JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY
IV Year B. Tech. Electrical and Electronics Engineering – I Sem.

RENEWABLE ENERGY SOURCES AND SYSTEMS

UNIT–I:
Fundamentals of Energy Systems
Energy conservation principle – Energy scenario (world and India) – Solar radiation**:** Outside earth's atmosphere – Earth surface – Analysis of solar radiation data – Geometry – Radiation on tilted surfaces – Numerical problems.
UNIT–II:
Solar Thermal Systems
Liquid flat plate collections**:** Performance analysis – Transmissivity – Absorptivity product collector efficiency factor – Collector heat removal factor – Numerical problems. Introduction to solar air heaters – Concentrating collectors and solar pond.

UNIT–III:
Solar Photovoltaic Systems
Balance of systems – IV characteristics – System design**:** storage sizing – PV system sizing – Maximum power point techniques**:** Perturb and observe (P&O) technique – Hill climbing technique.
UNIT–IV:
Wind Energy
Wind patterns – Types of turbines – Kinetic energy of wind – Betz coefficient – Tip–speed ratio – Efficiency – Power output of wind turbine – Selection of generator(synchronous, induction) – Maximum power point tracking.
UNIT–V:
Hydro and Tidal power systems
Basic working principle – Classification of hydro systems**:** Large, small, micro – measurement of head and flow – Energy equation – Types of turbines – Numerical problems.
Tidal power – Basics – Kinetic energy equation – Numerical problems – Wave power – Basics – Kinetic energy equation.
UNIT–VI:
Biomass, fuel cells and geothermal systems
Biomass Energy**:** Fuel classification – Pyrolysis – Direct combustion of heat – Different digesters and sizing.
Fuel cell**:** Classification – Efficiency – VI characteristics.
Geothermal**:** Classification – Dry rock and acquifer – Energy analysis.

UNIT-I

Energy conservation principle, Solar radiation

The sun is a sphere of intensely hot gaseous matter, having its core similar to thermo-nuclear fusion reaction. As a result, it emits continuously heat energy as a byproduct when hydrogen atoms are converted to helium atoms. Sun like any other block body radiates this heat energy in all directions in the cosmosphere. The basic concept of nuclear fusion is to produce a heavier nucleus by fusing or combining two nuclei of lower mass. The core of the sun is a continuous nuclear fusion reaction, where four protons of Hydrogen are converted into one Helium nucleus. In fact, the total mass of this Helium nucleus is less than the mass of four Hydrogen protons.

This means some amount of mass is lost in the reaction and is converted into Energy.

For every conversion of four protons of Hydrogen (total combined mass 4.0304) into one Helium Nucleus (mass is 4.0027) an amount of 0.0277 mass units of matter is lost in the form of heat energy. This is in accordance with the famous mass and heat energy relation expressed as

$\mathbf{E = mc^2}$ of Einstein.

Here E = Energy; m=mass & c = velocity of light.

This is the energy sun radiates and sustains the fauna and flora on earth caused by various seasonal changes.

The structure of the sun can be divided into three regions as

(a) Interior or core of sun

(b) Solar photosphere

(c) Solar atmosphere.

(a) Solar core is the fusion reactor from where 90% of the Sun's energy is generated. This core alone constitutes 40% of the total mass of the sun. The pressure in this region will be in the order a billion atmosphere and temperature in the range of 8×10^6 to 40×10^6 k. The density is almost 100 times to that of water.

(b) Solar photosphere is the zone from which light and heat are emitted out of sun. This indicates that the → interior core of sun is separated by this photosphere by a zone where there should be a drop in the density to facilitate radiation. This portion is known as convective zone and it is estimated that about 60000 K drop in temperature with concurrent drop in density to a tune of 10–8 g/cm^3 occur.

(c) This chromosphere is named due to its red colour, a gaseous field of 10,000km in thickness. This zone alone contributes to the total energy emitted by sun a factor of 10^{-3}. Apart from these three zones, there is a zone generally visible during eclipses, as a whitish layer. This is known as Corona. This contains low density mass with highly ionized gaseous mixture.

Schematic Expression of Sun's Structure

As Earth rotates around sun in a elliptical orbit, which is nearly circular. As a result, the distance from Sun and earth varies only a maximum of 3% to the mean distance which is 150×10^6 km. The radiation reaching the earth surface has to pass through its atmosphere. As a result, quality of radiation may vary along with energy content when measures above the atmosphere and when compared with radiation measuring on the surface of the earth (at sea level this radiation energy at mid noon is 1 kw/m^2).

The *radiation energy above the atmosphere is calculated as 1.353 kw/m^2, which is generally referred as solar constant* in outer space when earth is at mean distance from the sun.

Note: Solar constant is higher than the energy received on earth which is due to the atmosphere and the behavior of the light passing through the same.

Behavior of Solar Energy Radiation in the Atmosphere:

Radiation from sun without undergoing any change in direction or so, that reaches the surface of the earth is known as **direct or beam radiation.**

Beam Radiation – b (e.g. Gb): is the solar radiation received from the sun without having been scattered by the atmosphere (beam radiation is often referred to as direct solar radiation; to avoid confusion between subscripts for direct and diffuse, we use the term beam radiation, subscript "b").

Diffuse Radiation – d (e.g. Gd): is the solar radiation received from the sun after its direction has been changed by scattering by the atmosphere.

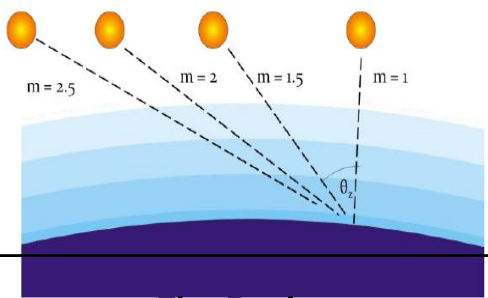
Air Mass

The distance travelled by this direct radiation in the atmosphere is equal to the mass of the atmospheric gaseous mass and is generally known as **"air mass".**

Air mass is the ratio of the path of direct beam in the atmosphere to the beam traveled when sun is overhead to the observer.

The radiation extinction effect of the atmosphere depends on different aspects like aerosol concentration, humidity and especially cloudiness, That can be determined only by measurement.

The radiation attenuation depends on the optical path way of the direct solar radiation through the atmosphere : the longer the way through the atmosphere the stronger its radiation attenuation.



It is defined as the ratio of the mass of the atmospheric through which beam Radiation passes to the mass it would pass through if the sun is directly overhead (i.e. at zenith).

Air mass, $m = L_n / L_o$

$$\text{Air mass, AM} = \frac{L_0 / \cos\theta_z}{L_0} = \frac{1}{\cos\theta_z} = \sec\theta_z$$

However, in the atmosphere, due to the presence of different gases, vapour, particles of matter/ dust, etc., the direct beam upon reaching the atmosphere will change its direction due to the phenomena of absorption and scattering. In the atmosphere, the solar radiation undergoes

- *absorption of short-wave ultra-violet rays by ozone layer*
- *and long-wave infra-red rays by carbon dioxide, vapour and others.*

Similarly, the above said substances also scatter the radiation in the atmosphere, a part of which finally reaches the earth. Hence, **total terrestrial radiation means, the radiation received through beam and diffuse radiation due to scattering.** This total radiation falling on earth's surface will be around 5-7 kwh/m2 or + 6000 kcal/m2/day.

Several radiation attenuating effects occur when radiation crosses the earth's atmosphere. Absorption and Scattering.

Atmospheric absorption :

Some constituents of the atmosphere absorb radiation of a certain spectral range.

Ozone (O_3) absorbs almost completely short-wave radiation at wavelengths below 290nm.

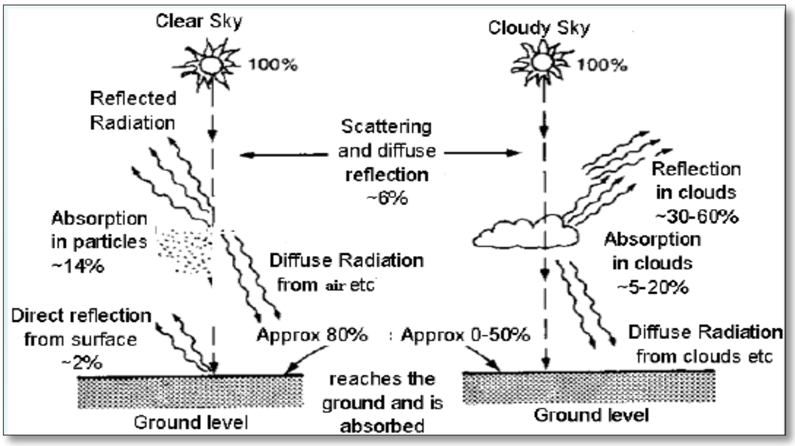
Water vapour absorbs strongly in the infrared part of the solar spectrum.

Carbone dioxide is another strong absorber of infrared radiation.

Due to both gases, H_2O and CO_2, the radiation transmission through the atmosphere is very low at wavelengths above 2.5µm.

Finally, oxygen and nitrogen absorb radiation over a large wavelength range.

Scattering is a process in which radiation is forced to deviate from a straight trajectory by non-uniformities in its way (molecules, dust particles etc.). In the case of solar radiation, two types of scattering are distinguished: Rayleigh-scattering and Mie-scattering. It depends especially on the size of the non-uniformities. Because of scattering processes, solar radiation reaches the Earth's surface partially as diffuse radiation.



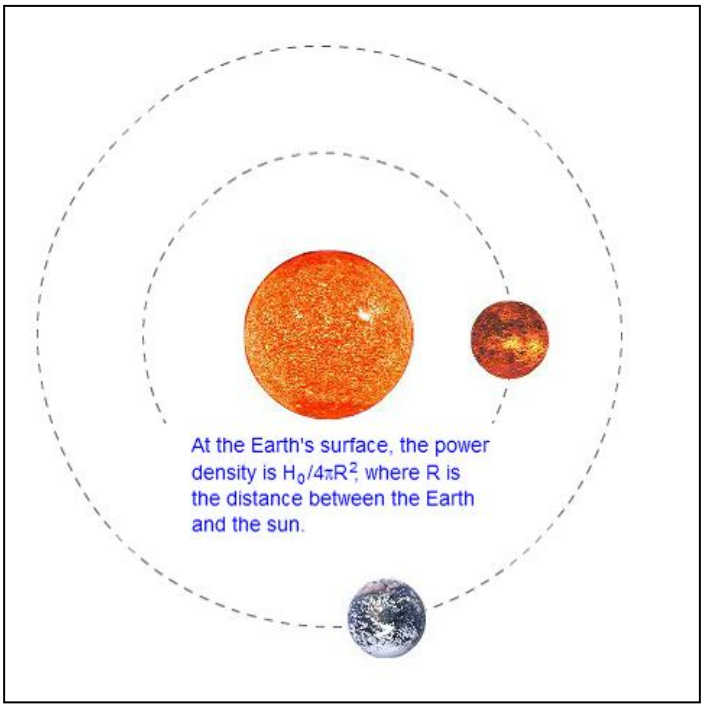
Total Solar Radiation (e.g. G): *is the sum of the beam and the diffuse solar radiation on a surface (the most common measurements of solar radiation are total radiation on a horizontal surface, oftenreferred to as global radiation on the surface.*

30% is reflected. 17% is absorbed by the atmosphere. 53% reaches the earth surface: 31% direct Air mass radiation 22% diffuse radiation .

India has a total land mass area measuring to 3.28 x 1011 square meters. At least if 1% of this radiation is utilized by employing solar devices with as little as with just 10% efficiency can yield us 492 x 109 kwhr / year of electricity.

Solar Radiation in Space

Only a fraction of the total power emitted by the sun impinges on an object in space which is some distance from the sun. The solar irradiance (H_0 in W/m^2) is the power density incident on an object due to illumination from the sun. At the sun's surface, the power density is that of a blackbody at about 6000K and the total power from the sun is this value multiplied by the sun's surface area. However, at some distance from the sun, the total power from the sun is now spread out over a much larger surface area and therefore the solar irradiance on an object in space decreases as the object moves further away from the sun.



Thermal radiation

When we heat objects sufficiently, they will begin to emit light. At first they will glow in dim reddish light. When we continue to heat them up, they will glow more intensely and the color of the emitted light will change towards yellow and later white. The experience that we can make objects glow by heating them up is a hint on the dependency of the emitted electromagnetic radiation on temperature. Indeed, the emission behavior of a body depends on its temperature as well as on the object´s material and surface properties. The radiation which is emitted by bodies due to their temperature is called thermal radiation.

Now, there is a common useful idealization in radiation physics. Imagine a body that neither reflects any incident light nor lets it pass through, i.e., it absorbs all the incident electromagnetic radiation. Such a body is called a black body or an ideal radiator. Black bodies do not exist in reality.

Planck's Law's defines the amount of energy emitted as a function of the temperature and the wavelength of the source

$$\frac{dE(\lambda,T)}{d\lambda} = E^{*}(\lambda,T) = \frac{2\pi hc^{2}}{\lambda^{5}(\exp(\frac{hc}{\lambda kT})-1)}$$

where $h = 6.626 \cdot 10^{-34}$Js is the Planck constant,

$k = 1.38 \cdot 10^{-23} \frac{\mathrm{J}}{\mathrm{K}}$ the Boltzmann constant and

$c = 2.998 \cdot 10^{8} \frac{\mathrm{m}}{\mathrm{s}}$ the speed of light.

Integrating Planck's distribution with respect to wavelength, for instance, yields the Stefan-Boltzmann Law, which states that the radiant energy emitted by a surface is proportional to its temperature taken to the fourth power.

$$\int E^{*}(\lambda, T)d\lambda = L = \sigma T^{4} \ (\mathrm{W\ m^{-2}})$$

σ is the Stefan-Bolztmann constant (5.67 10-8 W m^{-2} K^{-4}). This equation is especially useful for it helps us gauge the radiative temperatures of the sun.

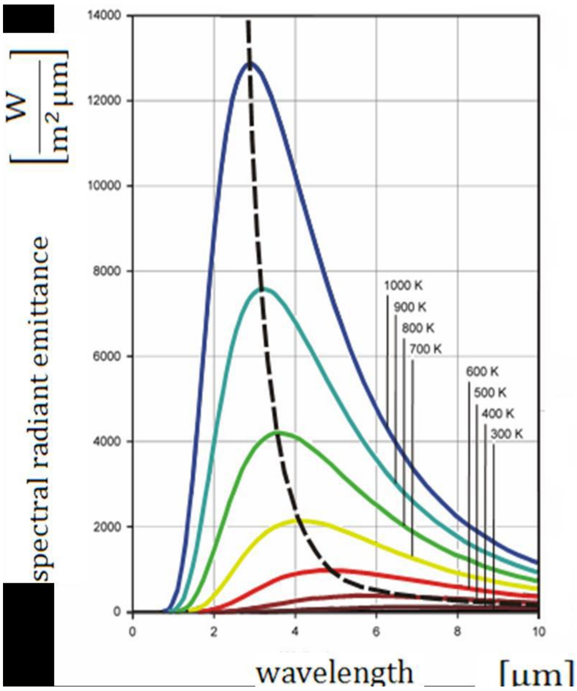
Wien's Law is derived by examining the maximum of a function. It tells what is the wavelength of that radiating source when E is maximal.

$$\frac{\partial E^{*}(T, \lambda)}{\partial \lambda} = 0$$

It states that the wavelength at the point of maximum spectral radiant emittance M is inversely proportional to the temperature:

$$\lambda_{max} = \frac{b}{T}$$

where $b = 2.8978 \cdot 10^{-3}$mK. This relation permits to derive the temperature of a body from the spectrum of the radiation it emits.



Observations:

1. First, for each temperature there is a maximum of radiation intensity at a certain wave length.
2. At the left and at the right side of the maximum, the spectral radiant emittance M declines continuously.
3. The wavelength for which the maximum appears varies with temperature.

The higher the temperature the smaller is the wavelength of the radiation at the maximum.

4. The discontinuous black line in the following figure indicates the location of the power maximum for different temperatures.

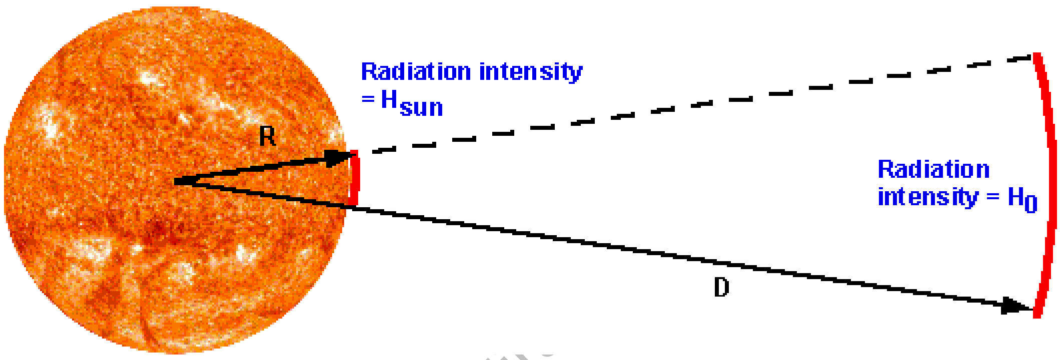
These three interconnected laws, Planck´s black-body radiation law, Wien's displacement law and the Stefan-Boltzmann law helpto understand thermal radiation and solar radiation in particular.

SUMMARY

- Planck's Law defines the spectral distribution energy radiating of a black body surface of a given temperature.

- Integrating Planck's Law with respect to wavelength from zero to infinity produces the Stefan-Boltzmann Law which states that the amount of energy radiating from a black body is proportional to its temperature to the fourth power.
- Differentiating Planck's Law with respect to wavelength and solving for the maximum value (the wavelength when the derivative is zero) produces Wien's Law, which states that the maximum wavelength is inversely proportional to surface temperature
- One can derive how hot the sun is by knowing its spectral distribution and solving for Wien's Law. It can also be derived from geometrical considerations knowing the solar constant, the distance between Earth and the Sun, the Sun's radius and the Stefan-Bolzmann law.

The solar irradiance on an object some distance D from the sun is found by dividing the total power emitted from the sun by the surface area over which the sunlight falls.



At a distance, D, from the sun the same amount of power is spread over a much wider area so the solar radiation power intensity is reduced.

Solar Radiation Outside the Earth's Atmosphere

Solar constant

The power of solar radiation per unit area at the outer border of the Earth´s atmosphere is nearly constant and the value is called the solar constant. Note well, we are not speaking about the irradiance on the Earth's surface, but about the radiant power outside the terrestrial atmosphere.

The solar constant depends basically on three parameters: the temperature of the Sun, more precisely of the photosphere which emits the major part of the radiation that leaves the Sun, the size of the Sun, and the distance between Sun and Earth.

can be considered to be 5777K. Additionally, we know that the Sun radius r_S is about $6.965 \cdot 10^8$m and that the mean Sun-Earth distance r_{SE} amounts to approximately 1.496×10^{11}m.[8] On the basis of these three parameters and considering the Sun as a black body (and thus simplifying the complex reality, yet we know that it is only approximately a black body), we can calculate the solar radiation power arriving at the Earth.

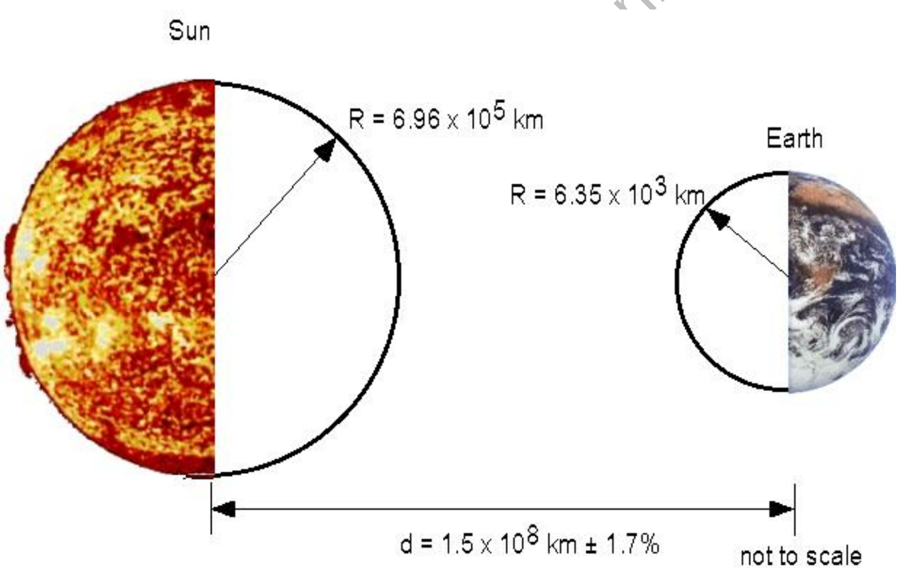
First, the Stefan-Boltzmann law permits to calculate the total solar radiation power:

$$\begin{aligned} P_S &= \sigma T^4 \cdot 4\pi {r_S}^2 \\ &= 5.67 \cdot 10^{-8} \cdot 5777^4 \cdot 4\pi \cdot (6.965 \cdot 10^8)^2 \text{ W} \\ &= 3.85 \cdot 10^{26} \text{ W} \end{aligned}$$

With this power, the Sun emits radiation into the space. No radiation gets lost on its way. Thus, the same radiant energy that leaves the Sun and arrives at Earth. That means that the irradiance at Earth, i.e. the solar constant, can be calculated as:

Solar constant =Total solar radiation power divided by the area of the Earth

$$G_{SC} = P_S/4\pi {r_{SE}}^2 = 3.85 \cdot 10^{26}\text{W}/4\pi(1.496 \cdot 10^{11}\text{m})^2 \approx 1367 \frac{\text{W}}{\text{m}^2}$$



Extraterrestrial Solar Radiation

The eccentricity of the earth's orbit is such that the distance between the sun and the earth varies by 1.7%.

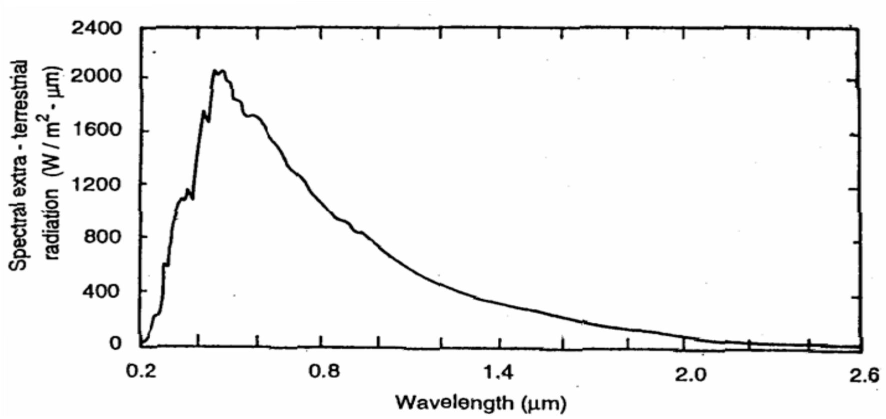
Variation of Extraterrestrial Radiation

Solar radiation varies with the day of the year as the sun-earth distance varies.

A simple equation with accuracy adequate for most engineering calculations is:

$$Gon = Gsc(1 + 0.033 \cos\frac{360n}{365})$$

where Gon is the extraterrestrial radiation incident on the plane normal to the radiation on the nth day of the year.



Two sources of variation in extraterrestrial radiation must be considered:

a) the variation in the radiation emitted by the sun.

For engineering purposes, in view of the uncertainties and variability of atmospheric transmission, the energy emitted by the sun can be considered to be fixed.

variation of the earth-sun distance, that leads to variation of extraterrestrial radiation flux in the range of ± 3.3%.

Radiation and Its Spectrum

Radiation: Radiation is a transport process, in which energy propagates through a medium or through empty space. In general, in this chapter electromagnetic radiation is considered.

Radiant energy: energy of electromagnetic waves (unit: joule [J])

Radiant power: radiant energy per unit time (unit: watt [W], joule per second

Js-1])

Radiant emittance: emerging radiant power per unit area of emitting surface (unit: watt per square metre [Wm-2])

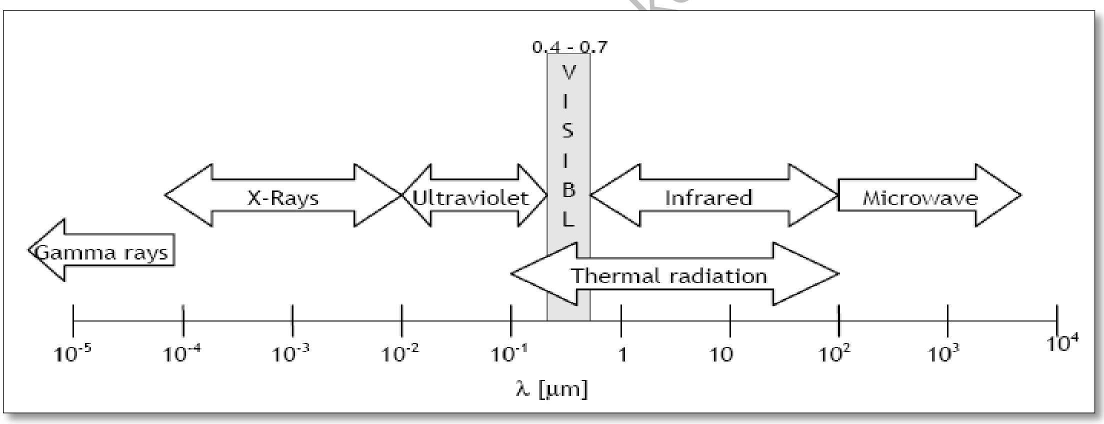
Irradiance, G [W/m2]: is the rate at which radiant energy (energy flux) is incident on a surface per unit area of surface.

