth–sun line with the surface of the earth at the solstices and the definition of the Arctic and Antarctic circles by extreme parallel sun rays

The declination angle (δ) can be approximately obtained as,

$$\text{Sin}\,(\delta) \approx 0.39795 \times \cos\,[0.98563 \times (n - 173)] \tag{2.7}$$

Where, the argument of the cosine here is in degrees and n is the total number of days calculated from January 1. The annual variation of the declination angle is shown in Figure 2.6.

A formula that gives an approximation of declination in degrees based on the day number (e.g., 01 Jan = 1, 02 Jan = 2, etc.) is shown below.

$$\delta = 23.45 \times \sin\,[360 \times (284 + n)/365] \tag{2.8}$$

2.3.4 Latitude Angle (ϕ)

The latitude angle (ϕ) is the angle between a line drawn from a point on the earth's surface to the centre of the earth and the earth's equatorial plane. The intersection of the equatorial plane with the surface of the earth forms the equator and is designated as 0° latitude.

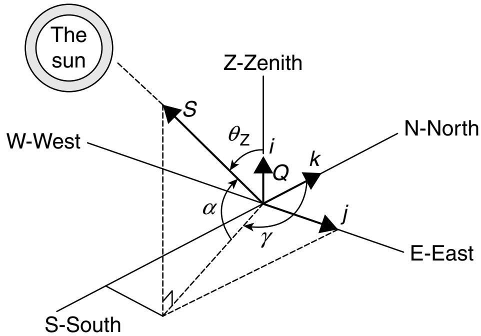
The earth's axis of rotation intersects the earth's surface at +90° S latitude (North Pole) and –90° latitude (South Pole). Any location on the surface of the earth can be then defined by the intersection of a longitude angle and a latitude angle.

Other latitude angles of interest are the Tropic of Cancer (+23.45° latitude) and the Tropic of Capricorn (–23.45° latitude). These represent the maximum tilts of the North and South Poles towards the sun. The other two latitudes of interest are the Arctic Circle (66.55° latitude) and Antarctic Circle (–66.5° latitude) representing the intersection of a perpendicular to the earth–sun line when the South and North Poles are at their maximum tilts towards the sun. The tropics represent the highest latitudes where the sun is directly overhead at solar noon, and the Arctic and Antarctic circles represent the lowest latitudes where there are 24 h of daylight or darkness. All of these events occur either at the summer or winter solstices.

2.3.5 Solar Altitude Angle (α)

It is defined as the angle between the central ray from the sun and a horizontal plane containing the observer, as shown in Figure 2.7. The earth's surface coordinates system for the observer at showing the Surface Azimuth angle (γ), the solar altitude angle (α), and the solar zenith angle (θ_Z) for a central sun ray along direction vector S. As an alternative, the sun's altitude may be described in terms of the solar zenith angle (θ_Z), which is simply the complement of the solar altitude angle (α) or

$$\theta_Z = 900 - \alpha;\ \text{(in degrees)} \tag{2.9}$$



Source: www.powerfromthesun.net/Book/chapter03/chapter03.html

Figure 2.7 Solar altitude angle (α)

2.3.6 Solar Elevation Angle (α)

It is the elevation angle of the sun. That is, the angle between the direction of the geometric centre of the sun's apparent disk and the (idealized) horizon. It can be calculated, to a good approximation, using the following formula:

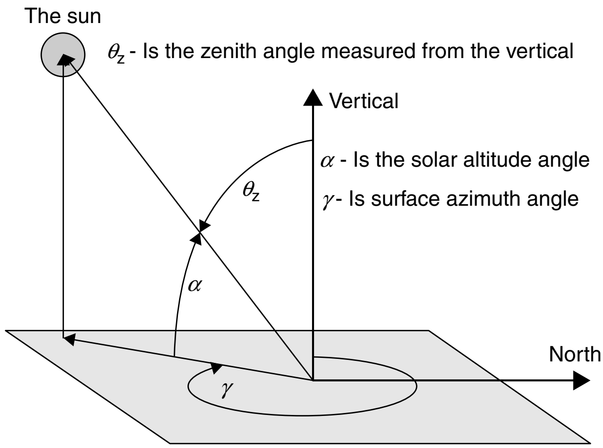
$$\sin \alpha = \cos \phi \cdot \cos \delta \cdot \cos \omega + \sin \phi \cdot \sin \delta \tag{2.10}$$

Where α = the solar elevation angle
ω = the hour angle in the local solar time
ϕ = the local latitude

2.3.7 Surface Azimuth Angle (γ)

$$\theta_z = 90° - \alpha \text{ (in degrees)}$$

The other angle defining the position of the sun is the surface azimuth angle (γ). It is the angle measured clockwise on the horizontal plane from the north-pointing coordinate axis to the projection of the sun's central ray.



Source: //www.esrl.noaa.gov/gmd/grad/solcalc/azelzen.gif

Figure 2.8 Surface azimuth angle

The surface azimuth angle is the azimuth angle of the sun. It is most often defined as the angle from due north in a clockwise direction.

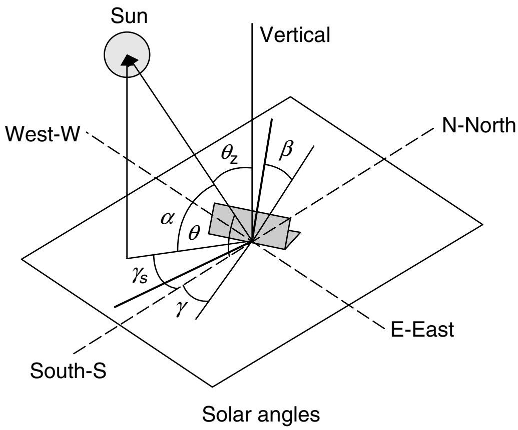
It can be calculated in various ways, and it has been explained in different ways during various periods. It can be calculated, to a good approximation, using the following formula; however, angles should be interpreted with care due to the inverse sign, i.e., $x = \sin^{-1}(y)$ has more than one solution, only one of which will be correct.

$$\sin(\gamma) = [-\sin(\omega) \times \cos(\delta) / \cos(\alpha)] \tag{2.11}$$

2.3.8 Relationship Between Different Sun–Earth Angles

Let us consider and define different earth–sun angles before establishing a relation between them as shown in Figure 2.9.

1. α = *Solar altitude angle*: It is defined as the angle between the central ray from the sun and a horizontal plane containing the observer.
2. β = *Slope angle*: It is defined as the angle between tilted and horizontal surfaces.
3. γ = *Surface azimuth angle*: It is the angle made in the horizontal plan between the line due south and the projection and of the normal to the surface on the horizontal plane.
4. γ_s = *Solar azimuth angle*: It is the angle made in horizontal plane between the line due south and the projection of line of site of the sun on the horizontal plane.



α - Is the solar altitude angle

β - Is the slope angle between the tilted and horizontal surface

γ - Is the surface azimuth angle

γ_s - Is the solar azimuth angle

δ - Is the declination angle

θ - Is the angle of incidence

θ_z - Is the zenith angle

Φ - Is the latitude angle

ω - Is the hour angle

Source: http://www.tboake.com/carbon-aia/strategies1a.html

Figure 2.9 Different solar angles

5. δ = *Declination angle*: It is the angle made by the line joining the centre of the sun and earth with its projection on the equatorial plane (Figs 2.6 and 2.7).
6. θ = *Angle of incidence*: The angle of incidence of a ray to a surface is measured as the difference in angle between the ray and the normal vector of the surface at the point of intersection.
7. θ_z = *Zenith angle*: It is simply the complement of the solar altitude angle (α).
8. ϕ = *Latitude angle*: The latitude angle (ϕ) is the angle between a line drawn from a point on the earth's surface to the centre of the earth and the earth's equatorial plane.
9. $\delta\omega$ = *Hour angle*: The hour angle is the angular distance between the meridian of the observer and the meridian whose plane contains the sun.

It has been established that,

$$\cos\theta = \sin\phi \times (\sin \cdot \delta \cos\beta + \cos\delta \cdot \cos\gamma \cdot \cos\omega \cdot \sin\beta)$$
$$+ \cos\phi (\cos\delta \cdot \cos\omega \cdot \cos\beta - \sin\delta \cdot \cos\gamma \cdot \sin\beta)$$
$$+ \cos\delta \cdot \sin\gamma \cdot \sin\omega \cdot \sin\beta \tag{2.12}$$

The expressions for incidence angle (θ) can be further simplified as given below.

For horizontal surface, slope or tilt angle $\beta = 0°$ and the angle of incidence θ becomes zenith angle θ_Z of the sun. Therefore,

$$\cos\theta_Z = \cos\phi \cdot \cos\delta \cdot \cos\omega + \sin\phi \cdot \sin\delta \tag{2.13}$$

Example 2.3

Calculate zenith angle of the sun at Lucknow (26.750 N) at 9:30 am on February 16, 2012.

Solution Total No. of days counted from January 1, 2012, till February 16, 2012, $n = 47$

From Eq. (2.8), the declination angle is given by

$$\delta = 23.45 \times \sin[360 \times (284 + n)/365]$$
$$= 23.45 \times \sin[360 \times (284 + 47)/365]$$
$$= -12.95° = -13° \text{ (approximately)}$$

From Eq. (2.2), hour angle is given by $\omega = 1/4 \times t_m$
Where $t_m = 12{:}00 - 9{:}30 = 150$ min; therefore, $\omega = 1/4 \times 150 = 37.5$ (since time is before solar noon, negative sign will be taken)
From Eq. (2.13), $\cos\theta_Z = \cos\phi \cdot \cos\delta \cdot \cos\omega + \sin\phi \cdot \sin\delta$

$$= \cos(26.75) \cdot \cos(-13) \cdot \cos(-37.5) + \sin(26.75) \cdot \sin(26.75)$$
$$= 0.589$$

Therefore, $\theta_Z = \cos^{-1}(0.589) = 53.914$

With vertical surface $\beta = 90°$, and then

$$\cos\theta = \sin\phi\cdot\cos\delta\cdot\cos\gamma\cdot\cos\omega - \cos\phi\cdot\sin\delta\cdot\cos\gamma\cdot + \cos\delta\cdot\sin\gamma\cdot\sin\omega \quad (2.14)$$

Horizontal surface $\beta = 0$,

$$\cos\theta = \sin\phi\cdot\sin\delta + \cos\phi\cdot\cos\delta\cdot\cos\omega \quad (2.14a)$$

The angle θ in this case is the zenith angle θ_Z. The complement of zenith angle is called the solar altitude angle.

For surface facing due south $\gamma = 0°$,

$$= \sin\delta\cdot\sin(\phi - \beta) + \cos\delta\cdot\cos\omega\cos(\phi - \beta) \quad (2.14b)$$

And for vertical surface facing due south $\beta = 90°$, $\gamma = 0°$

The solar azimuth angle γ_s is the angular displacement from south of the projection of the beam radiation on the horizontal plane.

Therefore, the solar azimuth γ_s can be written as

$$\sin\gamma_s = \cos\delta\cdot\sin\omega/\cos\alpha \quad (2.15)$$

Equation (2.15) can be solved for the sunset hour angle ω_{ss} when $\theta_Z = 90°$.

Therefore,

$$\cos\omega_{ss} = -\sin\phi\cdot\sin\delta/\cos\phi\cdot\cos\delta = -\tan\phi\times\tan\delta \quad (2.16)$$

2.3.9 Sunrise, Sunset, and Day Length Equations

The sunrise equation can be used to derive the time of sunrise and sunset for any solar declination and latitude in terms of local solar time (LST) when sunrise and sunset actually occur.

$$\cos\omega = -\tan\phi\times\tan\delta$$

Where

ω = the hour angle at either sunrise (when negative value is taken) or sunset (when positive value is taken)

ϕ = the latitude of the observer on the earth

δ = the sun declination angle

Since the hour angle at local solar noon is zero, with each 15° of longitude equivalent to 1 h, the sunrise and sunset from local solar noon is derived as follows:

$$T_H = 1/15\times\omega_{ss} = 1/15\cos^{-1}(-\tan\phi\times\tan\delta) \quad (2.17)$$

Therefore, daylight hour is given by $2T_H$.

Example 2.4

Find the solar altitude angle at 2 h after local solar noon on 1 June 2012 for a city, which is located at 26.75° N latitude. Moreover, find the sunrise and sunset hours and the day length.

Solution The declination on June 1 ($n = 153$) is

$$\delta = 23.45\times\sin[360\times(284 + 153)/365] = 22.17° \text{ approximately}$$

to use a fossil fuel (typically natural gas) as a supplementary fuel, allowing electricity to be generated when the sun is not shining.

3.4.6.2.2 Disadvantages The heliostat solar tower system produces a fluid temperature greater than that of the single-axis tracking, parabolic trough, and linear Fresnel system, but less than that of the two-axis tracking, parabolic dish–Stirling engine system. Thus, it cannot achieve efficiency for conversion of electricity from thermal energy as high as that of the parabolic dish–Stirling engine system.

3.5 PARABOLIC DISH–STIRLING ENGINE SYSTEM

The major parts of a parabolic dish–Stirling engine system are as follows:

1. *Solar dish concentrator*: Parabolic dish systems that generate electricity from a central power converter collect the absorbed sunlight from individual receivers and deliver it via a heat-transfer fluid to the power conversion systems. The need to circulate heat-transfer fluid throughout the collector field raises design issues such as piping layout, pumping requirements, and thermal losses.
2. *Power conversion unit*: The power conversion unit includes the thermal receiver and the heat engine. The thermal receiver absorbs the concentrated beam of solar energy, converts it to heat, and transfers the heat to the heat engine. A thermal receiver can be a bank of tubes with a cooling fluid circulating through it. The heat transfer medium usually employed as the working fluid for an engine is hydrogen or helium. Alternate thermal receivers are heat pipes wherein the boiling and condensing of an intermediate fluid are used to transfer the heat to the engine. The heat engine system takes the heat from the thermal receiver and uses it to produce electricity. The engine–generators have several components; a receiver to absorb the concentrated sunlight to heat the working fluid of the engine, which then converts the thermal energy into mechanical work; an alternator attached to the engine to convert the work into electricity, a waste-heat exhaust system to vent excess heat to the atmosphere, and a control system to match the engine operation to the available solar energy. This distributed parabolic dish system lacks thermal storage capabilities, but can be hybridized to run on fossil fuel during periods without sunshine. The Stirling engine is the most common type of heat engine used in dish–engine systems.
3. *Tracking system*: A parabolic dish system uses a computer to track the sun and concentrate the sun's rays onto a receiver located at the focal point in front of the dish. In some systems, a heat engine, such as a Stirling engine, is linked to the receiver to generate electricity. Parabolic dish systems can reach 1,000 °C at the receiver, and achieve the highest efficiencies for converting solar energy to electricity in the small-power capacity range.

3.6 WORKING OF STIRLING OR BRAYTON HEAT ENGINE

After the array of mirrors focuses the sunlight, the concentrated sunlight then heats up the working fluid to temperatures of around 750°C within the receiver. The heated high temperature working fluid is then used in either a Stirling or Brayton heat engine cycle to produce mechanical power via

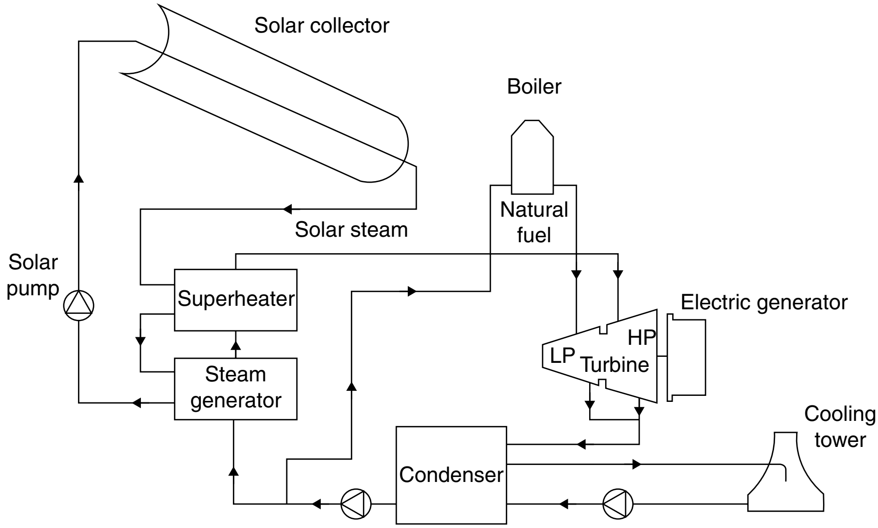


Figure 3.15 Schematic of solar electric generation

rotational kinetic energy and then electricity for utility use with an electric generator. An example of a Brayton cycle used to produce electricity for a parabolic dish power plant is shown in Figure 3.15. In the cycle, the concentrated sunlight focused on the solar fluid heats up the compressed working fluid of the cycle, i.e., 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 and make the cycle more efficient.

3.7 SOLAR COLLECTOR SYSTEMS INTO BUILDING SERVICES

Although the operating costs of solar energy conversion system are generally low, the initial cost of purchasing and installing such system are high when compared to fossil fuel or other conventional energy system. Hence, the choice between solar energy systems against a conventional one must be cost effective on a long term basis (based on economic evaluation).

Since the availability of solar energy is intermittent and unpredictable it is rarely cost effective to have energy demands from solar energy alone. A solar system able to meet all the energy demands under the worst operating conditions for a long period would be greatly oversized.

The most economical way is to have

1. The solar system meets the basic energy demand while operating at its full capacity.
2. Let an auxiliary or backup system carry the peak load and unusual load.

The right proportion of solar versus auxiliary energy supply is to be determined by economics.

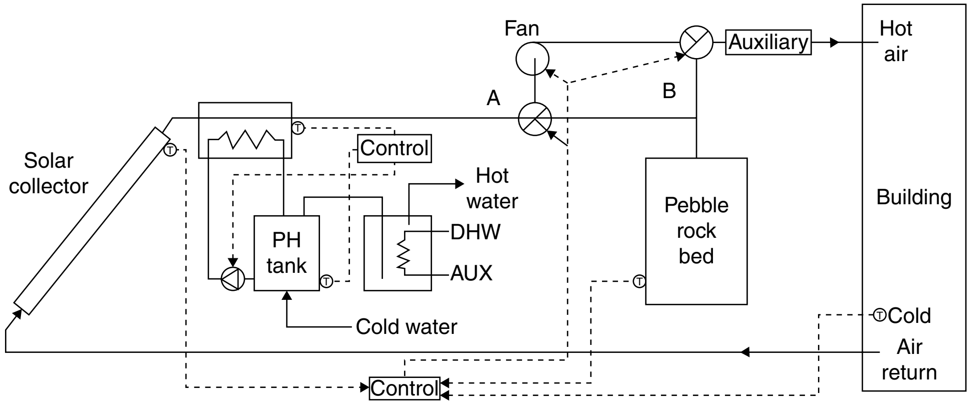


Figure 3.16 Schematic of solar air heating system

Schematic representation of a typical space heating system with air collectors is given in Figure 3.16. Dampers is indicated for the solar rock-bed charging mode. The main components of the building heating systems are as follows:

1. Air handling unit: a fan and two motor-driven dampers.
2. Heat storage unit (rock bed)
3. Temperature control system
4. Solar collectors

Depending on the position of dampers A and B, three modes of system operation can be achieved.

1. *Dampers A and B open*: This is the normal day time solar heating mode. The storage unit is bypassed. If the temperature sensor in the top of the collector array is below a necessary limit required for space heating, the auxiliary furnace is automatically turned on.
2. *Damper A open and damper B closed*: This mode is used whenever solar heat is collected but no space heating is required at the same time. The fan blows the solar heated air through the rock bed for thermal storage.
3. *Damper A closed and damper B open*: This mode is used during cloudy periods or during the night hours. The return air from the building is now pulled through the rock bed, where it picks up solar heat. The auxiliary furnace is activated automatically if the temperature is insufficient to meet the demand.

3.8 SOLAR WATER HEATING SYSTEMS

Most solar water heating systems have two main parts: a solar collector and a storage tank. The most common collector is called a flat plate collector. It consists of a thin, flat, rectangular box with a transparent cover that faces the sun mounted on the roof of building or home. Small tubes run through the box and carry the fluid – either water or other fluid, such as an antifreeze solution – to be heated. The tubes are attached to an absorber plate, which is painted with special coatings to absorb the heat. The heat builds up in the collector, which is passed to the fluid passing through the tubes.

An insulated storage tank holds the hot water. It is similar to water heater, but larger in size. In the case of systems that use fluids, heat is passed from hot fluid to the water stored in the tank through a coil of tubes. Solar water heating systems can be either active or passive systems.

1. The active systems, which are most common, rely on pumps to move the liquid between the collector and the storage tank.
2. The passive systems rely on gravity and the tendency for water to naturally circulate as it is heated.

3.8.1 Active Solar Water Heating Systems

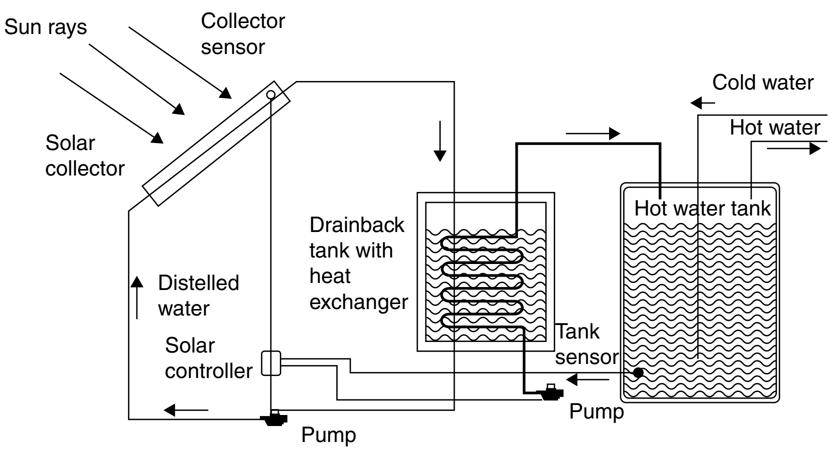
The active water systems that can be used to heat domestic hot water are the same as the ones that provide space heat. A space heat application will require a larger system and additional connecting hardware to a space heat distribution system.