Irradiation or Radiant Exposure, I or H [J/m2]: is the incident energy per unit area on a surface, found by integration of irradiance over a specified period (usually an hour or a day).

Insolation is a term applying specifically to solar energy irradiation. The symbol H is used for insolation for a day. The symbol I is used for insolation for an hour (or other period if specified).

The Sun spectrum

The sun emits a spectrum of electromagnetic radiation. Electromagnetic Radiation consists of discrete packets of photons. Radiation is an electromagnetic mechanism that allows energy to be transported, at the speed of light, through regions of space devoid of matter. Electromagnetic radiation moves at the speed of light, c, 2.998 108 m/ s, in a vacuum, with wave-like motion. The speed of light is proportional to the product of the wavelength of the radiation (λ) and the frequency at which it oscillates (v), λv= c . The Sun emits a nearly continuous spectrum of energy, ranging from very short wave and high energy packets of quanta, to low energy and long wave lengths. Even the Sun is NOT a black body radiator.But radiation power of the Sun resemble the spectrum and the intensity of the radiation of a black body at around 5780 K.

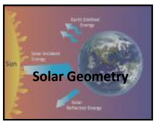


On earth, there are 4 wavebands of electromagnetic radiation that are of particular interest. These are the ultraviolet, photosynthetically active, near infrared and infrared bands Ultraviolet (0.29 to 0.38 μm).

This band possess high energy. It can damage molecular bonds. Its presences leads to the photochemical formation of ozone in the troposphere. It has a moderate impact on photomorphogenesis. Its flux density is relatively low since most ozone is absorbed in the stratosphere. Therefore, about zero to 4% of incoming solar radiation is in this band.

Near Infrared band (NIR) (0.71 to 4.0 µm). This wave band is not visible, but contributes to the heat budget of organisms.

Long wave or terrestrial radiation (3.0 to 100 µm). This is the radiation emitted by bodies on earth. Its flux density is a function of the surfaces temperature and emissivity. Any body warmer that 0 K emits radiation.



RELATIONSHIP BETWEEN CLOCK TIME AND SOLAR TIME

Solar radiation calculations must be made in terms of solar time. Time reckoned from midnight at the Greenwich meridian (zero longitude) is known as Greenwich Civil Time or Universal Time. Such time is expressed on an hour scale from zero to 24. Thus, midnight is Oh and noon is 12h. Local Civil Time is reckoned from the precise longitude of the observer.

Solar time: Time corresponding to the position of sun i.e., based on hour angle

Standard time : Time corresponding to the position of sun at a reference place known as standard longitude for a country L_{std}.

Solar time is the time used in all of the sun-angle relationships; it does not coincide with local clock time (standard time).

It is necessary to convert standard time to solar time by applying two corrections:

1. There is a constant correction for the difference in longitude between the observer's meridian (local longitude, L_{loc}) and the meridian on which the local standard time is based (longitude of the standard meridian for the local time zone, L_{std}). In fact, the sun takes 4 min to transverse 1°of longitude.

2. The second correction is from the equation of time, which takes into account the perturbations in the earth's rate of rotation which affect the time the sun crosses the observer's meridian

The difference between Local Solar Time, LST and Local Civil Time, LCT is called the Equation of Time, E.

$$LST = LCT \pm \frac{4\ minutes}{1\ degree}(L_{LST} - L_{LOC}) + \mathbf{E}$$

The negative sign is applicable for Eastern hemisphere.

LST = Local Solar Time [hr]

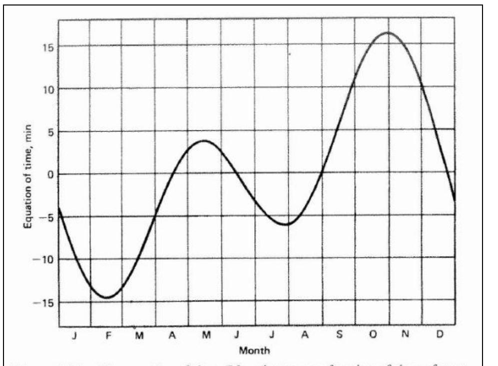


Figure 1.5.1 The equation of time E in minutes as a function of time of year.

LCT = Local Clock Time [hr]

Lstd = Standard Meridian for the local time zone [degrees west]

L_{loc} = Longitude of actual location [degrees west]

E = Equation of Time [hr]

Where E= 9.87 sin(2B) - 7.53 cosB - 1.5sinB

and $B = \frac{360(n-81)}{364}$

Once Local Solar Time is established, the solar hour angle, ω can be calculated

$\omega = 15\,(12 - LST) Degrees$

Sunrise and sunset hour angle is given by

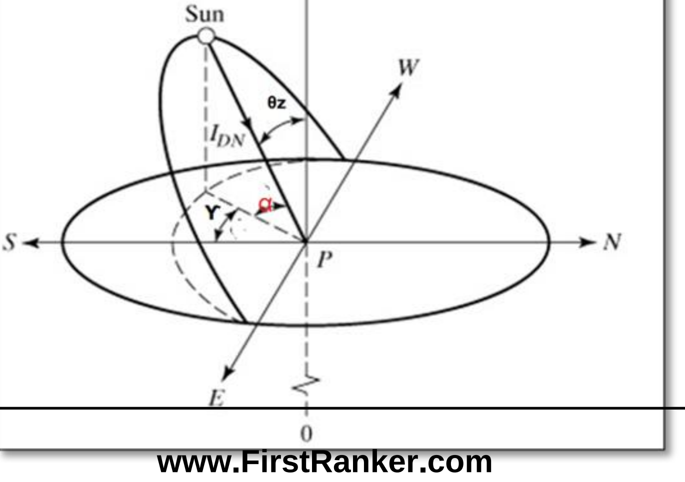
$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta)$$

Time difference between noon sunrise or sunset (hour)

$$h_{ss/sr} = \frac{1}{15}\left[\cos^{-1}(-\tan\phi\tan\delta)\right]$$

Day length

$$S_{max} = \frac{2}{15}\left[\cos^{-1}(-\tan\phi\tan\delta)\right]$$



Definitions w.r.t Solar rays :

Point P represents the position of the observer, point O is the center of the earth, and IDN is a vector representing the sun's rays.

The zenith angle θz is the angle between the sun's rays and local vertical, i.e. a line perpendicular to the horizontal plane at P.

The altitude angle α is the angle in a vertical plane between the sun's rays and the projection of the sun's rays on the horizontal plane. It follows that $\alpha + \theta z = \pi/2 = 90^{O}$.

The solar azimuth angle ϒ is the angle in the horizontal plane measured from south to the horizontal projection of the sun's rays. it is positive for west wise.

Summary of the sign convention is:

l: north latitudes are positive, south latitudes are negative

δ: the declination is positive when the sun's rays are north of the equator, i.e. for the summer period in the northern hemisphere, March 22 to September 22 approximately

ω: the hour angle is Positive before solar noon

ϒ: the sun's azimuth angle is positive when measured west wise.

Definitions w.r.t Surface :

The sun's angle of incidence, θ is the angle between the solar rays and the surface normal.

$$\begin{aligned}\cos\theta = &\sin\phi(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta)\\ &+\cos\phi(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta)\\ &+\cos\delta\sin\omega\sin\gamma\sin\beta\end{aligned}$$

Vertical surface, $\beta = 90^\circ$

$$\begin{aligned}\cos\theta = &\sin\phi\cos\delta\cos\gamma\cos\omega\\ &+\cos\phi\sin\delta\cos\gamma + \cos\delta\sin\omega\sin\gamma\end{aligned}$$

Horizontal surface, $\beta = 0^\circ$ / Zenith angle θ_z

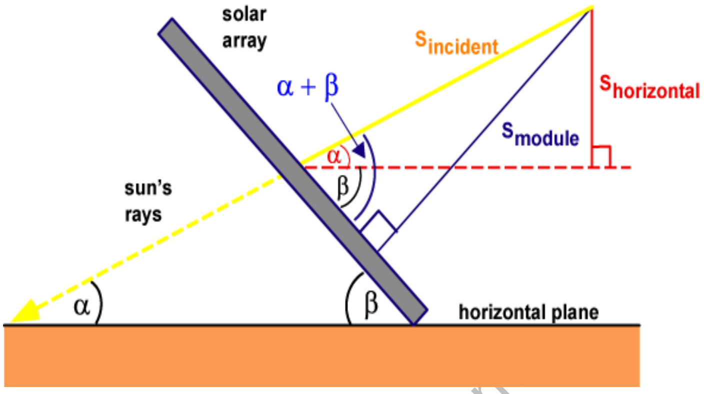
$$\cos\theta = \cos\theta_z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$$

For a horizontal surface, the surface normal is the local vertical, i.e., θ= θz.

Solar radiation on tilted surface

The power incident on a PV module depends not only on the power contained in the sunlight, but also on the angle between the module and the sun. When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight (in other words, the power density will always be at its maximum when the PV module is perpendicular to the sun). However, as the angle between the sun and a fixed surface is continually changing, the power density on a fixed PV module is less than that of the incident sunlight.

The amount of solar radiation incident on a tilted module surface is the component of the incident solar radiation which is perpendicular to the module surface. The following figure shows how to calculate the radiation incident on a tilted surface (S_{module}) given either the solar radiation measured on horizontal surface (S_{horiz}) or the solar radiation measured perpendicular to the sun ($S_{incident}$).



Monthly average daily global radiation

$$\frac{\overline{H}_g}{\overline{H}_c} = a + b\left(\frac{\overline{S}}{\overline{S}_{max}}\right)$$

where

$\overline{H}_g$ = monthly average of the daily global radiation on a horizontal surface at a location (kJ/m^2-day)

$\overline{H}_c$ = monthly average of the daily global radiation on a horizontal surface at the same location on a clear day (kJ/m^2-day)

$\overline{S}$ = monthly average of the sun shine hours per day at a location (h)

$\overline{S}_{max}$ = monthly average of the maximum possible sun shine hours per day at the location (h)

a,b = constants obtained by fitting data

$\overline{H}_c$ is replaced by $\overline{H}_o$ due to difficulties in deciding what constitutes a clear sky where $\overline{H}_o$ is called monthly average of the daily extraterrestrial radiation.

Hence

$$\frac{\overline{H}_g}{\overline{H}_o} = a + b\left(\frac{\overline{S}}{\overline{S}_{max}}\right)$$

Monthly average daily global radiation

$\overline{H}_o$ is the mean of the value H_o for each day of the month.
H_o is obtained by integrating over the day length as follows

$$H_o = \frac{24}{\pi} I_{sc}\left(1+0.033\cos\frac{360n}{365}\right)\left(\frac{2\pi}{360}\omega_s \sin\phi\sin\delta+\cos\phi\cos\delta\sin\omega_s\right)$$

$\overline{H}_o$ is determined the particular day in each month on which extraterrestrial radiation is nearly equal to the monthly mean value.
the dates on which $\overline{H}_o = H_o$ are as follows
Jan 17, Feb 16, Mar 16, Apr 15, May 15, Jun 11, Jul 17, Aug 16,
Sept 15, Oct 15, Nov 14, Dec 10. Dates are almost middle of the month.

Hourly global, beam and diffuse radiation Under cloudless skies

$I_g = I_b + I_d$

where

$I_g =$ hourly global radiation

$I_b =$ hourly beam radiation

$I_d =$ hourly diffuse radiation

Now, $I_b = I_{bn}\cos\theta_z$

where

$I_{bn} =$ beam radiation in the direction of the rays

$\theta_z =$ angle of incidence on a horizontal surface, i.e. the zenith angle

Total Solar Radiation on Tilted Surfaces

$I = I_b r_b + I_d r_d + (I_b + I_d) r_r$

Beam radiation:

$\cos\theta = \sin\delta\sin(\phi-\beta)+\cos\delta\cos\omega\cos(\phi-\beta)$

while for a horizontal surface

$\cos\theta_z = \sin\phi\sin\delta+\cos\phi\cos\delta\cos\omega$

Hence,

$$r_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta\sin(\phi-\beta)+\cos\delta\cos\omega\cos(\phi-\beta)}{\sin\phi\sin\delta+\cos\phi\cos\delta\cos\omega}$$

Reflected radiation:

Reflection of electromagnetic **radiation** from a smooth surface. The reflectivity of a surface is a measure of the amount of **reflected radiation**. It is **defined** as the ratio of the intensities of the **reflected** and incident **radiation**.

Diffuse radiation

The tilt factor 'r_d 'for a diffuse radiation is ratio of the diffuse radiation flux falling on the tilted surface to that falling on a horizontal surface. the value of tilt factor depends on the distribution of diffuse radiation over the sky and on the portion of the sky dome seen by the tilted surface.

$$r_d = (1+\cos\beta)/2$$

$(1+\cos\beta)/2$ is radiation shape factor for a tilted surface w.r.t the sky

Since $(1+\cos\beta)/2$ is the radiation shape factor for a tilted surface w.r.t the sky, it follows that $(1-\cos\beta)/2$ is the radiation shape factor w.r.t. the surrounding ground.

reflectivity is ρ

the tilt factor for reflected radiation is

$$r_r = \rho(1-\cos\beta)/2$$

Unit – II - Solar Thermal Systems

S*olar Collectors*

Solar collectors are used to collect the solar energy and convert the incident radiations into thermal energy by absorbing them. This heat is extracted by flowing fluid (air or water or mixture with antifreeze) in the tube of the collector for further utilization in different applications. The collectors are classified as;

• Non concentrating collectors

• Concentrating (focusing) collectors

Non Concentrating Collectors

In these collectors the area of collector to intercept the solar radiation is equal to the absorber plate and has concentration ratio of 1. Flat Plate Collectors (Glaze Type) Flat plate collector is most important part of any solar thermal energy system. It is simplest in design and both direct and diffuse radiations are absorbed by collector and converted into useful heat. These collectors are suitable for heating to temperature below 100oC. The main advantages of flat plate collectors are:

• It utilizes the both the beam as well as diffuse radiation for heating.

• Requires less maintenance.

Disadvantages

• Large heat losses by conduction and radiation because of large area.

• No tracking of sun.

• Low water temperature is achieved.

The constructional details of flat plate collector is given below

(a) Insulated Box: The rectangular box is made of thin G.I sheet and is insulated from sides and bottom using glass or mineral wool of thickness 5 to 8 cm to reduce losses from conduction to back and side wall. The box is tilted at due south and a tilt angle depends on the latitude of location. The face area of the collector box is kept between 1 to 2 m2.

(b) Transparent Cover: This allows solar energy to pass through and reduces the
convective heat losses from the absorber plate through air space. The transparent
tampered glass cover is placed on top of rectangular box to trap the solar energy and sealed by rubber gaskets to prevent the leakage of hot air. It is made of plastic/glass but glass is most favourable because of its transmittance and low surface degradation.

However with development of improved quality of plastics, the degradation quality has been improved. The plasticsare available at low cost, light in weight and can be used to make tubes, plates and cover but are suitable for low temperature application 70-120oC with single cover plate or up to 150oC using double cover plate. The thickness of glass cover 3 to 4 mm is commonly used and 1 to 2 covers with spacing 1.5 to 3 cm are generally used between plates. The temperature of glass cover is lower than the absorber plate and is a good absorber of thermal energy and reduces convective and radiative losses of sky.

(c) Absorber Plate: It intercepts and absorbs the solar energy. The absorber plate is madeof copper, aluminum or steel and is in the thickness of1 to 2 mm. It is the most important part of collector along with the tubes products passing the liquid or air to be heated. The plate absorbs the maximum solar radiation incident on it through glazing (cover plate) and transfers the heat to the tubes in contact with minimum heat losses to atmosphere. The plate is black painted and provided with selective material coating to increase its absorption and reduce the emission. The absorber plate has high absorption (80-95%) and low transmission/reflection.

(d) Tubes: The plate is attached to a series of parallel tubes or one serpentine tube through which water or other liquid passes. The tubes are made of copper, aluminum or steel in the diameter 1 to 1.5 cm and are brazed, soldered on top/bottom of the absorber water equally in all the tubes and collect it back from the other end. The header pipe is made of same material as tube and of larger diameter. Now-a-days the tubes are made of plastic but they have low thermal conductivity and higher coefficient of expansion than metals. Copper and aluminum are likely to get corroded with saline liquids and steel tubes within
hibitors are used at such places.

Removal of Heat: These systems are best suited to applications that require low temperatures. Once the heat is absorbed on the absorber plate it must be removed fast and delivered to the place of storage for further use. As the liquid circulates through the tubes, it absorbs the heat from absorber plate of the collectors. The heated liquid moves slowly and the losses from collector will increase because of rise of high temperature of collectorand will lower the efficiency. Flat-plate solar collectors are less efficient in cold weather than in warm weather. Factors affecting the Performance of Flat Plate Collector.

The different factors affecting the performance of system are:

(a) Incident Solar Radiation: The efficiency of collector is directly related with solar

radiation falling onit and increases with rise in temperature.

(b) Number of Cover Plate: The increase in number of cover plate reduces the internal convective heat losses but also prevents the transmission of radiation inside the collector. More than two cover plate should not be used to optimize the system.

(c) Spacing: The more space between the absorber and cover plate the less internal heat losses. The collector efficiency will be increased. However on the other hand, increase in space between them provides the shading by side wall in the morning and evening and reduces the absorbed solar flux by 2-3% of system. The spacing between absorber and cover plate is kept 2-3 cm to balance the problem.

(d) Collector Tilt: The flat plate collectors do not track the sun and should be tilted at angle of latitude of the location for an average better performance. However with changing declination angle with seasons the optimum tilt angle is kept Φ =15o. The collector is placed with south facing at northern hemisphere to receive maximum radiation throughout the day.

(e) Selective Surface: Some materials like nickel black (α= 0.89, ε= 0.15) and black chrome (α= 0.87, ε= 0.088), copper oxide (α= 0.89, ε= 0.17) etc. are applied chemically on the surface of absorber in a thin layer of thickness 0.1 μm. These chemicals have high degree of absorption (α) to short wave radiation (< 4 μm) and low emission (ε) of long wave radiations (> 4 μm). The higher absorption of solar energy increase the temperature of absorber plate and working fluid. The top losses reduce and the efficiency of the collector increases. The selective surface should be able to withstand high temperature of 300-400oC, cost less, should not oxidize and be corrosive resistant. The property of material should not change with time.

(f) Inlet Temperature: With increase in inlet temperature of working fluid the losses increase to ambient. The high temperature fluid absorbed the less heat from absorber plate because of low temperature difference and increases the top loss coefficient. Therefore the efficiency of collector get reduced with rise in inlet temperature.

(g) Dust on cover Plate: The efficiency of collector decreases with dust particles on the cover plate because the transmission radiation decreases by 1%. Frequent cleaning is required.

Collector Efficiency in the Steady State

We must calculate the temperatures T_b and T_c from the radiation fluxes and the ambient temperature T_a.

First assume a value for q_{ca} and solve equation (2) for T_c. Now equation (1) shows that

$q_{ca} = h_{bc}(T_b - T_c) + \varepsilon_{bc}\sigma(T_b^4 - T_c^4)$, ...(3)

from the heat balance of the glass cover in the steady state. This equation is solved for T_b. Finally q_{ba} is found from equation (1).

Repeat the calculation for different values of q_{ca} to obtain q_{ba} as a function of T_b. This is easy to do numerically with a programmable calculator.

Let q_{out} be the heating power output of the collector per unit area. It can be varied within the feasible limits by controlling the operating conditions of the collector. The heat balance for the black plate gives

$q_{abs} = q_{ba} + q_{out}$,

where q_{abs} depends on I_b, θ, and I_d; and the heat loss rate q_{ba} is known as a function of T_b. The **overall efficiency**

$\eta = q_{out}/q_{in}$

is therefore known as a function of the radiation fluxes and the black plate temperature T_b.

Simplifications in the Theory

In practical flat-plate solar collectors the temperature of the flat plate is not uniform. In tube-in-sheet designs the temperature of the sheet between the tubes is higher than the temperature of the tubes. Furthermore, the temperature of the tubes is higher at the outlet ends than at the inlet ends. The use of a single black plate temperature T_b is therefore a simplification.

Another simplification is to put

$q_{abs} = \gamma . q_{in}$,

where γ is the **optical efficiency**, which is equal to the mean transmittance-absorptance product $(\tau.\alpha)_m$.

The heat balance equation is then written

$q_{out} = \gamma.q_{in} - U(T_b - T_a)$,

where U is the **overall heat loss coefficient** between the black plate and the surroundings. The efficiency is now given by

$\eta = q_{out}/q_{in} = \gamma - U(T_b - T_a)/q_{in}$.

Thus γ is the efficiency when $T_b = T_a$. Often U is assumed to be constant, and the **stagnation temperature** T_{max} obtained when no heat is extracted from the collector is estimated to be

$T_{max} = T_a + \gamma.q_{in}/U$.

In reality, because of the non-linear relations between the heat losses and the temperature differences, U varies with $T_b - T_a$. With good approximation we can write

$q_{out} = \gamma.q_{in} - U_1(T_b - T_a) - U_2(T_b - T_a)^2$

and

$\eta = \gamma - U_1(T_b - T_a)/q_{in} - U_2(T_b - T_a)^2/q_{in}$,

where U_2 is small compared with U_1. The graph of η versus $(T_b - T_a)$ is slightly curved. (See Fig. 1.)

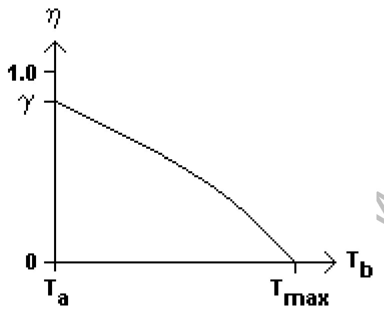


Fig. 1. The efficiency of a flat plate collector.

If the solar radiation falling on the collector changes rapidly, due to the passage of clouds, the collector will take time to change its temperature because of its heat capacity. This may be important and require separate analysis. The theory of non-steady state processes in solar collectors is very complicated, and is ignored in steady state calculations

Practical Collector Performance Parameters

In practice it is convenient to use the fluid temperature T_f instead of the black plate temperature T_b. The total heat extraction rate Q_{out} from a collector of area A is then written

$Q_{out} = AF'[\gamma.q_{in} - U(T_f - T_a)]$, ...(1)

where F' is called the **collector efficiency factor**. In good designs F' is nearly unity. F'.γ is the effective transmittance-absorptance product; and F'U is the heat loss coefficient between the fluid and its surroundings.

We may define the thermal resistance R between the black plate and the fluid by the equation

$q_{out} = (T_b - T_f)/R$,

and derive equation (1) from the heat balance equation between the black plate and the surroundings. It is then found that

F' = 1/(1 + RU).

Consider a fluid with mass flow rate m and specific heat capacity c flowing a total distance L through a collector of area A. The heating of the fluid with respect to distance x through the collector is given by

$mc(dT(x)/dx) = (A.F'/L)[\gamma.q_{in} - U(T(x) - T_a)]$.

Assume U is constant. Then this is a first order non-homogeneous linear differential equation. It can be solved to give the basic equation relating the inlet and outlet fluid temperatures T_{in} and T_{out} as follows:

$[\gamma.q_{in} - U(T_{in} - T_a)]\exp(-AF'U/mc) = [\gamma.q_{in} - U(T_{out} - T_{in})]$. .....(2)

Often the performance of a collector is written in terms of the fluid inlet temperature T_{in} and a **heat removal factor** F_R, as follows

$Q_{out} = AF_R[\gamma.q_{in} - U(T_{in} - T_a)]$. .....(3)

Writing $Q_{out} = mc(T_{out} - T_{in})$, and eliminating T_{out} with the help of (2), shows that

$F_R = (mc/AU)[1 - \exp(-AF'U/mc)]$. .....(4)

For small flow F_R is small and the fluid temperature approaches the stagnation temperature T_{max}. For large flow F_R is large, but the rise in fluid temperature is small.

The Absorption of Solar Radiation

A flat-plate solar collector usually has a non-selective or a selective black plate with one or two glass covers a few centimeters above the black plate, and a well insulated back. The length of the plate is typically about 2m. Edge effects are usually small.

The transmittance $\tau(\theta)$ of a glass cover for solar radiation depends on the angle of incidence θ. Typical values for clear glass are given in Table 1.

The absorptance $\alpha(\theta)$ of the black plate for solar radiation also depends on the angle of incidence θ. Table 2 shows typical values for $\alpha(\theta)$ and the product $\tau(\theta).\alpha(\theta)$.

The solar irradiance I_{in} incident on the cover glass is given by

$I_{in} = I_b \cos\theta + I_d$,

where I_b is the beam solar irradiance, θ is the angle of incidence, and I_d is the diffuse irradiance.

If there is one glass cover the solar irradiance on the black plate is

$\tau(\theta).I_b \cos\theta + \tau_m I_d$,

where τ_m is the mean value of $\tau(\theta)$. The solar radiation flux q_{abs} absorbed by the black plate is given by

$q_{abs} = \tau(\theta).\alpha(\theta)\, I_b \cos\theta + (\tau.\alpha)_m I_d$,

where $(\tau.\alpha)_m$ is the mean value of $\tau(\theta).\alpha(\theta)$. The mean value of $\tau(\theta).\alpha(\theta)$ can be found by means of integrals over the hemispherical sky as follows:

$(\tau.\alpha)_m = [\int_0^{\pi/2} \tau(\theta).\alpha(\theta).\sin\theta.\cos\theta.d(\theta)] / [\int_0^{\pi/2} \sin\theta.\cos\theta.d(\theta)]$.

For one glass cover the result is approximately $(\tau.\alpha)_m = 0.70$

Heat Losses

The glass cover behaves nearly as a black body for long-wave radiation. We can assume that the emittance ε_c of the glass cover is 0.95.

The emittance ε_b of the black plate for long-wave radiation depends on whether the surface is non-selective or selective. Typically we have

$\varepsilon_b = 0.92$ for a non-selective surface,
$\varepsilon_b = 0.10$ for a selective surface.

We shall consider a collector with one glass cover. Let

T_a = ambient temperature,
T_b = black plate temperature,
T_c = glass cover temperature,

where absolute temperatures must be used for radiation calculations.

Heat is lost by conduction through the back insulation. It can be reduced to a low rate by inexpensive insulation materials. Typically the back loss might be given by the formula

$h_{ba}(T_b - T_a)$,

where the heat transfer coefficient is $h_{ba} = 0.3 W/m^2K$.

Heat is lost from the black plate to the glass cover by convection and radiation. Experience has shown that, for free convection the Nusselt number Nu in air spaces between parallel plates with Grashof numbers Gr in the range 10^4 to 10^7, we have

Nu = 0.152 $Gr^{0.281}$ for horizontal plates,
Nu = 0.093 $Gr^{0.310}$ for plates tilted at an angle 45°.

Here

$Gr = g.\beta(T_b - T_c)L^3/\nu^2$,

where we assume as a typical example for air:

g = acceleration of gravity == $9.8 m/s^2$,
β = coefficient of thermal expansion = 1/T, T = 60°C = 333K,
Tb – Tc = 80°C – 40°C = 40K,
L = spacing = 50mm = 0.05m,
ν = kinematic viscosity = $0.194\times10^{-4} m^2/s$.

This gives Gr = 3.91×10^5, which is within the range 10^4 to 10^7 mentioned above.

Assume a tilt angle 15°. Then we estimate, by interpolation, Nu = 0.132 $Gr^{0.291}$ = 5.572.

Also since

Nu = hL/k,

where

h = heat transfer coefficient,
L = 0.05m,
k = thermal conductivity of air = 0.02750W/mK,

we have h = $3.06 W/m^2K$. This calculation shows that in general the heat transfer coefficient h is a function of T_b and T_c.

For the heat loss by radiation between the black plate and the glass cover we have the expression

$[\sigma.(T_b^4 - T_c^4)] / [\varepsilon_b^{-1} + \varepsilon_c^{-1} - 1] = \varepsilon_{bc}.\sigma(T_b^4 - T_c^4)$,

where σ is the Stefan-Boltzman constant $56.7\times10^{-9} W/m^2K^4$.

Thus the total heat loss q_{ba} from the black plate can be written

$q_{ba} = h_{ba}(T_b - T_a) + h_{bc}(T_b - T_c) + \varepsilon_{bc}.\sigma.(T_b^4 - T_c^4)$, ...(1)

where h_{bc} depends on T_b and T_c, and on the angle of tilt of the collector.

The heat loss from the glass cover to the surroundings must be the same, in the steady state, as the heat loss from the black plate to the glass cover. We have for the heat loss from the glass cover

$q_{ca} = h_{ca}.(T_c - T_a) + \varepsilon_c.\sigma.T_c^4 - \varepsilon_c.L$, ...(2)

where the convection heat transfer coefficient h_{ca} is difficult to estimate because it is partly due to free convection and partly due to forced convection by wind blowing over the collector. The following formula is recommended:

$h_{ca} = 2.8 + 3.0V$ W/m^{2}K,

where V is the wind speed in meters per second. The second term $\varepsilon_c.\sigma.T_c^4$ in equation (2) is the long-wave radiation from the glass cover, and the third term $\varepsilon_c.L$ is the long-wave radiation absorbed by the glass cover from the sky.

The average index of refraction of glass for the solar spectrum is 1.526. Calculate the reflectance of one surface of glass at normal incidence and at 60 degrees. Also calculate the transmittance of two covers of nonabsorbing glass at normal incidence and at 60 degrees.

At normal incidence:

$$r = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} = \left(\frac{0.526}{2.526}\right)^2 = 0.0434$$

At an incidence angle of 60°

$$\theta_2 = \sin^{-1}\left(\frac{\sin 60}{1.526}\right) = 34.58$$

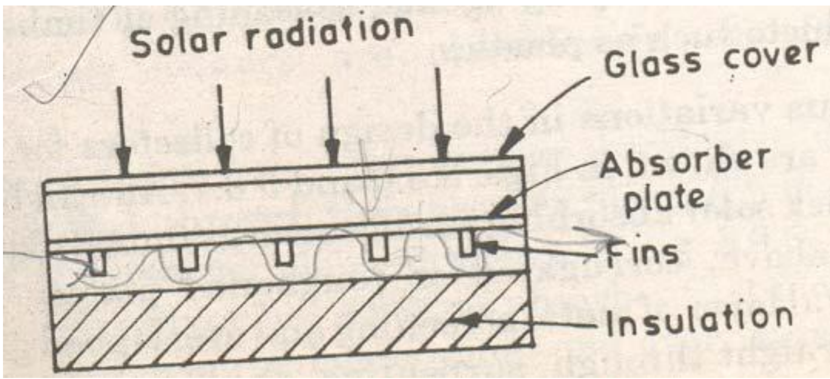
$$r = \frac{1}{2}(r_1 + r_2) = \frac{1}{2}\left[\frac{\sin^2(-25.42)}{\sin^2(94.58)} + \frac{\tan n^2(-25.42)}{\tan n^2(94.58)}\right] = 0.093$$

$$\tau_r(0) = \frac{1 - 0.0434}{1 + 3(0.0434)} = 0.85$$

$$\tau_r(60) = \frac{1}{2}\left[\frac{1 - 0.185}{1 + 3(0.185)} + \frac{1 - 0.001}{1 + 3(0.001)}\right] = 0.76$$

Solar Air Heaters

Air stream is heated by the back side of the collector plate in flat plate collector. Fins attached to the plate increase the contact surface. The back side of the collector is heavily insulated with mineral wool or some other material. If the size of collector is large, a blower is used to draw air into the collector and transmit the hot air to dryer.



The most favorable orientation of a collector for heating only is facing due south at an inclination angle to the horizontal equal to the latitude plus 15°. The use of air as the heat transport fluid eliminates both freezing and corrosion problems and small air leaks are of less concern than water leaks.

Disadvantages:

1. Need of handling larger volumes of air than liquids due to low density of air as working substance.

2. Thermal capacity of the air is low.

3. They have relatively high fluid circulation costs (especially if the rock heat storage unit is not carefully designed)

4. They have relatively large volumes of storage (roughly three times as much volume as for water heat-storage)

5. They have a higher noise level.

6. The system has difficulty of adding conventional absorption air-conditioners to air systems

7. The space is required for ducting.

Types of Air Heaters

1. Non porous absorber in which air stream does not flow through the absorber plate

2. Porous absorber that includes slit and expanded material, transpired honey comb and over lapped glass plate

1. Non-porous absorber plate type collectors: A non-porous absorber may be cooled by the air stream flowing over both sides of the plate. In most of the designs, the air flows behind the absorbing surface. Air flow above the upper surface increases the convection losses from the cover plate and therefore is not recommended if the air inlet temperature rise at the collector are large.

Transmission of the solar radiation through the transparent cover system and its absorption is identical to that of a liquid type flat-plate collector. To improve collection efficiency selective coating may be applied provided there is no much cost.

Due to low heat transfer rates, efficiencies are lower than liquid solar heaters under the same radiation intensity and temperature conditions. Performance of air heaters is improved by:

(a) Roughening the rear of the plate to promote turbulence and improve the convective heat transfer coefficient

(b) Adding fins to increase heat transfer surface. Usually turbulence is also increased which enhances the convective heat transfer. Absorption of solar radiation is improved due to surface radioactive characteristics and the geometry of the corrugations, which help in trapping the reflected radiation.

2. Collectors with porous absorbers: The main drawback of the non-porous absorber plate is the necessity of absorbing all incoming radiation over the projected area from a thin layer over the surface, which is in the order of a few microns. Unless selective coatings are used, radiative losses from the absorber plate are excessive, therefore, the collection efficiency cannot be improved. Too many surfaces and too much restriction to air flow will require a larger fan and a larger amount of energy to push the air through. The energy required for this cancels out saving from using solar energy, particularly if fan is electrical and if the amount of energy which is burned at the power plant to produce the electrical energy is included.

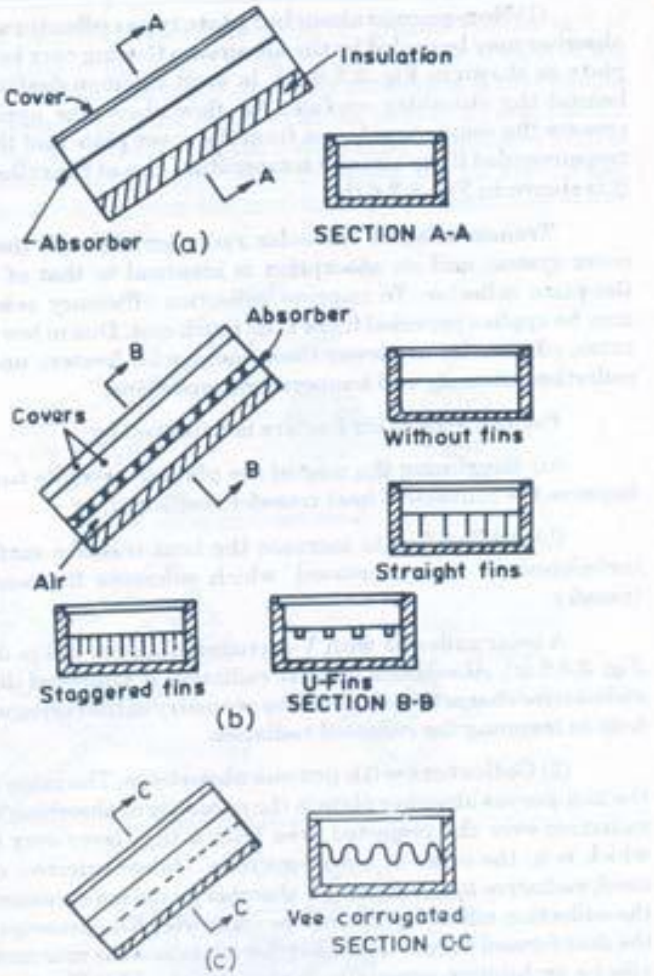
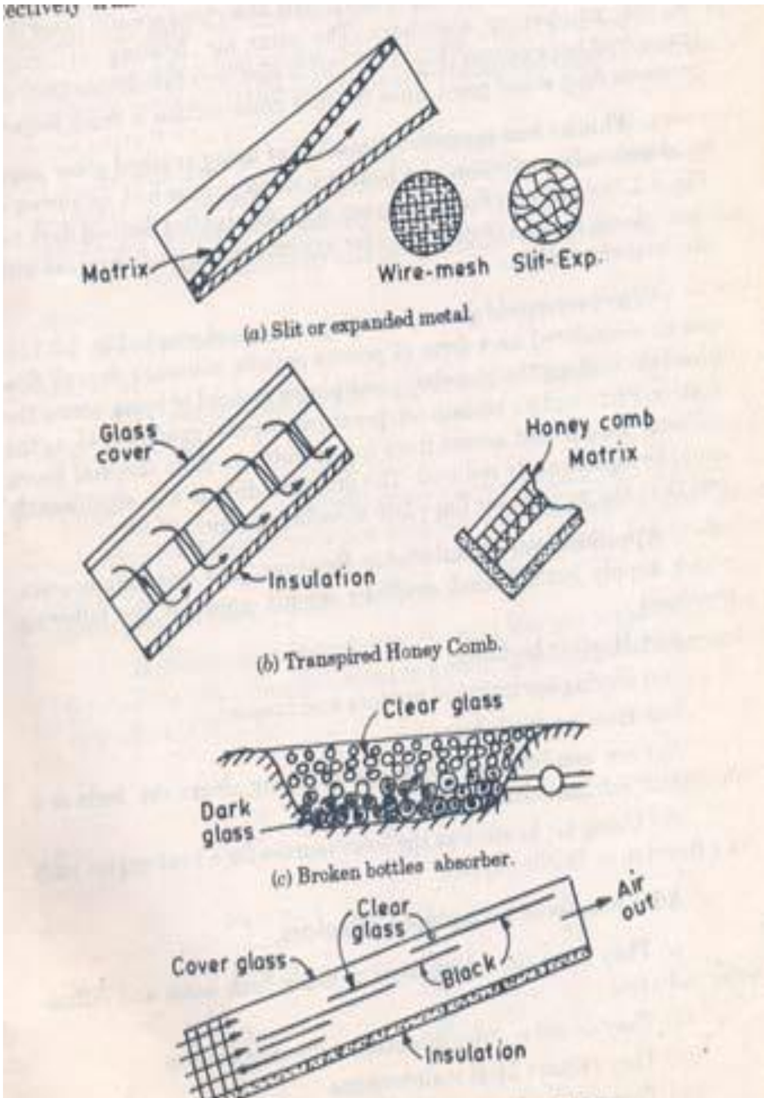


Fig. 3.3.6. Non-porous type air heaters.

Basically air heaters are classified in the following two categories.



(a) Slit or expanded metal.
(b) Transpired Honey Comb.
(c) Broken bottles absorber.
(d) Over-lapped-glass plate air-heating collector.
Fig. 3.3.7. Sketches of porous absorber-type air heaters.

The solar air heating utilizing a transpired honey comb is also favourable since the flow cross section is much higher. Crushed glass layers can be used to absorb solar radiation and heat the air. A porous bed with layers of broken bottles can be readily used for agricultural drying purposes with minimum expenditure. The overlapped glass plate air heater can be considered as a form of porous matrix, although overall flow direction is along the absorber plates instead of being across the matrix.

Applications of Solar air heaters

• Heating buildings

• Drying agricultural produce and lumber

• Heating green houses

• Air conditioning buildings utilizing desiccant beds or absorption refrigeration process

• Heat sources for a heat engine such as a Brayton or Stirling cycle

Unit – III - Solar Photovoltaic Systems

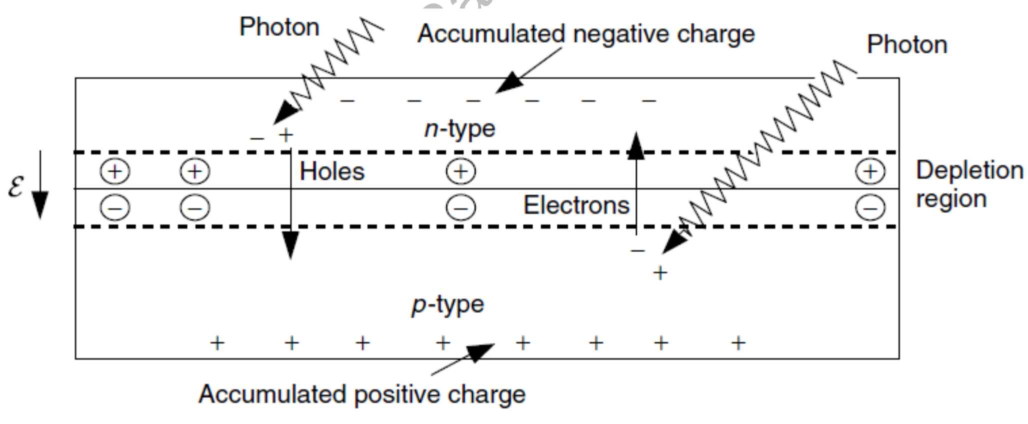
PhotoVoltaic Cells

Solar cells can convert the energy of sunlight directly into electricity. Consumer appliances used to provide services such as lighting, water pumping, refrigeration, telecommunications, and television can be run from photovoltaic electricity.

Construction :

Solar cells rely on a quantum-mechanical process known as the ‘‘photovoltaic effect’’ to produce electricity. A typical solar cell consists of a p n junction formed in a semiconductor material similar to a diode. Figure 1 shows a schematic diagram of the cross section through a crystalline solar cell. It consists of a 0.2–0.3mm thick monocrystalline or polycrystalline silicon wafer having two layers with different electrical properties formed by ‘‘doping’’ it with other impurities (e.g., boron and phosphorus).

Working : An electric field is established at the junction between the negatively doped (using phosphorus atoms) and the positively doped (using boron atoms) silicon layers. If light is incident on the solar cell, the energy from the light (photons) creates free charge carriers, which are separated by the electrical field. An electrical voltage is generated at the external contacts, so that current can flow when a load is connected. The photocurrent (Iph), which is internally generated in the solar cell, is proportional to the radiation intensity.



IV curve of a solar cell

The IV curve of a solar cell is the superposition of the IV curve of the solar cell diode in the dark with the light-generated current. The light has the effect of shifting the IV curve down into the fourth quadrant where power can be extracted from the diode. Illuminating a cell adds to the normal "dark" currents in the diode so that the diode law becomes:

$$I = I_0 \left[\exp\left(\frac{qv}{nKT}\right) - 1\right] - I_L$$

where I_L = light generated current.

The equation for the IV curve in the first quadrant is:

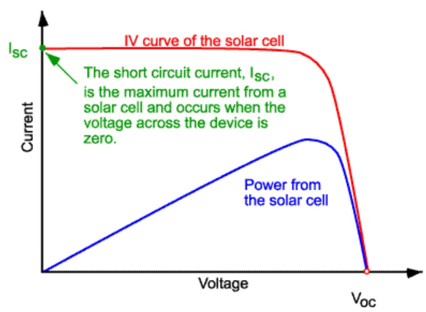
$$\boldsymbol{I=I_L-I_0\,[\exp\,(\tfrac{qv}{nKT})\;-1\,]}$$

The -1 term in the above equation can usually be neglected. The exponential term is usually >> 1 except for voltages below 100 mV. Further, at low voltages the light generated current I_L dominates the I_0 (...)term so the -1 term is not needed under illumination.

$$I=I_L-I_0[\exp(\tfrac{qv}{nKT})\,]$$

Several important parameters which are used to characterise solar cells are discussed in the following pages. The short-circuit current (I_{SC}), the open-circuit voltage (V_{OC}), the fill factor (FF) and the efficiency are all parameters determined from the IV curve.

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as I_{SC}, the short-circuit current is shown on the IV curve below.



IV curve of a solar cell showing the short-circuit current.

The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell.

The short-circuit current depends on a number of factors which are described below:

- **the area of the solar cell.** To remove the dependence of the solar cell area, it is more common to list the short-circuit current **density** (J_{sc} in mA/cm^2) rather than the short-circuit current;
- **the number of photons** (i.e., the power of the incident light source). Isc from a solar cell is directly dependant on the light intensity as discussed in Effect of Light Intensity;
- **the spectrum of the incident light.** For most solar cell measurement, the spectrum is standardised to the AM1.5 spectrum;
- **the optical properties** (absorption and reflection) of the solar cell (discussed in Optical Losses); and

- **the collection probability** of the solar cell, which depends chiefly on the surface passivation and the minority carrier lifetime in the base.

When comparing solar cells of the same material type, the most critical material parameter is the diffusion length and surface passivation. In a cell with perfectly passivated surface and uniform generation, the equation for the short-circuit current can be approximated as:

$$J_{SC} = qG\left(L_n + L_p\right)$$

where G is the generation rate, and L_n and L_p are the electron and hole diffusion lengths respectively. Although this equation makes several assumptions which are not true for the conditions encountered in most solar cells, the above equation nevertheless indicates that the short-circuit current depends strongly on the generation rate and the diffusion length.

Silicon solar cells under an AM1.5 spectrum have a maximum possible current of 46 mA/cm^2. Laboratory devices have measured short-circuit currents of over 42 mA/cm^2, and commercial solar cell have short-circuit currents between about 28 mA/cm^2 and 35 mA/cm^2.

In an ideal device every photon above the bandgap gives one charge carrier in the external circuit so the the highest current is for the lowest bandgap.

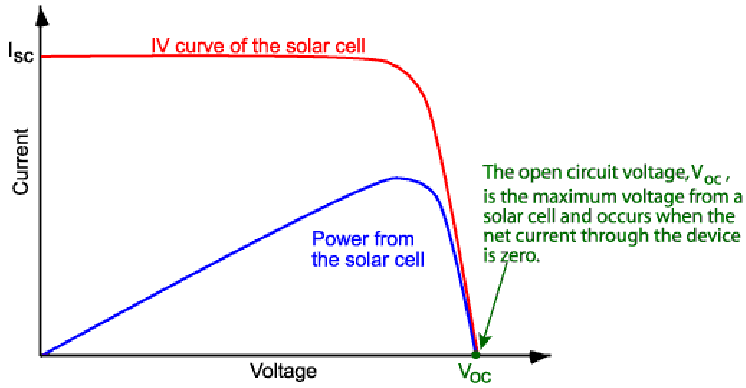
Illuminated Current and Short Circuit Current (I_L or I_{sc} ?)

I_L is the light generated current inside the solar cell and is the correct term to use in the solar cell equation. At short circuit conditions the externally measured current is $I_{sc.}$ Since I_{sc} is usually equal to I_L, the two are used interchangeably and for simplicity and the solar cell equation is written with I_{sc} in place of I_L. In the case of very high series resistance (> 10 Ωcm^2) I_{sc} is less than I_L and writing the solar cell equation with I_{sc} is incorrect.

Another assumption is that the illumination current I_L is solely dependent on the incoming light and is independent of voltage across the cell. However, I_L varies with voltage in the case of drift-field solar cells and where carrier lifetime is a function of injection level such as defected multicrystalline materials.

Open-Circuit Voltage

The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The open-circuit voltage is shown on the IV curve below.



IV curve of a solar cell showing the open-circuit voltage.

An equation for V_{oc} is found by setting the net current equal to zero in the solar cell equation to give:

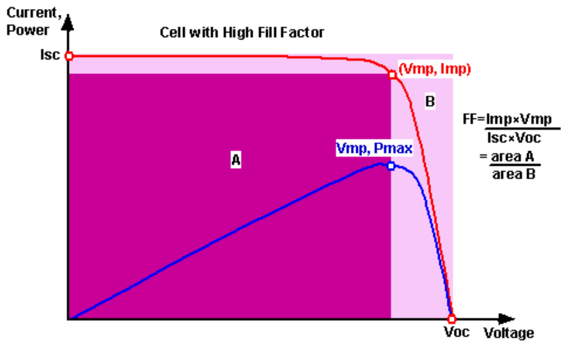
$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

The above equation shows that V_{oc} depends on the saturation current of the solar cell and the light-generated current. While I_{sc} typically has a small variation, the key effect is the saturation current, since this may vary by orders of magnitude. The saturation current, I_0 depends on recombination in the solar cell. Open-circuit voltage is then a measure of the amount of recombination in the device. Silicon solar cells on high quality single crystalline material have open-circuit voltages of up to 730 mV under one sun and AM1.5 conditions, while commercial devices on multicrystalline silicon typically have open-circuit voltages around 600 mV.

V_{OC} as function of bandgap for a cell with AM 0 and AM 1.5. The V_{OC} increases with bandgap as the recombination current falls. There is drop off in V_{OC} at very high band gaps due to the very low I_{SC}.

fill factor

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}. Graphically, the FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the IV curve. The FF is illustrated below.



Graph of cell output current (red line) and power (blue line) as function of voltage. Also shown are the cell short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) points, as well as the maximum power point (V_{mp}, I_{mp}). Click on the graph to see how the curve changes for a cell with low FF.

As FF is a measure of the "squareness" of the IV curve, a solar cell with a higher voltage has a larger possible FF since the "rounded" portion of the IV curve takes up less area. The maximum theoretical FF from a solar cell can be determined by differentiating the power from a solar cell with respect to voltage and finding where this is equal to zero. Hence:

The above equations show that a higher voltage will have a higher possible FF. However, large variations in open-circuit voltage within a given material system are relatively uncommon. For example, at one sun, the difference between the maximum open-circuit voltage measured for a silicon laboratory device and a typical commercial solar cell is about 120 mV, giving maximum FF's respectively of 0.85 and 0.83. However, the variation in maximum FF can be significant for solar cells made from different materials. For example, a GaAs solar cell may have a FF approaching 0.89.

The above equation also demonstrates the importance of the ideality factor, also known as the "n-factor" of a solar cell. The ideality factor is a measure of the junction quality and the type of recombination in a solar cell. For the simple recombination mechanisms discussed in Types of Recombination, the n-factor has a value of 1. However, some recombination mechanisms, particularly if they are large, may introduce recombination mechanisms of 2. A high n-value not only degrades the FF, but since it will also usually signal high recombination, it gives low open-circuit voltages.

A key limitation in the equations described above is that they represent a maximum possible FF, although in practice the FF will be lower due to the presence of parasitic resistive losses, which are discussed in Effects of Parasitic Resistances. Therefore, the FF is most commonly determined from measurement of the IV curve and is defined as the maximum power divided by the product of I_{sc}*V_{oc}, i.e.:

$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}}$$

Efficiency

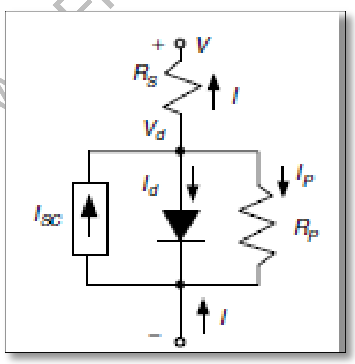
The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. Terrestrial solar cells are measured under AM1.5 conditions and at a temperature of 25°C. Solar cells intended for space use are measured under AM0 conditions. The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$P_{max} = V_{OC} I_{SC} FF$$

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

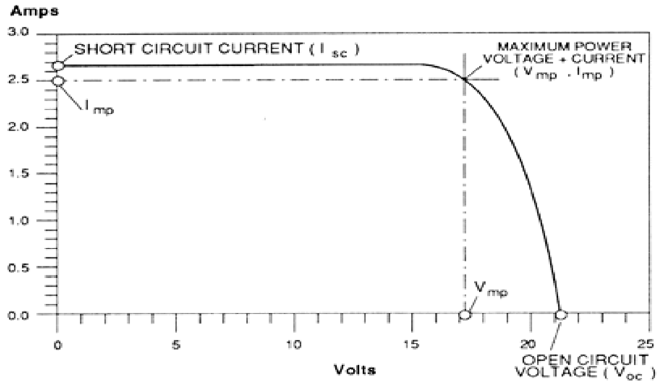
where V_{oc} is the open-circuit voltage;
where I_{sc} is the short-circuit current; and
where FF is the fill factor
where η is the efficiency.