3.8.1.1 Parts of Water Heating Systems

There are five major components in active solar water heating systems:

1. Collector(s) to capture solar energy.
2. Circulation system to move a fluid between the collectors to a storage tank
3. Storage tank
4. Backup heating system
5. Control system to regulate the overall system operation

A typical active water heating system that exhibits effectiveness, reliability, and low maintenance is shown in Figure 3.17.



Source: http://biddecor.blogspot.in/2015/02/solar-water-heating.html

Figure 3.17 A typical hot water system

It uses distilled water as the collector circulating fluid. The collectors in this system will only have water in them when the pump is operating. This means that in the case of power failure as well as each night, there will be no fluid in the collector that could possibly freeze or cool down and delay the start-up of the system when the sun is shining. This system is very reliable and widely used. It requires that the collectors are mounted higher than the drain back tank or heat exchanger. This may be impossible to do in a situation where the collectors must be mounted on the ground. The fluids that are circulated into the collectors are separated from the heated water that will be used in the home by a double-walled heat exchanger. A heat exchanger is used to transfer the heat from the fluids circulating through the collectors to the water used in the home. The fluids that are used in the collectors can be water, oil, an antifreeze solution, or refrigerant. The heat exchangers should be double-walled to prevent contamination of the household water. The controller in these systems will activate the pumps to the collectors and heat exchanger when design temperature differences are reached. The heat exchanger may be separated from the storage tank or built into it. The systems that use antifreeze fluids need regular inspection (at least every 2 years) of the antifreeze solution to verify its viability. Oil or refrigerant circulating fluids are sealed into the system and will not require maintenance. A refrigerant system is generally more costly and must be handled with care to prevent leaking any refrigerant. This hot water system can be used for heating swimming pools and spas. Lower cost unglazed (no glass cover) collectors are available for this purpose.

3.8.2 Active Solar Space Heating

The active solar space heating system can use the same operational components as the domestic water heating systems as shown in Figure 3.18, but ties into a heating distribution system that can use heated fluids as a heat source.

The distribution system includes hydronic radiator, floor coil systems, and forced air systems.

The fluid that is heated and stored (typically water) and can be distributed into the house heating system in the following ways:

1. *Air distribution system*: The heated water in the storage tank is pumped into a coil located in the return air duct whenever the thermostat calls for heat. The controller for the solar

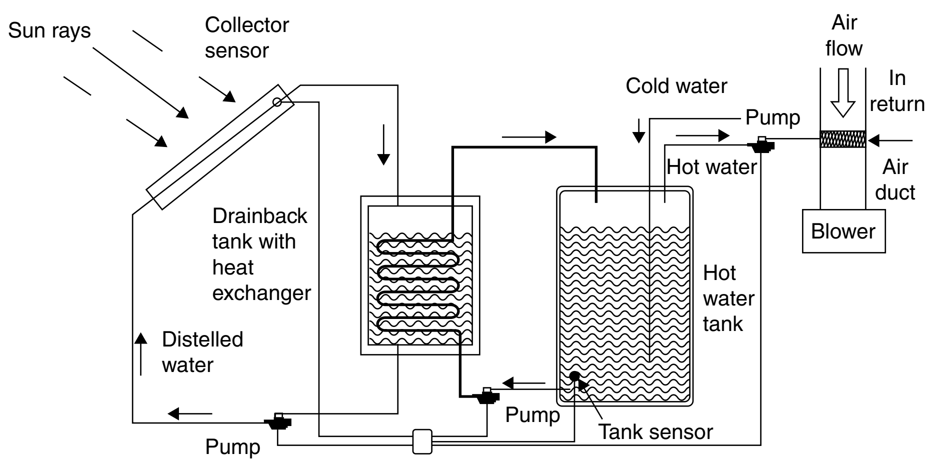


Figure 3.18 Typical space heating system

system will allow the pumping to occur if the temperature in the solar heated water is above a minimum amount needed to make a positive contribution to heating the home. An auxiliary heater can be used in two ways. It can add heat to the solar storage tank to maintain a minimum operating temperature in the storage tank at all times. In this case, the coil from the solar system will be located at the air handler supply plenum rather than in the return air duct. The auxiliary heater can also be a conventional furnace that will operate less often due to the warm air entering the air handler from the solar coil in the return duct.

2. *Hydronic system with radiators*: The heated water is circulated in series with a boiler into radiators located in the living spaces. Modern baseboard radiators operate effectively at 140°C. Solar heating systems can very often reach that temperature. Using the solar system's heated water as the source of water for the boiler will reduce the boiler's energy use, particularly if it senses the incoming temperature and will not operate when that temperature is above the required distribution temperature.
3. *Hydronic system with in-slab heat*: The solar heated water is pumped through distribution piping located in the floor of the home. Lower temperatures are used in this type of system (the slab is not heated above 80° in most cases). The auxiliary heat can be connected in series with the solar system's heated output water or it can be connected to the solar tank to provide a minimum temperature.

The space heating system, like the domestic water heating system, must be backed up by an auxiliary heating system. It is not practical to size a solar system to provide a home's entire heat requirement under the worst conditions. The system would become too large, too costly, and oversized for most of the time. The storage system should be sized to approximately 1.5 gallons of storage for each square foot of collector area.

3.9 PASSIVE SOLAR WATER HEATING SYSTEMS

A passive solar water heating system uses natural convection or household water pressure to circulate water through a solar collector to a storage tank or to the point of use. Active systems employ pumps and controllers to regulate and circulate water. Although passive system is generally less efficient than active systems, the passive approach is simple and economical.

Passive water heating systems must follow the same parameters for installations as that of active systems – south facing non-shaded location with the collector tilted at the angle of our latitude. Since the storage tank and collector are combined or in very close proximity, roof structural capacities must accommodate the extra weight of a passive system.

3.9.1 Types of Passive Water Heaters

Two types of passive water heaters are batch and thermosiphon systems.

3.9.1.1 Batch System

The batch system is the simplest of all solar water heating systems, as depicted in Figure 3.19. It consists of one or more metal water tanks painted with a heat absorbing black coating and placed in an insulating box or container with a glass or plastic cover that admits sunlight to strike the tank directly. The batch system's storage tank is the collector as well. These systems will use the existing house pressure to move water through the system. Each time a hot water tap

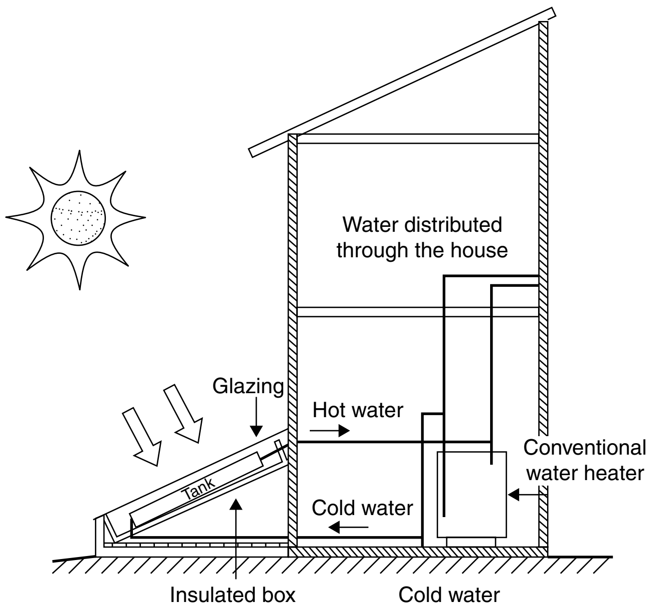
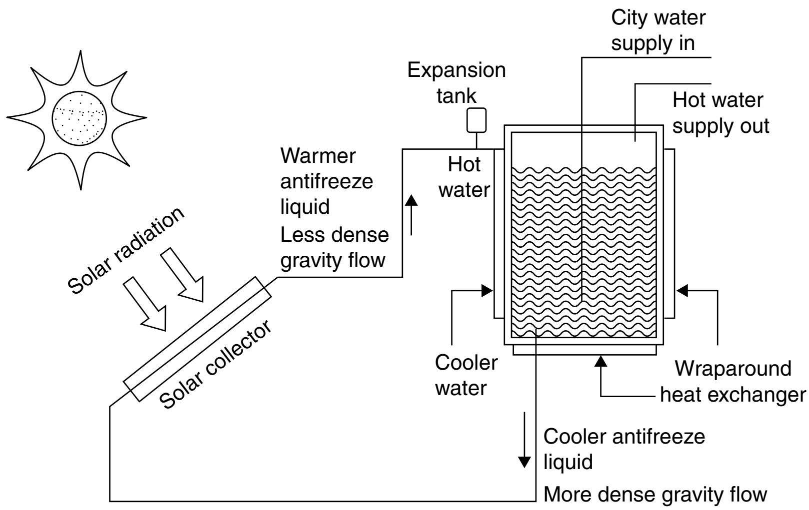


Figure 3.19 A typical schematic of batch domestic water heating system

is opened, heated water from the batch system tank is removed and replaced by incoming cold water. The piping that connects to and from the batch heater needs to be highly insulated. On a cold night, when no one is drawing hot water, the water in the pipes is standing still and vulnerable to freezing. In many applications, insulated polybutylene piping is used because the pipe can expand if frozen. The water in the batch heater itself will not freeze because there is adequate mass to keep it from freezing.



Source: http://solarheatcool.sustainablesources.com/

Figure 3.20 Thermosiphon system

Since the tank that is storing the heated water is sitting outside, there will be heat loss from the tank during the night. This can be minimized by an insulating cover placed on the heater in the evening. The most effective use of a batch water heater is to use hot water predominantly in the afternoon and evenings when the temperature in the tank will be the highest.

3.9.1.2 Thermosiphon Systems

The thermosiphon system uses a flat plate collector and a separate storage tank that must be located higher than the collector as shown in Figure 3.20. The collector is similar to those used in active systems.

The storage tank located above the collector receives heated water coming from the top of the collector into the top of the storage tank. Colder water from the bottom of the storage tank will be drawn into the lower entry of the solar collector to replace the heated water that was thermosiphoned upward. The storage tank may or may not use a heat exchanger. The thermosiphon system is more costly and complex than the batch system. In our area, it is best to use an indirect system (one that employs a heat exchanger). In that case, antifreeze can be used in the system eliminating freeze ups.

3.10 APPLICATIONS OF SOLAR WATER HEATING SYSTEMS

The following are a few industrial applications of solar water heaters.

1. *Hotels*: bathing, kitchen, washing, laundry applications
2. *Dairies*: ghee (clarified butter) production, cleaning and sterilizing, pasteurization
3. *Textiles*: bleaching, boiling, printing, dyeing, curing, ageing, and finishing
4. *Breweries and distilleries*: bottle washing, work preparation, boiler feed heating
5. *Chemical/bulk drugs units*: fermentation of mixes, boiler feed applications
6. *Electroplating or galvanizing units*: heating of plating baths, cleaning, degreasing applications
7. *Pulp and paper industries*: boiler feed applications, soaking of pulp.

3.11 ACTIVE SOLAR SPACE COOLING

Solar space cooling is quite costly to implement. It is best to use a solar system that serves more than just the cooling needs of a house to maximize the return on investment and not leave the system idle when cooling is not required. Significant space heating and/or water heating can be accomplished with the same equipment used for the solar cooling system. Active solar absorption cooling system is presented in Figure 3.21 in which (T) represents the sequence of flow.

Heat from solar collectors separates a low boiling refrigerant in a generator that receives the pressurized refrigerant from an absorber. Solar heat can also be used in the evaporation stage of the cycle.

3.16.3 Disadvantages

The following are some disadvantages related to the principle of solar cooking.

1. Solar cooking requires good weather with relatively steady sunshine.
2. Solar cooking cannot completely replace the conventional wood, gas, or kerosene fire.
3. Solar cooking is only possible during the daytime and not in the mornings and evenings (except with storage-type solar cookers).
4. Most types of solar cookers require industrially manufactured components. These can easily be destroyed, and it is difficult or impossible to repair or replace them with local material.
5. Some solar cooking boxes do not attain high temperatures. This requires long cooking time.
6. Boiling, roasting, and grilling require high temperatures, and thus, it is only possible in a few types of solar cookers
7. Some reflector-type solar cookers demand understanding, skill, and almost constant attention when handling and cooking with them.
8. The person doing the cooking has to stay out in the sun to avoid the risks of being dazzled or burnt.
9. Generally, families that need solar cookers mostly cannot afford them.

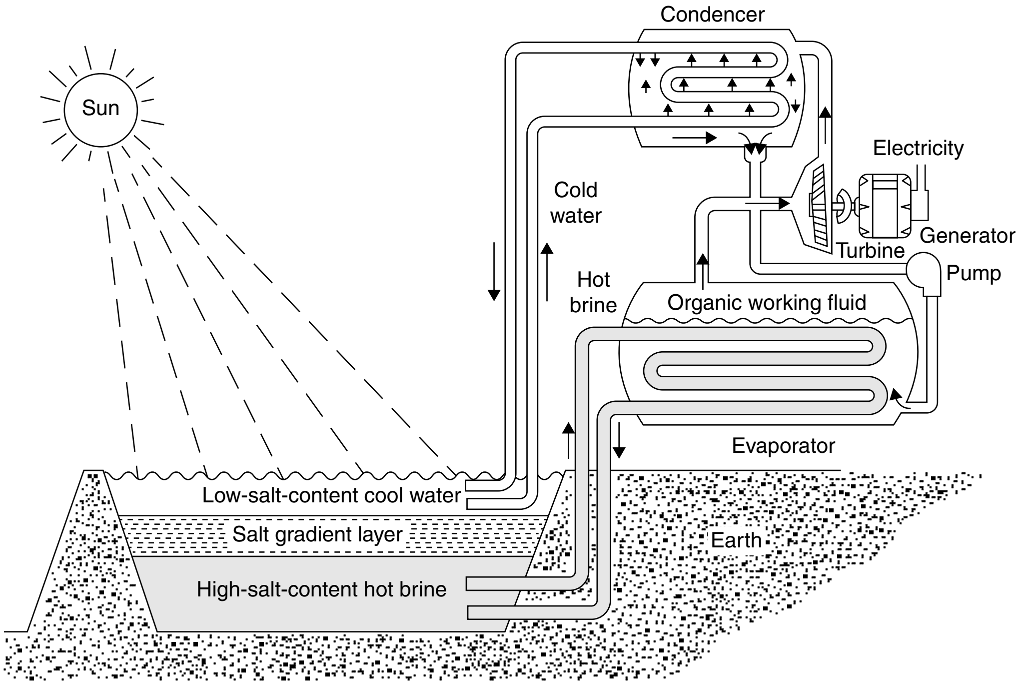
3.17 SOLAR POND

One of the best ways of harnessing solar energy is through solar ponds. It is basically a pool of water that collects and also stores solar energy. The peculiarity of the solar pond is that it has layers of salt solutions of differing concentrations, and thus, different densities to a certain depth. Once this depth is reached, then water with uniform, high salt concentration is obtained. The solar pond is a relatively low technology and low cost approach for harvesting solar energy. To develop a solar pond, pond is filled with three layers of water as shown in Figure 3.28.

1. The top layer is cold and has relatively little salt content.
2. Next is the intermediate insulating layer that has a salt gradient that maintains a density gradient. It is this density gradient that helps in preventing heat exchange with the natural convection of water.
3. The bottom layer is hot up to 100°C and has a high salt content.

It is because of these different salt contents in the different layers of water that the different layers have different densities. With the different densities in the water, the development of convection currents is prevented, which would have transferred heat to the surface of the pond, and then to the air above. Without these convection currents, heat is trapped in the salty bottom layer of the solar pond, which is used for heating of buildings, industrial processes, generation of electricity, and other purposes. In addition to the abovementioned uses, solar ponds can also be used in water desalination and for storage of thermal energy.

In this system, a large salty lake is used as a plate collector. With the right salt concentration in the water, the solar energy can be absorbed at the bottom of the lake. The heat is insulated by different densities of the water, and at the bottom, the heat can reach 90°C, which is high enough to run a vapour cycle engine; at the top of the pond, the temperature can reach 30°C. There are



Source: http://www.powerfromthesun.net/Book/chapter06/chapter06.html

Figure 3.28 Solar pond

three different layers of water in a solar pond: the top layer has less concentration of salt, the intermediate layer acts as a thermal insulator, and finally, the bottom layer has a high concentration of salt. These systems have a low solar to electricity conversion efficiency, less than 15% (having an ambient temperature of 20°C and storage heat of 80°C). One advantage of this system is that because the heat is stored, it can run day and night if required. Further, due to its simplicity, it can be constructed in rural areas in developing countries.

3.17.1 Advantages of Solar Pond

There are many advantages of using a solar pond to meet the energy requirements of a place.

1. The greatest advantage lies in the fact that it has a low cost per unit area of collection and also an inherent capacity for storage purposes. In addition to this, it is possible to easily construct solar ponds over large areas with which it is possible for the diffusion of solar resources to get concentrated on a grand scale.
2. Not only is a solar pond a great source of generation of electricity, it produces many environmental advantages when compared to the use of other fossil fuels for producing electricity. With a solar pond, the greatest advantage to the environment is that the heat energy is provided without the burning of any fuel, which reduces pollution.
3. Another advantage is that because there is no use of conventional energy resources for creating electricity in solar ponds, conventional energy resources are conserved. Further, the third

advantage of solar ponds to the environment is that it is coupled with desalting units that are used for purifying contaminated impaired water while the pond itself is the receptacle for waste products.

SUMMARY

- Solar thermal systems have the flexibility of being used for off-grid applications also. It includes solar water heaters (using both flat plate collectors and evacuation tube collectors), solar mass cooking, and comfort cooling applications.
- Solar collectors (or solar thermal collectors) are devices or systems designed to capture and use solar radiation for heating air or water and for producing steam to generate electricity.
- Flat plate collectors are the most common and widely used style of solar thermal collector for domestic hot water applications.
- For solar water heating systems in home and solar space heating, flat plate collectors are the most common type of solar collector used.
- When high temperatures above 120°C are required, such as for steam production, concentrating collectors are often used.
- A concentrating collector uses mirrors to concentrate the sunlight onto an absorber tube or panel, allowing much higher temperatures to be reached. Such collectors normally require 1 or 2 axis tracking to follow the sun and ensure optimal reflection angle.
- Collector Concentration Ratio (CCR) is the ratio of Aa//Ad. A collector is defined as concentrating if its absorber (fin) area Ad is smaller than the aperture area Aa. It is also used as a measure for classifying collectors. Since this ratio approximately determines the operating temperature, such method of classification is equivalent to classifying collectors by its operating temperature range.
- Heliostat is a mirror-based system used to continuously reflect sunlight onto a central receiver.
- Solar cooking technology has been given a lot of attention in recent years in developing countries. Solar cookers are primarily used to cook food and pasteurize water, although additional uses are continually being developed.
- Solar pond is basically a pool of water that collects and also stores solar energy. The peculiarity of the solar pond is that it has layers of salt solutions of differing concentration and thus, different densities to a certain depth. Once this depth is reached, then water with uniform, high salt concentration is obtained. Solar pond is a relatively low cost technology for harvesting solar energy.

REVIEW QUESTIONS

1. What are solar collectors? Give their classification and compare them based on construction and area of applications.
2. With neat sketches, discuss important parts of any flat plate solar collector. Further, discuss material aspects of individual parts.

serving a rapidly growing market, which is expected to rise to 3,000 GW by 2030. However, the cost of photovoltaic electricity production is still too high to be competitive with nuclear or fossil energy.

Photovoltaic conversion is the process of direct conversion of light into electricity at the atomic level. Some materials exhibit a property known as the photoelectric effect that causes them to absorb photons of light and release electrons. When free electrons are captured, electricity is generated. The photoelectric effect was first noted by a French physicist, Edmund Becquerel, in 1839, who found that certain materials would produce small amounts of electric current when exposed to light. In 1905, Albert Einstein described the nature of light and the photoelectric effect on which photovoltaic technology is based, for which he later won a Nobel Prize in physics.

In simple terms, It is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Solar cells are devices that convert solar energy directly into electricity via the photovoltaic effect. Photovoltaic converter is the other name for solar cells. They are responsible for producing energy out of sunlight it receives. Photovoltaic or solar cells are made of special materials that are semiconductors. These semiconductors produce electricity when sunlight falls onto its surface. Solar electric cells are simple cells to use, they do not require anything but sunlight to operate; they are long lasting, reliable, and easy to maintain. Normally, solar panels' lifetime is 25 years or more.

4.1 NEED FOR SOLAR CELLS

The development of solar cell use has been advocated because of the following needs

1. For low maintenance, long lasting sources of electricity suitable for places remote from both the main electricity grid and the people, that is, satellites, remote site water pumping, outback telecommunications stations, and lighthouses;
2. For cost effective power supplies for people living in the remote areas that have no access to the main electricity grid; for example, aboriginal settlements, outback sheep and cattle stations, and some home sites in grid-connected areas.
3. For non-polluting and silent sources of electricity, i.e., tourist sites, caravans, and campers
4. For a convenient and flexible source of small amounts of power, that is, calculators, watches, light meters, and cameras;
5. For renewable and sustainable power, as a means of reducing global warming.

Together these needs have produced a growing market for photovoltaic (solar cells) that has stimulated innovation. As the market has grown, the cost of cells and systems has declined, and new applications have been discovered.

4.1.1 Components of a Solar Cell System

These include solar cell panels, one or more batteries, a charge regulator or controller for a standalone system, an inverter for a utility grid-connected system, requirement of alternating current (AC) rather than direct current (DC), wiring, and mounting hardware or a framework.

4.1.2 Key Elements of Silicon Solar Cell

The basic elements of a solar cell is described in Figure 4.1.