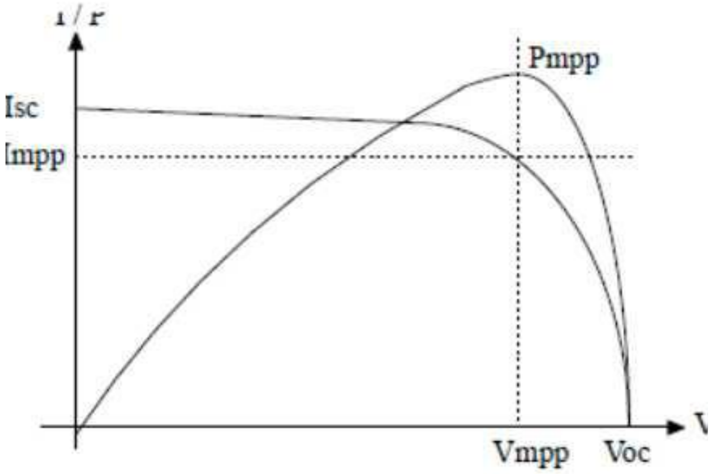
A Equivalent Circuit of a PV cell:



A simplified equivalent circuit of a solar cell consists of a current source in parallel with a diode as shown in Fig. 2a. A variable resistor is connected to the solar cell generator as a load. When the terminals are short-circuited, the output voltage and also the voltage across the diode are both zero. The entire photocurrent (Iph) generated by the solarradiation then flows to the output. The solar cell current has its maximum (Isc).

A solar cell can be operated at any point along its characteristic current–voltage curve, as shown in Fig. 3. Two important points on this curve are the open circuit voltage (Voc) and short-circuit current (Isc). The open-circuit voltage is the maximum voltage at zero current, whereas the short circuit current is the maximum current at zero voltage. For a silicon solar cell under standard test conditions, Voc is typically 0.6–0.7 V, and Isc is typically 20–40mA for every square centimeter of the cell area. To a good approximation, Isc is proportional to the illumination level, whereas Voc is proportional to the logarithm of the illumination level.





A plot of power (P) against voltage (V) for this device shows that there is a unique point on the I-V curve at which the solar cell will generate maximum power. This is known as the maximum power point (Vmp, Imp). To maximize the power output, steps are usually taken during fabrication to maximize the three basic cell parameters: open-circuit voltage, short-circuit current, and fill factor (FF)—a term describing how ‘‘square’’ the I-V curve is, given by

$$\text{Fill Factor} = \frac{Vmpp * Impp}{Vsc * Isc}$$

Advantages of PV Cells

Solar energy produces no air pollution, thermal pollution, or water pollution, nor does acquiring solar energy disrupt a natural environment. The sun simply shines whether we use the energy or not. Solar energy is a completely sustainable energy source. Solar energy is one of the last free resources available to us, and it is available to us in such vast quantities we could never use all of it at any given time. Because the sun shines everywhere, and not just where people are, it can be used in places where electricity may not be otherwise available or practical.

Solar electric generation has the highest power density (global mean of 170 W/m^2) among renewable energies.[88]

Solar power is pollution-free during use. Production end-wastes and emissions are manageable using existing pollution controls. End-of-use recycling technologies are under .

PV installations can operate for 100 years or even more with little **maintenance or intervention after their initial set-up,** so after the initial capital cost of building any solar power plant**, operating costs are extremely low** compared to existing power technologies.

Grid-connected solar electricity can be used locally thus reducing transmission/distribution losses (transmission losses in the US were approximately 7.2% in 1995).[93]

Compared to fossil and nuclear energy sources, very little research money has been invested in the development of solar cells, so there is considerable room for improvement. Nevertheless, experimental high efficiency solar cells already have efficiencies of over 40% in case of concentrating photovoltaic cells[94] and efficiencies are rapidly rising while mass-production costs are rapidly falling.

Disadvantages of PV cells:

- **Less efficient and costly equipment :**Most photovoltaics are only 17-20% efficient. There are some experimental and developmental technologies being used in laboratories and by the space industry that are more efficient, but even those maximize at 43%. However, no energy is output in delivering the energy source to the PV panel; it is already right there to use, and does not require any initial energy or materials to get it to the site of use.
- **Intermittently available: & Reliability Depends On Location**
- Because the sun is not shining constantly all the time in any given location, it cannot be counted on for continuous energy. The amount of solar energy available to an entity depends completely on the latitude, climate, time of day, and amount of air pollution present. Clouds or particulate matter in the air will lessen the amount of solar energy available to use in a PV cell. Higher latitudes do not receive as intense of sunlight as more tropical areas, and therefore will not be able to produce as much power through photovoltaics. All of these limit the degree to which photovoltaics can be used.

- **Environmental Impact of PV Cell Production :** The entire production process does have a negative environmental impact, primarily from the energy required to produce the PV cell. There is a very small amount of heavy metals, such as lead and cobalt, produced in the purification of the materials being used, but that is far outshadowed by the amount of carbon dioxide and other air pollutants produced when the electricity necessary for production is generated. Replacing conventional, fossil fuel based electrical power generation will significantly reduce this impact. Furthermore, because the site of heavy metal toxicity is kept isolated at just production facilities, it can be more closely monitored and regulated than if the materials were more wide-spread.

- Exhaustion of raw materials
- CO_2 emission during fabrication process
- Acidification
- Disposal problems of hazardous semiconductor material

Peak watt is the amount of power output a PV module produces at Standard Test Conditions (STC) of a module operating temperature of 25°C in full noontime sunshine (irradiance) of 1,000 Watts per square meter)

Applications of PV Cells

- **Water Pumping:** PV powered pumping systems are excellent ,simple ,reliable – life 20 yrs
- **Commercial Lighting:** PV powered lighting systems are reliable and low cost alternative. Security, billboard sign, area, and outdoor lighting are all viable applications for PV
- **Consumer electronics:** Solar powered watches, calculators, and cameras are all everyday applications for PV technologies.
- **Telecommunications**

Residential Power: A residence located more than a mile from the electric grid can install a PV system more inexpensively than extending the electric grid

ARRAY DESIGN

The major factors influencing the electrical design of the solar array are as follows:

• The sun intensity

• The sun angle

• The load matching for maximum power

• The operating temperature

These factors are discussed in the following subsections.

***SUN INTENSITY*:**

The magnitude of the photocurrent is maximum under a full bright sun (1.0sun). On a partially sunny day, the photocurrent diminishes in direct proportion to the sun intensity. At a lower sun intensity, the I-V characteristic

shifts downward as shown above. On a cloudy day, therefore, the short-circuit current decreases significantly. The reduction in the open-circuit voltage, however, is small. The photo conversion efficiency of the cell is insensitive to the solar radiation in the practical working range. This means that the conversion efficiency is the same on a bright sunny day as on a cloudy day.

We get a lower power output on a cloudy day only because of the lower solar energy impinging on the cell.

***SUN ANGLE*:**

The cell output current is given by I = Iocosθ, where Io is the current with normal sun (reference), and θ is the angle of the sun line measured from the normal. This cosine law holds well for sun angles ranging from 0 to about 50°.

Beyond 50°, the electrical output deviates significantly from the cosine law, and the cell generates no power beyond 85°, although the mathematical cosine law predicts 7.5% power generation.

SHADOW EFFECT:

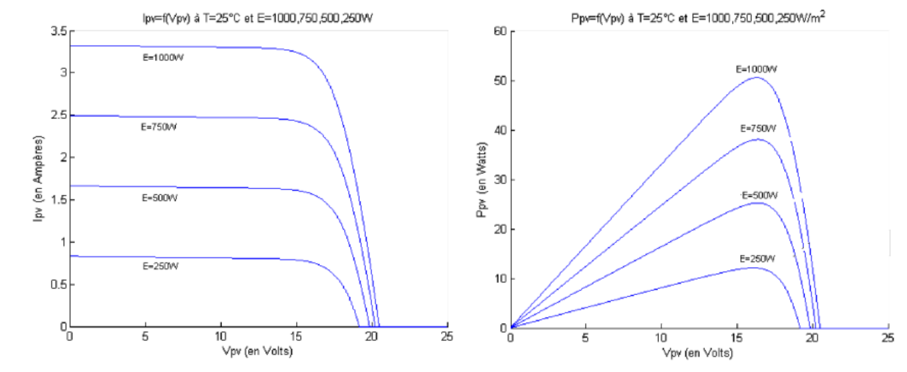


Fig.3. Solar irradiance influence on PV characteristic, at 25°C
Current versus Voltage and Power versus Voltage of the PV characteristics

The array may consist of many parallel strings of series-connected cells.. A large array may get partially shadowed due to a structure interfering with the sun line. If a cell in a long series string gets completely shadowed, it loses the photo-voltage but still must carry the string current by virtue of its being in series with all other cells operating in full sunlight. Without internally generated voltage, the shadowed cell cannot produce power. Instead, it acts as a load, producing local I^2R loss and heat. The remaining cells in the string must work at higher voltage to make up the loss of the shadowed cell voltage.

TEMPERATURE EFFECTS:

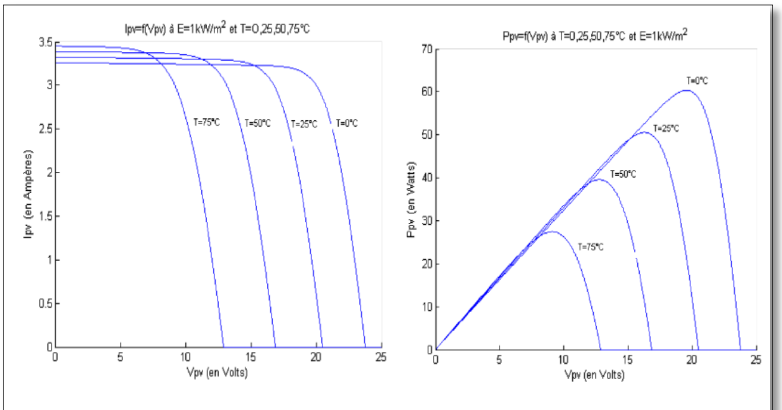


Fig.4. Temperature influence on PV characteristic, at 1000 W/m²
Current versus Voltage and Power versus Voltage of the PV characteristics

With increasing temperature, the short-circuit current of the cell increases, whereas the open-circuit voltage decreases. The effect of temperature on PV power is quantitatively evaluated by examining the effects on the current and the voltage separately

EFFECT OF CLIMATE:

On a partly cloudy day, the PV module can produce up to 80% of its full sun power. It can produce about 30% power even with heavy clouds on an extremely overcast day. Snow does not usually collect on the module, because it is angled to catch the sun. If snow does collect, it quickly melts. Mechanically, the module is designed to withstand golf-ball-size hail.

ELECTRICAL LOAD MATCHING:

The operating point of any power system is the intersection of the source line and the load line. If the PV source having the I-V and P-V characteristics shown in Figure is supplying power to a resistive load R1, it will operate at point A1.If the load resistance increases to R2 or R3, the operating point moves to A2 or A3, respectively. The maximum power is extracted from the module when the load resistance is R2. Such a load that matches with the source is always necessary for the maximum power extraction from a PV source.

SUN TRACKING:

More energy is collected by the end of the day if the PV module is installed on a tracker with an actuator that follows the sun. There are two types of sun trackers:

• One-axis tracker, which follows the sun from east to west during the day.

• Two-axis tracker, which follows the sun from east to west during the day, and from north to south during the seasons of the year.

BALANCE-OF-SYSTEM

A Solar PV Balance-of-System or BOS refers to the components and equipment that move DC energy produced by solar panels through the conversion system which in turn produces AC electricity.

Most often, BOS refers to all components of a PV system other than the modules. In addition to inverters and racking, this includes the cables/wires, switches, enclosures, fuses, ground fault detectors, and more... BOS applies to all types of solar applications (i.e. commercial, residential, agricultural, public facilities, and solar parks)

BOS components include the majority of the pieces, which make up roughly 10%-50% of solar purchasing and installation costs, and account for the majority of maintenance requirements. Essentially it is through the balance-of-system components that we: control cost, increase efficiency, and modernize solar PV systems.

Introduction

This calculation outlines the sizing of a standalone solar photovoltaic (PV) power system. Standalone PV systems are commonly used to supply power to small, remote installations (e.g. telecoms) where it isn't practical or cost-efficient to run a transmission line or have alternative generation such as diesel gensets.
Although this calculation is biased towards standalone solar PV systems, it can also be used for hybrid systems that draw power from mixed sources (e.g. commercial PV, hybrid wind-PV systems, etc). Loads must be adjusted according to the desired amount that the solar PV system will supply.
This calculation is based on crystalline silicon PV technology. The results may not hold for other types of solar PV technologies and the manufacturer's recommendations will need to be consulted.

Why do the calculation?

This calculation should be done whenever a solar PV power system is required so that the system is able to adequately cater for the necessary loads. The results can be used to determine the ratings of the system components (e.g. PV array, batteries, etc).

When to do the calculation?

The following *pre-requisite information* is required before performing the calculation:

- Loads required to be supported by the solar PV system
- Autonomy time or minimum tolerable downtime (i.e. if there is no sun, how long can the system be out of service?)
- GPS coordinates of the site (or measurements of the solar insolation at the site)
- Output voltage (AC or DC)

Calculation Methodology

The calculation is loosely based on AS/NZS 4509.2 (2002) "Standalone power systems - System design guidelines". The methodology has the following six steps:

- Step 1: Estimate the solar irradiation available at the site (based on GPS coordinates or measurement)
- Step 2: Collect the loads that will be supported by the system
- Step 3: Construct a load profile and calculate design load and design energy
- Step 4: Calculate the required battery capacity based on the design loads
- Step 5: Estimate the output of a single PV module at the proposed site location
- Step 6: Calculate size of the PV array

MAXIMUM POWER POINT TRACKING (MPPT)

- **MPPT is an** *algorithm* used for extracting maximum available power from an energy source, under certain conditions.
- MPPT is not a mechanical tracking system It is a fully electronic system

In case of a resistive load, as *R* increases, the operating point where the PV and resistance *I –V* curves intersect moves along the PV *I –V* curve from left to right. In fact, that suggests a simple way to actually measure the *I –V* curve for PV module. By using a variable resistance, called a potentiometer, or *pot,* as the load, and then varying its resistance, pairs of current and voltage can be obtained, which can be plotted to give the module *I –V* curve. Since power delivered to any load is the product of current and voltage, there will be one particular value of resistance that will result in maximum power: Rm=Vm/Im, where *Vm* and *Im* are the voltage and current at the maximum power point (MPP).

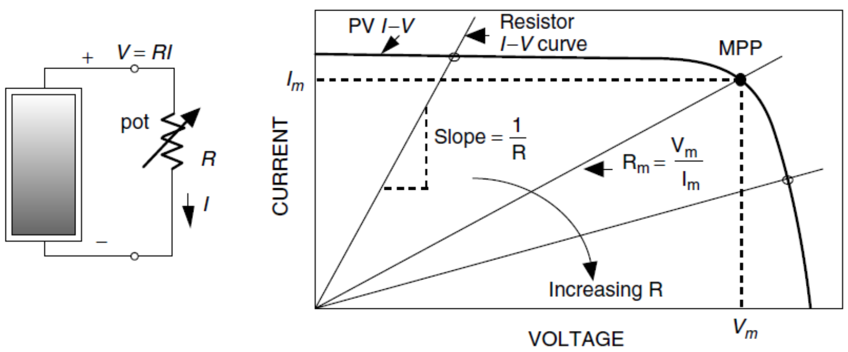
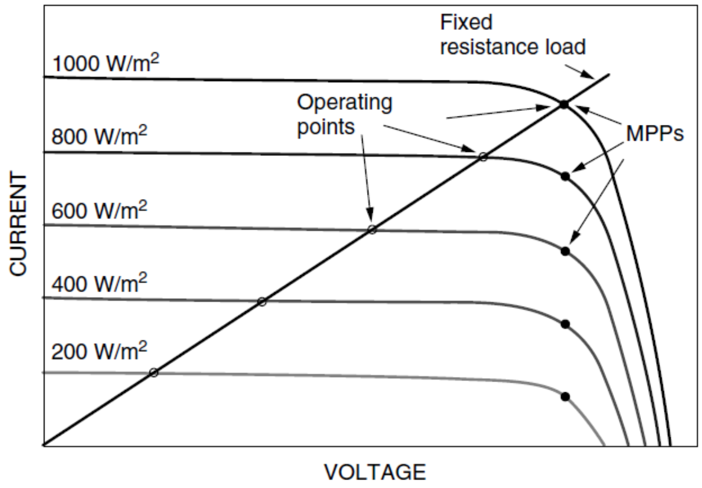


Figure 9.5 A module supplying power to a resistive load. As resistance changes, the operating point moves around on the PV *I – V* curve.



Under the special conditions at which modules are tested, the MPP corresponds to the rated voltage *VR* and current *IR* of the module. That means the best value of resistance, for maximum power transfer, should be *VR*/*IR* under 1-sun, 25◦C, AM 1.5 conditions. As Fig. 9.6 shows, however, with a fixed resistance the operating point slips off the MPP as conditions change and the module becomes less and less efficient. Later, a device called a *maximum power point tracker* (MPPT) will be introduced, the purpose of which is to keep the PVs operating at their highest efficiency point at all times.

The efficiency of a PV module with a fixed resistance load designed for 1-sun conditions will decline with changing insolation. The solid maximum power point (MPP) dots show the operating points that would result in maximum PV efficiency.

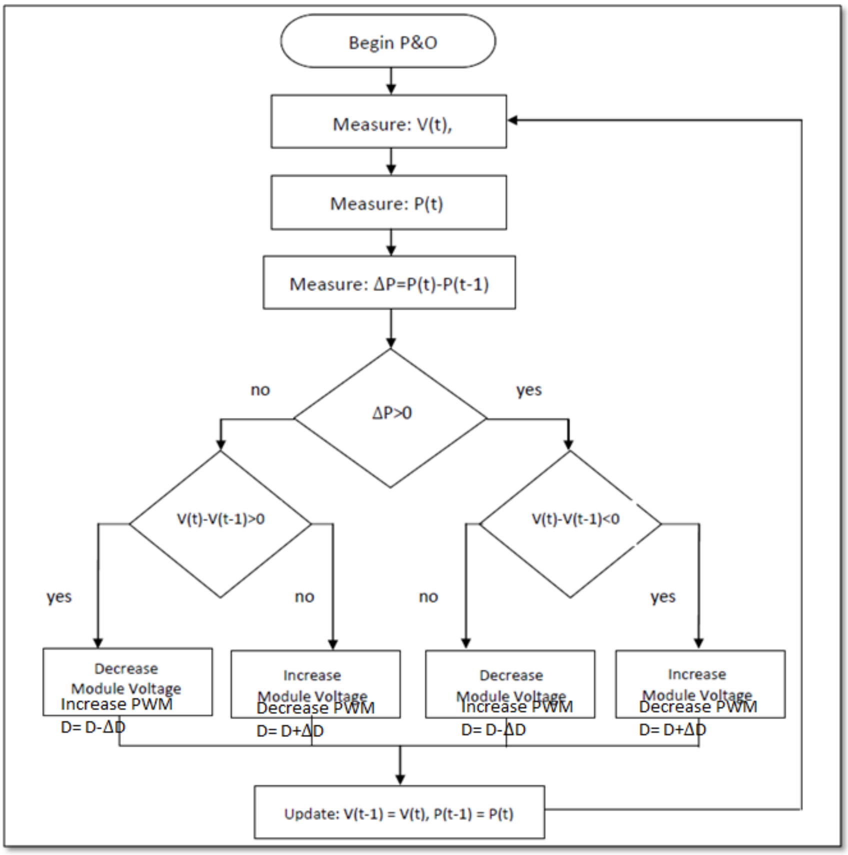
Some of the Common MPPT Algorithms :

1.Perturb and observe Method (P & O Method) :

In this method the controller adjusts the voltage by a small amount from the array and measures power; if the power increases, further adjustments in that direction are tried until power no longer increases. This is called the perturb and observe method and is most common, although this method can result in oscillations of power output. It is referred to as a *hill climbing* method, because it depends on the rise of the curve of power against voltage below the maximum power point, and the fall above that point. Perturb and observe is the most commonly used MPPT method due to its ease of implementation. Perturb and observe method may result in top-level efficiency, provided that a proper predictive and adaptive hill climbing strategy is adopted.

- **Advantages :** simple to implement, High efficiency

- **Disadvantages : P**ower obtained *oscillates* around the maximum power point, in steady state operation .



As the name suggests, this method works by perturbing the system by increasing or decreasing the PV module operating voltage and observing its impact on the output power supplied by the module. As shown by the flow chart in *Figure 1*, PV system controller change PV module output with a small step in each control cycle. The step size is generally fixed and it can be increased or decreased. Both PV module output voltage and output current can be the control object, so this process is called “perturbation”. Then, by comparing PV array output power of the cycles before and after the perturbation, this method determines the maximum power point.

If the power output is increased at a particular cycle, then according to this method, the system controller will change the step in the same direction as the previous cycle and checks for further increase in power of PV module. While if the output power observed is decreased, then the system controller change the step in direction opposite to the previous cycle. In this way, the actual operating point of PV module can move closer to the maximum power point, and finally in steady state, oscillates around the maximum power point in a very small area. This causes a power loss which depends on the step width of a single perturbation. If the step width is large, the MPPT algorithm will be responding quickly to sudden changes in operating conditions with the trade-off of increased losses under stable or slowly changing conditions. If the step width is very small the losses under stable or slowly changing conditions will be reduced, but the system will be only able to respond very slowly to rapid changes in temperature or insolation. The value for the ideal step width is system dependent and needs to be determined experimentally.

2. Incremental conductance

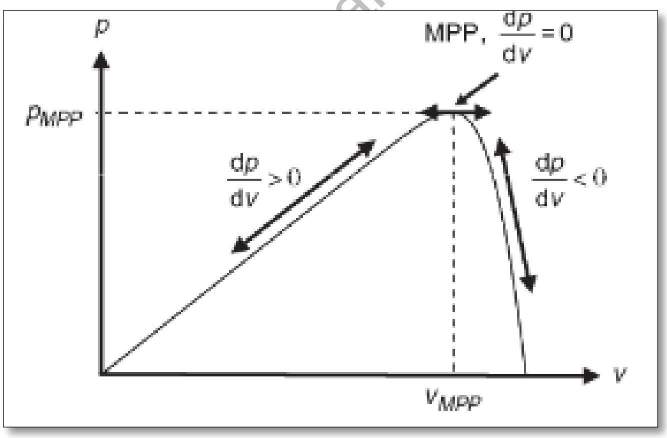
In the incremental conductance method, the controller measures incremental changes in PV array current and voltage to predict the effect of a voltage change. This method requires more computation in the controller, but can track changing conditions more rapidly than the perturb and observe method (P&O). Like the P&O algorithm, it can produce oscillations in power output.[14] This method utilizes the incremental conductance (dI/dV) of the photovoltaic array to compute the sign of the change in power with respect to voltage (dP/dV).[15]

The incremental conductance method computes the maximum power point by comparison of the incremental conductance (I_Δ / V_Δ) to the array conductance (I / V). When these two are the same (I / V = I_Δ / V_Δ), the output voltage is the MPP voltage. The controller maintains this voltage until the irradiation changes and the process is repeated

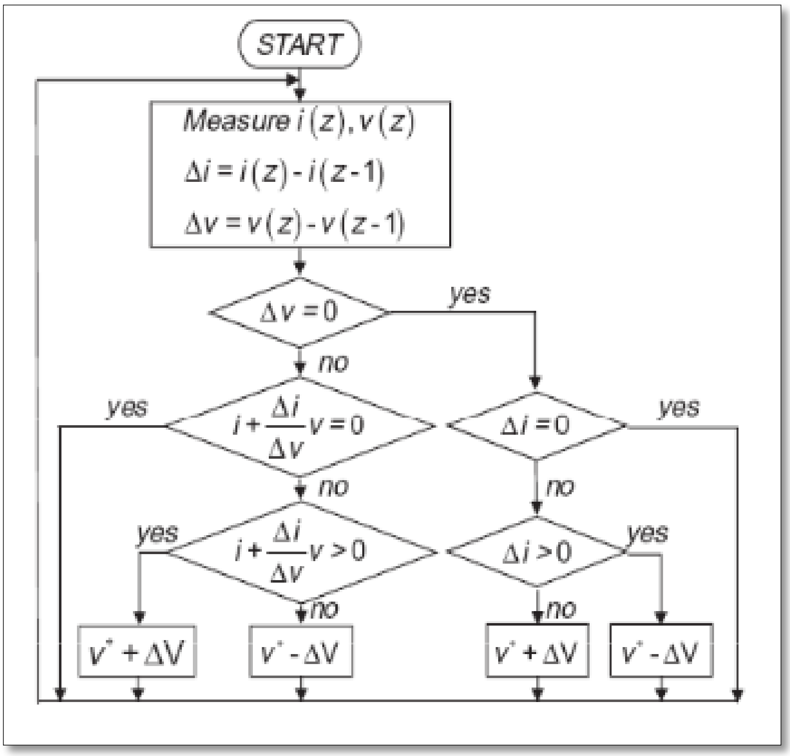
Based on slope of p-v curve:

$$\frac{dp}{dv} = \frac{d(vi)}{dv} = i + v\frac{di}{dv} \qquad \frac{i}{v} + \frac{di}{dv} = 0$$

$$di \approx \Delta i = i(z) - i(z-1)$$
$$dv \approx \Delta v = v(z) - v(z-1)$$



Zero at MPP, Negative on right of MPP , Positive on left of MPPThe MPP can be tracked by comparing the instantaneous conductance (I/V) to the I incremental conductance.



Types of PV Power Systems

1.Grid connected or *utility interactive* (UI) system in which PVs are supplying power to a building. The PV array may be pole-mounted, or attached externally to the roof, or it may become an integral part of the skin of the building itself. PV roofing shingles and thin-film PVs applied to glazing serve dual purposes, power, and building structure, and when that is the case the system is referred to as *building-integrated photovoltaics* (BIPV).

The photovoltaics in a grid-connected system deliver dc power to a power conditioning unit (PCU) that converts dc to ac and sends power to the building. If the PVs supply less than the immediate demand of the building, the PCU draws supplementary power from the utility grid, so demand is always satisfied. If, at any moment, the PVs supply more power than is needed, the excess is sent back onto the grid, potentially spinning the electric meter backwards. The system is relatively simple since failure-prone batteries are not needed for back-up power, although sometimes they may be included if utility outages are problematic.

Features : Their relative simplicity can result in high reliability; their maximum-power-tracking unit assures high PV efficiency; their potential to be integrated into the structure of the building means that there are no additional costs for land.

3.off-grid, stand-alone system

with battery storage and a generator for back-up power. In this particular system, an inverter converts battery dc voltages into ac for conventional household electricity, but in very simple systems everything may be run on dc and no inverter may be necessary. The charging function of the inverter allows the generator to top up the batteries when solar is insufficient.

Stand-alone PV systems can be very cost effective in remote locations where the only alternatives may be noisy, high-maintenance generators burning relatively expensive fuel, or extending the existing utility grid to the site, which can cost thousands of dollars per mile. These systems suffer from several inefficiencies,

however, including battery losses and the fact that the PVs usually operate well off of the their most efficient operating point. Moreover, inefficiencies are

often increased by mounting the array at an overly steep tilt angle to supply relatively uniform amounts of energy through the seasons, rather than picking an angle that results in the maximum possible annual energy delivery. These systems also require much more attention and care than stand-alone systems; and if generator usage is to be minimized (or eliminated), those using the energy mayneed to modify their lifestyles to accommodate the uneven availability of power as the seasons change or the weather deteriorates.

3.Photovoltaics directly coupled to their loads, without any batteries or major power conditioning equipment. The most common example is PV water pumping in which the wires from the array are connected directly to the motor running a pump.

When the sun shines, water is pumped. There is no electric energy storage, but potential energy may be stored in a tank of water up the hill for use whenever it is needed. These systems are the ultimate in simplicity and reliability and are the least costly as well. But they need to be carefully designed to be efficient.

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Stand-alone PV systems can be very cost effective in remote locations where the only alternatives may be noisy, high-maintenance generators burning relatively expensive fuel, or extending the existing utility grid to the site, which can cost thousands of dollars per mile. These systems suffer from several inefficiencies,however, including battery losses and the fact that the PVs usually operate well off of the their most efficient operating point. Moreover, inefficiencies are often increased by mounting the array at an overly steep tilt angle to supply relatively uniform amounts of energy through the seasons, rather than picking an angle that results in the maximum possible annual energy delivery. These systems also require much more attention and care than stand-alone systems; and if generator usage is to be minimized (or eliminated), those using the energy may need to modify their lifestyles to accommodate the uneven availability of power as the seasons change or the weather deteriorates.

3.Photovoltaics directly coupled to their loads, without any batteries or major power conditioning equipment. The most common example is PV water pumping in which the wires from the array are connected directly to the motor running a pump.

When the sun shines, water is pumped. There is no electric energy storage, but potential energy may be stored in a tank of water up the hill for use whenever it is needed. These systems are the ultimate in simplicity and reliability and are the least costly as well. But they need to be carefully designed to be efficient.

Unit – IV - Wind Energy

The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator. The turbine is mounted on a tall tower to enhance the energy capture. Numerous wind turbines are installed at one site to build a wind farm of the desired power generation capacity. Obviously, sites with steady high wind produce more energy over the year.

Two distinctly different configurations are available for turbine design, the horizontalaxis configuration (Figure 3.1) and the vertical-axis configuration. The horizontal-axis machine has been the standard in Denmark from the beginning of the wind power industry. Therefore, it is often called the Danish wind turbine. The vertical-axis machine has the shape of an egg beater and is often called the Darrieus rotor after its inventor. It has been used in the past because of its specific structural advantage. However, most modern wind turbines use a horizontal axis design. Except for the rotor, most other components are the same in both designs, with some differences in their placements.

SPEED AND POWER RELATIONS

The kinetic energy in air of mass m moving with speed V is given by the following in joules:

$$\text{kinetic energy} = \frac{1}{2}mV^2 \tag{1}$$

The power in moving air is the flow rate of kinetic energy per second in watts:

$$\text{power} = \frac{1}{2}(\text{mass flow per second})V^2 \tag{2}$$

If

P= mechanical power in the moving air (watts),

ρ = air density (kg/m3),

A= area swept by the rotor blades (m2), and

V= velocity of the air (m/sec),

then the volumetric flow rate is AV, the mass flow rate of the air in kilograms per second is ρAV, and the mechanical power coming in the upstream wind is given by the following in watts:

$$P = \frac{1}{2}(\rho AV)V^2 = \frac{1}{2}\rho AV^3 \tag{3}$$

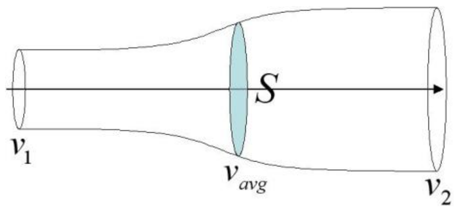
Two potential wind sites are compared in terms of the specific wind power expressed in watts per square meter of area swept by the rotating blades. It is also referred to as the power density of the site, and is given by the following expression in watts per square meter of the rotor-swept area:

$$\text{specific power of the site} = \frac{1}{2}\rho V^3 \tag{4}$$

This is the power in the upstream wind. It varies linearly with the density of the air sweeping the blades and with the cube of the wind speed. The blades cannot extract all of the upstream wind power, as some power is left in the downstream air that continues to move with reduced speed.

POWER EXTRACTED FROM THE WIND

Betz Criteria



The Betz results are at first glance a little hard to understand. For example, why is the maximum Betz efficiency 59.3%, when a speed ratio of [V2/V1 = .333] implies the air passing through the rotor has lost 88.9% of its kinetic energy? The left side of the betz curve shows a maximum efficiency of 50% when the exiting air (V2) has no axial velocity. Is this realistic?

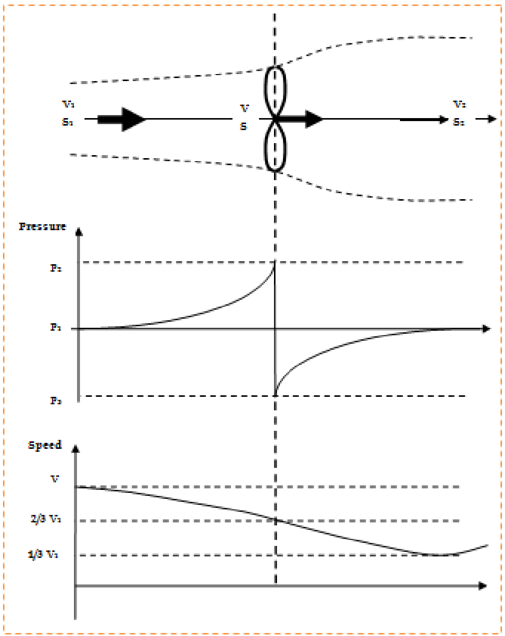
This depicts dynamic fluid throughout a thin rotor (blue), which provides the energy to the rotor and loses some kinetic energy with reducing the velocity v1 to v2.

The answer to the second question is easy. 50% efficiency at [V2 = 0] is not realistic, the model breaks down at very low exit speeds. The Betz model assumes a constant density fluid and that implies the cross sectional area of the flow varies inversely with axial speed. At [V2 = 0] the cross sectional area is infinite! Mathematically the exiting air does not 'pile up' because it is spreading radially, but radial kinetic energies are not accounted for in the Betz model.

To show that 59.3% Betz efficiency is indeed consistent with a loss of 88.9% of kinetic energy in the air passing through the rotor a physical picture is helpful. The equations for power extracted from the air flow apply to the 'milk bottle' shaped flow shown in the figure at the beginning of this article. The upstream flow (V1) has a cross sectional area less than the rotor area (S). As the flow approaches the rotor, it begins to lose energy, and as it passes through the rotor the equations show it expands to exactly the rotor area (S).

The last step in calculating the Betz efficiency (C_p) is to divide the calculated power extracted from the flow by a reference power value. The Betz analysis uses for its power reference, reasonably, the power of air upstream moving at V1 contained in a cylinder with the cross sectional area of the rotor (S).

The key to understanding why the Betz limit is lower than implied by the speed ratio is to understand that some of the air in the Betz reference cylinder does not pass through the rotor. The area of the flow that will pass through the rotor is upstream smaller than the rotor area. It expands to the rotor area as it reaches the rotor, implying that roughly half the energy transfer from the air to the rotor occurs before passage through the rotor. Thus it must be the case that the air just outside the flow gets pushed radially outward as the rotor is approached just enough so that it bypasses the rotor. The Betz equations do not include any terms for air that bypasses the rotor, its contribution to the extracted power is assumed to be zero.



Pressure and speed variation in an ideal model of a wind turbine.

The actual power extracted by the rotor blades is the difference between the upstream and downstream wind powers. Using Equation 3.2, this is given by the following equation in units of watts:

$$P_o = \frac{1}{2}(\text{mass flow per second})\left\{V^2 - V_o^2\right\} \qquad (5)$$

where

Po= mechanical power extracted by the rotor, i.e., the turbine output power,

V= upstream wind velocity at the entrance of the rotor blades, and

Vo= downstream wind velocity at the exit of the rotor blades.

Let us leave the aerodynamics of the blades to the many excellent books available on the subject, and take a macroscopic view of the airflow around the blades. Macroscopically, the air velocity is discontinuous from V to Vo at the “plane” of the rotor blades, with an "average" of .(V + Vo). Multiplying the air density by the average velocity, therefore, gives the mass flow rate of air through the rotating blades, which is as follows:

$$\text{mass flow rate} = \rho A \frac{V + V_o}{2} \tag{6}$$

The mechanical power extracted by the rotor, which drives the electrical generator, is therefore:

$$P_o = \frac{1}{2}\left[\rho A \frac{(V + V_o)}{2}\right](V^2 - V_o^2) \tag{7}$$

Rotor efficiency vs. Vo/V ratio has a single maximum.

The preceding expression is algebraically rearranged in the following form:

$$P_o = \frac{1}{2}\rho A V^3 \frac{\left(1 + \frac{V_o}{V}\right)\left[1 - \left(\frac{V_o}{V}\right)^2\right]}{2} \tag{8}$$

The power extracted by the blades is customarily expressed as a fraction of the upstream wind power in watts as follows:

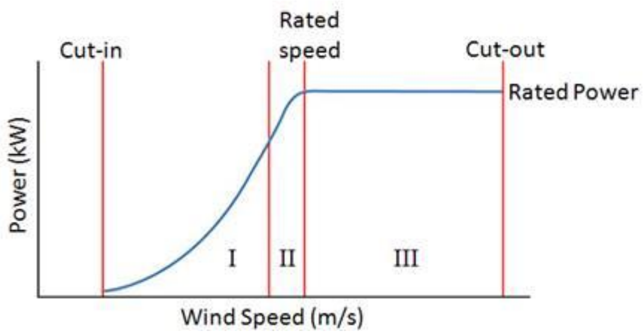
$$P_o = \frac{1}{2}\rho A V^3 C_p \tag{9}$$

Where

$$C_p = \frac{\left(1 + \frac{V_o}{V}\right)\left[1 - \left(\frac{V_o}{V}\right)^2\right]}{2} \tag{10}$$

Comparing Equation 3 and Equation 9, we can say that Cp is the fraction of the upstream wind power that is extracted by the rotor blades and fed to the electrical generator. The remaining power is dissipated in the downstream wind. The factor Cp is called the power coefficient of the rotor or the rotor efficiency.

The Power Curve



It is important to understand the relationship between power and wind speed to determine the required control type, optimization, or limitation. The power curve, a plot you can use for this purpose, specifies how much power you can extract from the incoming wind. Figure below contains an ideal wind turbine power curve.

The **cut-in and cut-out speeds** are the operating limits of the turbine. By staying in this range, you ensure that the available energy is above the minimum threshold and structural health is maintained. The rated power, a point provided by the manufacturer, takes both energy and cost into consideration. Also, the rated wind speed is chosen because speeds above this point are rare and also that the bulk of energy extracted above the rated wind speed is not cost-effective.

Region I: consists of low wind speeds and is below the rated turbine power. Turbine is run at the maximum efficiency to extract all power. In other words, the turbine controls with optimization in mind.

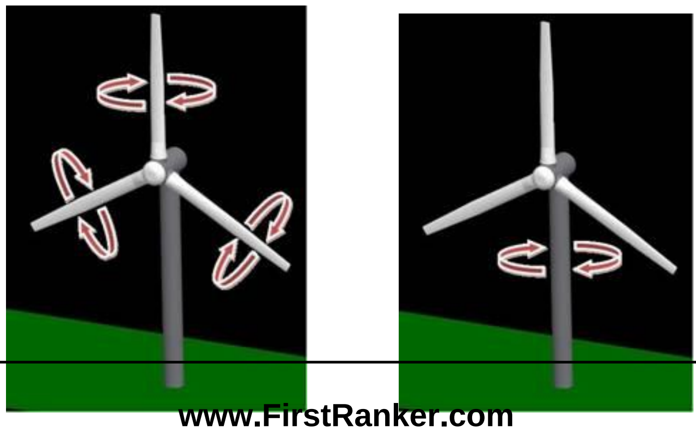
Region III: consists of high wind speeds and is at the rated turbine power. The turbine controls with limitation of the generated power in mind when operating in this region.

Region II is a transition region mainly concerned with keeping rotor torque and noise low.

Control Methods

Different control methods to either optimize or limit power output.

1. by controlling the generator speed
2. blade angle adjustment – Pitch control
3. rotation of the entire wind turbine - Yaw control



Pitch control Yaw control

Pitch control To maintain the optimum blade angle to achieve certain rotor speeds or power output.

Pitch adjustment to stall and furl, two methods of pitch control. By *stalling a wind turbine*, you increase the angle of attack, which causes the flat side of the blade to face further into the wind.

Furling decreases the angle of attack, causing the edge of the blade to face the oncoming wind. Pitch angle adjustment is the most effective way to limit output power by changing aerodynamic force on the blade at high wind speeds.

Yaw refers to the rotation of the entire wind turbine in the horizontal axis. Yaw control ensures that the turbine is constantly facing into the wind to maximize the effective rotor area and, as a result, power. Because wind direction can vary quickly, the turbine may misalign with the oncoming wind and cause power output losses.

SPEED CONTROL

The wind turbine technology has changed significantly in the last 25 yr.1 Large wind turbines being installed today tend to be of variable-speed design, incorporating pitch control and power electronics. Small machines, on the other hand, must have simple, lowcost power and speed control. The speed control methods fall into the following categories:

No speed control whatsoever: In this method, the turbine, the electrical generator, and the entire system are designed to withstand the extreme speed under gusty winds. Yaw and tilt control: The yaw control continuously orients the rotor in the direction of the wind. It can be as simple as the tail vane or more complex on modern towers. Theoretical considerations dictate free yaw as much as possible. However, rotating blades with large moments of inertia produce high gyroscopic torque during yaw, often resulting in loud noise. A rapid yaw may generate noise exceeding the local ordinance limit. Hence, a controlled yaw is often required and used, in which the rotor axis is shifted out of the wind direction when the wind speed exceeds the design limit. Pitch control: This changes the pitch of the blade with changing wind speed to regulate the rotor speed. Large-scale power generation is moving towards variable-speed rotors with power electronics incorporating a pitch control. Stall control: Yaw and tilt control gradually shifts the rotor axis in and out of the wind direction. But, in gusty winds above a certain speed, blades are shifted (profiled) into a position such that they stall and do not produce a lift force. At stall, the wind flow ceases to be smooth around the blade contour, but separates before reaching the trailing edge. This always happens at a high pitch angle. The blades experience a high drag, thus lowering the rotor power output. This way, the blades are kept under the allowable speed limit in gusty winds. This not only protects the blades from mechanical overstress, but also protects the electrical generator from overloading and overheating. Once stalled, the turbine has to be restarted after the gust has subsided.

TURBINE RATING

The method of assessing the nominal rating of a wind turbine has no globally accepted standard. The difficulty arises because the power output of the turbine depends on the square of the rotor diameter and the cube of the wind speed. The rotor of a given diameter, therefore, would generate different power at different wind speeds. A turbine that can generate 300 kW at 7 m/sec would produce 450 kW at 8 m/sec wind speed. What rating should then be assigned to this turbine? Should we also specify the rated speed? Early wind turbine designers created a rating system that specified the power output at some arbitrary wind speed. This method did not work well because everyone could not agree on one speed for specifying the power rating.

The "rated" wind speeds varied from 10 to 15 m/sec under this practice. Manufacturers quoted on the higher side to claim a greater output from the same design. Such confusion in quoting the rating was avoided by some European manufacturers who quoted only the rotor diameter. But the confusion continued as to the maximum power the machine can generate under the highest wind speed in which the turbine can continuously and safely operate. Many manufacturers have, therefore, adopted the combined rating designations x/y, the generator's peak electrical capacity followed by the wind turbine diameter. For example, a 300/30-kW/m wind system means a 300-kW electrical generator and a 30-m diameter turbine. The specific rated capacity (SRC) is often used as a comparative index of the wind turbine designs. It measures the power generation capacity per square meter of the blade-swept area, and is defined as follows in units of kW/m2: The SRC for a 300/30 wind turbine is 300/π × 152 = 0.42 kW/m2. It increases with diameter, giving favorable economies of scale for large machines, and ranges from approximately 0.2 kW/m2 for a 10-m diameter rotor to 0.5 kW/m2 for a 40-m diameter rotor. Some aggressively rated turbines have an SRC of 0.7 kW/m2, and some reach as high as 1 kW/m2. The higher-SRC rotor blades have higher operating stresses, which result in a shorter fatigue life. All stress concentration regions are carefully identified and eliminated in high-SRC designs. Modern design tools, such as the finite element stress analysis and the modal vibration analysis, can be of great value in rotor design.

Turbine rating is important as it indicates to the system designer how to size the electrical generator, the plant transformer, and the connecting cables to the substation and the transmission link interfacing the grid. The power system must be sized on the peak capacity of the generator. Because turbine power depends on the cube of the wind speed, the system-design engineer matches the turbine and the generator performance characteristics. This means selecting the rated speed of the turbine to match with the generator. As the gearbox and generator are manufactured only in discrete sizes, selecting the turbine's rated speed can be complex. The selection process goes through several iterations, trading the cost with benefit of the available speeds. Selecting a low rated speed would result in wasting much energy at high winds. On the other hand, if the rated speed is high, the rotor efficiency will suffer most of the time.

MAXIMUM ENERGY CAPTURE

The wind power system design must optimize the annual energy capture at a given site. The only operating mode for extracting the maximum energy is to vary the turbine speed with varying wind speed such that at all times the TSR is continuously equal to that required for the maximum power coefficient Cp. The theory and field experience indicate that the variable-speed operation yields 20 to 30% more power than with the fixed-speed operation. Nevertheless, the cost of variable-speed control is added. In the system design, this trade-off between energy increase and cost increase has to be optimized. In the past, the added costs of designing the variable pitch rotor, or the speed control with power electronics, outweighed the benefit of the increased energy capture. However, the falling prices of power electronics for speed control and the availability of high-strength fiber composites for constructing high-speed rotors have made it economical to capture more energy when the speed is high. The variable-speed operation has an indirect advantage. It allows controlling the active and reactive powers separately in the process of automatic generation control. In fixed-speed operation, on the other hand, the rotor is shut off during high wind speeds, losing significant energy. The pros and cons of fixed- and variable speed operations are listed in Table. Almost all major suppliers now offer variable-speed systems in combination with pitch regulation. Potential advantages of the variable-speed system include active grid support, peak-power-tracking operation, and cheaper offshore foundation structure. The doubly fed induction generator is being used in some large wind turbines such as NEG Micon's 4.2-MW, 110-m diameter machines and multi-megawatt GE machines. It is an emerging trendsetting technology in the variable-speed gear-driven systems, primarily because only the slip frequency power (20 to 30% of the total) has to be fed through the frequency converter. This significantly saves power electronics cost.

Advantages of Fixed- and Variable-Speed Systems

Fixed-Speed System	Variable-Speed System
Simple and inexpensive electrical system	Higher rotor efficiency, hence, higher energy capture per year
Fewer parts, hence, higher reliability	Low transient torque
Lower probability of excitation of mechanical resonance of the structure	Fewer gear steps, hence, inexpensive gear box
No frequency conversion, hence, no current harmonics present in the electrical system	Mechanical damping system not needed; the electrical system could provide damping if required
Lower capital cost	No synchronization problems
	Stiff electrical controls can reduce system voltage sags

As seen earlier, operating the wind turbine at a constant TSR corresponding to the maximum power point at all times can generate 20 to 30% more electricity per year. However, this requires a control scheme to operate with a variable speed to continuously generate the maximum power. Two possible schemes for such an operation are as follows:

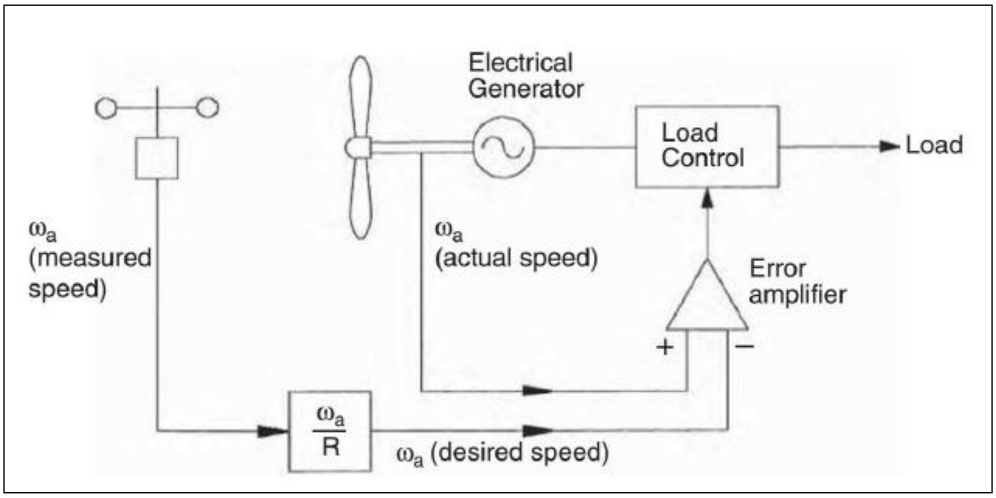
CONSTANT-TSR SCHEME

In this scheme the machine is continuously operated at its optimum TSR, which is a characteristic of the given wind turbine. This optimum value is stored as the reference TSR in the control computer. The wind speed is continuously measured and compared with the blade tip speed. The error signal is then fed to the control system, which changes the turbine speed to minimize the error. At this time the rotor must be operating at the reference TSR, generating the maximum power. This scheme has the disadvantage of requiring the local wind speed measurements, which could have a significant error, particularly in a large wind farm with shadow effects. Being sensitive to the changes in the blade surface, the optimum TSR gradually changes with age and environment. The computer reference TSR must be changed accordingly many times, which is expensive.

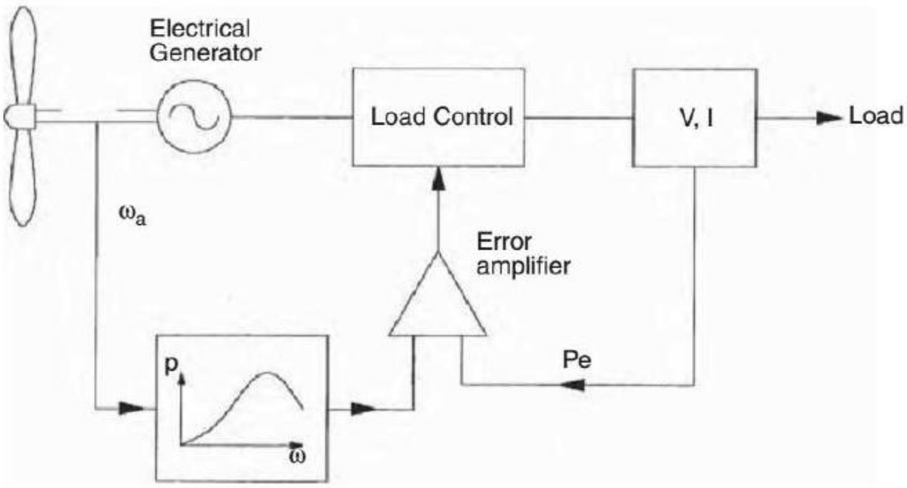
Besides, it is difficult to determine the new optimum TSR with changes that are not fully understood or easily measured.