The following are the basic elements:

1. *Substrate*: It is an unpolished p-type wafer referred to as p-region base material. The important parameters to be kept in mind while choosing a wafer for solar cells are its orientation, resistivity, thickness, and doping. Typical thickness of wafers used for solar cells is 180–300 μm. The typical resistivity values are in 1–2 Ωcm. The doping should be close to $5 \times 10^{15}/cm^3$ to $1 \times 10^{16}/cm^3$. The wafer can be single crystalline or multi-crystalline.
2. *Emitter*: The emitter formation involves the doping of silicon with pentavalent impurities such as phosphorus, arsenic, and antimony. However, for solar cell applications, phosphorus is the widely used impurity. The doping is done by the process of diffusion. The basic idea is to introduce the wafer in an environment rich in phosphorus at high temperatures. The phosphorus diffuses in, due to the concentration gradient, and it can be controlled by varying the time and temperature of the process. Commonly used diffusion technique makes use of POCl3 as the phosphorus source. The process is done at temperatures of 850°C to 1,000°C. The typical doping concentration will be of the order of $1 \times 10^{19}/cm^3$. The junction depths are in the range of 0.2–1 μm. This is also commonly known as *n*-region diffused layers
3. *Electrical contacts*: These are essential to a photovoltaic cell since they bridge the connection between the semiconductor material and the external electrical load. It includes

   (a) *Back contact*: It is a metallic conductor completely covering back. The back contact of a cell is located on the side away from the incoming sunlight and is relatively simple. It usually consists of a layer of aluminium or molybdenum metal.

   (b) *Front contact*: Current collection grid of metallic finger type is arranged in such a way that photon energy falls on n-region diffused layers. The front contact is located on the side facing the light source and is more complicated. When light falls on the solar cell,

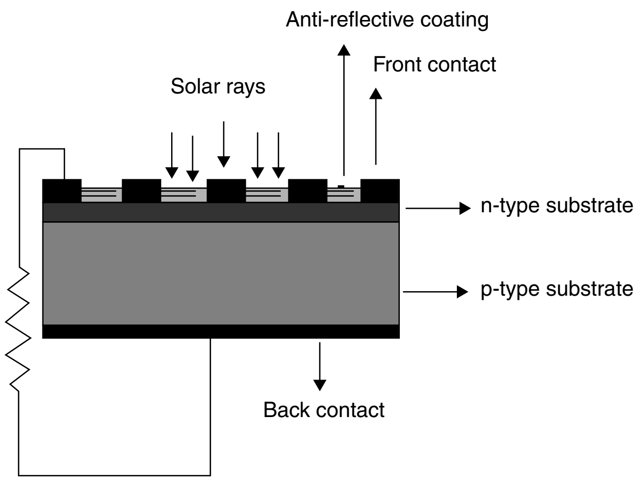


Figure 4.1 Basic elements of a photovoltaic cell

a current of electrons flow over the surface. If contacts are attached at the edges of the cell, it will not work well due to the great electrical resistance of the top semiconductor layer; only a small number of electrons will make it to the contact. To collect the maximum current, the contacts must be placed across the entire surface of a solar cell. This is done with a grid of metal stripes or fingers. However, placing a large grid, which is opaque, on the top of the cell shades active parts of the cell from the light source; as a result, this significantly reduces the conversion efficiency. To improve the conversion efficiency, the shading effect must be minimized.

(c) *Anti-reflective coatings*: Anti-reflective coatings are applied to reduce surface reflection and maximize cell efficiency in solar glass and silicon solar cell manufacturing. It helps to reduce the reflection of desirable wavelengths from the cell, allowing more light to reach the semiconductor film layer, increasing solar cell efficiency. When a thin-film nano-coating of anti-reflection coating of silicon dioxide (SiO_2) and titanium dioxide (TiO_2) is applied, there seems to be an increase in cell efficiencies by 3–4%.

4.1.2.1 Important Requirements of Solar Cell (Photovoltaic Cell)

Following are the important factors that need careful attention in the design of solar cells:

1. *Photon energy of solar light*: Photons with a certain level of energy can free electrons in the semiconductor material from their atomic bonds to produce an electric current. The energy of a photon must be larger than the bandgap energy to free an electron. However, photons with more energy than the bandgap energy will expand that extra amount as heat when freeing electrons.

2. *Bandgap energy of semiconductors*: When light falls on crystalline silicon, electrons within the crystal lattice can be freed. This level of energy is known as the bandgap energy. It is defined as the amount of energy required to dislodge an electron from its covalent bond and allow it to become part of an electrical circuit.

   Thus, it is important for a solar cell to be tuned through slight modifications to the silicon's molecular structure to optimize the photon energy. An efficient solar cell converts as much sunlight as possible into electricity.

3. *Photon energy absorption*: Photons are absorbed in the p-layer of solar cell. It is important that this p-layer absorbs maximum possible photons and also releases many electrons as possible up to maximum extent.

4. *Electron conduction*: The material design to free electrons as close to the junction as possible allows the electric field to send the free electrons through the conduction layer and into the electrical circuit, which is the another challenge of fabrication process. By optimizing these characteristics, the solar cell conversion efficiency is improved.

5. *Electric contact resistance*: Another important aspect in the solar cell design is to minimize the electrical resistance losses when applying grid contacts to the solar cell material. These losses relate to:

   (a) The material properties of the solar cell that oppose the flow of an electric current and results in heating.

(b) The shading effects must be balanced against electrical resistance losses in designing grid contacts.

The usual approach is to design grids with many thin, conductive fingers spreading to every part of the cell surface. The fingers of the grid must be thick enough to conduct well (with low resistance), but thin enough not to block the incoming light. This type of grid maintains low resistance losses while shading only ~3–5% of the cell surface.

6. *Antireflective Coating*: Silicon is a highly reflective material behaving as a mirror, thereby reflecting more than one-third of the solar light falling on it. Minimization of the amount of solar light reflected is also an important factor to improve the conversion efficiency of a solar cell.

4.1.3 Creating P-type and N-type Semiconductors

In a crystalline silicon solar cell, p-type silicon must contact n-type silicon to create the built-in electrical field. The process of doping, which is used to create these materials, introduces an atom of another element into silicon crystal to alter its electrical properties. The dopant, which is the introduced element, has either three or five valence electrons, which is one less or one more than silicon that have four valence electrons.

4.1.3.1 N-type Semiconductors

Phosphorus atoms, which have five valence electrons, are used to dope n-type silicon because phosphorus provides its fifth free electron. A phosphorus atom occupies the same place in the crystal lattice that was formerly occupied by the silicon atom it replaced. Four of its valence electrons take over the bonding responsibilities of the four silicon valence electrons that they had replaced. However, the fifth valence electron remains free, having no bonding responsibilities. When phosphorus atoms are substituted for silicon in a crystal, many free electrons become available.

The most common method of doping is to coat a layer of silicon material with phosphorus, and then, heat the surface. This allows the phosphorus atoms to diffuse into the silicon. The temperature is then reduced so the rate of diffusion drops to zero. Other methods of introducing phosphorus into silicon include gaseous diffusion, a liquid dopant spray-on process, and a technique in which phosphorus ions are precisely driven into the surface of the silicon.

However, the n-type silicon cannot form an electric field by itself. It also needs p-type silicon. Boron, which has only three valence electrons, is used for doping p-type silicon. Boron is introduced during silicon processing, when the silicon is purified for use in photovoltaic devices. When a boron atom takes a position in the crystal lattice formerly occupied by a silicon atom, a bond will be missing an electron. In other words, there is an extra positively charged hole.

4.1.3.2 P-type Semiconductors

In a photovoltaic cell, photons are absorbed in the p-layer. Therefore, it is important that this layer be ‘tuned’ to the properties of incoming photons so it can absorb as many as possible and, thus, free up as many electrons as possible. The design of the p-layer must also keep the electrons from meeting up with holes and recombining with them before they can escape from the PV cell. To accomplish these goals, p-layers are designed to free electrons as close to the junction as possible, so that the electric field can help to send the free electrons through the conduction layer (the *n*-layer) and in the electrical circuit.

By optimizing these characteristics, the PV cell's conversion efficiency (how much light energy is converted into electrical energy) is improved.

4.1.3.3 Fabrication of Silicon Solar Cell

It includes

1. Pure silicon is placed in an induction furnace where it melts.
2. Boron is then added to the melt from which p-type crystals are withdrawn.
3. The p-type base material is then placed in a diffusion furnace containing a gaseous n-type dopant like phosphorous.
4. n-type dopant is allowed to diffuse on to the surface, thus forming p–n junction.
5. Metal conductor grids are added as back and front contact for current collection.

4.2 SOLAR CELL MATERIALS

Many combinations of materials and methods of fabrication of photovoltaic cells are now either in practical use or in various developmental stage. However, silicon is the most widely used basic material because of its suitability and its availability in abundance. More than 80% of solar cells currently produced are crystalline silicon solar cells. Nearly all of the other 20% are developed as amorphous silicon solar cells. Silicon wafers have long been the primary base for assembly.

The absorption coefficient of a material indicates how far light with a specific wavelength (or energy) can penetrate the material before being absorbed. A small absorption coefficient means that light is not readily absorbed by the material. Again, the absorption coefficient of a solar cell depends on two factors: the material making up the cell, and the wavelength or energy of the light being absorbed.

The bandgap of a semiconductor material is the minimum energy needed to move an electron from its bound state within an atom to a free state. This free state is where the electron can be involved in conduction. The lower energy level of a semiconductor is called the 'valence band.' The higher energy level where an electron is free to roam is called the 'conduction band.' The bandgap (often symbolized by Eg) is the energy difference between the conduction band and the valence band.

Solar cell material has an abrupt edge in its absorption coefficient, because light with energy lesser than the material's bandgap cannot free an electron, it is not absorbed. A solar cell consists of semiconductor materials.

4.2.1 Silicon

This remains the most popular material for solar cells, including these types:

1. Monocrystalline or single crystal silicon
2. Multi-crystalline silicon

3. Polycrystalline silicon
4. Amorphous silicon

Polycrystalline wafers are made by a casting process in which molten silicon is poured into a mould and allowed to set. Then, it is sliced into wafers. As polycrystalline wafers are made by casting, they are significantly cheaper to produce, but not as efficient as monocrystalline cells. The lower efficiency is due to imperfections in the crystal structure resulting from the casting process.

Amorphous silicon, one of the thin-film technologies, is made by depositing silicon onto a glass substrate from a reactive gas like silane (SiH_4). This type of solar cell can be applied as a film to low cost substrates such as glass or plastic. Other thin-film technologies include thin multi-crystalline silicon, copper indium diselenide or cadmium sulphide cells, cadmium telluride or cadmium sulphide cells and gallium arsenide cells. There are many advantages of thin-film cells including easier deposition and assembly, the ability to be deposited on inexpensive substrates or building materials, the ease of mass production, and the high suitability to large applications.

Other types of PV materials that show commercial potential include copper indium diselenide ($CuInSe_2$), cadmium telluride (CdTe), and amorphous silicon as the basic material.

4.2.2 Thin Film

Thin-film solar cells use layers of semiconductor materials only a few micrometres thick. Thin-film technology has made it possible for solar cells to now double as these materials:

1. Rooftop or solar shingles
2. Roof tiles
3. Building facades
4. Glazing for skylights or atria

Thin-film photovoltaic cells made of CuInSe or CdTe that are being increasingly employed along with amorphous silicon. The recently discovered cells based on mesoscopic inorganic or organic semiconductors commonly referred to as ‘bulk’ junctions due to their three-dimensional structure. These junctions are very attractive alternatives that offer the prospect of very low cost fabrication. The prototype of this family of devices is the dye-sensitized solar cell (DSC), which accomplishes the optical absorption and the charge separation processes by the association of a sensitizer as light-absorbing material with a wide bandgap semiconductor of mesoporous or nano-crystalline morphology. Further, research is booming in the area of third generation photovoltaic cells where multi-junction devices and a recent breakthrough concerning multiple carrier generation in quantum-dot absorbers offer promising perspectives.

4.3 PRACTICAL SOLAR CELLS

Solar cells are now manufactured from a number of different semiconductors that are summarized in the following points. In addition, there is considerable activity to commercially manufacture the dye-sensitized solar cells.

Under short-circuit condition $V = 0$, $I = I_S$, which is the short-circuit current generated by the light-dependent current source.

Under open-circuit condition $I = 0$, maximum open-circuit voltage becomes V_{OC}

Substitution of Equation (4.5) in Equation (4.6) gives

$$I = I_S - I_0\,[\mathrm{Exp}\,(eV/kT) - 1] \tag{4.8}$$

Applying open-circuit conditions, $I = 0$, $V = V_{OC}$

$$\mathrm{Exp}\,(eV_{OC}/kT) - 1 = I_S/I_0 \tag{4.9}$$

or

$$V_{OC} = (kT/e)\,[\ln\{(I_S/I_0) + 1\}] \tag{4.10}$$

4.5.4 *I–V* Characteristics of Solar Cells

The voltage output of the cell (V), in general, can be obtained as

$$V = (kT/e)\log_e\,[1 + (I_S - I)/I_0] \tag{4.11}$$

Equation (4.11) represents the I–V characteristic of solar cell and it is shown in Figure 4.7 under different illumination levels.

On an I–V characteristic, the vertical axis refers to the current (I) and the horizontal axis refers to voltage (V). The actual I–V curve typically passes through two significant points:

1. The short-circuit current (I_{SC}) is the current produced when the positive and negative terminals of the cell are short-circuited and the voltage between the terminals is zero, which corresponds to a load resistance of zero.

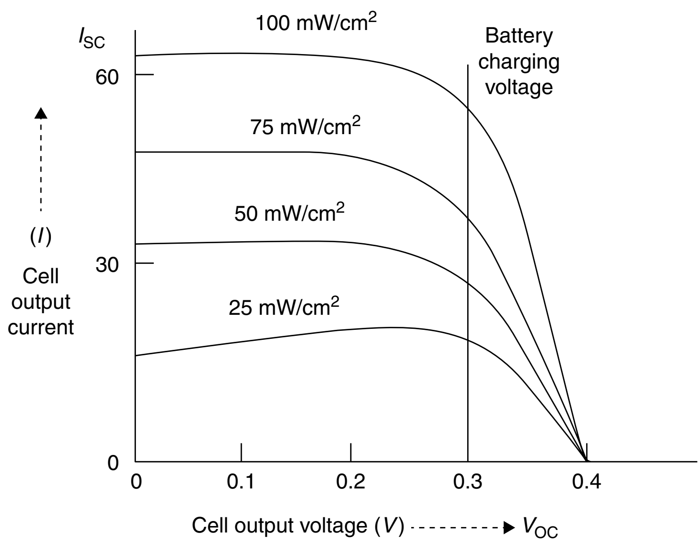


Figure 4.7 *I–V* characteristics of a typical solar cells under different illumination levels

2. The open-circuit voltage (V_{OC}) is the voltage across the positive and negative terminals under open-circuit conditions when the current is zero, which corresponds to a load resistance of infinity.

The cell may be operated over a range of voltages and currents.

4.5.4.1 Output Power

The cell output power $P = I \times V$

The output power depends on the value of load resistance for a given light intensity.

$$P = [I_S - I_0 \{\text{Exp}\,(eV/kT) - 1\}] \times V \tag{4.12}$$

Since $P = I \times V$, the maximum power occurs when the product of IV has it maximum value.

4.5.4.2 Maximum Output Power of the Cell

Differentiating Equation (4.12) with respect to V and setting the derivative equal to zero yields the value of external load voltage (V_{MP}) that gives the maximum output power.

Thus, from $dP/dV = 0$ and substituting $V = V_{MP}$ in the resulting equation yields,

$$[I_S - I_0 \{\text{Exp}\,(eV_{MP}/kT) - 1\}] + V_{MP}\,[-I_0 \{(e/kT)\,\text{Exp}\,(eV_{MP}/kT)\}] = 0 \tag{4.13}$$

This can be rearranged as

$$[\text{Exp}\,(eV_{MP}/kT]\,[1 + eV_{MP}/kT] = (1 + I_S/I_0) \tag{4.14}$$

Equation (4.13) is an implicit equation for V_{MP} that maximizes the power in terms of short-circuit current ($I_{S)}$, the reverse saturation current (I_0), and the absolute temperature (T). If all these parameters are known, the value of V_{MP} can be evaluated from Equation (4.12) or (4.14) by either trial and error method or numerical method or graphical method.

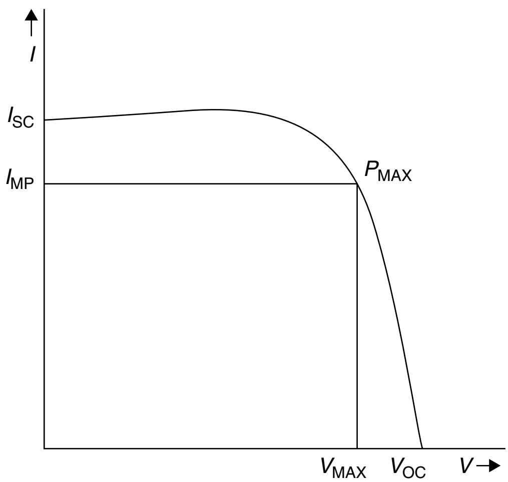


Figure 4.8 The *I–V* characteristic of an ideal solar cell

The load current (I_{MP}) that maximizes the output power can be found by substituting Equation (4.14) in Equation (4.8) as follows:

$$I_{MP} = I_S - I_0\,[(eV_{MP}/kT) - 1] = I_S - I_0\,[\{(1 + I_S/I_0)/(1 + eV_{MP}/kT)\} - 1]$$

$$= \{(eV_{MP}/kT)/(1 + eV_{MP}/kT\}\,(I_S - I_0) \qquad (4.15)$$

The maximum power P_{MAX} produced by the conversion device is reached at a point on the characteristic where the product IV is maximum. This is shown graphically in Figure 4.8, where the position of the maximum power point represents the largest area of the rectangle shown.

4.6 EFFICIENCY OF SOLAR CELLS

Energy conversion efficiency (η) is defined as the ratio of power output of cell (in watts) at its maximum power point (P_{MAX}) and the product of input light power (E, in W/m^2) and the surface area of the solar cell (S in m^2) under standard conditions

$$\eta = \text{maximum output power}/(\text{irradiance} \times \text{area}) = P_{MAX}/(E \times S) \qquad (4.16)$$

The performance of a photovoltaic device defines the prediction of the power that the cell will produce. Current–voltage (I–V) relationships, which measure the electrical characteristics of solar cell devices, are represented by I–V curves (see Figs. 4.7 and 4.8). These I–V curves are obtained by exposing the cell to a constant level of light while maintaining a constant cell temperature, varying the resistance of the load, and measuring the current that is produced.

By varying the load resistance from zero (a short circuit) to infinity (an open circuit), researchers can determine the highest efficiency as the point at which the cell delivers maximum power. The power is the product of voltage and current. Therefore, on the I–V curve, the maximum-power point (P_{MAX}) occurs where the product of current and voltage is a maximum. No power is produced at the short-circuit current with no voltage or at open-circuit voltage with no current. Therefore, the maximum power generated is expected to be somewhere between these two points. Maximum power is generated at only one place on the power curve, at about the 'knee' of the curve. This point represents the maximum efficiency of the solar device at converting sunlight into electricity.

4.6.1 Fill Factor

Another term defining the overall behaviour of a solar cell is the fill factor (FF). It is a measure of squareness of the I–V characteristics of the solar cell and is defined as

$$\text{FF} = \text{Maximum output power}/(\text{open-circuit voltage} \times \text{short-circuit current})$$

It is the available power at the maximum power point (P_{MAX}) divided by the product of open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}) as

$$\text{FF} = P_{MAX}/(V_{OC} \times I_{SC}) = (V_{MP} \times I_{MP})/(V_{OC} \times I_{SC}) \qquad (4.17)$$

where V_{MP} and I_{MP} are the voltage and current at the maximum power point.

Equation (4.17) can be redefined as,

$$\text{FF} = (\eta \times S \times E)/(V_{OC} \times I_{SC}) \qquad (4.18)$$

The fill factor is directly affected by the values of the cell's series and shunt resistances. Increasing the shunt resistance (R_{SH}) and decreasing the series resistance (R_S) lead to a higher fill factor, thus resulting in greater efficiency, and bringing the cell's output power closer to its theoretical maximum.

Example 4.1

For a typical photovoltaic cell, the following performance parameters are obtained from the *I–V* characteristics.
Open-circuit voltage (V_{OC}) = 0.611
Short-circuit current (I_{SC}) = 2.75
Voltage corresponding to cell maximum power output (V_{MP}) = 0.5
Current corresponding to cell maximum power output (I_{MP}) = 2.59
Calculate fill factor of the cell.

Solution Fill factor $= (V_{MP} \times I_{MP})/(V_{OC} \times I_{SC})$

$$= (0.5 \times 2.59)/(0.611 \times 2.75) = 0.7707$$

4.6.2 Factors Limiting the Efficiency of the Cell

1. *Wavelength of solar spectrum*: Cell response to only a portion of wavelength available in the solar spectrum. Photon with wavelength > 1.1 μm does not have sufficient energy to create electron–hole pair in silicon cell.
2. *Temperature*: Normal operating temperature of silicon cells can reach 60°C in peak sunlight and these temperature decreases the efficiency of the cells. Therefore, it is important to provide heat sinks of the best quality available. Gallium arsenide cells are capable of operating at high temperature where focused energy can be used.
3. *Mounting of the cells*: It should be to a heat sink (usually an aluminium plate) either heat conductive but electrically insulated. This will reduce operating temperatures and make the cell more efficient. In case free water source is available, heat sinks can be water cooled.
4. *Arrangement and maintenance of solar cell*: The negative side of the cells usually faces the sun and has antireflection coatings. These coatings should be protected from dust, bird dropping, by a clear plastic or glass cover. Accumulated dust on the cover will reduce the output power by about 10%.
5. *Position of the cell*: The cell or panel should be positioned either facing south in the north of equator or facing north in the south of equator for maximum power output and fixed panel applications. The angle off the ground should be equal to the latitude of the place for year around average or can be changed monthly to face the sun at noon for more efficiency.

4.7 PHOTOVOLTAIC PANELS (SERIES AND PARALLEL ARRAYS)

As single solar cell has a working voltage and current of about 0.5 V and 50 mA, respectively, they are usually connected together in series (positive to negative) to provide larger voltages.

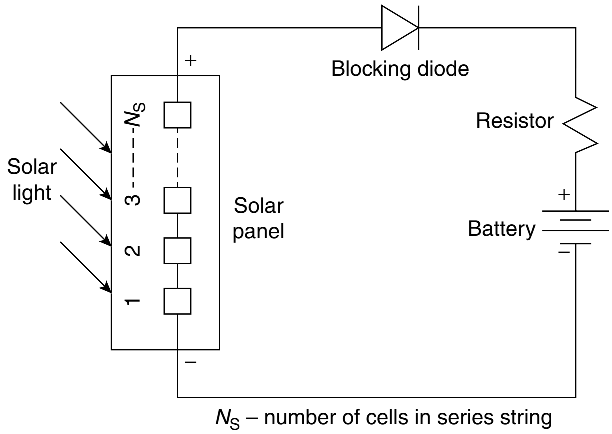


Figure P4.8 Battery charging by solar panel

Battery charging voltage output of solar panel = 50 × 0.3 = 15 V
Existing battery voltage + diode voltage = 11.5 + 0.6 = 12.1 V
Battery current = (15 – 12.1)/80 = 36.25 mA

4.8 APPLICATION OF SOLAR CELL SYSTEMS

In late 1980s and early 1990s, the major markets for solar panels were remote area power supplies and consumer products (watches, toys, and calculators). However, in the mid-1990s, a major effort was launched to develop building-integrated solar panels for grid-connected applications.

4.8.1 Solar Water Pumps

There are more than 10,000 solar powered water pumps in use in the world today. They are widely used on farms to supply water to livestock. In developing countries, they are used extensively to pump water from wells and rivers to villages for domestic consumption and irrigation of crops. In solar water pumping system, the pump is driven by motor run by solar electricity instead of conventional electricity drawn from utility grid. A solar photovoltaic water pumping system consists of a photovoltaic array mounted on a stand and a motor-pump set compatible with the photovoltaic array. It converts the solar energy into electricity, which is used for running the motor pump set. The pumping system draws water from the open well, bore well, stream, pond, canal, etc.

4.8.2 Solar Vehicle

It is an electric vehicle powered completely or significantly by direct solar energy. Usually, photovoltaic (PV) cells contained in solar panels convert the sun's energy directly into electric energy. The term 'solar vehicle' usually implies that solar energy is used to power all or part of a vehicle's propulsion. Solar power may be also used to provide power for communications or controls or other auxiliary functions.

4.8.3 Solar Lanterns

When the Petromax-type solar lantern is plugged into a solar photovoltaic cell, its rechargeable battery stores the electricity produced so that it can be used to light home or power a radio. When fully charged, the lantern will give light for 4 to 5 h, and the radio will run for 15 h. If both are used simultaneously, the listening and lamp time will be shorter.

4.8.4 Solar Panels on Spacecraft

Spacecraft operating in the inner solar system usually rely on the use of photovoltaic solar panels to derive electricity from sunlight. In the outer solar system, where the sunlight is too weak to produce sufficient power, radioisotope thermal generators (RTGs) are used as a power source.

4.8.5 Grid-connected Photovoltaic Power Systems

These are power systems energized by photovoltaic panels that are connected to the utility grid. Grid-connected photovoltaic power systems comprise photovoltaic panels, battery charging regulators, solar inverters, power conditioning units, and grid-connected equipments. When conditions are right, the grid-connected PV system supplies the excess power, beyond consumption by the connected load, to the utility grid. Residential grid-connected photovoltaic power systems that have a capacity less than 10 kW can meet the load of most consumers. It can feed excess power to the grid, which, in this case, acts as a battery for the system.

4.8.6 Cathodic Protection Systems

Cathodic protection is a method of protecting metal structures from corrosion. It is applicable to bridges, pipelines, buildings, tanks, wells, and railway lines. To achieve cathodic protection, a small negative voltage is applied to the metal structure and this prevents it from oxidizing or rusting. The positive terminal of the source is connected to a sacrificial anode that is generally a piece of scrap metal, which corrodes instead of the structure. Photovoltaic solar cells are often used in remote locations to provide this voltage.

4.8.7 Electric Fences

Electric fences are widely used in agriculture to prevent stock or predators from entering or leaving an enclosed field. These fences usually have one or two 'live' wires that are maintained at about 500 V DC. These give a painful, but harmless shock to any animal that touches them. This is generally sufficient to prevent stock from pushing them over. These fences are also used in wildlife enclosures and secure areas. They require a high voltage, but very little current and they are often located in remote areas where the cost of electric power is high. These requirements can be met by a photovoltaic system involving solar cells, a power conditioner, and a battery.

4.8.8 Remote Lighting Systems

Lighting is often required at remote locations where the cost of power is too high to use the grid. Such applications include security lighting, navigation aids, (e.g., buoys and beacons), illuminated road signs, railway crossing signs, and village lighting. Solar cells are suited to such applications, although a storage battery is always required in such systems. They usually consist of a solar photovoltaic panel, a battery charging regulator, a storage battery, power conditioner, and a low voltage, high-efficiency DC fluorescent lamp. These systems are very popular in remote areas, especially in developing countries and this is one of the major applications of solar cells.

4.8.9 Telecommunications and Remote Monitoring Systems

Good communications are essential for improving the quality of life in remote areas. However, the cost of electric power to drive these systems and the high cost of maintaining conventional systems has limited their use. Solar panel has provided a cost-effective solution to this problem through the development of remote area telecommunications repeater stations. These stations typically consist of a receiver, a transmitter, and a solar cell-based power supply system. Thousands of these systems have been installed around the world and they have an excellent reputation for reliability and relatively low costs for operation and maintenance.

Similar principles apply to solar powered radios and television sets, emergency telephones, and monitoring systems. Remote monitoring systems may be used for collecting weather data or other environmental information and for transmitting it automatically via radio to the home base.

4.8.10 Rural Electrification

Storage batteries are widely used in remote areas to provide low-voltage electrical power for lighting and communications as well as for vehicles. A photovoltaic-powered battery charging system usually consists of a small solar cell array and a charge controller. These systems are widely used in rural electrification projects in developing countries.

4.8.11 Water Treatment Systems

In remote areas, electric power is often used to disinfect or purify drinking water. Photovoltaic cells are used to power a strong ultraviolet light that can be used to kill bacteria in drinking water. This can be combined with a solar-powered water pumping system. Desalination of brackish water can be achieved via PV-powered reverse osmosis systems.

SUMMARY

- Photovoltaic conversion is the process of direct conversion of light into electricity at the atomic level. Some materials exhibit a property known as the photoelectric effect that causes them to absorb photons of light and release electrons. When free electrons are captured, electricity is generated.
- Single junction silicon solar cells produce approximately 0.5–0.6 V_{OC} (open circuit voltage), so they are usually connected together in series to provide larger voltages.
- An important feature of solar cells is that the voltage of the cell does not depend on its size and remains fairly constant with changing light intensity. However, the current in a device is almost directly proportional to light intensity and size. The output current varies depending on the size of the cell. In general, a typical commercially available silicon cell produces a current between 28 and 35 milliamps per square centimetre.

vehicles, as a heat source, and for many other uses. The advantage of using hydrogen as an energy carrier is that when it combines with oxygen, the only by-products are water and heat. No greenhouse gasses or other particulates are produced by the use of hydrogen fuel cells.

2. *Hydrogen can be produced locally from numerous sources*: Hydrogen can be produced either centrally, and then distributed, or onsite where it will be used. Hydrogen gas can be produced from methane, gasoline, biomass, coal, or water. Each of these sources brings with it different amounts of pollution, technical challenges, and energy requirements.
3. *A sustainable production system if hydrogen is produced from electrolysis of water*: Electrolysis is the method of separating water into hydrogen and oxygen. Renewable energy can be used to power electrolysers to produce hydrogen from water. Using renewable energy provides a sustainable system that is independent of petroleum products and is non-polluting. Some of the renewable sources used to power electrolyses are wind, hydro, solar, and tidal energy. After the hydrogen is produced in an electrolyser, it can be used in a fuel cell to produce electricity. The by-products of the fuel cell process are water and heat. If fuel cells operate at high temperatures, the system can be set up as a co-generator, with the waste energy used for heating.

5.2 HYDROGEN PRODUCTION TECHNOLOGIES

The choice of production methods will vary depending on the availability of feedstock or resource, the quantity of hydrogen required, and the required purity of hydrogen. Researchers are developing a wide range of processes for producing hydrogen economically and in an environmentally friendly way. These processes can be divided into three major research areas:

1. Thermochemical production technologies
2. Electrolytic production technologies
3. Photolytic production technologies

5.2.1 Thermochemical Production Technologies

Hydrogen bound in organic matter and in water makes up 70% of the earth's surface. Breaking up these bonds in water allows us produce hydrogen, and then, to use it as a fuel. There are numerous processes that can be used to break these bonds. Following sections discuss a few methods for producing hydrogen that are currently used or are under research and development. Most of the hydrogen now produced on an industrial scale by the process of steam reforming, or as a by-product of petroleum refining and chemical production.

5.2.1.1 Steam Reforming

Steam reforming uses thermal energy to separate hydrogen from the carbon components in methane and methanol and involves the reaction of these fuels with steam on catalytic surfaces. The first step of the reaction decomposes the fuel into hydrogen and carbon monoxide. Then, a 'shift reaction' changes the carbon monoxide and water to carbon dioxide and hydrogen. These reactions occur at temperatures of 200ºC or greater.

Steam reforming of natural gas is currently the least expensive method and is responsible for more than 90% of hydrogen production worldwide. Natural gas is first cleared from sulphur compounds. It is then mixed with steam and send over a nickel–alumina catalyst inside a tubular reactor heated externally, where carbon monoxide (CO) and hydrogen (H_2) are generated. This step is followed by a catalytic water-gas shift reaction that converts the CO and water to hydrogen and carbon dioxide (CO_2). The hydrogen gas is then purified.

The endothermic reforming reaction is:

$$CH_4 + H_2O + 206\ (kJ/kg) \Rightarrow CO + 3H_2 \tag{5.1}$$

It is usually followed by the exothermic shift reaction:

$$CO + H_2O \Rightarrow CO_2 + H_2 + 41(kJ/kg) \tag{5.2}$$

The overall reaction is:

$$CH_4 + 2H_2O + 165\ (kJ/kg) \Rightarrow CO_2 + 4H_2 \tag{5.3}$$

The residual stream from the initial purification step is part of the fuel gas burned in the reformer in order to supply the required heat. Hence, the CO_2 contained in this gas is currently vented with the flue gas. If CO_2 were to be captured, an additional separation step would be needed.

The technology is suitable for large reformers (e.g., 100,000 tons per year), where yields higher than 80% can be achieved. Small-scale reformers especially designed for feeding small fuel cells show low efficiencies.

The production of hydrogen from natural gas is an integral part of the strategy to introduce hydrogen into the transportation and utility energy sectors, by reducing the cost of conventional and developing innovative hydrogen production processes that rely on cheap fossil feedstocks. Today, nearly all hydrogen production is based on fossil raw materials. Worldwide, 48% of hydrogen is produced from natural gas, 30% from oil (mostly consumed in refineries), 18% from coal, and the remaining 4% via water electrolysis.

Modification of the conventional steam methane reforming (SMR) process to incorporate an adsorbent in the reformer to remove CO_2 from the product stream may offer a number of advantages over conventional processes. Disturbing the reaction equilibrium in this way drives the reaction to produce additional hydrogen at lower temperatures than conventional SMR reactors.

Although still in the research stage, the cost of hydrogen from this modified process is expected to be 25%–30% lower, primarily because of reduced capital and operating costs. In addition, the adsorption of the CO_2 in the reforming stage results in a high-purity CO_2 stream from the adsorbent regeneration step. This has interesting implications in a carbon-constrained world.

5.2.1.2 Partial Oxidation or Ceramic Membrane Reactor

Scientists are developing a ceramic membrane reactor for the simultaneous separation of oxygen from air and the partial oxidation of methane. If successful, this process could result in improved production of hydrogen and/or synthesis gas when compared to conventional reformers.

In the partial oxidation process, natural gas (or other liquid or gaseous hydrocarbons) and oxygen are injected into a high-pressure reactor. The oxygen to carbon ratio is optimally set for maximizing the yield of CO and H_2 and avoiding the formation of soot. Further steps and equipment remove the large amount of heat generated by the oxidation reaction, shift the CO with water to CO_2 and H_2, and remove the CO_2, which can then be captured, and purify the hydrogen produced. This process needs oxygen, which is usually provided by an air distillation plant. Partial oxidation can also be helped by an oxidation catalyst. It is then called catalytic partial oxidation.

The partial oxidation reaction for natural gas is:

$$CH_4 + \frac{1}{2} O_2 \Rightarrow CO + 2\,H_2 \tag{5.4}$$

After the partial oxidation reaction, the process gas is similar to that of the steam reforming process. Since the reaction is exothermic, a heating system is not required, which is a major advantage resulting in size and capital cost reduction. However, partial oxidation is typically less energy efficient than steam reforming.

5.2.1.3 Biomass Gasification and Pyrolysis

The thermal processing techniques for plant material (biomass) and fossil fuels are similar, with a number of the downstream unit operations being essentially the same for both feedstocks. Using agricultural residues and wastes, or biomass specifically grown for energy uses, hydrogen can be produced via pyrolysis or gasification.

Biomass pyrolysis produces a liquid product (bio-oil) that, like petroleum, contains a wide spectrum of components that can be separated into valuable chemicals and fuels.

Unlike petroleum, bio-oil contains a significant number of highly reactive oxygenated components derived mainly from constitutive carbohydrates and lignin. These components can be transformed into products, including hydrogen. Co-product strategies are designed to produce high value chemicals, like phenolic resins, in conjunction with hydrogen.

5.2.2 Electrolytic Production Technologies

Another way to produce hydrogen is by electrolysis. Electrolysis separates the elements of water—H_2 and oxygen (O)—by charging water with an electrical current. Adding an electrolyte like salt improves the conductivity of the water and increases the efficiency of the process. The charge breaks the chemical bond between the hydrogen and the oxygen and splits apart the atomic components, creating charged particles called ions. The ions form at two poles: the anode, which is positively charged, and the cathode, which is negatively charged. Hydrogen gathers at the cathode and the anode attracts oxygen.

Electrolysis is the process of producing hydrogen and oxygen from water in an electrochemical cell. Two types of electrochemical methods, alkaline or proton exchange membrane (PEM), are used in commercially available equipment commonly referred to as electrolysers.

An alkaline electrolyser immerses the two electrodes, the cathode and the anode, into an aqueous alkaline electrolyte, typically a solution of sodium or potassium hydroxide, and a voltage is applied across the electrodes. The resulting migration of ions in solution results in the production of hydrogen at the cathode and oxygen at the anode according to the following equation:

$$\text{Cathode reaction} \qquad 4H_2O + 4e^- — 2H_2 + 4OH^- \tag{5.5}$$

$$\text{Anode reaction} \qquad 4OH^- — O_2 + 2H_2O + 4e^- \tag{5.6}$$

In a PEM electrolyzer, the mobile ion is a proton in an electrolyte that is a proton-conducting polymer memebarane. In this case, the reactions at the electrodes are as follows:

Cathode reaction $4H^+ + 4e^- — 2H_2$ (5.7)

anode reaction $2H_2O — O_2 + 4H^+ + 4e^-$ (5.8)

Currently, the best conversion efficiency (i.e., overall system efficiency for converting electrical power to power stored as hydrogen) for commercial electrolysers is approximately 70%.

5.2.2.1 Water Electrolysis

Until the 1950s, water electrolysers were in widespread use for hydrogen (or oxygen) production. Currently, electrolysis provides only a small percentage of the world's hydrogen, most of which is supplied to applications requiring small volumes of high purity hydrogen (or oxygen, such as for breathing atmospheres for submarines). There is significant renewed interest in the use of electrolysers to produce hydrogen as a fuel for automotive applications, with a number of refuelling stations installed around the world. In addition, research continues in the integration of intermittent renewable resources (PV and wind) with electrolysers for producing hydrogen that has to be used as a fuel or for energy storage.

5.2.2.2 Steam Electrolysis

Steam electrolysis is a variation of the conventional electrolysis process. Some of the energy needed to split the water is added as heat instead of electricity, making the process more efficient than conventional electrolysis. At 2,500°C, water decomposes into hydrogen and oxygen. This heat could be provided by a solar energy concentrating device to supply the heat. The problem here is to prevent the hydrogen and oxygen from recombining at the high temperatures used in the process.

5.2.2.3 Photoelectrolysis

Multi-junction cell technology developed by the PV industry is being used for photoelectrochemical (PEC) light harvesting systems that generate sufficient voltage to split water and are stable in a water or electrolyte environment. Theoretical efficiency for tandem junction systems is 42%; practical systems could achieve 18% –24% efficiency; low-cost multi-junction amorphous silicon (a-Si) systems could achieve 7% –12% efficiency. This is one of the advantages of a direct conversion hydrogen generation system. Not only does it eliminate most of the costs of the electrolyser, but it also has the possibility of increasing the overall efficiency of the process. Research results for the development of PEC water splitting systems have shown a solar-to-hydrogen efficiency of 12.4% for the lower heating value (LHV) of hydrogen using concentrated light. Low-cost a-Si tandem designs with appropriate stability and performance are also being developed. An outdoor test of the a-Si cells resulted in a solar-to-hydrogen efficiency of 7.8% LHV under natural sunlight.

5.2.2.4 Thermochemical Water Splitting

Thermochemical water splitting uses chemicals such as bromine or iodine assisted by heat. This causes the water molecule to split. It takes several steps—usually three—to accomplish this entire process.

Several high-temperature thermochemical reactions are under study, which have high efficiency and practical applicability with nuclear heat sources.

One of the most promising may be the sulphur–iodine (SI) cycle, where three chemical reactions achieve the dissociation of water:

$$I_2 + SO_2 + 2H_2O \Rightarrow 2HI + H_2SO_4(120°C) \tag{5.9}$$

$$H_2SO_4 \Rightarrow SO_2 + H_2O + ½\, O_2(830\text{–}900°C) \tag{5.10}$$

$$2HI \Rightarrow I_2 + H_2(300\text{–}450°C) \tag{5.11}$$

The overall reation being:

$$H_2O \Rightarrow H_2 + ½\, O_2 \tag{5.12}$$

The efficiency of the sulphur–iodine process increases from 30% at 750°C to 60% at 1,000°C. Other thermochemical cycles show efficiencies of 40%–50% at typical temperatures of 700°C.

Several high-temperature nuclear reactors have been developed that could produce heat at the required temperature. The high-temperature helium reactor and the molten-salt reactor appear to offer the best perspectives for hydrogen production. Other reactor types may be used if efficient hydrogen production processes can be developed at temperatures of 500°C.

5.2.2.5 *By-product of Sodium or Potassium Chloride Electrolysis*

Hydrogen is a by-product of sodium or potassium chloride electrolysis that produces chlorine and caustic soda or potash:

$$NaCl + H_2O + \text{electricity} \Rightarrow ½\, Cl_2 + NaOH + ½\, H_2 \tag{5.13}$$

$$KCl + H_2O + \text{electricity} \Rightarrow ½\, Cl_2 + KOH + ½\, H_2 \tag{5.14}$$

Chlorine is one of the most common chemicals in the world. It is produced in huge quantities.

5.2.2.6 *Reversible Fuel Cells or Electrolysers*

Operating the proton exchange membrane (PEM) fuel cell ‘in reverse’ as an electrolyser is possible, but optimum operating conditions for the power production mode and for the hydrogen production mode are significantly different. Design issues for the reversible fuel cell system include thermal management, humidification, and catalyst type and loading.

5.2.3 Photolytic Production Technologies

Solar energy can be used to convert water to hydrogen and oxygen directly. Electricity need not be produced by photovoltaic cell. Hydrogen production can be achieved by using either photo-electrochemical or photo-biological methods.

5.2.3.1 *Photoelectrochemical Processes*

Photoelectrochemical processes use two types of electrochemical systems to produce hydrogen. One uses soluble metal complexes as a catalyst, while the other uses semiconductor surfaces. When the soluble metal complex dissolves, the complex absorbs solar energy and produces an electrical charge that drives the water-splitting reaction. This process mimics photosynthesis.

The other method uses semiconducting electrodes in a photochemical cell to convert optical energy into chemical energy. The semiconductor surface serves two functions: to absorb solar energy and to act as an electrode. Light-induced corrosion limits the useful life of the semiconductor.

5.2.3.2 Biological and Photobiological Processes

Certain photosynthetic microbes produce hydrogen in their metabolic activities using light energy. By employing catalysts and engineered systems, hydrogen production efficiency could reach 24%. Photo-biological technology holds great promise but because oxygen is produced along with the hydrogen, the technology must overcome the limitation of oxygen sensitivity of the hydrogen-evolving enzyme systems. Researchers are addressing this issue by screening for naturally occurring organisms that are more tolerant of oxygen, and by creating new genetic forms of the organisms that can sustain hydrogen production in the presence of oxygen. A new system is also being developed that uses a metabolic switch (sulphur deprivation) to cycle algal cells between the photosynthetic growth phase and the hydrogen production phase.

Unlike cyanobacteria or algae, photosynthetic bacteria do not oxidize water. However, they do evolve hydrogen from biomass (previously generated from sunlight, water, and carbon dioxide). These bacteria use several different enzymatic mechanisms with near-term commercial potential for biological hydrogen production from biomass. One mechanism, in particular, looks promising for applications as a biological conditioning agent for upgrading thermally generated fuel gases to a level where they can be directly injected into hydrogen fuel cells. This same system has the potential to subsequently evolve into a second-generation photo-biological method to produce hydrogen from water.

From the abovementioned points, it is evident that biological and photo-biological processes use algae and bacteria to produce hydrogen. Under specific conditions, the pigments in certain types of algae absorb solar energy. The enzyme in the cell acts as a catalyst to split the water molecules. Some bacteria are also capable of producing hydrogen, but unlike algae, they require a substrate to grow on. The organisms not only produce hydrogen, but also can clean up pollution as well.

When considering the production process, the cost of electricity required for the electrolysis process is one of the barriers to sustainable energy. Besides electrolysis, the production of hydrogen has been accomplished by a catalytic reaction of waste aluminium. The end products are hydrogen and alumina that can be reused to make aluminium.

With increasing use of hydrogen and technical advances, the costs of production, distribution, and product manufacturing will become increasingly affordable. By continuing to build partnerships between business, government, universities, and non-profit organizations, hydrogen will be the foundation of a sustainable energy economy.