PEAK-POWER-TRACKINGSCHEME

The power vs. speed curve has a single well-defined peak. If we operate at the peak point, a small increase or decrease in the turbine speed would result in no change in the power output, as the peak point locally lies in a flat neighborhood. In other words, a necessary condition for the speed to be at the maximum power point is as follows: Maximum power operation using rotor tip speed control scheme.



Maximum power operation using power control scheme.



This principle is used in the control scheme. The speed is increased or decreased in small increments, the power is continuously measured, and $\Delta P/\Delta\omega$ is continuously evaluated. If this ratio is positive — meaning we get more power by increasing the speed — the speed is further increased. On the other hand, if the ratio is negative, the power generation will reduce if we change the speed any further. The speed is maintained at the level where $\Delta P/\Delta\omega$ is close to zero. This method is insensitive to errors in local wind speed measurement, and also to wind turbine design. It is, therefore, the preferred method. In a multiple-machine wind farm, each turbine must be controlled by its own control loop with operational and safety functions incorporated.

Unit – V - Hydro and Tidal power systems

Hydro installations and plants are long-lasting with routine maintenance, e.g. turbines for about fifty years and longer with minor refurbishment,dams and waterways for perhaps hundred years. Long turbine life is due to the continuous, steady operation without high temperature or other stress. Consequently established plant often produces electricity at low cost (<4 Eurocent/kWh) with consequent economic benefit.

Hydro turbines have a rapid response for power generation and so the power may be used to supply both base load and peak demand requirementson a grid supply. Power generation efficiencies may be as high as 90%.

Turbines are of two types:

1 Reaction turbines, where the turbine is totally embedded in the fluid and powered from the pressure drop across the device.

2 Impulse turbines, where the flow hits the turbine as a jet in an open environment, with the power deriving from the kinetic energy of theflow.

Reaction turbine generators may be reversed, so water can be pumped to high levels for storage and subsequent generation at an overall efficiency of about 80%.

The main disadvantages of hydro-power are associated with effects other than the generating equipment, particularly for large systems. These include possible adverse environmental impact, effect on fish, silting of dams, corrosion of turbines in certain water conditions, social impact of displacement of people from the reservoir site, loss of potentially productive land (often balanced by the benefits of irrigation on other land) and relatively large capital costs compared with those of fossil power stations.

Classification
The classification of hydro electric plants based upon :
(a) Quantity of water available (b) Available head (c) Nature of load

The classification acording to Quantity of water available is
(i) Run-off river plants with out pondage : These plants does not store water; the plant uses water as it comes.The plant can use water as and when available.Since these plants depend for their generting capacity primarily on the rate of flow of water, during rainy season high flow rate may mean some quantity of water to go as waste while during low run-off periods, due to low flow rates,the generating capacity will be low.-off river plants with pondage : In these plants pondage permits storage of water during off peak periods and use of this water during peak periods.Depending on the size of pondage provided it may be possible to cope with hour to hour fluctuations.This type of plant can be used on parts of the load curve as required,and is more useful than a plant with out storage or pondage.
When providing pondage tail race conditions should be such that floods do not raise tail-race water level,thus reducing the head on the plant and impairing its effectiveness.This type of plant is

comparitively more reliable and its generating capacity is less dependent on avilable rate of flow of water.

(iii) Reservoir Plants :A reservoir plant is that which has a reservoir of such size as to permit carrying over storage from wet season to the next dry season.Water is stored behind the dam and is available to the plant with control as required.Such a plant has better capacity and can be used efficiently through out the year.Its firm capacity can be increased and can be used either as a base load plant or as a peak load plant as required.It can also be used on any portion of the load curve as required. Majority of the hydroelectric plants are of this type.

The classification according to availability of water head is

(i) Low-Head (less than 30 meters) Hydro electric plants :"Low head" hydro-electric plants are power plants which generally utilize heads of only a few meters or less. Power plants of this type may utilize a low dam or weir to channel water, or no dam and simply use the "run of the river". Run of the river generating stations cannot store water, thus their electric output varies with seasonal flows of water in a river. A large volume of water must pass through a low head hydro plant's turbines in order to produce a useful amount of power. Hydro-electric facilities with a capacity of less than about 25 MW (1 MW = 1,000,000 Watts) are generally referred to as "small hydro", although hydro-electric technology is basically the same regardless of generating capacity.

(ii) Medum-head(30 meters - 300 meters) hydro electric plants :These plants consist of a large dam in a mountainous area which creates a huge reservoir. The Grand Coulee Dam on the Columbia River in Washington (108 meters high, 1270 meters wide, 9450 MW) and the Hoover Dam on the Colorado River in Arizona/Nevada (220 meters high, 380 meters wide, 2000 MW) are good examples. These dams are true engineering marvels. In fact, the American Society of Civil Engineers as designated Hoover Dam as one of the seven civil engineering wonders of the modern world, but the massive lakes created by these dams are a graphic example of our ability to manipulate the environment - for better or worse. Dams are also used for flood control, irrigation, recreation, and often are the main source of potable water for many communities. Hydroelectric development is also possible in areas such as Niagra Falls where natural elevation changes can be used.

(iii) High-head hydro electric plants :"High head" power plants are the most common and generally utilize a dam to store water at an increased elevation. The use of a dam to impound water also provides the capability of storing water during rainy periods and releasing it during dry periods. This results in the consistent and reliable production of electricity, able to meet demand. Heads for this type of power plant may be greater than 1000 m. Most large hydro-electric facilities are of the high head variety. High head plants with storage are very valuable to electric utilities because they can be quickly adjusted to meet the electrical demand on a distribution system.

The classification according to nature of load is

(i) Base load plants :A base load power plant is one that provides a steady flow of power regardless of total power demand by the grid. These plants run at all times through the year except in the case of repairs or scheduled maintenance.

Power plants are designated base load generation, efficiency and safety at set outputs. Baseload power plants do not change production to match power consumption demands since it is always cheaper to run them rather than running high cost combined cycle plants or combustion turbines. Typically these plants are large enough to provide a majority of the power used by a grid, making them slow to fire up and cool down. Thus, they are more effective when used continuously to cover the power baseload required by the grid.

Each base load power plant on a grid is allotted a specific amount of the baseload power demand to handle. The base load power is determined by the load duration curve of the system. For a typical power system, rule of thumb states that the base load power is usually 35-40% of the maximum load during the year.Load factor of such plants is high.
Fluctuations, peaks or spikes in customer power demand are handled by smaller and more responsive types of power plants.

(ii) Peak load plants :Power plants for electricity generation which, due to their operational and economic properties, are used to cover the peak load. Gas turbines and storage and pumped storage power plants are used as peak load power plants.The efficiency of such plants is around 60 -70%.

The available vertical fall ''H''. (a) vertical fall: trigonometric methods are most suitable, (b) sloping site: the head is measured with the help of dumpy levels and a theodolite and (c) For high head measurement: an altimeter with good accuracy is used.

Measurement of Water Flow Rate (Q)

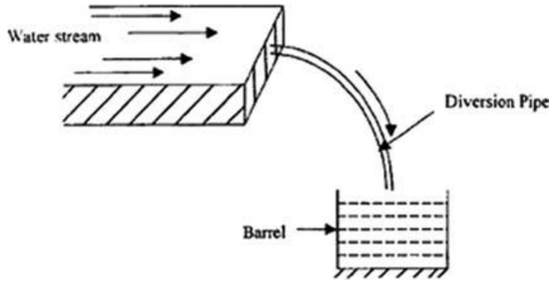
Flow rate is also an important parameter to measure the shaft power in the water turbine. The flow rate of the water stream (Q) is measured with the following equation.

$$Q = (\text{volume of fluid passing in time } \Delta t)/\Delta t \qquad (6.32a)$$

$$= (\text{mean speed of fluid } u)(\text{cross sectional area } A) \qquad (6.32b)$$

$$= \int u \cdot \hat{n}\, dA \qquad (6.32c)$$

where ^n is the unit vector normal to the elemental area dA.
The following methods to measure flow rate (Q) are used
(i) Bucket method: This is shown in Figure 6.11a. It is a simple way of measuring flow in very small streams. The entire flow is diverted into a bucket or barrel and the time for the container to fill is recorded. The flow rate is obtained by simply dividing the volume of the container with the filling time.
(ii) Floating method: In this case, the flow rate is measured by multiplying the mean velocity of flow by the cross-sectional area. The flow speed varies from the bottom to the top of the channel. The flow speed is zero on the bottom of the stream because of viscous



Current meter: A current meter is an instrument for measuring the velocity of a flow channel. It consists of a shaft with a revolving element containing cup and a tail on which flat vanes are fixed. The current meter is suspended by means of a cable and is held vertically immersed in the stream of water to the required depth such that the revolving element is facing towards the upstream direction. The revolving element is free to rotate and the speed of rotation is related to the stream velocity. A simple mechanical counter records the number of revolutions of the revolving element of the current meter placed at a desired depth. By averaging the observations taken throughout the cross section, the average speed of the flow is determined. Then by multiplying the average speed by the cross-sectional area the rate of water flow Q is obtained.

(iv) Use of a weir: A weir is similar to a small dam constructed across a river. By measuring the height of upstream water surface, the rate of flow can be determined.

Measurement of Head, H

For nearly vertical falls, trigonometric methods (perhaps even using the lengths of shadows) are suitable; whereas for more gently sloping sites, the use of level and pole is straightforward. Note that the power input to the turbine depends not on the geometric (or total) head H_t as measured

this way, but on the available head H_a:

$H_a = H_t - H_f$ (8.2)

where H_f allows for friction losses in the pipe and channels leading from

the source to the turbine (see Section 2.6). By a suitable choice of pipework

it is possible to keep $H_f <\sim H_t/3$, but according to (2.14) H_f increases in

proportion to the total length of pipe, so that the best sites for hydro-power

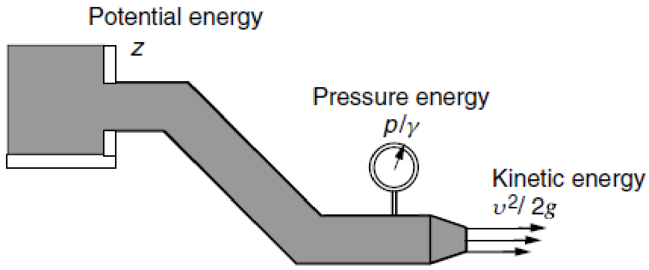
have steep slopes.

defines the mean speed u of the flow. Since the flow speed is zero on the bottom of thestream (because of viscous friction), the mean speed will be slightly lessthan the speed us on the top surface. For a rectangular cross-section,for example, it has been found that u ≈ 0.8us where us can be measured by simply placing a float, e.g. a leaf, on the surface and measuring the time it takes to go a certain distance along the stream. For best results the measurement should be made where the stream is reasonably straight and of uniform cross-section.The cross-sectional area A can be estimated by measuring the depth at several points across the stream and integrating across the stream inthe usual way

$$A \approx \frac{1}{2}y_1 z_1 + \frac{1}{2}(y_2 - y_1)(z_1 + z_2) + \frac{1}{2}(y_3 - y_2)(z_2 + z_3) + \frac{1}{2}(y_4 - y_3)z_3$$

Power From a Micro-Hydro Plant

The energy associated with water manifests itself in three ways: as potential energy, pressure energy, and kinetic energy. The energy in a hydroelectric system starts out as potential energy by virtue of its height above some reference level - in this case, the height above the powerhouse. Water under pressure in the penstock is able to do work when released, so there is energy associated with that pressure as well. Finally, as water flows there is the kinetic energy that is associated with any mass that is moving. Figure 4.17 suggests the transformations between these forms of energy as water flows from the forebay, through the penstock, and out of a nozzle.



4.17 Transformations of energy from potential, to pressure, to kinetic.

It is convenient to express each of these three forms of energy on a per unit of weight basis, in which case energy is referred to as *head* and has dimensions of length, with units such as "feet of head" or "meters of head." The total energy is the sum of the potential, pressure, and kinetic head and is given by

$$\text{Energy head} = z + \frac{p}{\gamma} + \frac{v^2}{2g} \tag{4.3}$$

where z is the elevation above a reference height (m) or (ft), p is the pressure (N/m2) or (lb/ft2), γ is the specific weight (N/m3) or (lb/ft3), v is the average velocity (m/s) or (ft/s), and g is gravitational acceleration (9.81 m/s2) or (32.2 ft/s2).

In working with micro-hydropower systems, especially in the United States, mixed units are likely to be incurred, so Table 4.5 is presented to help sort them out. The power theoretically available from a site is proportional to the difference in elevation between the source and the turbine, called the *head* H, times the rate at which water flows from one to the other, Q. Using a simple dimensional analysis, we can write that

$$\text{Power} = \frac{\text{Energy}}{\text{Time}} = \frac{\text{Weight}}{\text{Volume}} \times \frac{\text{Volume}}{\text{Time}} \times \frac{\text{Energy}}{\text{Weight}} = \gamma QH$$

Substituting appropriate units in both the SI and American systems results in the following key relationships for water:

$$P(W) = 9810\, Q(\text{m}^3/\text{s})\, H(\text{m}) = Q(\text{gpm})\, H(\text{ft}) \quad (4.5)$$

While (4.5) makes no distinction between a site with high head and low flow versus one with the opposite characteristics, the differences in physical facilities are considerable. With a high-head site, lower flow rates translate into smaller diameter piping, which is more readily available and a lot easier to work with, as well as smaller, less expensive turbines. Home-scale projects with modest flows and decent heads can lead to quick, simple, cost-effective systems.

The head H given in (4.5) is called the *gross head*, call it H_G, because it does not include pipe losses that decrease the power available for the turbine. The *net head*, H_N, will be the gross head (the actual elevation difference) minus the head loss in the piping. Those losses are a function of the pipe diameter, the flow rate, the length of the pipe, how smooth the pipe is, and how many bends, valves, and elbows the water has to pass through on its way to the turbine. Figure 4.18illustrates the difference between gross and net head.

Hydropower System Efficiency

In hydropower systems, even though the efficiency of each individual step is high, there is still a substantial energy loss in passing from the original power P_0 of the stream to the electrical output P_e, from the generator. Hence, the overall efficiency of the system becomes

$$\frac{P_e}{P_o} = \frac{P_j}{P_o} \times \frac{P_m}{P_j} \times \frac{P_e}{P_m} = \frac{H_a}{H_t}\eta_{jm}\eta_{me}$$

where η_{jm} is mechanical efficiency of the turbine.
η_{me} is the electrical efficiency of the generator
P_m is the mechanical power output from turbine
P_j is the power available in the jet of fluid
P_o is the power of water available in supply source
P_e is the electrical output for the generator.
H_a is the available head at the entrance of the turbine
H_t is the total head of the stream.

For $n_{jm} = \eta_{m\theta} = \frac{H}{H_t} = 0.9$, the overall system efficiency will be obtained as

$$\eta = 0.9 \times 0.9 \times 0.9 = 0.73$$

Classification of Hydropower Plant

Hydropower plants are classified on to the following basis.

(a) Based on Head

(i) low head: working under a heads less than 30 m;
(ii) medium head: working under heads between 30–300 m;
(iii) high head: working under heads more than 300 m.

(b) Based on Capacity

(i) micro: capacity up to 100 kW;
(ii) mini: capacity from 101 to 1000 kW;
(iii) small: capacity from 1001 to 6000 kW;
(iv) medium: capacity from 6001 to 10 000 kW;
(v) high: capacity more than 10 000 kW.

(c) On the Basis of Storage Being Provided:

(i) Run-of-river plant: This utilises the flow of water without storage being provided. Such plants would be based only on such rivers that have a minimum dry weather condition that makes the development worthwhile. A weir or barrage may be constructed across the river close to the power plant to maintain a givenwater level. These are generally low-head plants.
(ii) Reservoir plant: This utilises the flow from large storage reservoir developed by constructing dams across the rivers. These plants utilise the water for producing electricity according to the requirements throughout the year.
(iii) Pumped storage plant: This utilises the peak load of power station. They store water by pumping a portion of the water from the tailrace back to the reservoir during off-peak hours. The pumping is done by the same turbine generator (producing power) which now acts as a pump–motor set (consuming power). It is expensive.

On the Basis of Load Capacity

(i) Base-load plants: These plants cater for the base load of the system. Such plants are required to supply a constant power when connected to the grid. Thus, they run without stopping and are often remotely controlled, so fewer staff are required for such plants.
(ii) Peak-load plants: These plants supply power during peak loads. Pumped storage plants are peak-load plants. Run-off-river plants with pondage can operate both as peak-load and base-load plants as river flow permits.

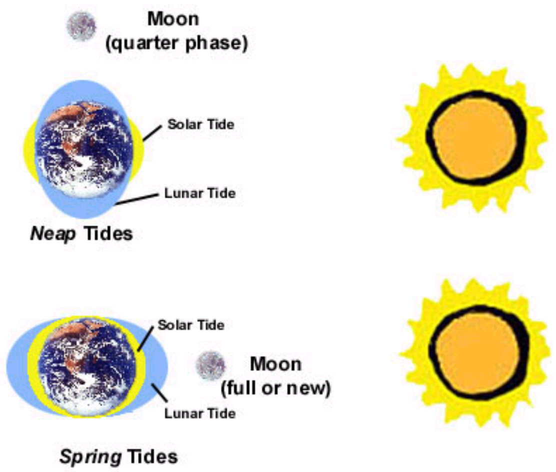
Construction of a barrage across a tidal river is bound to affect the conditions on both sides of the structure. Water movement patterns will be changed, sedimentation movement will be affected and the conditions at the margins of the estuary on both the landward and seaward side of the barrage will be altered. This could have a serious effect on marine and avian life.**The major effect of the barrage will be on water levels and water movement.**
Water levels will be altered on both sides of the barrage and the tidal reach may change behind the barrage, although the effect will be reduced as the distance from the barrage increases. Some areas which were regularly exposed at low tide will be continuously under water after the barrage is constructed. Though the volume of water flowing down the river should remain the same, patterns of movement will be changed. Sedimentation will be affected in complex ways. The tidal waters of an estuary frequently bear a great deal of sediment. Some is brought in from the sea, some carried downstream by the river. Changes in current speeds and patterns caused by the interpolation of a barrage will affect the amount of sediment carried by the water and the pattern of its deposition.

This will, in turn, affect the ecosystems that depend on the sediment.

Other areas of concern involve animal species. The effect on fish, particularly migratory species, is significant. Fish gates can be built to permit species to cross the barrage. Many can also pass through the sluice gates.However there is a danger that fish will pass through the turbines too, being injured in the process. Various methods have been explored to discourage fish from the vicinity of the turbines, with patchy success.

Many birds live on mud flats in estuaries. There is a possibility that such mud flats would disappear after a barrage had been built, and with them the birds whose habitat they formed. Salt marshes adjacent to estuaries are also likely to be affected. Studies have been conducted on potential UK barrage sites but much work remains to be done in this area. Against these potentially adverse effects should be balanced with the absence of any emissions such as carbon dioxide, sulphur dioxide and the oxides of nitrogen. Unlike a traditional hydropower scheme, there is little possibility of generating methane within the reservoir of a tidal plant. A tidal plant is also a sustainable source of electricity.

Tides are caused principally by the gravitational pull of the moon on the world'oceans. The sun also plays a minor role, not through its radiant energy but in the form of its gravitational pull, which exerts small additional effect on tidal rhythms. And the rotation of the earth is also a factor in the production of tides.



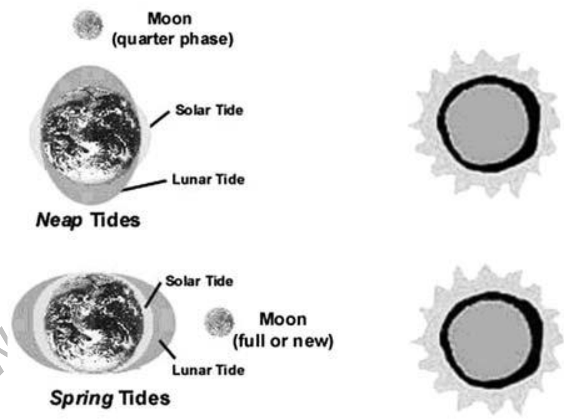
(Figure 1)

Tidal cycles are calculated using harmonic constants defined by the rhythmic movements of the sun, moon, and earth. The earth is spinning, precessing, and pulsating in concert with its celestial neighbors in an ever-changing and infinite series of movements that causes the oceans to rise and fall. This complex pattern has been closely observed for eons and is now known and mathematically predictable, down to the finest detail across the broadest reaches of time. It is possible, if it strikes one's fancy, to know the precise tidal level at a specific location at a specific moment 100 years or 1000 years in the future. Wind and weather cause changes under extreme

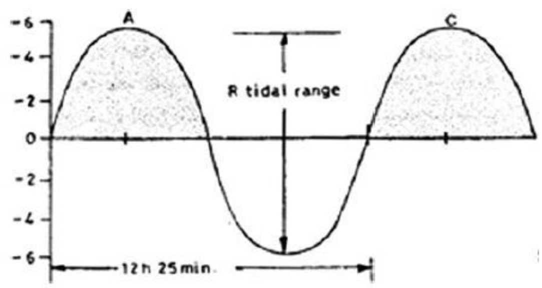
conditions ("tidal surges") and these events are not specifically predictable, but the basic harmonic changes in water levels caused by the tides are eminently predictable.On a global scope, the tides are meters high bulge in the level of the ocean that moves across the globe every 24 hours and 50 minutes. As this bulge nears land, it is changed in amplitude by the decreasing depth and anomalies of the seabed. At the extremes, some tidal ranges are as small as 6 inches and some are as large as 60 feet.
Broad-mouthed estuaries create the largest tidal ranges and long straight coastlines tend to have the smallest. The power available (per unit area) in any specific location is a function of the square of the tidal range and thus the largest tidal ranges are the most attractive areas for tidal power generation. The amount of water available in an offshore tidal power generator is a function of the area of seabed impounded. It is most economical to build an impoundment structure in a shallow area, so it follows that the most attractive sites for offshore tidal power generation are those where the tidal range is high and there are broad tidal flats at minimal depth.

Working principle

The rise and fall of the sea level can power electric-generating equipment. The gearing of the equipment is tremendous to turn the very slow motion of the tide into enough displacement to produce energy. Tidal barrages, built across suitable estuaries, are designed to extract energy from the rise and fall of the tides, using turbines located in water passages in the barrages. The potential energy, due to the difference in water levels across the barrages, is converted into kinetic energy in the form of fast moving water passing through the turbines. This, in turn, is converted into rotational kinetic energy by the blades of the turbine, the spinning turbine then driving a generator to produce electricity. The diagram demonstrates power generation cycle of a tidal power.



When sun and moon are in line whether pulling on the same side or on the opposite side (full or new moons) the gravitational attraction combine together causes high tides, known as spring tides. Conversely, when sun and moon are orthogonal, their gravitational forces pulls water in different directions causing the bulges to cancel each other, giving place to neap tides. The maximum power is produced during spring tide while the minimum is during the neap tide.



The tides of the sea.

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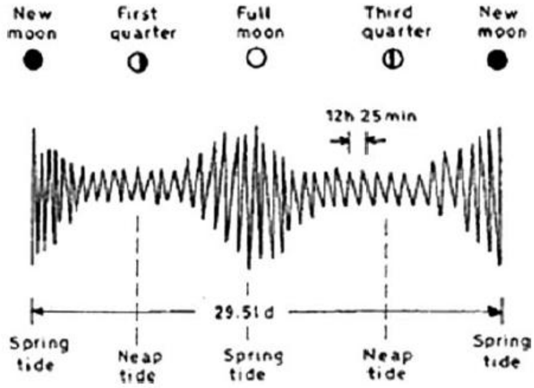


Relative high and low tides.

Tidal phenomenon is periodic. The periodicity varies according to the lunar and solar gravitational effects, respective movements of the moon and sun, and other geographical peculiarities. The mean interval between conjunctions of the sun and moon (new moon to new moon) has a cycle of 29.53 days, which is known as Synodic month or lunation. There are three different types of tidal phenomena at different locations of the earth [7]

A. Semidiurnal tides with monthly variation.

This type of tide has a period of 12h 25 min, due to the earth rotation relative to both sun and moon, consequently the tidal phenomenon occurs twice every 24h 50min 28s [8], so each landmass is exposed to two high tides and two low tides during each period of rotation [9], as it is shown in *Fig 2.4.*. The amplitude of the tide varies according to the lunar month, with higher tidal range at full moon and new moon, when sun and moon are aligned. Neap tides occur during half-moon as the resultant gravitational pull is minimum. However, as is shown in *Fig 2.4.* , one of the tides has greater range than the other, having a higher high and a lower low, therefore, a greater tidal flow while water is coming in and going out during the period between high and low level. Furthermore, the tidal output peaks and troughs four times a day as the tide comes in and out twice daily..