5.3 HYDROGEN ENERGY STORAGE

When compared to the electrical energy, the development of safe, reliable, compact, and cost-effective hydrogen storage technologies is one of the most technically challenging barriers to the widespread use of hydrogen as a usable form of energy. To be competitive with conventional vehicles, hydrogen-powered cars must be able to travel more than 450 km between fills. This is

5.5.1 At Home Sector

Fuel cells are ideal for residential zones. They are virtually silent with no moving parts and provide reliable power 24/7. In addition, a fuel cell, which is large enough to power an entire home, is about the size of a traditional AC unit. Fuel cells already power thousands of homes in Japan and are beginning to power similarly in the United States.

5.5.2 At Work Sector

Fuel cells can be produced in stacks large enough to power the large office buildings, but only occupy the area of couple of parking spaces. Again, fuel cells are a great fit in this situation, as they are noiseless, environmentally friendly, and efficient. Distributed power from fuel cells does not rely on transmission lines, and thus eliminates the need for backup power generators.

5.5.3 At Transport and Industrial Sectors

Fuel cells are just as mobile as human beings. Fuel cells can power cars, buses, airplanes, cell phones, laptops, and more. With nearly 10 times the lifespan of batteries on a single charge, fuel cells can keep powered no matter where the road takes the transport vehicles.

Hydrogen is an ideal replacement for fossil fuels such as coal, oil and natural gas in furnaces, internal combustion engines, turbines, and jet engines. Today, environmental pressures are concentrating on the hydrogen research and the development efforts to utilize hydrogen as an alternative fuel to power our mobility and transportation needs. In electrified vehicles, for example, it is used to run fuel cells that convert hydrogen efficiently (back) to electricity. The application spectrum of fuel cells is vast. They have the potential to replace conventional power generators such as combustion engines or even large batteries in cars, buses, forklift trucks (FLTs), submarines, and backup and power plants.

5.6 ADVANTAGES OF HYDROGEN ENERGY

1. Uncoupling of primary energy sources and utilization.
2. Hydrogen is a gas; thus, it is easier to store than to store electricity.
3. Hydrogen can be obtained from any primary energy source, including renewable energy source.
4. Decentralized production is possible. Hydrogen is viewed as capable of providing services where electricity is not available, in particular as a fuel for vehicles and energy storage in remote areas.
5. Very efficient when used in fuel cells.
6. Very good experience of hydrogen as a chemical reactant (ammonia, methanol, and oil refining).
7. Very good safety records (for a specific range of applications).

5.7 DISADVANTAGES OF HYDROGEN ENERGY

1. Poor overall energy efficiency when produced from electricity made with fossil fuels.
2. Very low density and poor specific volume energy density.
3. Need for high pressures and very low temperatures if stored in the liquid phase.
4. Specific safety problems and poor public acceptance (Hindenburg syndrome and Apollo Challenger space shuttle).
5. No existing infrastructures for transport, distribution, and storage.
6. Rather high cost (till today).

5.8 PROBLEMS ASSOCIATED WITH HYDROGEN ENERGY

The serious problems that are affecting the development of hydrogen for household and transport applications are as follows:

1. *Hydrogen storage*: The concerns surrounding the storage of hydrogen are a major issue. It must be stored at extremely low temperatures and high pressure. A container capable of withstanding these specifications is larger than a standard gas tank. Hydrogen storage could be viewed as a problem by consumers.
2. *High reactivity of hydrogen*: Hydrogen is extremely reactive. It is combustible and flammable. The Hindenburg disaster, where a hydrogen-filled blimp exploded and many people died, has caused a fear of hydrogen
3. *Cost and methods of hydrogen fuel production*: Current production of hydrogen takes a lot of energy. If one has to burn fossil fuels to make hydrogen, what has really been gained? New, clean energy technology or hydrogen production methods will need to be developed for hydrogen vehicles to make sense.
4. *Consumer demand*: Another problem for hydrogen fuel is consumer demand and the cost to change all gasoline filling stations and vehicle production lines into hydrogen. The major transport companies will not start to produce hydrogen vehicles until there is consumer demand. Why would a person pay for an expensive hydrogen vehicle?
5. *Cost of changing the infrastructure*: To accommodate hydrogen equipment and appliances.

SUMMARY

- Hydrogen is an energy carrier but not a source of energy. Therefore, it must be produced.
- Hydrogen is a clean burning fuel that can be produced in virtually unlimited quantities at a very low cost. It can be readily converted into electricity when needed either through mechanical energy or directly through electrochemical fuel cells.
- Hydrogen is an industrial raw material for ammonia synthesis, petroleum reforming, fat hardening, and a number of other chemical industries.
- Hydrogen is an extremely environment friendly fuel; when it burns, it releases only water vapour into the atmosphere, but the problem is that it is not easy to store.

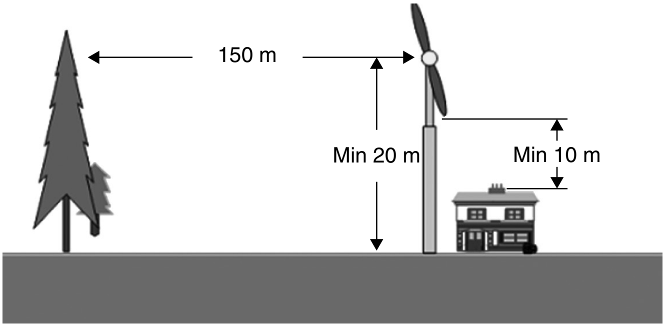


Figure 6.2 Installation of wind turbine (simple rule of thumb)

air is created, and if a wind turbine is located in this zone of turbulence, the result will be poor energy production and increased wear and tear on the turbine. One way to get above the zone of turbulence is to put the wind turbine on a tall tower.

Figure 6.2 is an illustration of a simple rule of thumb that is often used to specify a minimum tower height for a residential-sized wind turbine. The rule of thumb is to make sure that the tower is tall enough so that the entire turbine rotor is at least 10 m above the tallest obstacle within 150 m of the tower. Because trees grow and towers do not, the growth of trees over the lifetime of the wind turbine (typically 20–30 years between major rebuilds) should be considered in installation.

This should really be regarded as an absolute minimum for a wind turbine; at 10 m above an obstacle, there will still be some amount of turbulence and additional clearance is highly desirable. Changes in height of obstacles should be kept in mind as well. For example, if the obstacle like trees that are expected to grow up to 20 m high, it is advisable to use a 33-m tower.

Likewise, a 20-m tower should only be used when the terrain is very flat with no obstacles in a wide area around; for example, at the edge of the sea, or on top of a cliff with a clear area around it, or in the tundra. For most situations, a 20-m tower will only save a little money up front, while short selling energy production in the long run. To go beyond the rule of thumb, the airflow over any blunt obstruction, including a tree, tends to create a ‘bubble’ of turbulent air of twice the height of the obstacle, extending 20 times the height of the obstacle behind it. Therefore, your 10-m high house disturbs the air up to 200 m away. The tree line with 33 m trees disturbs the air up to 70 m high at a distance of 300 m away (see Fig. 6.3). Wind turbine may be located either upwind of the obstructions, or far enough downwind. Notice from Figure (6.3) that preference should be given to a site upwind of obstructions, but keep in mind that tall features downwind of the turbine can also influence the wind going through the blades, as shown in Figure (6.3).

Upwind and downwind are relative to the prevailing wind direction, where the wind blows from most of the time. A wind atlas can sometimes tell about prevailing wind direction, and if there is one at all. Some sites have winds that did not read the rule book, and there it is equally likely to blow from more than one direction.

The airflow that close to the building is generally very turbulent, leading to premature failure and poor power production. It is usually noisy too. Every wind turbine has some amount of vibration associated with it, and this too will be transmitted inside the house. We know, the thought of bolting a little turbine to the house, just over the roof line, to offset your electricity use (as that salesman put it) is appealing. The harsh reality is that it does not work. Several studies were done, involving dozens of roof-top turbines. They all concluded that those turbines do not work. Their energy production is negligible and some were even net users of electricity (because their inverters draw power, even when nothing is going into the grid). It is necessary to say 'no' to building-mounted turbines.

6.5.2 Considerations and Guidelines for Site Selection

When looking for a place for a wind turbine, engineers consider factors such as wind hazards, characteristics of the land that affect wind speed, and the effects of one turbine on nearby turbines in wind farms. The following important factors need careful considerations:

1. *Hill effect*: When it approaches a hill, wind encounters high pressure because of the wind that has already built up against the hill. This compressed air rises and gains speed as it approaches the crest, or top of the hill. The installation of wind turbines on hilltops takes advantage of this increase in speed.
2. *Roughness or the amount of friction that earth's surface exerts on wind*: Oceans have very little roughness. A city or a forest has a great deal of roughness, which slows the wind.
3. *Tunnel effect*: The increase in air pressure undergoes when it encounters a solid obstacle. The increased air pressure causes the wind to gain speed as it passes between, for example, rows of buildings in a city or between two mountains. Placing a wind turbine in a mountain pass can be a good way to take advantage of wind speeds that are higher than those of the surrounding air.
4. *Turbulence*: Rapid changes in the speed and direction of the wind, often caused by the wind blowing over natural or artificial barriers are called turbulence. Turbulence causes not only fluctuations in the speed of the wind but also wear and tear on the turbine. Turbines are mounted on tall towers to avoid turbulence caused by ground obstacles.
5. *Variations in wind speed*: During the day, winds usually blow faster than they do at the night because the sun heats the air, setting air currents in motion. In addition, wind speed can differ depending on the season of the year. This difference is a function of the sun, which heats different air masses around earth at different rates, depending on the tilt of the earth towards or away from the sun.
6. *Wake*: Energy can neither be created nor destroyed. As wind passes over the blades of a turbine, the turbine seizes much of the energy and converts it into mechanical energy. The air coming out of the blade sweep has less energy because it has been slowed. The abrupt change in the speed makes the wind turbulent, a phenomenon called wake. Because of wake, wind turbines in a wind farm are generally placed about three rotor diameters away from one another in the direction of the wind, so that the wake from one turbine does not interfere with the operation of the one behind it.
7. *Wind obstacles*: Trees, buildings, and rock formations are the main obstacles in the installation of wind turbines. Any of these obstacles can reduce wind speed considerably and

increase turbulence. Wind obstacles like tall buildings cause wind shade, which can considerably reduce the speed of the wind, and therefore, the power output of a turbine.

8. *Wind shear*: It is the differences in wind speeds at different heights. When a turbine blade is pointed straight upward, the speed of the wind hitting its tip can be, for example, 9 miles (14 km) per hour, but when the blade is pointing straight downward, the speed of the wind hitting its tip can be 7 miles (11 km) per hour. This difference places stress on the blades. Further, too much wind shear can cause the turbine to fail.

Choosing the right site for wind turbine is the most important decision. Further, the location plays a vital part in the performance and efficiency of a wind turbine. The following guidelines can be followed to evaluate site for the installation of wind turbines:

1. Turbines work best when on high and exposed sites. Coastal sites are especially good.
2. Town centres and highly populated residential areas are usually not suitable sites for wind turbines.
3. Avoid roof-mounted turbines as there is no guarantee that these devices will not damage property through vibration.
4. The farther the distance between the turbine and the power requirement, the more power will be lost in the cable. The distance of the cabling will also impact the overall cost of the installation.
5. Turbulence disrupts the air flow that can wear down the blades and reduces the lifecycle of the turbine. It is recommended that installing a turbine may be considered only when the distance between the turbine and the nearest obstacle is more than twice the height of the turbine, or when the height of the turbine is more than twice the height of the nearest obstacle.
6. Small turbines require an average wind speed of over 4.5 m/s to produce an efficient level of electricity.
7. If site is in a remote location, connecting wind turbine to the national grid will be very expensive and it may be worth considering an off-grid connection instead using battery storage.

6.5.3 Wind Turbine Power Output Variation with Steady Wind Speed

Figure 6.7 gives the power output from a wind turbine variation with steady wind speed.

There are five important characteristic wind speeds and they are as follows:

1. Start-up speed is the speed at which the rotor and blade assembly begin to rotate.
2. The cut-in wind speed is the speed when the machine begins to produce power.
3. The design wind speed is the speed when the windmill reaches its maximum efficiency.
4. The rated wind speed is the speed when the machine reaches its maximum output power.
5. The furling wind speed is the speed when the machine furls to prevent damage at high wind speeds.

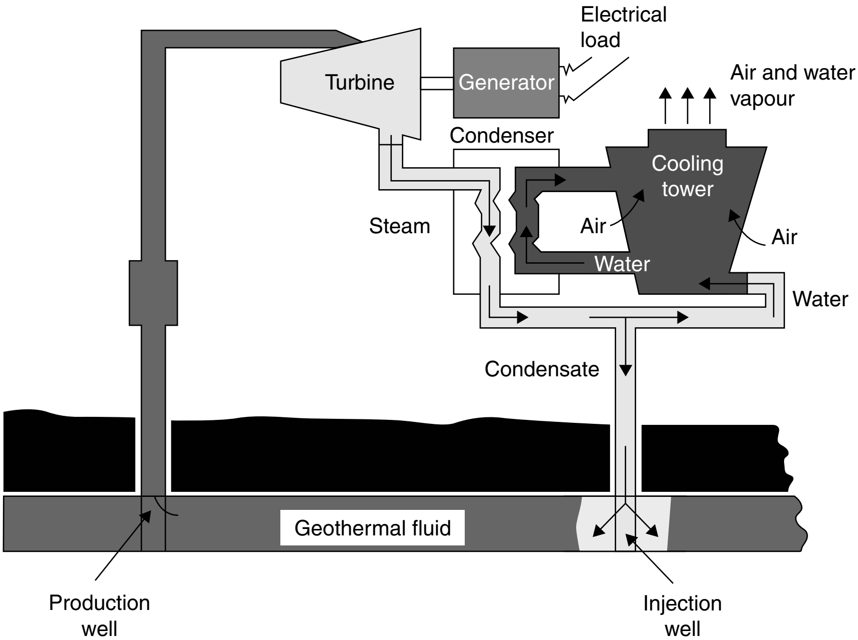


Figure 7.2 Dry steam geothermal electric power plant

that power the generator. Dry steam systems are relatively simple, requiring only steam and condensate injection piping and minimal steam cleaning devices. A dry steam system requires a rock catcher to remove large solids, a centrifugal separator to remove condensate and small solid particulates, condensate drains along the pipeline, and a final scrubber to remove small particulates and dissolved solids. Today, steam plants make up a little less than 40% of U.S. geothermal-electricity production, all located at The Geysers in California.

7.5.2 Flash Geothermal Power Plants

The term flash steam refers to the process where high-pressure hot water is flashed (vaporized) into steam inside a flash tank by lowering the pressure. This steam is then used to drive around turbines. Flash steam is today's most common power plant type. The first geothermal power plant that used flash steam technology was the Wairakei Power Station in New Zealand, which was built already in 1958.

At high pressure below earth's surface, the water exists as compressed liquid. Pipeline is installed to tap into the resource. When the compressed liquid water reaches the surface at atmospheric pressure then, a portion of it immediately flashes to steam. The steam portion is redirected into a steam turbine, where power is produced. The exhaust is then piped to a condenser where it is returned to liquid. This hot liquid water can then be used for further heating applications prior to the reinjection into the rock.

Flash steam plants are the most common type of geothermal power generation plants in operation today. Fluid at temperatures greater than 182°C is pumped under high pressure into a tank at

1. Photosynthesis production of organic matters.
2. Collection and processing of plant materials.
3. Fermentation of the organic matters, leading to liquid and gaseous fuels and storage.

Sugar crops, trees, grains, and grasses are various aquatic fuel sources and have relative potentials on each other utilized in any biomass production schemes. Sugar crops and algal crops seem to be the most promising crops of importance suitable for bioenergy conversion in India.

8.2 KEY ISSUES

The following are the key issues that must be investigated before the economic viability of a refuse-derived fuel (RDF) scheme:

1. Collection of waste from doorsteps, commercial places, community dump, and final disposal sites.
2. The volume and nature of refuse to be processed.
3. The type of efficient RFD process required and market for fuel products.
4. The required potential users and the revenue obtainable.
5. The economy of the alternative method of disposal of the refuse.
6. The utilization of solar thermal energy for increasing the temperatures of digesters.

8.3 WASTE RECOVERY MANAGEMENT SCHEME

A simple waste, refuse resource recovery scheme can be understood from Figure 8.1, which represents the various important scheme components as energy use and solid waste generation, transportation, storage, energy recovery, treatment, and final disposal of the waste.

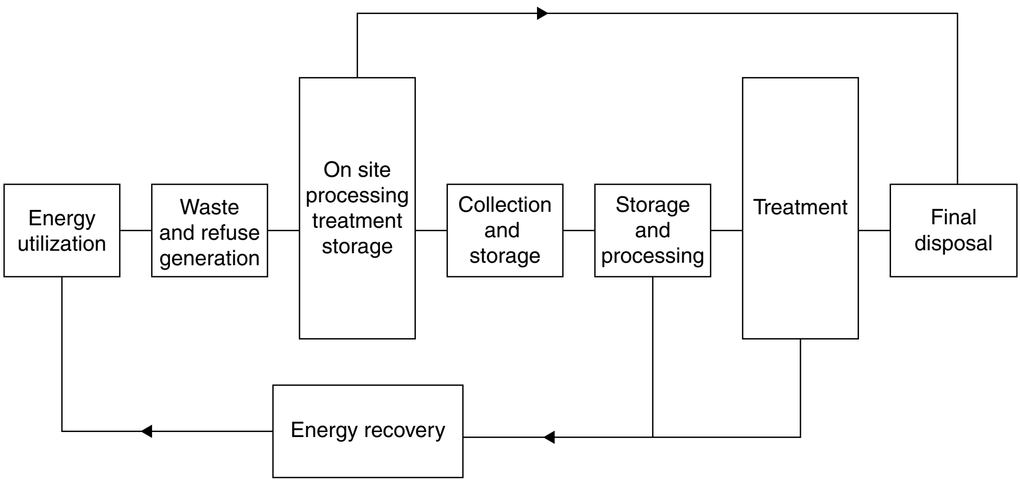


Figure 8.1 Schematic representation of waste refuse energy management

The major part of waste obtained after the energy utilization are non-organic that have diversified nature and characteristics, and thus, their identification and separation from the main waste stream by improved techniques are an essential parameter of any energy recovery scheme. On-site processing of waste for the reduction of in-home compactors and industrial shredders through improved technology should be employed, which may be environmentally acceptable. Collection and transportation components of the waste energy conversion scheme are the most expensive components owing to many varying social, technical, and other reasons. A careful cost analysis and implementation of this vital component will minimize the running cost of the scheme. The storage of waste for resource recovery and final disposal after suitable treatment is another component of scheme and selection of storage station and other associated problems invite careful attention. Normally, two types of energy recovery systems are used:

1. Separation of metals, paper, and glass from the remaining waste through the process such as size reduction, screening, vibrating sorting, and electronic scanning; however, a truly homogeneous, inexpensive separation system will provide competitive input to waste energy utilization.
2. Conversion of the remaining waste product to usable form of energy and energy conversion may include the following:
   (a) Generation of methane gas (biogas conversion) or other fuels (biological conversion)
   (b) Generation of electricity either from (a) or through thermo-mechanical process
   (c) Composting of fertilizers

8.3.1 Treatment

Here, the treatment means that those process designed to reduce waste to innocuous forms without or after energy recovery. The most familiar techniques are the burning of waste at high temperatures in the presence of oxygen (known as incineration) and the breaking down of the complex compounds using heat in the absence of oxygen (known as pyrolysis). However, treatment techniques should be selected so as to be accepted socially, environmentally, and economically. The cheapest method for final disposal of waste before or after energy recovery is a systematic burial in ground.

8.4 ADVANTAGES AND DISADVANTAGES OF WASTE RECYCLING

Significant advantages and disadvantage of waste recycling are discussed in this section.

8.4.1 Advantages of Waste Recycling

Recycling is a process of using old or waste products into new products; this is an important step towards energy conservation (to reduce energy usage and reduce the consumption of fresh raw materials) and reduction in pollution (to reduce air, water, land pollution, and greenhouse emissions).

1. *Reduced damage to environment*: This is the foremost advantage of recycling and this promotes environmental protection in a balanced manner. For instance, let us consider the case

of cutting down trees for paper production; here, individuals can create balance by recycling old used papers and new paper products made from trees. In such a way, deforestation and felling is reduced. Natural resources are conserved this way.

2. *Reduced consumption of energy*: Large amount of energy is consumed when raw materials are processed during manufacturing. Therefore, recycling helps reduce energy consumption making production process beneficial and cost effective. It leads to reduced utilization of raw materials. It ensures additional energy availability and saving money. It reduces the creation of waste at source.
3. *Reduced environmental impact and pollution*: At present, industrial waste is major source of pollution. Recycling industrial products such as plastics and cans help a lot in cutting down levels of pollution for the reason that these materials are being reused instead of being thrown away irresponsibly. It saves on requirement of open landfill spaces, the surroundings clean and healthy. It also reduces environmental impact of traditional methods of waste treatment and disposal.
4. *Mitigate global warming*: Recycling aids in alleviating or lessening global warming and its harsh effects. Today, massive waste is being burned producing large amount of greenhouse gas emissions. Therefore, recycling is an effective way of ensuring that the process of burning is reduced and waste are regenerated and converted to useful and eco-friendly products without creating harmful impact to the environment.
5. *Promotes sustainable utilization of resources*: Recycling promotes sustainable and wise use of resources. This activity helps ensure that there is no discriminate use of materials and resources saving them for possible use in the future.

8.4.2 Disadvantages of Waste Recycling

1. *High cost of recycling*: The establishment of separate facilities in order to process products and make them reusable is cost effective. This might somehow trigger pollution in terms of transporting the materials and cleaning activities.
2. *Durability and small life span of recycled items*: The durability and efficiency of recycled products does not guarantee 100%. Recycled products are sometimes taken from cheap and overused materials; therefore, there is no assurance that it can last for long.
3. *Unsafe and unhygienic process*: Recycling sites and processes are often unhygienic and unsafe and this might pose dangers to your health.

8.4.3 Status of Municipal Solid Wastes Management in India

Municipalities in India spend hardly between 10% and 50% of their budget on solid waste management (SWM), but most of this is consumed in the salaries of sanitation workers and transport of waste, while a minute proportion is spent on its scientific disposal. The abysmal state of affairs with regard to the collection and transport of waste is all too well known. However, the implications of the negligence in waste treatment and disposal, such as untreated and unprocessed garbage left in open dumpsites, and its grave consequences for public health and the environment are not fully understood. They are the main cause of river water, land, and air pollutions.

1. Biomass is reduced to charcoal
2. Charcoal is converted at suitable temperature to produce CO and H_2

Typically, the volumetric composition of biomass-based producer gas is as follows:

CO : 20%–22%,
H_2 : 15%–18%,
CH_4 : 2%–4%,
CO_2 : 9%–11% and
N_2 : 50%–54%.

9.5 GASIFIER AND THEIR CLASSIFICATIONS

Biomass gasifier may be considered as a chemical reactor in which biomass goes through several complex physical and chemical processes and producer or syngas is produced and recovered.

There are two distinct types of gasifier:

1. *Fixed bed gasifier*: In this gasifier, biomass fuels move either countercurrent or concurrent to the flow of gasification medium (steam, air, or oxygen) as the fuel is converted to fuel gas. They are relatively simple to operate and have reduced erosion.

   Since there is an interaction of air or oxygen and biomass in the gasifier, they are classified according to the way air or oxygen is introduced in it. There are three types of gasifier as shown in Figure 9.2.

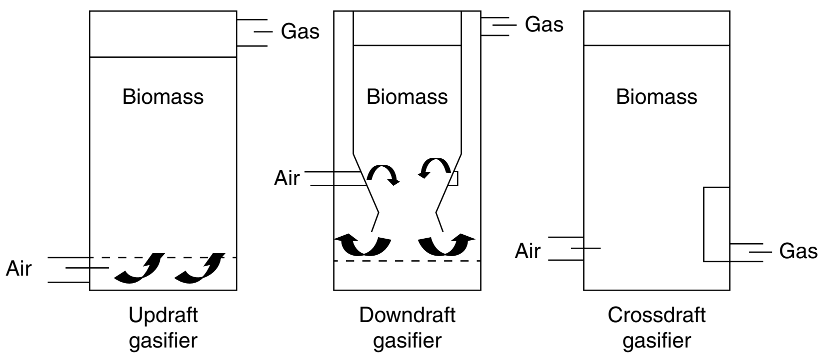


Figure 9.2 Types of fixed bed gasifiers

   (a) *Downdraft gasifiers*: In the downdraft gasifier, the air is passed from the layers in the downdraft direction. Single throat gasifiers are mainly used for stationary applications, whereas double throat gasifier is used for varying loads as well as automotive purposes.
   (b) *Updraft gasifiers*: Updraft gasifier has air passing through the biomass from bottom and the combustible gases come out from the top of the gasifier.
   (c) *Cross draft gasifiers*: It is a very simple gasifier and is highly suitable for small outputs. With slight variation, almost all the gasifiers fall in the abovementioned categories.

Table 9.2 Advantages and Disadvantages of Fixed Bed Gasifiers

	Updraft Gasifier	Downdraft Gasifier	Cross-draft Gasifier
Comparative features	1. It works on coal, briquettes, and other fuels (fuel flexibility).	1. It works on woody biomass and charcoal (fuel specific).	1. Type of fuel usage restricted to only low ash fuels such as wood, charcoal, and coke.
	2. Comparatively low quality gas having tar and particulate matter.	2. High quality gas.	2. Good quality gas.
	3. Suitable for thermal applications.	3. Suitable for power (IC engines) and thermal applications.	3. Suitable for heat and power applications.
	4. Gas is drawn out of the gasifier from the top of the fuel bed, while the gasification reactions take place near the bottom. The air comes in at the bottom and produced syngas leaves from the top of the gasifier.	4. Air is introduced into downward flowing packed bed or solid fuels and gas is drawn off at the bottom. Hence, fuel and gas move in the same direction.	4. Air enters from one side of the gasifier, and fuel is released from the opposite side.
	5. It tolerates higher ash content, higher moisture content, and greater size variation in fuel.	5. It is sensitive to ash content, moisture content, and size variation in fuel.	5. Flexible gas production.

The choice of one type of gasifier over other is dictated by the fuel, its final available form, its size, moisture content, and ash content. Table 9.2 lists the comparative features of various types of fixed bed gasifiers.

2. *Fluidized bed gasifier*: In fluidized bed gasifier, an inert material (such as sand, ash, or char) is utilized to make bed and that acts as a heat transfer medium

9.6 CHEMISTRY OF REACTION PROCESS IN GASIFICATION

Four distinct processes take place in a gasifier when fuel makes its way to gasification:

1. *Drying zone of fuel*: In this zone, the moisture content of biomass is removed to obtain the dry biomass. Some organic acids also come out during the drying process. These acids give rise to corrosion of gasifiers.
2. *Pyrolysis zone*: In this zone, the tar and other volatiles are driven off. The products depend upon temperature, pressure, residence time, and heat losses. However, following general remarks can be made about them.

(a) Up to the temperature of 200°C, only water is driven off.
(b) Between 200°C and 280°C carbon dioxide, acetic acid, and water are given off.
(c) The real pyrolysis, which takes place between 280°C and 500°C, produces large quantities of tar and gases containing carbon dioxide. Besides light tars, some methyl alcohol is also formed.
(d) Between 500°C and 700°C, the gas production is small and contains hydrogen.

3. *Combustion(oxidation) zone*: In this zone, carbon from the fuel combust and forms carbon dioxide with the oxygen in the air by the reaction:

$$C + O_2 \rightarrow CO_2 + \text{Heat}$$

Because of the heat emitted during the reaction, the temperature rises until a balance between heat supply and heat loss occurs.

4. *Reduction zone*: The hot gas passes through the reduction zone after the combustion zone. As there is no free oxygen in this zone that causes inflammable carbon dioxide gas to react with the carbon in the fuel and forms flammable carbon monoxide gas. This reaction is endothermic (demands heat) and occurs at temperature exceeding about 1,000°C. Carbon monoxide is the most important flammable elements in the produced gas obtained from the reduction reaction as

$$C + CO_2 + \text{heat} \rightarrow 2CO \tag{9.3}$$

Another important endothermic reaction in the reduction zone is the water–gas shift reaction. It is the reaction of water vapour and carbon to give carbon monoxide and hydrogen

$$C + H_2O + \text{Heat} \rightarrow CO + H_2 \tag{9.4}$$

Both gasses are flammable, and the heating value of the gas is increased. If there is still surplus of water in the reduction zone, then carbon monoxide may react with water vapour and form carbon dioxide and hydrogen. This reaction is exothermic (emits heat) and decreases the heating value of the produced gas. The reaction is

$$CO + H_2O - \text{Heat} \rightarrow CO_2 + H_2 \tag{9.5}$$

Equations (9.3) and (9.4) are main reduction reactions and being endothermic have the capability of reducing gas temperature. Consequently, the temperatures in the reduction zone are normally 800°C–1,000°C. The lower the reduction zone temperature (~700°C–800°C), lower is the calorific value of gas.

The gas also contains measurable amounts of particulate material and tar. The heating value of the gas ranges from 4,000 to 5,000 kJ/m^3, which is a relatively low value when compared to the heating value of other gaseous fuels like natural gas.

The conversion efficiency of a gasifier is defined as the ratio of the heat content in the producer gas to the heat content in the biomass supplied and is usually around 75%.

Although there is a considerable overlap of the processes, each can be assumed to occupy a separate zone where fundamentally different chemical and thermal reactions take place.

Figure 9.3 shows schematically an updraft gasifier with different zones and their respective temperatures. Figure 9.4 for downdraft and Figure 9.5 for cross-draft also show these regions.

It is also estimated that for a simple family size of five persons and four cows and buffaloes, animal dung (leaving the use of human excreta for social problems) will produce about 175 cubic feet of biogas per day which will be sufficient for family requirements of cooking and lighting. In addition, rural housewives using the biofuel are spared the irritating smoke coming out of traditional cooking on raw biomass material and reduced labour required for cleaning the cooking equipments and utensils. The digested material, which comes out of the plant, is enriched manure.

10.3 ANAEROBIC DIGESTION

It is a biological process that produces a gas (commonly known as biogas) in the absence of oxygen and has major components of methane (CH_4) and carbon dioxide (CO_2).

Anaerobic digestion of methane gas production is a series of processes in which microorganism break down biodegradable material in the absence of oxygen which completes through following steps:

1. In the first step, the organic matter (e.g. plants residues, human and animal wastes and residues) is decomposed (hydrolysis) to break down the organic material into usable-sized molecules such as sugar.
2. Conversion of decomposed matter into organic acids is the second step.
3. Finally, organic acids are converted to biogas (methane gas).

10.3.1 Process Stages of Anaerobic Digestion

The biological and chemical stages of anaerobic digestion are shown in Figure 10.1. These are divided into the following four main stages:

1. Hydrolysis
2. Acedogenesis
3. Acetogenesis
4. Methanogenesis

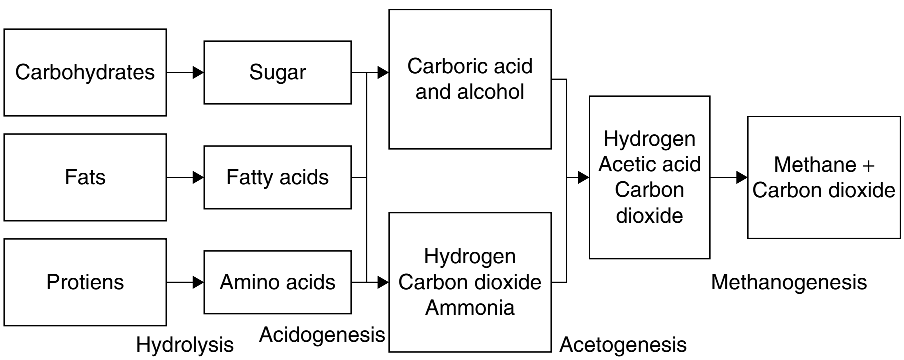


Figure 10.1 Process of anaerobic digestion

The four main stages are explained as follows.

10.3.1.1 Hydrolysis

The process of breaking large biomass organic chains into their smaller constituent parts such as sugar, fatty acids, and amino acids and dissolving the smaller molecules into solution is called hydrolysis. This process assists bacteria in anaerobic digesters to access the energy potential of the material. Hydrolysis of these high-molecular-weight polymeric components of biomass completes the first step in anaerobic digestion.

Hydrogen and acetate products of first stage are directly used by methanogens. Other molecules with a chain length larger than that of acetate (e.g. volatile fatty acids) must first be catabolized into compounds and then used by methanogens.

10.3.1.2 Acidogenesis

Acidogenesis is the biological process in which the remaining components are broken down by acidogenetic (fermentative) bacteria. It creates voltaic fatty acids together with ammonia, carbon dioxide, and hydrogen sulphide, and other by-products.

10.3.1.3 Acetogenesis

In this stage of anaerobic digestion, simple molecules created through the acidogenesis phase are further digested to produce more acetic acid, carbon dioxide, and hydrogen.

10.3.1.4 Methanogenesis

Finally, the process of biogas production is completed by methanogenesis. In this stage of anaerobic digestion, the methanogens use intermediate products of the preceding stages and convert them into methane, carbon dioxide, and water which makes the majority of the biogas emitted from the system. Methanogenesis is sensitive to both high and low pH values.

A simplified generic chemical equation for the overall processes outlined earlier is as follows:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \tag{10.1}$$

The remaining indigestible material cannot be used by microbes and any dead bacterial remains constitute the digestate.

10.4 BIOGAS PRODUCTION

As already discussed, biogas originates from bacteria in the process of biodegradation of organic material under anaerobic (in the absence of oxygen) conditions.

Anaerobic processes either occur naturally or created in a controlled environment, namely a biogas plant in which organic wastes are put in an airtight container called digester to perform anaerobic digestion process.

10.4.1 Construction Parts of Biogas Plants

Figure 10.2 shows various parts of typical biogas plant. It is a brick and cement structure having the following five sections:

1. Mixing tank
2. Digester tank

3. The gas continuously produced in digester tank is accumulated at the top of the digester in the dome or gas holder.
   Normally, the outlet gas valve remains closed, and hence, the accumulated biogas in the dome exerts pressure on the slurry which starts moving in the inlet and outlet chamber due to which the level of slurry drops in digester and increases in the outlet chamber. This process continues till the slurry reaches to highest possible level in the inlet and outlet chamber because of increased gas pressure.
4. If the gas valve is still kept closed the biogas will further get accumulated in the dome and develop high pressure enough in the gas to start escaping through the inlet and outlet chambers to the atmosphere. The biogas creates bubbles in the slurry in inlet and outlet chambers during its escape, and froth is also formed.
5. An increase in the volume of slurry in the inlet and outlet chambers helps to calculate the amount of biogas generated within the digester.
6. Gas pipe valve can be opened partly or fully to provide biogas for different applications. Under this situation, slurry level in the digester increases while the level in inlet and outlet chambers reduces.
7. When the gas is being taken out from the gas outlet at the top of the dome, the slurry from the outlet chamber is removed and equivalent amount of fresh slurry is inducted into the digester to continue the process of fermentation and the formation of the biogas. Therefore, more is the biogas required, more continuous will be the fresh slurry of cow dung and water required. The size of the digester tank also decides the amount of the gas that can be generated by the biogas plant.

10.4.3 Types of Biogas Plants

Fixed dome and floating dome construction are the two types of biogas plants. Based on these types, several biogas plant models are developed.

10.4.3.1 Fixed Dome Type

Schematic of a fixed dome biogas plant is given in Figure 10.3. It consists of following parts.

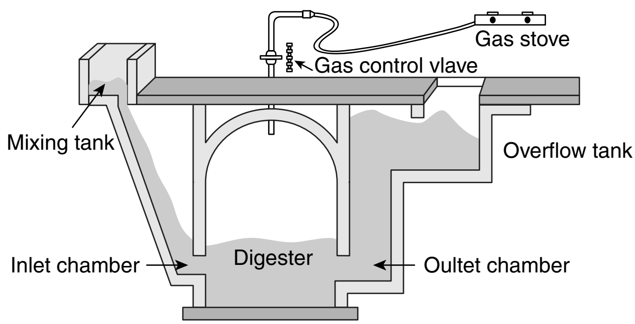


Figure 10.3 Fixed dome type biogas plant

1. *Mixing tank*: In mixing tank, the water and cattle dung are mixed together thoroughly in the ratio of 1:1 to form the slurry.
2. *Inlet chamber*: The mixing tank opens underground into a sloping inlet chamber.
3. *Digester*: Digester is a huge tank with a dome type ceiling. The ceiling of the digester has an outlet with a valve for the supply of biogas. The inlet chamber opens from below into the digester tank. The digester opens from below into an outlet chamber which is opened from the top into a small overflow tank.

10.4.3.1.1 Working Principle

The various forms of organic biodegradable biomass are collected and mixed with equal amount of water properly in the mixing tank to form slurry. The slurry is fed into the digester tank through inlet chamber and pipe, and the digester is partially filled by about half of its height. The feeding of slurry is then discontinued for about 60 days when anaerobic bacteria present in the slurry decomposes or ferments the biomass in the presence of water. Biogas is then formed and starts accumulating in the upper dome area of the biogas plants, and the pressure is exerted on the spent slurry to force it flow into the outlet chamber. Finally, the spent slurry overflows into the overflow tank from where it is manually removed and used as manure for agricultural crops and plants.

Gas control valve at the top of dome is opened partially or fully to supply required gas for particular applications. A functioning plant is fed continuously with the prepared slurry to obtain a continuous supply of biogas.

10.4.3.1.2 Advantages

Advantages of fixed dome-type biogas plant are as follows:

1. The costs of a fixed dome biogas plant are relatively low as compared to floating dome type.
2. It is simple in construction as no movable dome exists.
3. It is made up of concrete, bricks, and cements and long life of the plant (20 years or more) can be expected.
4. Underground and almost ground surface dome construction saves space and protect from physical damage to the plant.
5. The anaerobic digestion processes in the digester are little influenced by temperature fluctuation in day and night.

10.4.3.1.3 Disadvantages

Disadvantages of biogas plant are as follows:

1. Porosity and cracks in plant walls is the major drawbacks.
2. Maintenance is rather difficult.

10.4.3.2 Floating Type

The floating gas holder type of biogas plant is shown in Figure 10.4.

The construction and working principle of this biogas plants is similar to fixed dome type except that gas holder tank is made up of steel and placed on the top of digester circular tank and is movable up and down also shown in Figure 10.2.

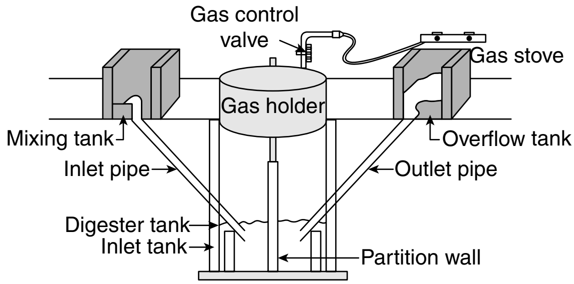


Figure 10.4 Floating dome-type biogas plant

10.4.3.2.1 Advantages Floating dome-type biogas plant has the following advantages:

1. Very efficient
2. Simple maintenance scheduling possible

10.4.3.2.2 Disadvantages Floating dome-type biogas plant has the following disadvantages:

1. Expensive
2. Steel drum may rust
3. Requires regular maintenance

10.4.4 Different Models of Biogas Plants

Several types of biogas plants are available in sizes and the capacities ranging from about 2 to 180 m^3 gas output per day. There are hardly three million biogas plants of small capacities are installed in India because of social acceptability and other problems.

The design model as shown in Figures 10.2 and 10.4 is called KVIC (Khadi and Village Industries Commission) model. A unit of this type with a gas capacity of 2 m^3/day costs approximately ₹15000. A number of other designs ranging in cost from ₹10000 to 25000 for the same capacity have also been developed. Large-sized community biogas plant is encouraged to assure better and economical utilization of animal and human wastes Control of several operating parameters, such as temperature and alkalinity of the slurry, sludge liquidity and build-up of scum on the surface of the slurry, gives good performance. Such control is obviously easier to achieve in community-sized plants.

10.4.4.1 Types of Fixed Dome Biogas Plants

Different types of fixed dome biogas plants are as follows:

1. *Chinese fixed dome type*: It has arch-type fixed dome as shown in Figure 10.3. The digester consists of a cylinder with round bottom and top. Several millions of such biogas plants have been constructed in China.
2. *Janata model*: In response to the Chinese fixed dome plant, Janata model was the first fixed-dome design constructed in India. It is not constructed anymore. The mode of construction leads to cracks and gas leakage in the gas holder, and hence, this model has no social acceptability.

3. *Deenbandhu model*: It is the successor of the Janata plant in India, with improved crack-proof design, which consumes less building material than the Janata plant with a hemisphere digester.
4. *CAMARTEC model*: It has a simplified structure of a hemispherical dome shell based on a rigid foundation ring only and was developed in Tanzania.

10.4.4.2 Types of Floating Drum Plants

There are different types of floating drum plants and are as follows:

1. KVIC model is the oldest and most widespread floating drum biogas plant from India.
2. Pragati model is developed with a hemisphere digester.
3. Ganesh model is constructed with angular steel and plastic foil.
4. Arati biogas model has low-cost floating drum plants made of plastic water containers or fiberglass drums.
5. BORDA model combines the static advantages of hemispherical digester with the process stability of the floating drum and the longer lifespan of a water jacket plant.

10.5 BENEFITS OF BIOGAS

A biogas energy system has whole range of benefits for the users, the society, and the environment. It includes the following:

1. *Production of energy (heat, light, and electricity)*: The calorific value of biogas is about 6 kWh/m^3, which is equivalent to about half a litre of diesel oil. The net calorific value depends on the efficiency of the burners or appliances. It replaces the conventional and traditional cooking and heating fuels and therefore permits the conservations of energy and fuels.

   The small- and medium-sized units (up to 6 m^3) are generally used for providing gas for cooking and lighting purposes. Large units (or communal units) produce this gas in large quantities and can be used to power engines and generators for mechanical work or power generation.
2. *Transformation of organic wastes into high-quality organic fertilizer*: The biogas plant is considered as a perfect fertilizer-making machine. There is no better way to digest or compost manure and other organic material than in a biogas plant. Output from the digester (digested manure) is actually a high-quality organic fertilizer. It has been analysed that the fertilizer, which comes from a biogas plant, contains three times more nitrogen than the best compost made through open air digestion.

   This nitrogen is already present in the manure. The nitrogen is preserved when waste is digested in an enclosed biogas plant, whereas the same nitrogen evaporates away as ammonia during open air composting. The biogas plant does not make extra nitrogen, it does not create nitrogen, and it merely preserves the nitrogen that is already there.
3. *Health benefits of biogas and the improvement of hygienic conditions (reduction of pathogens, worm eggs, and flies)*: Significant health benefits are achieved by the use of pure biogas. It has been found that non-biogas users have more respiratory diseases than those who use biogas plants.

5. *Inputs and outputs use frequency*: Frequency of utilization of biogas and feedstock inputting in biogas plants, influence the selection of a particular design, and the size of various components of biogas plants.

10.7 BIOGAS PLANT FEEDS AND THEIR CHARACTERISTICS

Any biodegradable organic material can be used as inputs for processing inside the biodigester. However, for economic and technical reasons, some materials are more preferred as inputs than others. If the inputs are costly or have to be purchased, then the economic benefits of outputs such as gas and slurry will become low.

Economic value of biogas and its slurry and reduced environmental cost of biodegradable wastes disposal in landfill are the two benefits of biogas energy.

One of the main attractions of biogas technology is its ability to generate biogas out of organic wastes that are in abundance and freely available. Cattle dung is most commonly used as an input mainly because of its availability. The potential gas production from some animal dung is given in Table 10.2.

In addition to the animal and human wastes, plant materials are also used to produce biogas and biomanure. Since different organic materials have different biochemical characteristics, their potential for gas production also varies.

Basic requirements for gas production or for normal growth of methanogens are achieved by mixing two or more of different organic materials and feeding to the biogas plants can be used together provided that some are met. Some characteristics of these raw organic inputs materials having significant impact on the level of gas production are described below.