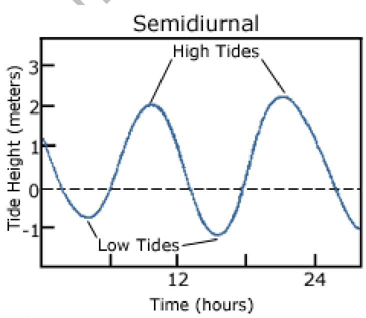
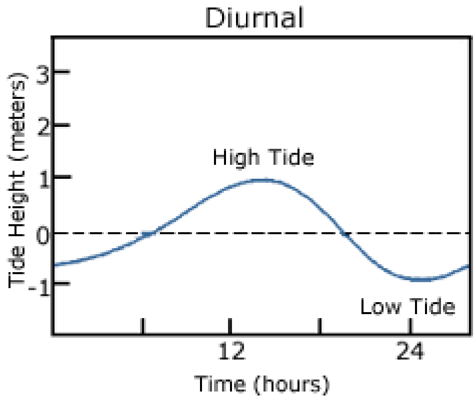


Fig. 2.4. Semidiurnal tide[IV]

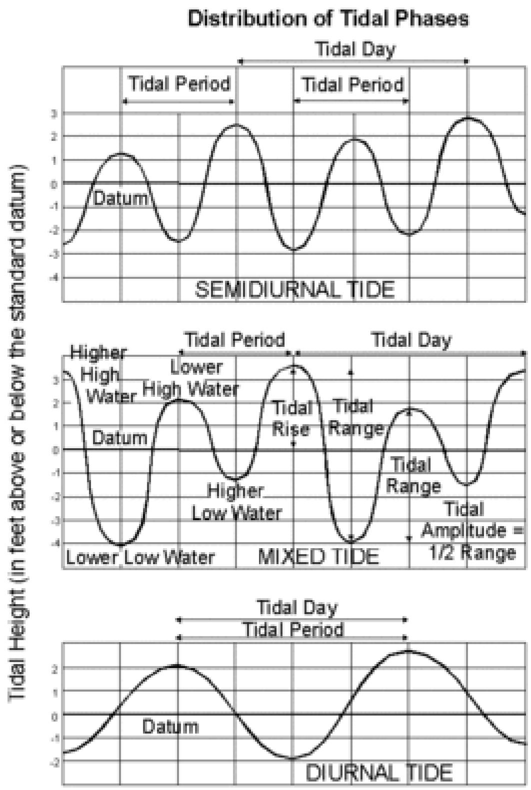
B. Diurnal tides with monthly variation



This type of tide is found in China Sea and Tahiti. In this case, the tidal period is of 24h 50 min 28s, a full revolution of the moon around the earth. During each earth rotation, a point of the earth surface will pass through different parts of the equilibrium tide envelope and therefore experience a diurnal variation in tide levels. [7]

C. Mixed tides

This type of tides combines the characteristics of diurnal and semidiurnal tides. Moreover, they can also display monthly and bimonthly variation. They are found in the Mediterranean Sea and at Saigon.



Energy Equation of Tidal Power

Tidal Power Calculation

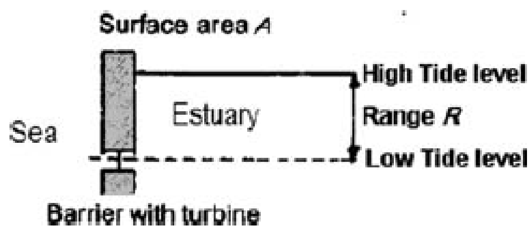
Let the water be trapped and stored at high tide in a basin and allowed to flow through a turbine at low tide, as shown in Figure 9.8.The basin has a constant surface area A. It remains covered in water at low tide. The trapped water having a mass rAR at a centre of gravity R/2 is assumed to run out at low tide. The maximum potential energy available per tide with water falls through R/2 is given by

$$\text{Energypertide} = (\rho A R) g \frac{R}{2}$$

where g is the acceleration due to gravity.

The average potential power averaged over the tidal period T becomes

$$\overline{P} = \frac{\rho A R^2 g}{2T} (W)$$



Advantage of tidal power energy

1. Renewable resource, it needs no fuel to maintain, and free of charge
2. Totally no pollution, unlike fossil fuels, it produces no greenhouse gases or other waste.
3. Predictable source of energy (compared with wind and solar), it is independent of weather and climate change and follows the predictable relationship of the lunar orbit
4. More efficient than wind because of the density of water
5. It will protect a large stretch of coastline against damage from high storm tides

Disadvantage of tidal power energy

1. Presently costly, very expensive to build and maintain (A 1085MW facility could cost about 1.2 billion dollars to construct and run)
2. Barrage has environmental affects

a) fish and plant migration
b) Silt and mud deposits
c) Waste and sewage blocks

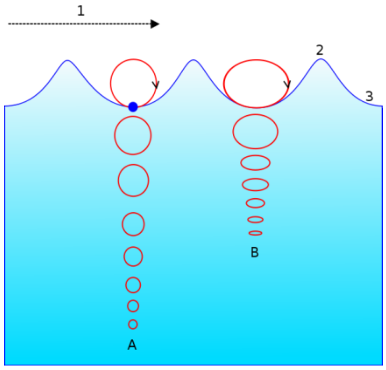
3. Technology is not fully developed
4. Only provides power for around 10 hours each day, when the tide is actually moving in or out

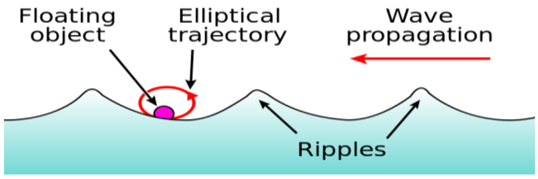
Wave Power:

Wave power is the transport of energy by ocean surface waves, and the capture of that energy to do useful work – for example, electricity generation, water desalination, or the pumping of water (into reservoirs). A machine able to exploit wave power is generally known as a wave energy converter (WEC).

Physical concepts

Waves are generated by wind passing over the surface of the sea. As long as the waves propagate slower than the wind speed just above the waves, there is an energy transfer from the wind to the waves. Both air pressure differences between the upwind and the lee side of a wave crest, as well as friction on the water surface by the wind, making the water to go into the shear stress causes the growth of the waves.[4]





When an object bobs up and down on a ripple in a pond, it experiences an elliptical trajectory.

Wave height is determined by wind speed, the duration of time the wind has been blowing, fetch (the distance over which the wind excites the waves) and by the depth and topography of the seafloor (which can focus or disperse the energy of the waves). A given wind speed has a matching practical limit over which time or distance will not produce larger waves. When this limit has been reached the sea is said to be "fully developed".

In general, larger waves are more powerful but wave power is also determined by wave speed, wavelength, and water density.

Motion of a particle in an ocean wave. A = At deep water. The orbital motion of fluid particles decreases rapidly with increasing depth below the surface. B = At shallow water (ocean floor is now at B). The elliptical movement of a fluid particle flattens with decreasing depth. 1 = Propagation direction. 2 = Wave crest. 3 = Wave trough.

Oscillatory motion is highest at the surface and diminishes exponentially with depth. However, for standing waves (clapotis) near a reflecting coast, wave energy is also present as pressure oscillations at great depth, producing microseisms.[4] These pressure fluctuations at greater depth are too small to be interesting from the point of view of wave power.

e waves propagate on the ocean surface, and the wave energy is also transported horizontally with the group velocity. The mean transport rate of the wave energy through a vertical plane of unit width, parallel to a wave crest, is called the wave energy flux (or wave power, which must not be confused with the actual power generated by a wave power device).

Factors effecting Wave Energy:

(i) wind speed and (ii) the distance of interaction of the wind with the water (the

fetch).

The periodic, up and down, to and fro motion of water in seas and oceans is known as 'ocean wave' as shown in Figure 11.18.

The important wave parameters with their notations are given below:

H = wave height. It is the distance from the trough to the crest (not to the height above sea level). It mainly depends on wind speed and the fetch. The value varies from 0.2 m to 3 m.

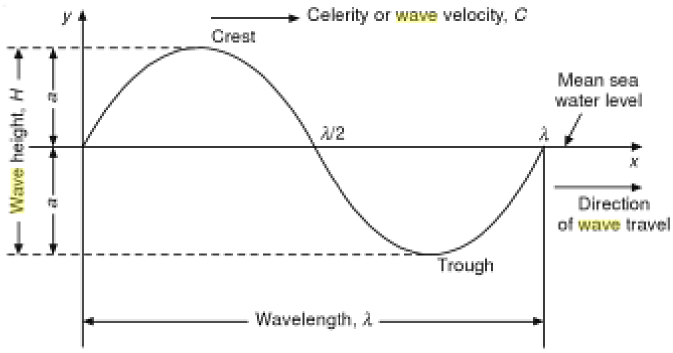


Figure 11.18 Representation of ocean wave.

a = amplitude of the wave = $H/2$

λ = wavelength

T = wave period which usually ranges from 4 s to 12 s

f = frequency expressed as the number of periods per second.

As a progressive wave moves, the crest line travels in a horizontal plane with a wave velocity or celerity C (wave velocity) in the direction of the x-axis, which also represents the mean sea-water level.

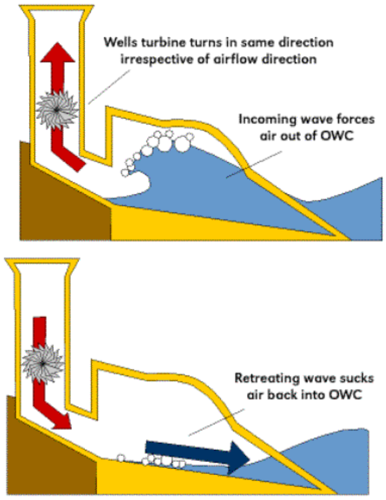
The frequency (f) is defined as the number of troughs or crests passing per second through a given point in the direction of wave motion.

The wavelength (λ) is the horizontal distance between two successive troughs or crests.

The wave velocity or celerity $\qquad C = \dfrac{\lambda}{T}$ m/s

Oscillating water column

- As a wave enters the collector, the surface of the water column rises and compresses the volume of air above it.
- The compressed air is forced into an aperture at the top of the chamber, moving past a turbine.
- As the wave retreats, the air is drawn back through the turbine due to the reduced pressure in the chamber.



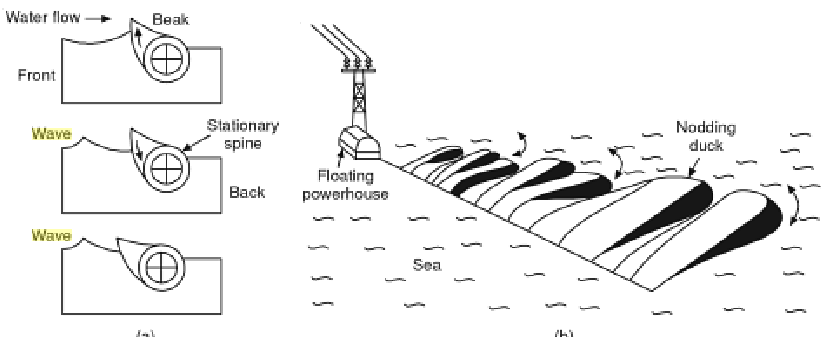
Overtopping device

Overtopping devices are long structures that use wave velocity to fill a reservoir to a greater water level than the surrounding ocean. The potential energy in the reservoir height is then captured with low-head turbines. Devices can be either on shore or floating offshore. Floating devices will have environmental concerns about the mooring system affecting benthic organisms, organisms becoming entangled, or EMF effects produced from subsea cables. There is also some concern regarding low levels of turbine noise and wave energy removal affecting the nearfield habitat.[22]

Oscillating wave surge converter

These devices typically have one end fixed to a structure or the seabed while the other end is free to move. Energy is collected om the relative motion of the body compared to the fixed point.

Oscillating wave surge converters often come in the form of floats, flaps, or membranes. Environmental concerns include minor risk of collision, artificial reefing near the fixed point, EMF effects from subsea cables, and energy removal effecting sediment transport.[22] Some of these designs incorporate parabolic reflectors as a means of increasing the wave energy at the point of capture. These capture systems use the rise and fall motion of waves to capture energy.[23] Once the wave energy is captured at a wave source, power must be carried to the point of use or to a connection to the electrical grid by transmission power cables.



Unit – VI - Biomass, fuel cells and geothermal systems

Biomass is a solid fuel that is a renewable resource of energy. The term ‘‘renewable’’ is defined as a material that can be restored when its initial stock is exhausted. In nature, biomass is formed by the process of inorganicmaterialmolecules (mainly chlorophyll) splitting water in organic cells (photolysis) in the presence of solar energy. The originating hydrogen along with carbon dioxide in the air forms the biomass (component of the carbon dioxide loop). Hence, broadly speaking, the term ‘‘renewable resource’’ is used as a synonym for ‘‘biomass’’ from a resource of geological origin. The energy source that causes the renewal of biomass is the Sun, which is renewable in nature.Further, biomass is also considered as a form of stored solar energy.

Biomass energy has the potential to supply a significant portion of America's energy needs, while revitalizing rural economies, increasing energy independence, and reducing pollution. Farmers would gain a valuable new outlet for their products. Rural communities could become entirely self-sufficient when it comes to energy, using locally grown crops and residues to fuel cars and tractors and to heat and power homes and buildings.

An **energy crop** is a plant grown as a low-cost and low-maintenance harvest used to make biofuels, such as bioethanol, or combusted for its energy content to generate electricity or heat. Energy crops are generally categorized as woody or herbaceous plants; many of the latter are grasses of the family *Graminaceae*.

Commercial energy crops are typically densely planted, high-yielding crop species which are processed to bio-fuel and burnt to generate power.
Woody crops such as willow[1] or poplar are widely utilised,
as well as temperate grasses such as *Miscanthus* and *Pennisetum purpureum* (both known as elephant grass).[2]
If carbohydrate content is desired for the production of biogas, whole-crops such as maize, Sudan grass, millet, white sweet clover and many others, can be made into silage and then converted into biogas

Biomass Energy Sources on the Farm

- **Biomass Residues:** Agricultural activities generate large amounts of biomass residues. While most crop residues are left in the field to reduce erosion and recycle nutrients back into the soil, some could be used to produce energy without harming the soil. Other wastes such as whey from cheese production and manure from livestock operations can also be profitably used to produce energy while reducing disposal costs and pollution.

- **Energy Crops:** Crops grown for energy could be produced in large quantities, just as food crops are. While corn is currently the most widely used energy crop, native trees and grasses are likely to become the most popular in the future. These perennial crops require less maintenance and fewer inputs than do annual row crops, so they are cheaper and more sustainable to produce.

- **Grasses:** Switchgrass appears to be the most promising herbaceous energy crop. It produces high yields and can be harvested annually for several years before replanting. Other native varieties that grow quickly, such as big bluestem, reed canarygrass, and wheat grass, could also be profitable.

- **Trees:** Some fast-growing trees make excellent energy crops, since they grow back repeatedly after being cut off close to the ground. These short-rotation woody crops can grow to 40 feet in less than eight years and can be harvested for 10 to 20 years before replanting. In cool, wet regions, the best choices are poplar and willow. In warmer areas, sycamore, sweetgum, and cottonwood are best.

- **Oil plants:** Oil from plants such as soybeans and sunflowers can be used to make fuel. Like corn, however, these plants require more intensive management than other energy crops.

Protecting the Land

With thoughtful practice and management, perennial energy crops can improve the soil quality of land that has been overused for annual row crops. The deep roots of energy crops enhance the structure of the soil and increase its organic content. Since tilling occurs infrequently, the soil suffers little physical damage from machinery. One study estimates that converting a corn farm of average size to switchgrass could save 66 truckloads of soil from erosion each year.

Perennial energy crops need considerably less fertilizer, pesticide, herbicide, and fungicide than annual row crops. Reduced chemical use helps protect ground and surface water from poisons and excessive aquatic plant growth. Furthermore, deep-rooted energy crops can serve as filters to protect waterways from chemical runoff from other fields and prevent sedimentation caused by erosion.

Finally, perennial energy crops can create more diverse habitats than annual row crops, attracting a wider variety of species such as birds, pollinators, and other beneficial insects, and supporting larger populations. Furthermore, the long harvest window for energy crops enables farmers to avoid nesting or breeding seasons.

Converting Biomass to Energy

Most biomass is converted to energy the same way it always has been—by burning it. The heat can be used directly for heating buildings, crop drying, dairy operations, and industrial processes. It can also be used to produce steam and generate electricity. For example, many electric generators and businesses burn biomass by itself or with other fuels in conventional power plants.

Biomass can also be converted into liquids or gases to produce electricity or transportation fuels. Ethanol is typically produced through fermentation and distillation, in a process much like that used to make beer. Soybean and canola oils can be chemically converted into a liquid fuel called biodiesel. These fuels can be used in conventional engines with little, if any, modification.

Biomass can be converted into a gas by heating it under pressure and without oxygen in a "gasifier." Manure too can be converted using a digester. The gas can then be burned to produce heat, steam, or electricity.

Other biogas applications are still in development, but show great potential. One promising technology is direct combustion in an advanced gas turbine to run a generator and produce electricity. This process is twice as efficient as simply burning raw biomass to produce electricity from steam. Researchers are also developing small, high-speed generators to run on biogas. These "microturbines" have no more than three moving parts and generate as little as 30 kilowatts, which could power a medium-sized farm. Several companies are also considering converting gasified biomass into ethanol as a less expensive alternative to fermentation.

Alternatively, biogas can be processed into hydrogen or methanol, which can then be chemically converted to electricity in a highly efficient fuel cell. Fuel cells can be large enough to power an entire farm or small enough to power a car or tractor.

Types of Biomass

1 **Woody:** The wood can be made available from forests and energy plantations. Wood have high density is ideal for direct combustion,
gasification and also for the production of ethanol and oils.
2 **Non-woody:** Small branches of trees, annually available agricultural residues like cotton stalk, maize, corn, pulses stalk, bagasse, tobacco etc terrestrial weeds like prosophis, lantana, parthenium and others. Though bulk densities are low well suited for gasification, direct combustion and for production of ethanol.
3 **Process residues:** The process residues like ricehusk, coconut shells saw dust, coir pith, groundnut shells, cashew nut shells, etc. The bulk densities are reasonable with advantage of suitable material for gasification and direct burning.
4 **Aquatic plants:** Water hyacinth, lemma, algae, marsh reeds, sea weeds etc. subjected to anaerobic fermentation for biogas. Direct combustion and gasification have limited application due to high moisture content.
5 **Plants oils and fluids:** Agricultural crops like groundnut, soybean, sunflower, sesame etc. yield vegetable oils which are suitable for diesel substitution also. However, these oils are basically edible in nature. The residues viz., oil cakes offer the opportunity for producing appreciable amounts of biogas and the slurry is a good soil conditioner and manure. For eg. oils from Neem, pongamia, mahua, sal and the like produce oils, which are basically non-edible in nature. As on today, these oils are mostly used in sectors like pharmaceuticals, lubricants, dying and others. There are above 120 species classified under non-edible grade oil category both tree-born and crop based. These oils have very high value for substitution for diesel.

Advantages and Disadvantages of biomass

Biomass has both advantages as well as disadvantages in being used as an

energy source which are enumerated below.
i. The biomass provides an effective low sulphur fuel.
ii. It provides an inexpensive and readily available source of energy, and
iii. Processing biomass materials for fuel reduce the environmental hazard.
The major problems or difficulties in utilizing biomass for solar energy conversion as well as a renewable source of energy are:
i. The relatively small percentage (less than 0.1%) of light energy is converted into biomass by plants.
ii. The relatively sparse and low concentration of biomass per unit area of land and water
iii. The scarcity of additional land suitable for growing plants.
iv. Scattered and seasonal availability of biomass
v. Their large volume and low bulk density associated with high moisture content that makes their collection and transport expensive and energy conversion relatively inefficient.
vi. The very abrasive nature due to silica cellulose structure causing high wear and tear in grinding machinery and fragile and porous nature of some agro industrial residues like rice husk makes them difficult to be stored in outdoor piles which become vulnerable to fire hazard and be air borne by the wind.
These methods are based on thermal, chemical and enzymatic conversion processes.
In dry process, material is transformed under high temperature
In wet process, Biological processes such as fermentation are involved.

Biomass Conversion to Biofuel

Fresh biomass in comparison with the conventional fossil fuels has the following relative inferior characteristics:
(i) they have only a modest thermal content;
(ii) they have a high moisture content that causes significant energy loss on combustion;
(iii) they usually have a low bulk density and hence become difficult for handling, storage and burning;
(iv) the physical form is often not homogeneous and hence becomes difficult for transportation and feeding to end use equipments.
The conversion processes of biomass usually involve the following:
(i) the reduction of the moisture content of the material, for simultaneous increase in its thermal value and ensure its preservation;
(ii) improving the handling characteristics of the material (converting them into fluid either gas or liquid).

Biomass Conversion

There are many biomass conversion routes to prepare energy efficient biofuels. The conversion routes are broadly divided in 4 categories. These are outlined as follows:

(i) Physical → Densification of biomass into solid briquettes

(ii) Agrochemical → Fuel (solid or liquid) extraction from freshly cut plant.

(iii) Thermochemical
- → Combustion
- → Carbonisation
- → Pyrolysis
- → Gasification
- → Liquefication
- → Anaerobic digestion to methane

(iv) Biochemical
- → Ethanol fermentation
- → Hydrogen formation for fuel cell

Energy production from Biomass

4.1 Direct combustion for heat

Biomass is burnt to provide heat for cooking, comfort heat (space heat), crop drying, factory processes and raising steam for electricity production and transport. Traditional use of biomass combustion includes (a) cooking with firewood, with the latter supplying about 10–20% of global energy use (a proportion extremely difficult to assess) and (b) commercial and industrial
use for heat and power, e.g. for sugarcane milling, tea or copra drying, oil palm processing and paper making. Efficiency and minimum pollution is aided by having dry fuel and controlled, high temperature combustion.

1. **Crop drying**

The drying of crops (e.g. fruit, copra, cocoa, coffee, tea), for storage and subsequent sale, is commonly accomplished by burning wood and the crop residues, or by using the waste heat from electricity generation. The material to be dried may be placed directly in the flue exhaust gases, but there is a danger of fire and contamination of food products.

2 **Process heat and electricity**

Steam process heat is commonly obtained for factories by burning wood or other biomass residues in boilers, perhaps operating with fluidized beds. It is physically sensible to use the steam first to generate electricity before the heat degrades to a lower useful temperature. The efficiency of electricity generation from the biomass may be only about 20–25% due to low temperature combustion, so 75–80% of the energy remains as process heat and a useful final temperature is maintained.

3. **Domestic cooking and heating**

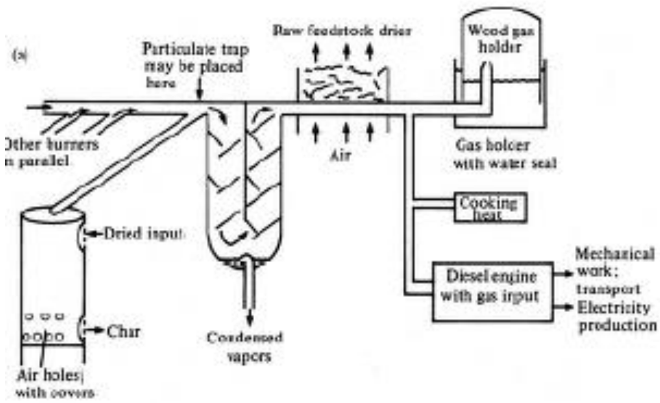
A significant proportion of the world's population depends on fuelwood or other biomass for cooking, heating and other domestic uses.

4 .**Pyrolysis (destructive distillation)**

Pyrolysis is a general term for all processes whereby organic material is heated or partially combusted to produce secondary fuels and chemical products. The input may be wood, biomass residues, municipal waste or indeed coal. The products are gases, condensed vapours as liquids, tars and oils, and solid residue as char (charcoal) and ash. Traditional *charcoal making* is pyrolysis with the vapours and gases not collected. *Gasification* is pyrolysis adapted to produce a maximum amount of secondary fuel gases.

The fuel products are more convenient,clean and transportable than the original biomass. The chemical products are important as chemical feedstock for further processes or as directly marketable goods. Partial combustion devices, which are designed
to maximise the amount of combustible gas rather than char or volatiles, are usually called *gasifiers*.

Large efficiencies of 80–90% can be reached. For instance gasifiers from wood can produce 80% of the initial energy in the form of combustible gas (predominantly H2 and CO – *producer gas*), suitable for operation in converted petroleum–fuelled engines.



Some Advantages of Pyrolysis of Biomass :

- Carbon neutrality
- Utilises otherwise waste biomass
- Potential to be self-sustaining energy-wise
- Increases bulk and energy density of biomass
- Source of valuable chemicals
- Biomass source can be decoupled from the energy utilisation

The three main variables in the pyrolysis process are:

- Reaction temperature.
- Biomass heating rate.
- Vapour residence time.

Anaerobic Digestion

Anaerobic digestion is the decomposition of organic waste by bacteria in an oxygen free environment to gaseous fuel. The process breaks down the organic matter into simpler organic compounds. The final product is a mixture of methane (CH4), carbon dioxide (CO2) and some trace gases known as biogas. The process is called anaerobic fermentation.

It has been known to exist forquite a long time. Biogas is also known as swamp gas, sewer gas, fuel gas, marsh gas, wet gas and in India more commonly as ‘‘gobar’’ gas. The main fuel component of biogas is methane gas. Biogas is produced in a digester by anaerobic fermentation. A digester is a sealed tank or container in which the biological requirements of anaerobic digestion are controlled to achieve fermentation and to produce biogas. Anaerobic digestion is a simple and low cost process that can be economically carried out is rural areas where organic wastes are generated in plenty. Biogas is a renewable and nonfossil fuel that is created as a byproduct of plant and animal materials. Wastes in large quantities on a renewable basis are also available from agricultural crops and residues, fruit and vegetable plants and municipal refuse.

What is Methanol?

Methanol is a liquid transportationfuel that can be produced from fossil or renewable domestic resources. In the United States, it is most commonly used as a chemical feedstock, extractant, or solvent,and as a feedstock for producing methyl tertiary butyl ether (MTBE),an octane-enhancing gasoline additive.It can also be used in neat (100% pure) form as a gasoline substitute,or in gasoline blends such as M85 (85% methanol and 15% gasoline).

The Production Process

Methanol can be produced from biomass through a thermochemical process known as gasification. The biomass is subjected to elevated temperatures and pressures (in some processes) to form a synthesis gas (syngas). The syngas (a mixture of carbon monoxide and hydrogen) is conditioned to remove impurities such as tars and methane,and to adjust the hydrogen-tocarbon monoxide ratio to 2:l. The syngas is then reacted over a catalyst at elevated temperatures and pressures to form methanol.