10.7.1 Carbon/Nitrogen (C/N) Ratio

The relationship between amount of carbon and nitrogen present in organic materials is expressed in terms of the carbon/nitrogen (C/N) ratio. A C/N ratio ranging from 20 to 30 is considered optimum for anaerobic digestion. For organic materials with very high C/N ratio, the nitrogen will be consumed rapidly by methanogens for meeting their protein requirements and left over carbon content of the material will not have any reaction process. This will reduce the biogas production.

For very low C/N, nitrogen will be liberated and accumulated in the form of ammonia (NH_4) which will increase the pH value of the content in the digester. A pH values higher than 8.5 will start showing toxic effect on methanogens population.

C/N ratio of a few commonly used materials are presented in Table 10.3.

Table 10.2 Gas Production Potential of Various Types of Dung

Types of Dung	Gas Production Per Kg Dung (m^3)
Cattle (cows and buffaloes)	0.023–0.040
Pig	0.040–0.059
Poultry (Chickens)	0.065–0.116
Human	0.020–0.028

Table 10.3 C/N Ratio of a Few Commonly Used Materials

Raw Materials	C/N ratio
Duck dung	8
Human excreta	8
Chicken dung	10
Goat dung	12
Pig dung	18
Sheep dung	19
Cow dung/buffalo dung	24
Water hyacinth	25
Elephant dung	43
Straw (maize)	60
Straw (rice)	70
Straw (wheat)	90
Saw dust	above 200

As evident from Table 10.3 animal waste, particularly cattle dung has an average C/N ratio of about 24. The plant materials, such as straw and sawdust, contain a higher percentage of carbon/nitrogen ratio whereas the human excreta have a C/N ratio as low as 8.

In order to bring the average ratio of the composite input to a desirable level materials with high C/N ratio could be mixed with those of low C/N ratio. In China, it is customary to load rice straw at the bottom of the digester upon which latrine waste is discharged as a means to balance C/N ratio.

10.7.2 Advantages

It includes the following:

1. Clean fuel of high calorific value and has a convenient ignition temperature.
2. No residue, smoke, and dust produced.
3. Non-polluting. Significant health benefits are achieved by the use of clean biogas.
4. Economical benefits of biogas and high-quality manure.
5. Provides nutrient rich (N and P) manure for plants.

10.7.3 Limitations

The limitations are as follows:

1. Initial cost of installation of the plant is high.
2. Inadequacy of organic raw materials and its continuity of supply.
3. Social acceptability.
4. Maintenance and repair of bio gas plants.

11.6.2 Tidal Stream Generator

It is often referred to as a tidal energy converter (TEC). It is a machine that extracts kinetic energy from moving masses of water in particular tides. A TEC device extracts energy from a tidal flow much in the same way that a windmill extracts energy from the wind. The following equation can be used to calculate the power output of either devices,

$$P = ½\, \rho A \eta_T V^3 \tag{11.8}$$

where P = power (W); ρ = density of seawater (kg/m^3); A = capture area (m^2); η_T = combined efficiency from water to electric wire; and V = flow speed (m/s).

The abovementioned power calculation is valid, provided the capture area of the tidal energy conversion device(s) is small in comparison to the cross-sectional area of the channel. The significant difference between wind and tidal power calculations is the typical range of flow speeds and the density of the fluid.

11.7 TIDAL POWER BASIN

The basin system is the most practical method of harnessing tidal energy. It is created by enclosing a portion of sea behind erected dams. The dam includes a sluice that is opened to allow the tide to flow into the basin during tide rise periods and the sluice is then closed. When the sea level drops, traditional hydropower technologies (water is allowed to run through hydro turbines) are used to generate electricity from the elevated water in the basin. From Equation 11.7, we can observe that the tidal power varies as the square of the head and since the head varies with the tidal range, the power available at different sites shows very wide variation. In order to overcome this wide variation in availability of tidal power, various tidal basin systems have, therefore, been developed. They are discussed in the following sections.

11.7.1 Single-basin System

This is the simplest way of power generation and the simplest scheme for developing tidal power is the single-basin arrangement as shown in Figure 11.1. Single water reservoir is closed off by constructing dam or barrage. Sluice (gate), large enough to admit the water during tide so that the loss of head is small, is provided in the dam.

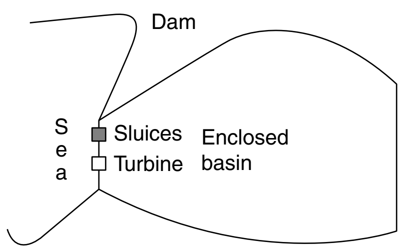


Figure 11.1 Single-basin system

The single-basin system has two configurations, namely:

1. *One-way single-basin system*: The basin is filled by seawater passing through the sluice gate during the high tide period. When the water level in the basin is higher than the sea level at low tide period, then power is generated by emptying the basin water through turbine generators. This type of systems can allow power generation only for about 5 h and is followed by the refilling of the basin. Power is generated till the level of falling tides coincides with the level of the next rising tide.
2. *Two-way single basin*: This system allows power generation from the water moving from the sea to the basin, and then, at low tide, moving back to the sea. This process requires bigger and more expensive turbine.

Single-basin system has the drawbacks of intermittent power supply and harnessing of only about 50% of available tidal energy.

Example 11.1

For a typical tidal power plant shown in Figure P11.1, the basin area is 25×10^6 m^2. The tide has a range of 10 m. However, turbine stops working when the head on it falls below 2 m. Assume that density of seawater is 1,025 kg/m^2, acceleration due to gravity is 9.81 m/s^2, combined efficiency of turbine and generator is 75%, and period of energy generation is 6 h and 12.5 min. Calculate:

1. Work done in filling or emptying the basin.
2. Average power
3. The energy generated in one filling process.

Solution

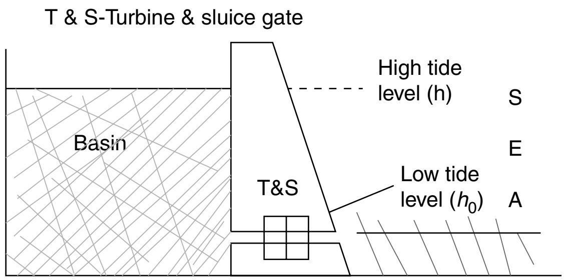


Figure P11.1 Single-basin tidal plant

1. Total work done in filling or emptying the basin

h_0

$$W = \int \rho g A h \, d(h) = \tfrac{1}{2} \rho g A (h^2 - h_0^2)$$

h

$$= (1/2) \times [1{,}025 \times 9.81 \times 25 \times 10^6 \times (10^2 - 2^2)]$$
$$= 17.6 \times 10^{12}$$

2. Average power

$$P_{av} = W/t = 17.6 \times 10^{12}/22{,}350 = 787.32 \times 10^6 \text{ W}$$

3. Energy generated

$$E = 0.75 \times 787.32 \times 106 \times 3{,}600/100 = 2.123 \times 10^9 \text{ kWh}$$

11.7.2 Two-basin Systems

An improvement over the single-basin system is the two-basin system. In this system, a constant and continuous output is maintained by suitable adjustment of the turbine valves to suit the head under which these turbines are operating.

A two-basin system regulates power output of an individual tide, but it cannot take care of the great difference in outputs between spring and neap tides. Therefore, this system provides a partial solution to the problem of getting a steady output of power from a tidal scheme.

This disadvantage can be overcome by the joint operation of tidal power and pumped storage plant. During the period, when the tidal power plant is producing more energy than required, the pumped storage plant utilizes the surplus power for pumping water to the upper reservoir. When the output of the tidal power plant is low, the pumped storage plant generates electric power and feeds it to the system. This arrangement, even though technically feasible, is much more expensive, as it calls for high installed capacity for meeting a particular load.

This basic principle of joint operation of tidal power with steam plant is also possible when it is connected to a grid. In this case, whenever tidal power is available, the output of the steam

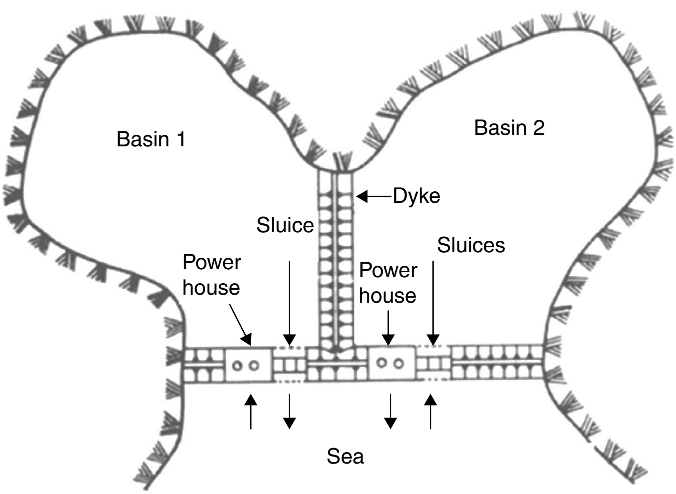


Figure 11.2 Two-basin system

plant will be reduced by that extent that leads to saving in fuel and reduced wear and tear of steam plant. This operation requires the capacity of steam power plant to be equal to that of tidal power plant and makes the overall cost of power obtained from such a combined scheme very high. In the system shown in Figure 11.2, the two basins close to each other, operate alternatively. One basin generates power when the tide is rising (basin getting filled up) and the other basin generates power while the tide is falling (basin getting emptied). The two basins may have a common power house or may have separate power house for each basin. In both the cases, the power can be generated continuously. The system could be thought of as a combination of two single-basin systems, in which one is generating power during tiding cycle, and the other is generating power during emptying.

11.7.3 Co-operating Two-basin Systems

This scheme consists of two basins at different elevation connected through the turbine. The sluices in the high- and low-level basin communicate with seawater directly, as shown in Figure 11.3. The high-level basin sluices are called the inlet sluices and the low level asoutlet sluices.

The basic operation of the scheme is as follows:

1. The rising tide fills the high-level basin through the sluiceways.
2. When the falling seawater level is equal to the water level in the high-level basin, the sluiceways are closed to prevent the outflowing high-level basin water back to the sea.
3. The water from high-level basin is then allowed to flow through the turbine generators to the low-level basin.
4. When the falling seawater level becomes lower than the rising water level in the low-level basin, the sluiceways are opened to allow water to flow into the sea from the low-level basin. This process continues until the water level in the low-level basin equals to the rising sea level. Then, the sluiceways are closed to prevent the filling of low-level basin from the seawater.

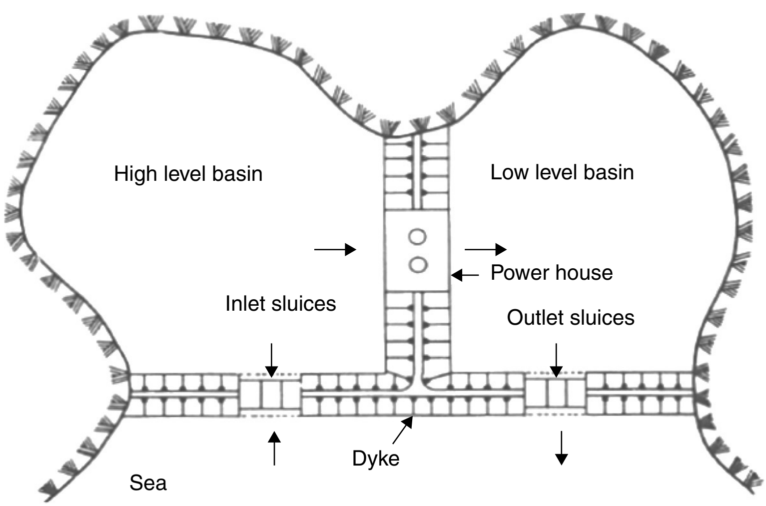


Figure 11.3 Co-operating two-basin systems

5. When the seawater again rises during the next rising tide equals to low level of high-level basin, sluices of high-level basin is again open for filling of water in high-level basin. Thus, the cycle is repeated.

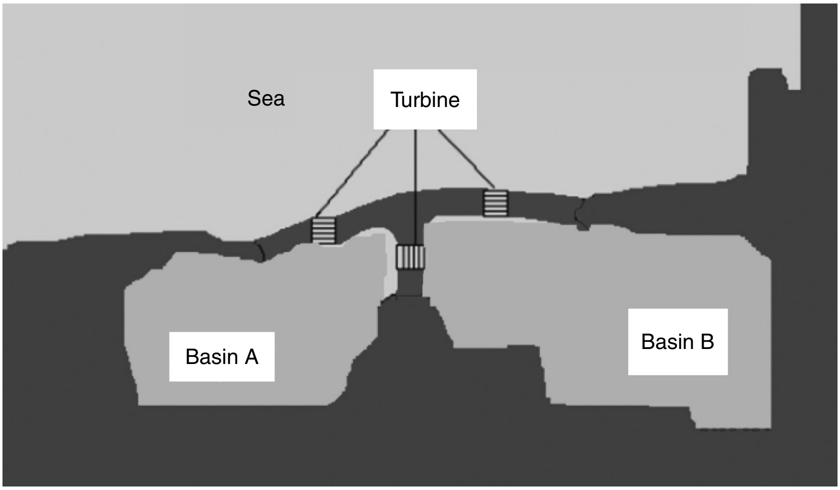


Figure 11.4 Co-ordinating two basin systems

Figure 11.4 gives another schematic diagram of co-coordinating two-basin tidal power stations. With two basins, one is filled at high tide and the other is emptied at low tide. Turbines are placed between the basins and between the basin and the sea. This two basin systems allow continuous power generation. However, they are very expensive to construct due to the cost of the extra length.

11.8 TURBINES FOR TIDAL POWER

Tidal power plants operate using a rapidly varying head of water, and therefore, their turbines must have high efficiency at varying head.

These are as follows:

1. The Kaplan type of water turbine operates quite favourably under these conditions.
2. The propeller type of turbine is also suitable because the angle of the blades can be altered to obtain maximum efficiency while water is falling.
3. A compact reversible horizontal turbine (bulb-type turbine) has been developed by French Engineer and it acts with equal efficiency both as a pump and as a turbine.

11.8.1 Bulb-type Turbine

The bulb-type turbine shown in Figure 11.5 consists of a steel shell completely enclosing the generator that is coupled to the turbine runner.

with enough consistency and force in many areas of the world to provide continuous waves along the shore line. It contains tremendous energy potential and wave power devices extract energy from either the surface motion of ocean waves or from pressure fluctuations below the surface. The movement of the ocean water and the changing water wave heights and speed of the swells are the main sources of wave energy. Kinetic energy in the wave motion is tremendous that can be extracted by the wave power devices from either the surface motion of ocean waves or from pressure fluctuations below the ocean surface.

12.2 MOTION IN THE SEA WAVES

When the wind blows across smooth water surface, air particles from the wind grab the water molecules they touch. Stretching of the water surface by the force or friction between the air and the water creates capillary waves (small wave ripples). Surface tension acts on these ripples to restore the smooth surface, and thereby, waves are formed.

The combination of forces due to the gravity, sea surface tension, and wind intensity are the main factors of origin of sea waves as shown in Figure 12.1, which illustrates the formation of sea waves by a storm. Wave size is determined by wind speed and fetches (defined as the distance over which the wind excites the waves) and by the depth and topography of these abed (which can focus or disperse the energy of the waves). Sea waves have a regular shape at far distance from the fetch and this phenomenon is called swell. Wave formation makes the water surface further rough and the wind continuously grips the roughened water surface, and thus, waves are intensified.

A wave is a forward motion of energy and not the water in deep sea. In true sense, the seawater does not move forward with a wave. Waves are characterized by the following parameters, as shown in Figure 12.2.

1. *Crest*: The peak point (the maximum height) on the wave is called the crest.
2. *Trough*: The valley point (the lowest point) on the wave is called the trough.
3. *Wave height* (H): Wave height is a vertical distance between the wave crest and the next trough (m).
4. *Amplitude* (a): It is defined as $H/2$ (m).
5. *Wave length* (λ): It is the horizontal distance either between the two successive crests or troughs of the ocean waves (m).

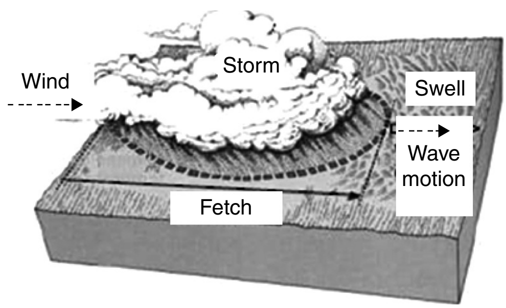


Figure 12.1 Sea wave formation by storm

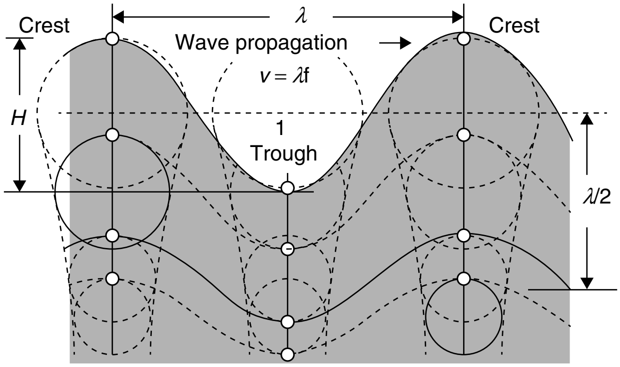


Figure 12.2 Sea wave propagation

6. *Wave propagation velocity* (v): The motion of seawater in a direction (m/s).
7. *Wave period* (T): It measures the size of the wave in time(s). It is the time required for two successive crests or two successive troughs to pass a point in space.
8. *Frequency* (f): The number of peaks (or troughs) that pass a fixed point per second is defined as the frequency of wave and is given by $f = 1/T$ (cycle/s).

12.3 POWER ASSOCIATED WITH SEA WAVES

It has been concluded by researchers through linear wave motion theory that the kinetic and potential energy (E) of a wave per meter of crest and unit of surface can be approximated as

$$E = \rho g a^2/2 \tag{12.1}$$

where ρ = density of water; g = gravitational acceleration; and a = amplitude of the wave (approximately equals to half its wave height H).

The power that a meter of crest holds can be obtained by multiplying the amount of energy transported by the group velocity.

In deep water, dispersion relation (k) is given as

$$k = \omega^2/g, \tag{12.2}$$

Further, group velocity $(V_g) = \omega/2k = g/2\omega$ (12.3)

The total power (P) is obtained as $P = EV_g = [\rho g\, a^2/2](g/2\omega) = \rho g^2 a^2/4\omega$ (12.4)

Further, wave period $(T) = 2\pi/\omega$ or $\omega = 2\pi/T$ and $a = H/2$

Therefore, $P = \rho g^2 a^2/4\omega = \rho g^2 H^2 T/32\pi$ (12.5)

For irregular waves of height H (m) and period T(s), an equation for power per unit of wavefront can be derived as

$$P_{irregular} = 0.4 \text{ (kW/m) of wavefront} \tag{12.6}$$

From the abovementioned equations, it is seen that the wave power is directly proportional to the square of wave height.

Table 12.2 Continued

Site	Average Wave Power kW/m (Annual)	Average Wave Power kW/m (June–August)
Ambolgarh	5.74	13.48
PawaPoint	5.36	13.10
Kunkeshwar	5.64	13.35
Wagapur	5.70	13.10

The Vengurla and Malvan rocks and Redi are on the top among the offshore locations. In the coastal location, however, Pawa and Ratnagiri top the list followed by Girye and Miyet point.

Vizhinjam fishing harbour, Kerala, is the site of a unique demonstration plant that converts sea wave energy to electricity and is given to the local grid. This plant has oscillating water column (OWC) converter in 1990.

12.5 DEVICES FOR HARNESSING WAVE ENERGY

There are three basic technologies for converting wave energy to electricity. They are as follows:

1. *Terminator devices*: It is a wave energy device oriented perpendicular to the direction of the wave and has one stationary and one moving part. The moving part moves up and down like a car piston in response to ocean waves and pressurizes air or oil to drive a turbine. An oscillating water column (OWC) converter is an example of terminator device. These devices generally have power ratings of 500 kW to 2 MW, depending on the wave parameters and the device dimensions.
2. *Attenuator devices*: These devices are oriented parallel to the direction of the waves and are long multi-segment floating structures. It has a series of long cylindrical floating devices connected to each other with hinges and anchored to the seabed. They ride the waves like a ship, extracting energy by using restraints at the bow of the device and along its length. The segments are connected to hydraulic pumps or other converters to generate power as the waves move across. Pelamis wave energy converter is one of the known examples of attenuator devices.
3. *Point absorber*: It is a floating structure with parts moving relative to each other owing to wave action but it has no orientation in any defined way towards the waves instead absorbs the wave energy coming from any direction. It utilizes the rise and fall of the wave height at a single point for energy conversion. The pressurized water creates up and down bobbin-type motion and drives a built-in turbine generator system to generate electricity. AquaBuOY WEC is an example of point absorber devices.
4. *Overtopping devices*: These devices have reservoirs like a dam that are filled by incoming waves, causing a slight build-up of water pressure. Gravity causes released water from reservoir to flow back into the ocean through turbine coupled to an electrical generator. Salter Duck WEC is the example of overtopping devices.

12.5.1 Float or Buoy Devices

This system is shown in Figure 12.4. A series of anchored buoys rise and fall with the wave that creates mechanical energy to drive electrical generator for generation of electricity, which is transmitted to ocean shore by underground cables.

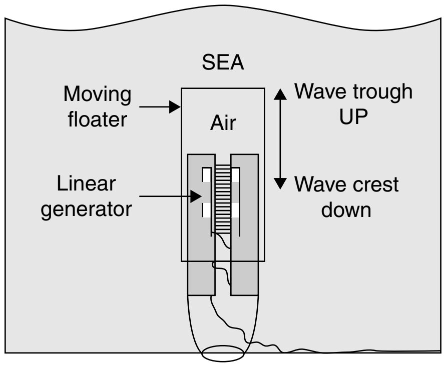


Figure 12.12 Archimedes waves swing device

12.5.8 Archimedes Wave Swing Devices

The Archimedes wave swing device (shown in Fig. 12.12) is an underwater buoy of which the upper part (floater) moves up and down in the wave, while the lower part stays in position. The floater (air-filled chamber) is pushed down under a wave crest (top) and moves up under a wave trough (valley). The interior of the system is pressurized with air and serves as an air spring. The mechanical power is converted into electrical power by means of a power take-off system (PTO). The PTO consists of a linear electrical generator and a nitrogen filled damping cylinder.