Manufacture of Methanol from Synthesis Gas

Introduction

- Synthesis gas is H_2+CO
- When synthesis gas is subjected to high pressure and moderate temperature conditions, it converts to methanol.
- Followed by this, the methanol is separated using a series of phase separators and distillation columns.
- The process technology is relatively simple.

Reactions

- Desired: $CO + 2H_2 \rightarrow CH_3\,OH$

  - Side reactions: $CO + 3H_2 \rightarrow CH_4 + H_2\,O$
    $2CO + 2H_2 \rightarrow CH_4 + CO_2$

All above reactions are exothermic

- Undesired reaction: $zCO + aH_2 \rightarrow$ alchohols + hydrocarbons.

  - Catalyst: Mixed catalyst made of oxides of Zn, Cr, Mn, Al.

Process Technology (Figure 13.1)

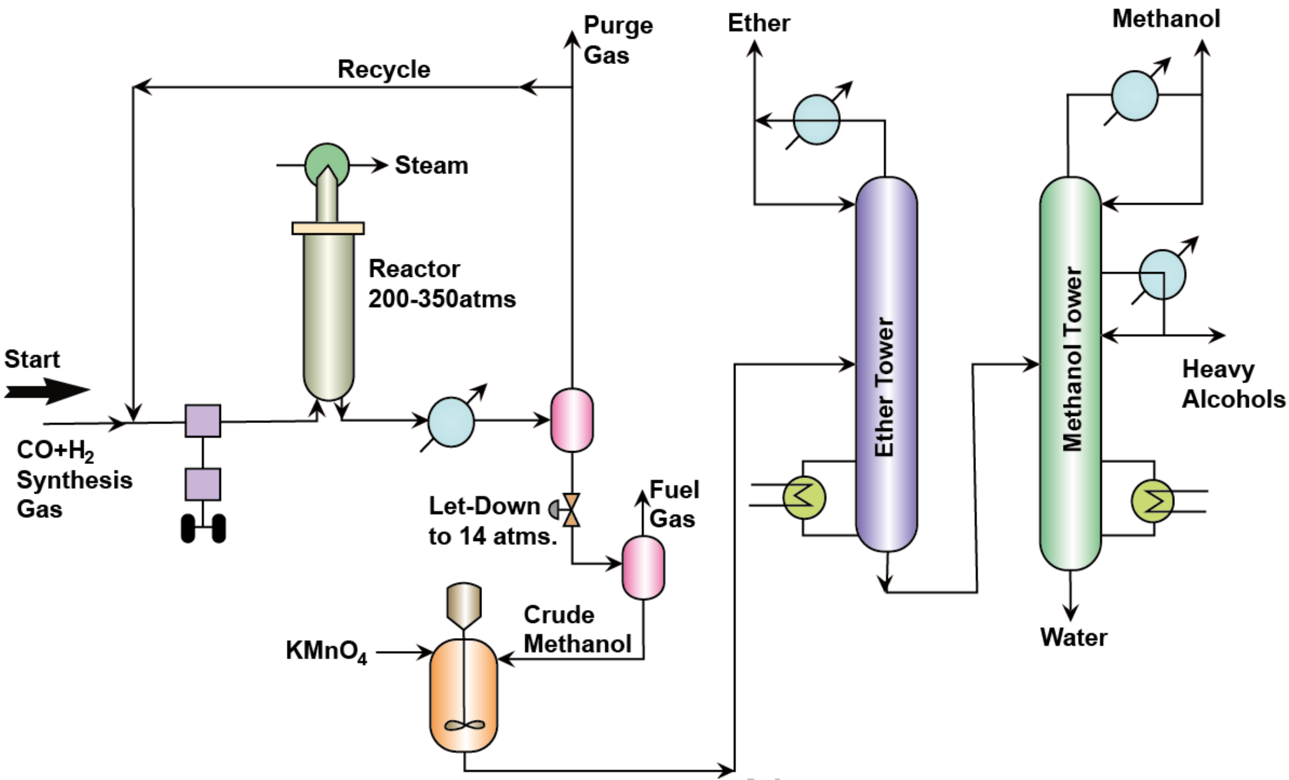


Figure 13.1 Flow sheet of manufacture of Methanol from Synthesis Gas

• H_2 and CO adjusted to molar ratio of 2.25.

• The mixture is compressed to 200 – 350 atms.

• Recycle gas (Unreacted feed) is also mixed and sent to the compressor.

• Then eventually the mixture is fed to a reactor. Steam is circulated in the heating tubes to maintain a temperature of 300 – 375°C.

• After reaction, the exit gases are cooled.

• After cooling, phase separation is allowed. In this phase separation operation methanol and other high molecular weight compounds enter the liquid phase and unreacted feed is produced as the gas phase.

• The gas phase stream is purged to remove inert components and most of the gas stream is sent as a recycle to the reactor.

• The liquid stream is further depressurized to about 14 atms to enter a second phase separator that produces fuel gas as the gaseous product and the liquid stream bereft of the fuel gas components is rich of the methanol component.

• The liquid stream then enters a mixer fed with $KMNO_4$ so as to remove traces of impurities such as ketones, aldehydes etc.

• Eventually, the liquid stream enters a distillation column that separates dimethyl ether as a top product.

• The bottom product from the first distillation column enters a fractionator that produces methanol, other high molecular weight alcohols and water as three different products.

Utilization of methanol
Neat methanol can be used in existing vehicles; however, engine modifications are required to facilitate cold starts and to replace materials that can be corroded by methanol and M85. Methanol has a higher octane rating than gasoline, which helps reduce engine "knock." It can also deliver greater fuel efficiency if the engine's compression ratio is properly adjusted.

CLASSIFICATION OF BIOGAS PLANTS :

Based on the process:

a) Continuous-Single & Double stage process b) Batch fed process

Based on the construction

a) floating gas holder plant (KVIC)

b) fixed dome digester

Based on the application:

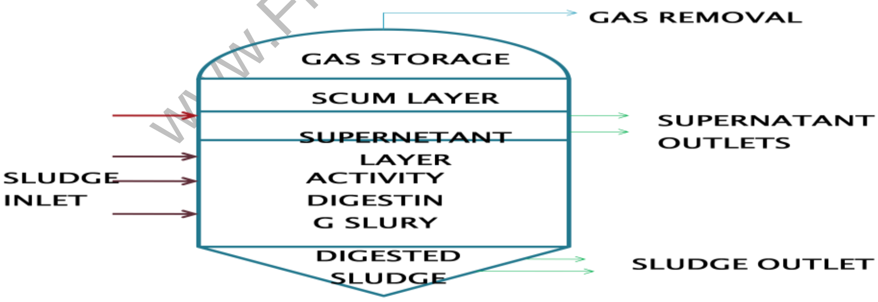
a) Small scale plant- for Family

b)Medium scale plant- for village

c) Industrial plant

1.Continuous plant

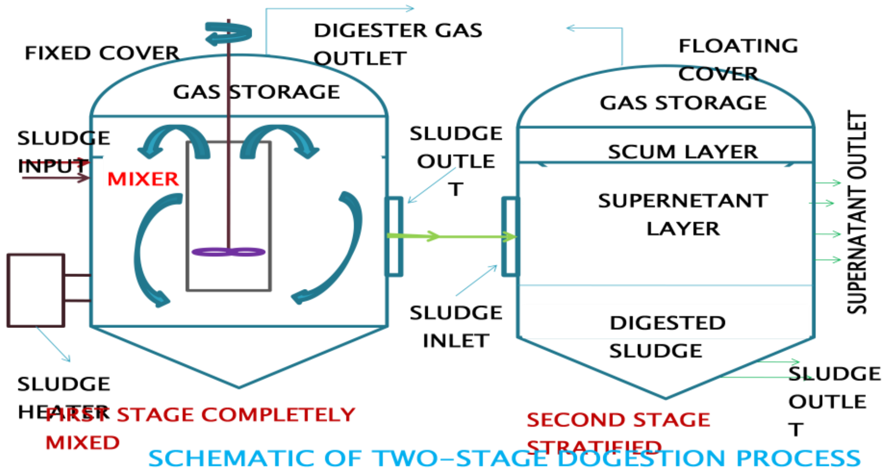
A single digester in which raw materials are charged regularly & the process goes on without interruption except for repair & cleaning etc. The raw material is self buffered or otherwise thoroughly mixed with the digesting mass where dilution prevents souring & the biogas production is maintained. The continuous process may be completed in a *single stage* or *double stage* process.



SCHEMATIC OF SINGLE PROCESS CONVENTIONAL DIGEST

i) The entire process of conversion of complex organic compounds into biogas is completed in a single chamber. The chamber is regularly fed with the raw materials while the spent residue keeps moving out. Series problems are encountered with agricultural residues when fermented in a single stage continuous process.

ii) Double stage process



SCHEMATIC OF TWO-STAGE DOGESTION PROCESS

The *acidogenic* stages & *methanogenic* stage are physically separated in to two chambers. The first stage of acid production is carried out in a separate chamber and only the diluted acids are fed in to the second chamber where bio-methanation takes place & the biogas can be collected from the second chamber.

Continuous-fed System :

- It will produce gas continuously
- It requires small digestion chamber.
- It needs lesser period for digestion
- It has less problems compared to batch type & it is easier in operation
- Suited for large-scale manure substrate bioreactor.
- Steady biogas production can be expected.
- May require auxiliary equipments.
- Requires high liquid content.
- Temperature, loading rate, and solid content need to be carefully monitored.

Batch-fed System :

- The simplest design.
- Low cost.
- The feedstock is loaded one batch at time.
- Irregular biogas production.
- Can operate on high solid content.
- Less susceptible to fluctuation of factors.
- Requires manual labor.:

b. The batch plant

The feeding is between intervals, & the plants emptied once the process of digestion is complete. A battery of digesters are charged along with lime, urea etc. & allowed to produce gas for 40-50 days. These are charged and emptied one by one in a synchronous manner which maintain a regular supply of the gas through a common gas holder. The bio gas supply may be utilised after 8-10 days. Their installation & operation being capital & labour intensive.

Main features of batch plant:

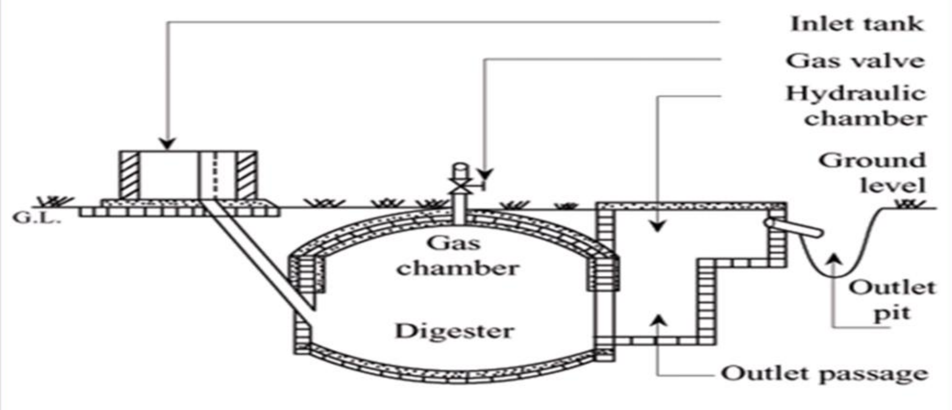
1. The gas production is intermittent.

2. It need several digesters for continuous gas production
3. Good for long fibrous materials.
4. Plant needs addition of fermented slurry to start the digestion process.
5. Plant is expensive.

2. The Dome & the Drum type

Two main types are known as Floating gas holder digester (KVIC) & Fixed dome digester(Chinese). There are different designs, cylindrical rectangular, spherical etc. The digester may be vertical or horizontal. They can be constructed above or underneath the ground. The floating gas holder digester is of masonry construction with the gas holder made with M S plates. The gas holder is separated from the digester.

fixed dome digester



Fixed dome type biogas digester

In the fixed dome digester , gas holder & digester are combined . The fixed dome is best suited for batch process especially when daily feeding is adopted in small quantities. Fixed dome digester is usually built below ground level & is suited for cooler regions. The pressure inside the digester varies as the gas collected. Local materials can be used in this construction.

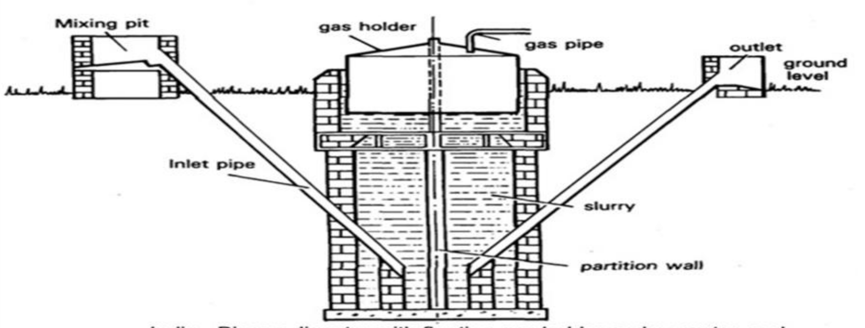
Advantages of Fixed dome type plant :

1. Low cost (only cement)
2. No corrosion trouble.
3. Temperature will be constant.
4. Cattle & human excreta and long fibrous stalks can be fed.
5. No maintenance.

Disadvantages of Fixed dome type plant :

1. Needs the services of skilled masons.
2. Gas production per cu m is less.
3. Scum formation is a problem as no stirring arrangement.
4. Variable gas pressure.

2. Floating gas holder digester(KVIC Model)



India - Biogas digester with floating gas holder and no water seal

Advantages of floating drum plant

1. Less scum troubles because solids are constantly submerged.
2. No separate pressure equalizing device needed
3. The danger of mixing oxygen with the gas to form an explosive mixture is minimized.
4. Higher gas production per cu m of the digester is achieved.
5. Floating drum has welded braces, which help in breaking the scum by rotation.
6. No problem of gas leakage.
7. Constant gas pressure

Disadvantages of floating drum plant :

1. Higher cost (steel & cement)
2. Heat is lost through the metal gas holder .
3. Gas holder requires painting once or twice a year. (humidity & location)
4. Flexible pipe joining the gas holder to the main pipe requires maintenance. (UV rays & rotation of the drum)

Factors considered for site location of Biogas Plant

- **Distance from residential areas**

The site should be located at suitable distance from residential areas in order to avoid inconveniences, nuisance and thereby conflicts related to odours and increased traffic to and from the biogas plant.

- **Direction of the dominating winds** must be considered in order to avoid wind born odours reaching residential areas.
- The site should **have easy access to infrastructure** such as to the electricity grid, inorder to facilitate the sale of electricity and to the transport roads in order to facilitate transport of feedstock and digestate.
- The **soil of the site** should be investigated before starting the construction.
- The chosen site **should not be located in a potential flood affected area.**
- The site should be located **relatively close (central) to the agricultural feedstock** production (manure, slurry, energy crops) aiming to minimise distances, time and costs of feedstock transportation.
- For cost efficiency reasons, the biogas plant should be located as **close as possible to potential users** of the produced heat.

- Alternatively, other potential heat users such as heat demanding industry, greenhouses etc. can be brought closer to the biogas plant site.
- The **size of the site** must be suitable for the activities performed and for the amount of biomass supplied.

Factors Affecting Biodigestion/Factors affecting production of biogas

1. pH or hydrogen-iron concentration (7-7.5)
2. Nutrients (C, H2, O2, N2, P & S)
3. Temperature (35-38 Degrees C)
4. Mixing or stirring or agitation of the content of the digester
5. Retention time or rate of feeding (30-45 days)
6. Type of feed stock
7. Toxicity due end product
8. Pressure
9. Acid accumulation inside the digester.
10. Total solid content of the feed material
11. Loading rate
12. Uniform feeding
13. Diameter to depth ratio (0.66 to 1.00)
14. Carbon to nitrogen ratio (30 :1)

Characteristics of A Fuel Cell

Just as real heat engines don't perform nearly as well as a perfect Carnot engine, real fuel cells don't deliver the full Gibbs free energy either.

Activation losses result from the energy required by the catalysts to initiate the reactions. The relatively slow speed of reactions at the cathode, where oxygen combines with protons and electrons to form water, tends to limit fuel cell power.

Ohmic losses result from current passing through the internal resistance posed by the electrolyte membrane, electrodes, and various interconnections in the cell. Another loss, referred to as *fuel crossover*, results from fuel passing through the electrolyte without releasing its electrons to the external circuit.

Mass transport losses result when hydrogen and oxygen gases have difficulty reaching the electrodes. This is especially true at the cathode if water is allowed to build up, clogging the catalyst.

For these and other reasons, real fuel cells, in general, generate only about 60–70% of the theoretical maximum.

Current and voltage for a typical fuel cell resembles to those photovoltaic cell.

Voltage at zero current, called the *open-circuit voltage*, is a little less than 1 V, which is about 25% lower than the theoretical value of 1.229 V.

Product of voltage and current, which is power. Since power at zero current, or at zero voltage, is zero, there must be a point somewhere in between at which power is a maximum. Maximum power corresponds to operation of the fuel cell at between 0.4and 0.5 V per cell. The three regions shown on the graph point out the ranges of currents in which activation, ohmic, and mass-transport losses are individually most important.

Over most of the length of the fuel cell *I* –*V* graph, voltage drops linearly as current increases. This suggests a simple equivalent circuit consisting of a voltage source in series with some internal resistance. Fitting the *I* –*V* curve in the ohmic regionthat yields the approximate relationship:

$V = 0.85 - 0.25J = 0.85 - 0.25I/A$)

where *A* is cell area (cm2), *I* is current (amps), and *J* is current density (A/cm2).

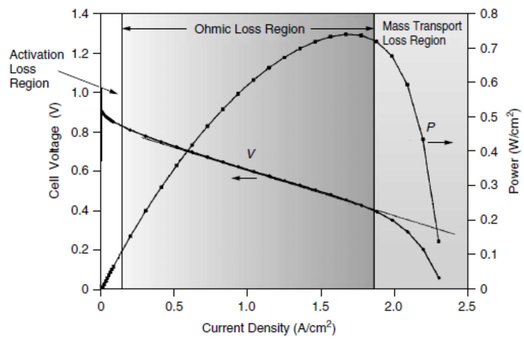


Figure 4.29 The voltage–current curve for a typical fuel cell. Also shown is the power delivered, which is the product of voltage and current.

Fuel Cells

Fuel cells are electrochemical devices that convert a fuel’s chemical energy directly to electrical energy without an intermediate combustion or thermal cycle. With no internal moving parts, fuel cells operate similar to batteries. An important difference is that batteries store energy, while fuel cells produce electricity continuously as long as fuel (usually natural gas or hydrogen) and air are supplied. Fuel cells electrochemically combine a fuel (typically hydrogen) and oxygen from air without burning, thereby dispensing with the inefficiencies and pollution of traditional energyconversion systems. Fuel cells emit virtually no pollution as the waste ‘‘exhaust’’ is simply water vapour and heat. In many applications, the waste heat can be used, making a fuel cell system much more efficient than conventional power supplies. In some applications, fuel cell systems can convert 80% of the energy available in the fuel into electrical and heat energy.

Working of Fuel Cell

The operation of a fuel cell is illustrated schematically in Figure below. The fuel cell consists of two gas-permeable electrodes separated by an electrolyte, which is a transport medium for electrically charged ions.

- Hydrogen gas, fuel in all current designs of fuel cells, enters the fuel cell through the anode, while oxygen is admitted through the cathode. Hydrogen is generated from biofuels and oxygen is supplied from the air.
- Depending on the fuel cell design, either positively charged hydrogen ions form at the anode or negatively charged ions containing oxygen form at the cathode.
- In either case, the resulting ions migrate through the electrolyte to the opposite electrode from which they are formed.
- Hydrogen ions migrate to the cathode where they react with oxygen to form water. Oxygen-bearing ions migrate to the anode where they react with hydrogen to form water.
- Both ionic processes release chemical energy in the form of electrons at the anode, which flow to the cathode through an external electric circuit. The flow of electrons from anode to cathode represents the direct generation of electric power from flameless oxidation of fuel.

Material Characteristic Requirements for Fuel Cells

Though the fuel cell appears to be a simple device, the requirements of electrodes (anode and cathode) and electrolyte are quite specific. These are listed as follows:

(a) Requirements of an Electrode

(i) It must be a good conductor, to transport electronic charges.

(ii) It must serve as a catalyst to convert hydrogen and oxygen molecules into their ions.

(iii) It must be chemically inert so that there should be no corrosion when it is in contact with an electrolyte.

(iv) It must be moldable into any shape and size as the stacking of fuel cells need to be done to generate the desired fuel cell power generation system.

(v) It must withstand high temperatures, as some fuel cells need to be operated at higher
temperature.

(b) Requirements of an Electrolyte

(i) It must be ionically conducting.

(ii) The two electrodes must be prevented from coming into electrical contact.

(iii) It must allow passage of ions from one electrode to the other.

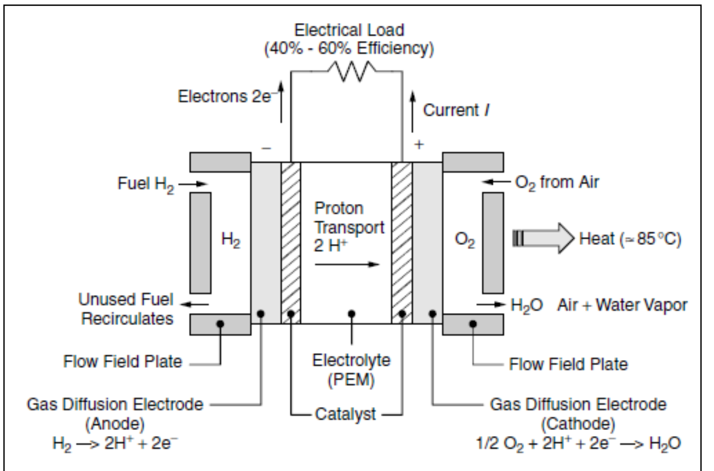


Figure 4.26 Basic configuration of a proton-exchange membrane (PEM) fuel cell.

Types of Fuel Cells

There are varieties of fuel cells developed working from room temperature to 1000^0C. These are classified mainly into two groups, low temperature fuel cells and high temperature fuel cells. The fuel cells can be classified further depending on the electrolyte used. These are of five types:

(i) alkaline fuel cells;
(ii) polymer membrane or proton-exchange membrane fuel cells;
(iii) phosphoric acid fuel cells;
(iv) molten carbonate fuel cells;
(v) solid oxide fuel cells.

Benefits from Fuel Cells

(i) The efficiency of fuel cells is as high as 50 to 70%.
(ii) Their nonpolluting nature facilitates the use in cities where power is needed, rather than far away.
(iii) A variety of fuel can be used including natural gas, hydrogen, methanol and biogas.
(iv) Fuel cells are finding many uses in stationary, mobile and portable applications, i.e. from
large buildings to cellphones.
(v) Fuel cells can virtually eliminate emissions of nitrous oxide, carbon monoxide, hydrocarbon and particulate matter.

There are three classes of geothermal region:

1 *Hyperthermal*. Temperature gradient ≥80 _Ckm−1. These regions are usually on tectonic plate boundaries. The first such region to be tapped for electricity generation was at Larderello in Tuscany, Italy in 1904. Nearly all geothermal power stations are in such areas.
2 *Semithermal*. Temperature gradient ∼40–80 _Ckm. Such regions are associated generally with anomalies away from plate boundaries. Heat extraction is from harnessing natural aquifers or fracturing dry rock. A well-known example is the geothermal district heating system for houses in Paris.

3 *Normal*. Temperature gradient <40 _Ckm. These remaining regions are associated with average geothermal conductive heat flow at ~0_06Wm−2. It is unlikely that these areas can ever supply geothermal heat at prices competitive to present (finite) or future (renewable) energy supplies.
In each class it is, in principle, possible for heat to be obtained by:
1 *Natural hydrothermal circulation*. In this, water percolates to deep aquifers to be heated to dry steam, vapour/liquid mixtures or hot water. Emissions of each type can be observed in nature. If pressure increases by steam formation at deep levels, spectacular geysers may occur, as at the Geysers near Sacramento in California and in the Wairakei area near Rotorua in New Zealand. Note, however, that liquid water is ejected, and not steam.
2 *Hot igneous systems*. These are associated with heat from semi-molten magma that solidifies to lava. The first power plant using this source was the 3MWe station in Hawaii, completed in 1982.
3 *Dry rock fracturing*. Poorly conducting dry rock, e.g. granite, stores heat over millions of years with a subsequent increase in temperature. Artificial fracturing from boreholes enables water to be pumped through the rock to extract the heat.

Dry rock and Hot Aquifer Analysis

We consider a large mass of dry material extending from near the earth's surface to deep inside the crust, (Figure 15.3). The rock has density _r, specific heat capacity *c*r and cross-section *A*. With uniform material and no convection, there will be a linear increase of temperature with depth. If *z* increases *downward* from the surface at *z* = 0,

Hot Aquifer Analysis

Assume heat is extracted from the rock uniformly in proportion to the temperature excess over *T*1 by a flow of water with volume flow rate $\dot{V}$, density _w and specific heat capacity *c*w. The water will be heated through a temperature difference of _ in the near perfect heat exchange process.

Analysis of Hot Aquifers

In the case of a hot aquifer, the heat resource lies within a layer of water deep beneath the ground surface as shown in Figure below. The thickness of the aquifer (h) is much less than the depth x_2 below the ground level. The water is all at temperature T_2. The fraction of the aquifer containing water has porosity p_0. With the remaining space, rock has the density of r_r, The minimum useful temperature is T_1.