It has the advantage of being a 'point' absorber that absorbs power from waves travelling in all directions, and extracts about 50% of the incident wave power in addition to the advantage of being able to survive despite rough sea conditions on the surface.

12.6 ADVANTAGES AND DISADVANTAGES OF WAVE POWER

12.6.1 Advantages

1. Sea waves have high energy densities and provide a consistent stream of electricity generation capacity.
2. Wave energy is clean source of renewable energy with limited negative environmental impacts.
3. It has no greenhouse gas emissions or water pollutants.
4. Operating cost is low and operating efficiency is optimal.
5. Damage to ocean shoreline is reduced.

12.6.2 Disadvantages

1. High construction costs.
2. Marine life is disrupted and displaced.
3. Damage to the devices from strong storms and corrosion create problems.
4. Wave energy devices could have an effect on marine and recreation environment.

13.3 OCEAN THERMAL ENERGY CONVERSION PLANTS

There are two different kinds of OTEC power plants, namely land-based power plant and floating power plant.

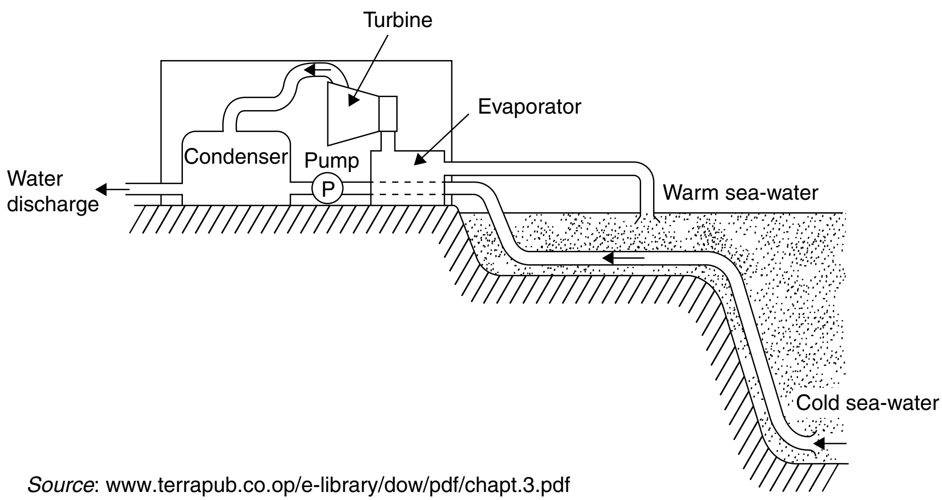
13.3.1 Land-based Power Plant

The land-based power plant will consist of a building as shown in Figure 13.1.

It is constructed on shore and accommodates all parts of OTEC plants. It requires laying down long pipes from plant site on shore to two extreme points of necessary temperature gradient. One pipe is used to collect warm ocean surface water through screened enclosure near the shore. Another long pipe lay down on the slope deep into the ocean to collect cold water.

A third pipe is used as outlet to discharge used water again in ocean via marine culture ponds deep down the ocean. Cost of pipe installation and maintenance is very expensive, and land-based plant is also very expensive. Since large electricity is used to pump water through long pipes, the net electricity reduces considerably.

Land-based OTEC plant has the advantage of savings on electrical transmission line and connectivity to electrical power grid.



Source: www.terrapub.co.op/e-library/dow/pdf/chapt.3.pdf

Figure 13.1 Land-based OTEC power plant

13.3.2 Floating Power Plant

Floating power plant is built on a ship platform exactly where required temperature gradient sufficient for OTEC plant is available. The working principle of ocean thermal energy conversion (OTEC) is same as that of land-based power plant. Undoubtedly, the cost savings exist on piping system, but long transmission line is required to transmit electrical power from plant to sea shore.

Owing to high installation cost of long underwater power cables and its inefficiency and many other associated problems, floating OTEC plants are considered for the production of fuels, such as hydrogen, on the platform itself by the electrolysis of water.

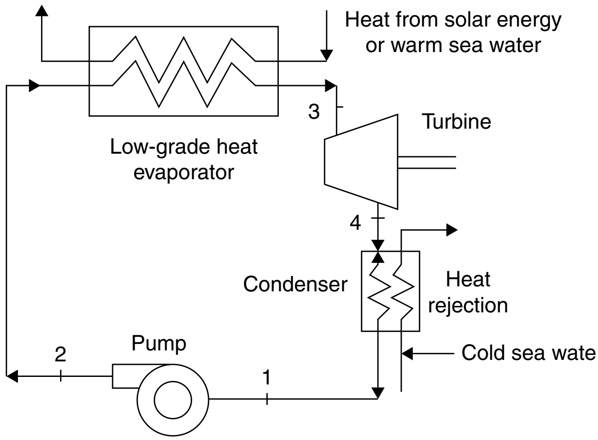


Figure 13.3 OTEC Rankine cycle

3. A condenser
4. A pump
5. A working fluid

In open-cycle OTEC, warm sea water is used as working fluid, whereas in closed-cycle type, low-boiling point ammonia or propane is used.

Warm ocean surface water flows into the evaporator which is the high-temperature heat source. A fluid pump is utilized to force the fluid in a heat evaporator where liquid fluid vapourizes. Then, the vapour of boiling fluid enters the turbine expander coupled with an electrical generator to generate electrical power. The vapour released from the turbine enters into condenser where it condenses. The cold deep sea water is pumped through the condenser for heat rejection from vapour fluid and condenses it as liquid fluid. The liquid fluid is again pumped through evaporator and cycle repeats.

As temperature difference between high- and low-temperature ends is large enough, the cycle will continue to operate and generate power.

13.4.1 Selection of Working Fluids

The steam Rankine cycle and organic Rankine cycle are the two main types used in OTEC systems, and the choice of working fluids plays an important role in design and performance of OTEC. Water is the only working fluid for steam Rankine cycle, but a large number of working fluid is available for organic Rankine cycle. The working fluid has the following properties:

1. *Chemical stability and compatibility*: Certain organic fluids are more prone to decompose when subjected to high pressure and temperature which results in material corrosion of different parts of plants, explosion etc. Thus, working fluid should be chemically stable and compatible with materials and structures of OTEC plants.
2. *Heat transfer coefficient*: Low-thermal resistance of working fluids improves heat transfer.

3. *Flash point*: A working fluid with a high flash point should be used in order to reduce flammability.
4. *Specific heat*: A working fluid with a low specific heat should be used to reduce load on the condenser.
5. *Latent heat*: A working fluid with a high latent heat should be used in order to raise the efficiency of heat recovery.
6. *Safety*: Working fluid should be non-corrosive, non-toxic, and non-inflammable having maximum allowable concentration and explosion limit for safe and efficient operation of OTEC plants.
7. *Environmental acceptability*: Low-toxicity working fluid minimizes water contamination. The environmental risk of OTEC plant is low.
8. *Cost and availability*: The ease of availability and low cost of working fluid is also important.

13.5 CLOSED CYCLE, OPEN CYCLE, AND HYBRID CYCLE

There are three types of OTEC cycle designs, namely open cycle, closed cycle, and hybrid cycle.

1. In an open cycle, warm sea water is pumped into a flash evaporator as working fluid where it boils at low pressure and converts into steam. This steam expands through low-pressure turbine which drives an electrical generator and generates electricity. The steam released from turbine condensed in a condenser by deep sea cold water as non-saline water. When non-condensable gases are separated and exhausted, the non-saline water is either pumped in marine culture ponds for freshwater applications or finally discharged in sea surface water.
2. In closed cycle, organic fluid flows in a separate closed-cycle loop called organic Rankine cycle. Warm sea surface water pumped through another pipe vapourizes working fluid in heat exchangers to drive turbine generator, The fluid vapour condenses into liquid form by deep sea water pumped in condenser by a separate pumping system, The process of pumping liquid fluid in an evaporator cycle is repeated.
3. A hybrid cycle is a combination of both closed and open cycle.

13.5.1 Open-cycle OTEC

An open-cycle OTEC uses the warm ocean surface water as working fluid. It is a non-toxic and environment friendly fluid. The major components of this system are shown in Figure 13.4. It consists of evaporator, low-pressure turbine coupled with electrical generator, condenser, marine culture ponds, non-condensable gas exhaust, and pumps. Evaporator used in an open-cycle system is a flash evaporator in which warm sea water instantly boils or flash in the chamber that has reduced pressure than atmosphere or vacuum. It results in reduced vapourization pressure of warm sea water. A large turbine is required to accommodate large volumetric flow rates of low-pressure steam, which is needed to generate electrical power, and is used with other plant components in a similar manner. During vapourization process in an evaporator, oxygen, nitrogen, and carbon dioxide dissolved in sea water are separated and are non-condensable. They are exhausted by non-condensable gas exhaust system. Condenser is used to condense vapour or

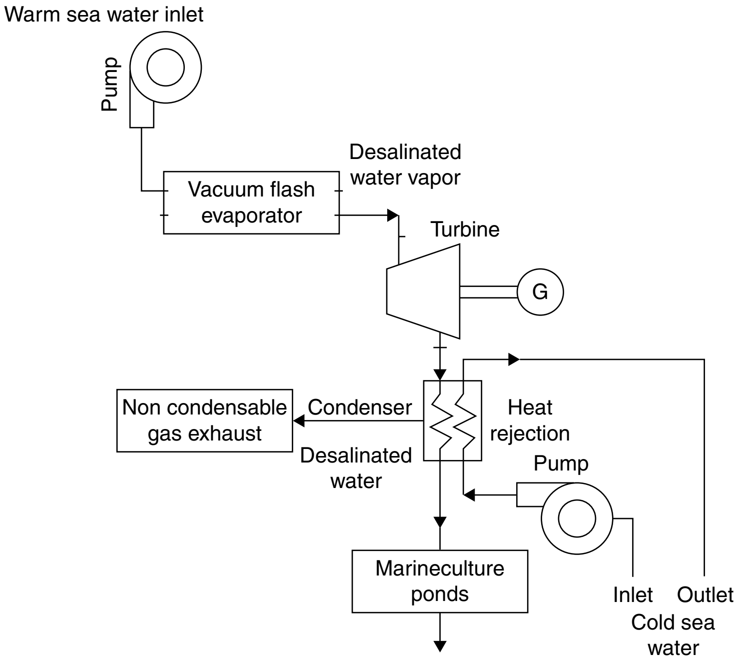


Figure 13.4 Open-cycle OTEC

steam released from steam turbine is condensed by cold deep sea water and returned back to sea. If a surface condenser is used, condensed steam (desalinated water) remains separated from cold sea water and is pumped into marine culture ponds. To avoid leakage of air in atmosphere and to prevent abnormal operation of plants, perfect sealing of all components and piping systems is essential. The working principles of open-cycle OTEC plants are explained as follows with the help of Figure 13.4.

1. The warm ocean surface water is pumped into flash evaporator where it is partially flashed into steam at a very low pressure. The remaining warm sea water is discharged into the sea.
2. The low-pressure vapour (steam) expands in turbine to drive a coupled electrical generator to produce electricity. A portion of electricity generated is consumed in plants to run pumps and for other work, and the remaining large amount of electricity is stored as net electrical power.
3. The steam with many gases (such as oxygen, nitrogen, and carbon dioxide) released from the turbine separated from sea water in an evaporator is pumped into condenser. The steam is cooled in a condenser by cold deep sea water.
4. The condensed non-saline water is discharged either directly in deep sea cold water or through the marine culture pond.
5. The non-condensable gases are compressed to pressure and exhausted simultaneously.
6. The warm ocean surface water is continuously pumped into evaporator and cycle repeats.

13.5.2 Closed-cycle OTEC

The schematic of closed-cycle OTEC is shown in Figure 13.5. It has different arrangement when compared to open-cycle OTEC. Organic fluid with low boiling point is used as working fluid. Ammonia liquid is the most widely used working fluid. Working fluid flows in a closed loop and perfectly sealed piping system. Working fluid circulates around the loop continuously. Warm ocean surface water flows through completely separate piping system and discharges in upper surface of ocean. Warm surface sea water and working fluid piping are placed very closely to each other in a heat exchanger to transfer warm sea water heat into working fluid. The cold deep sea water piping system is in contact with working fluid piping system in a condenser where working fluid condenses to its liquid state. Other components of both open- and closed-cycle OTECs are similar. Working principles of closed-cycle OTEC are as follows:

1. Working fluid is pumped through heat exchangers in a closed loop cycle which is perfectly leakage proof.
2. Warm sea surface water is pumped through separate pipe in heat exchanger in close contact with fluid closed loop cycle
3. Warm sea water transfer its heat energy to working fluid in heat exchanger and working fluid vapourizes.
4. The fluid vapour makes the turbine to rotate and drive an electrical generator to produce electricity.
5. Fluid vapour leaving the turbine is cooled and condensed as liquid fluid and is pumped again to repeat cycle.
6. Cold deep sea water is pumped through a separate pipe in condenser for providing efficient cooling of working fluid.

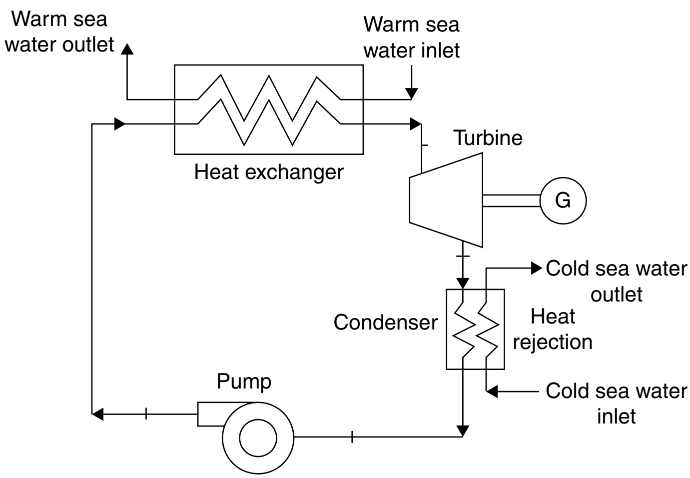


Figure 13.5 Closed-cycle OTEC plant

13.5.3 OTEC Hybrid Cycle

As shown in Figure 13.6, a hybrid cycle combines the features of both closed-cycle and open-cycle systems. Warm sea water is pumped into a vacuum chamber where it is used to flash and produces steam. Working fluid in another closed cycle loop is evaporated and vapourized by steam in vacuum chamber. The fluid vapour rotates the turbine and drive an electric generator to produce electricity.

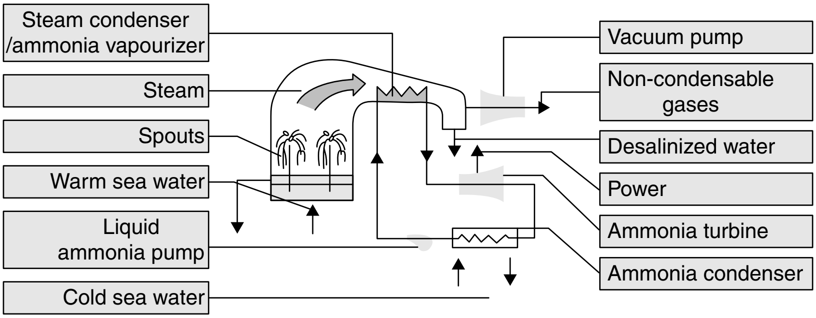
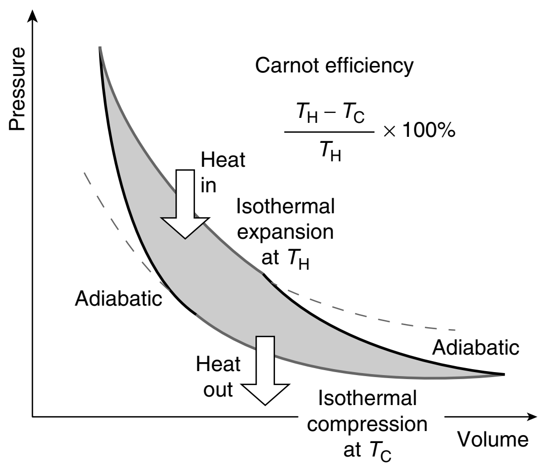


Figure 13.6 OTEC hybrid cycle

13.6 CARNOT CYCLE

The Carnot cycle is the most efficient thermodynamical cycle by exploiting the warm sea surface water and cold deep sea water.



Source: http://peswiki.com/index.php/PowerPedia:Carnot_heat_engine

Figure 13.7 Carnot efficiency P–V diagram

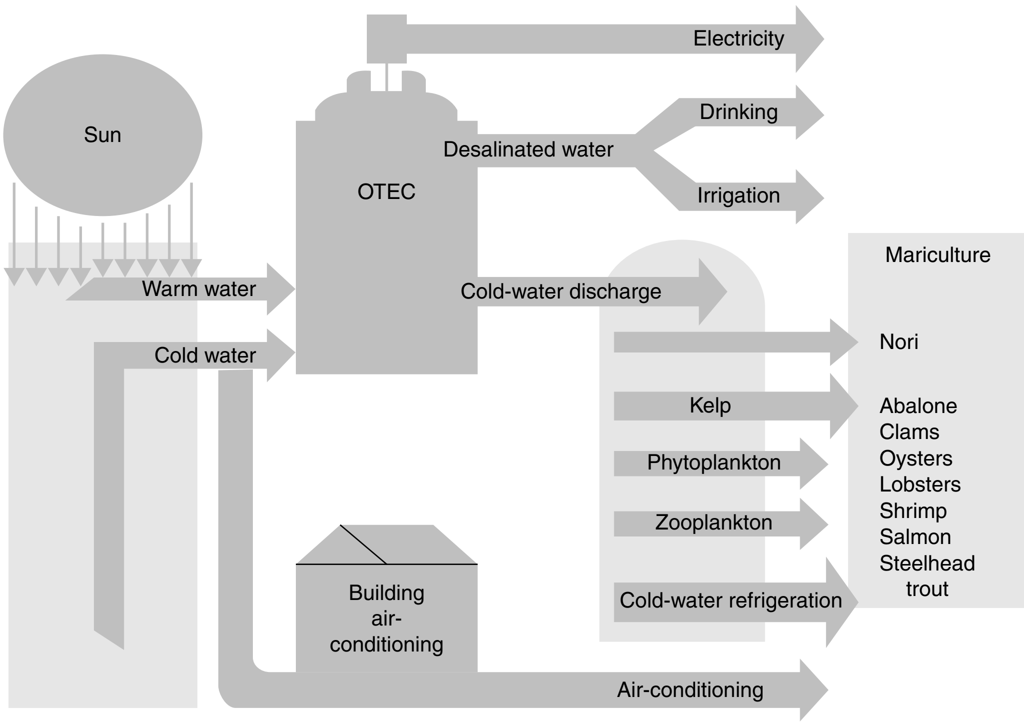
Let W be the work done by the system (energy exiting the system as work), Q_H be the heat put into the system (heat energy entering the system),

T_C be the absolute temperature of the sea surface and
T_H be the absolute temperature of the deep sea water hot reservoir.
Carnot efficiency (η) is given by the following equation:

$$\eta = W/Q_H = 1 - T_C/T_H \tag{13.1}$$

13.7 APPLICATION OF OTEC IN ADDITION TO PRODUCE ELECTRICITY

OTEC schematic diagram and applications are shown in Figure 13.8. Ocean thermal converting plants provide several products for use by mankind. These are explained as follows:



Source: http://www.homelandsecuritynewswire.com/

Figure 13.8 OTEC plant and applications

1. *Electricity*: Electrical energy is the primary product of OTEC plants. Laying down long transmission and distribution cables up to the sea shore for domestic and industrial applications is not practical from economic view point. OTEC plants are, therefore, considered for other products and applications.
2. *Hydrogen production*: Electricity produced from OTEC plants is used for separating water in hydrogen and oxygen by the method of electrolysis of water. Hydrogen is considered

as the second best usable form of energy after electricity. Use of deep sea cold water and OTEC electricity for hydrogen production signifies the important applications of OTEC plants.

3. *Ammonia and methanol production*: OTEC electricity can be used to obtain by-products, such as ammonia and methanol, that can be transported either by tankers or through pipe lines to on shore applications
4. *Desalinated water*: Desalinated water is produced in an open-cycle and hybrid-type OTEC plants through surface condenser. It is freshwater and widely used as water resource for drinking, agriculture, and industry.
5. *Aquaculture*: Nutrient-rich cold deep sea water provides sufficient environment for fish farming which may create a profitable business activities.
6. *Chilled soil agriculture*: Chilled soil agriculture is another application of OTEC plants. Cold deep sea water flowing through underground pipes chills the surrounding soil. The temperature difference is maintained between plant roots in the cool soil and plant leaves in the warm air, and thus, the tree and plants grows. The amount of food that can be produced in this way is very large, larger in market value than the electric power produced by the plant.
7. *Air conditioning*: Because the temperature is only a few degrees, cold water can be used as a fluid in air condition systems.

13.8 ADVANTAGES, DISADVANTAGES AND BENEFITS OF OTEC

13.8.1 Advantages

1. Ocean thermal energy is a renewable, clean natural resource available in abundance.
2. It is pollution-free and has no greenhouse effects.
3. It is a good source of freshwater and portable water.

13.8.2 Disadvantages

1. *High cost*: Electricity generated by OTEC plants is more expensive than electricity produced by chemical and nuclear fuels.
2. *Complexity*: OTEC plants must be located where a difference of about 20°C occurs year round. Ocean depths must be available fairly close to shore-based facilities for economic operation. Floating plant ships could provide more flexibility.
3. *Acceptability*: For the large-scale production of electricity and other products, OTEC plants are poorly acceptable due to their high costs.
4. *Ecosystem damage*: It is obvious by setting OTEC plants.
5. *Lower efficiency*: A higher temperature difference between ocean surface warm water and cold deep ocean water is required for highly efficient operation of plant.