Module-1

Energy Sources:- Energy storage can be defined as means of storing energy in a readily recoverable form when the supply exceeds the demand for use at other times. Storage of primary fuels (e.g. coal, oil and gas) is also a form of energy storage, but the term 'energy storage' generally applies to secondary energy rather than primary energy.

Classification:-
Energy resources can be classified on the basis of following criteria:

1. Based on Usability of Energy

a) Primary resources- Examples of primary energy resources are coal, crude oil, sunlight, wind, running rivers, vegetation and radioactive material like uranium etc.
These resources are generally available in raw forms and are therefore, known as raw energy resources. Generally, this form of energy cannot be used as such. These are located, explored, extracted, processed and are converted to a form as required by the consumer.

$$\text{Energy Yield Ratio} = \frac{\text{Energy received from raw energy source}}{\text{Energy spent to obtain raw energy source}}$$

(b) Secondary Resources The energy resources supplied directly to consumer for utilization after one or more steps of transformation are known as secondary or usable energy, e.g. electrical energy, thermal energy (in the form of steam or hot water), refined fuels or synthetic fuels such as hydrogen fuels, etc.

2. Based on Traditional Use

(a) Conventional Energy resources, which are being traditionally used, for many decades and were in common use around oil crisis of 1973, are called conventional energy resources, e.g. fossil fuels, nuclear and hydro resources.
(b) Non-conventional Energy resources, which are considered for large-scale use after the oil crisis of 1973, are called non-conventional energy sources, e.g. solar,wind, biomass, etc.

3. Based on Long-Term Availability

(a) Non-renewable Resources, which are finite and do not get replenished after their consumption, are called non-renewable e.g. fossil fuels, uranium, etc. They are likely to deplete with time.
(b) Renewable Renewable energy is energy obtained from sources that are essentially inexhaustible. Examples of renewable resources include wind power, solar power, geothermal energy, tidal power and hydroelectric power. The most important feature of renewable energy is that it can be harnessed without the release of harmful pollutants.

4. Based on Commercial Application

(a) Commercial Energy Resource-The energy sources that are available in the market for a definite price are known as commercial energy. Most important forms of commercial energy are electricity, coal and refined petroleum products. Applications of solar energy, wind energy, hydro energy for electricity and lifting water from the ground require technology are termed as commercial energy sources.
(b) Non-commercial Energy The energy sources that are not available in the commercial market for a price are classified as non-commercial energy. All energy sources which are available in nature like wind, sun, hydro etc. are non-commercial energy sources. Non-commercial energy sources include fuels such as firewood, cattle dung and agricultural wastes, which are traditionally gathered, and not bought at a price, used especially in rural households.

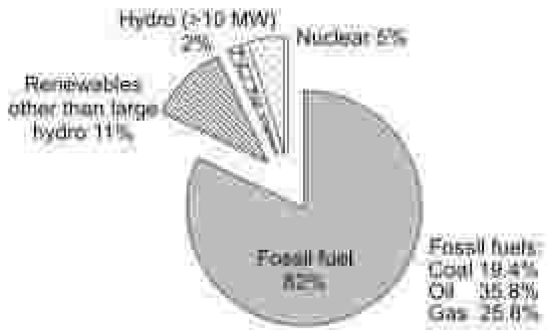
5. Based on origin

(a) Fossil fuels energy
(b) Nuclear energy

(c) Hydro energy
(d) Solar energy
(e) Wind energy
(f) Biomass energy
(g) Geothermal energy
(h) Tidal energy
(i) Ocean thermal energy
(j) Ocean wave energy

Consumption trend of Primary Energy resources

The global average consumption trend of various primary energy resources of the world is indicated in Fig. 1.



Percentage consumption of various primary energy resources

Fig .1

Importance of non-conventional energy sources

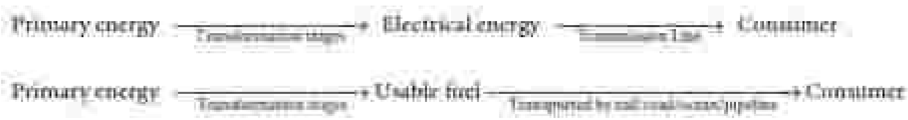
The concern for environment due to ever-increasing use of fossil fuels and rapid depletion of these resources has led to development of alternative sources of energy, which are renewable and environment friendly. Following points may be mentioned in this connection:

1. Conventional sources (except hydro) are non-renewable and finite assets. With present rate of consumption their availability is rapidly declining.
2. The demand of energy is increasing exponentially due to rapid industrialization and population growth, the conventional sources of energy alone will not be sufficient in the long run, to meet the growing demand.
3. Conventional sources (fossil fuels, nuclear) also cause pollution leading to degradation of the environment. Ultimately, their use has to be restricted within acceptable limits.
4. Large hydro resources affect wild life, cause deforestation and pose various social problems.

Due to these reasons it has become important to explore and develop nonconventional energy resources to reduce too much dependence on conventional resources. However, the present trend of developments of non-conventional sources indicate that these will serve as supplement rather than substitute for conventional sources for some more time to come.
Realizing the importance of non-conventional energy sources, in March 1981 the government of India established a Commission for Additional Sources of Energy (CASE) in the Department of Science and Technology, on the lines of the Space and Atomic Energy Commissions.

Energy Chain

The energy available from primary energy source is known as raw energy. This energy undergoes one or more transformation stages before supplying to consumer. The sequence of energy transformations between primary and secondary energy (usable energy) is known as energy chain or energy route.



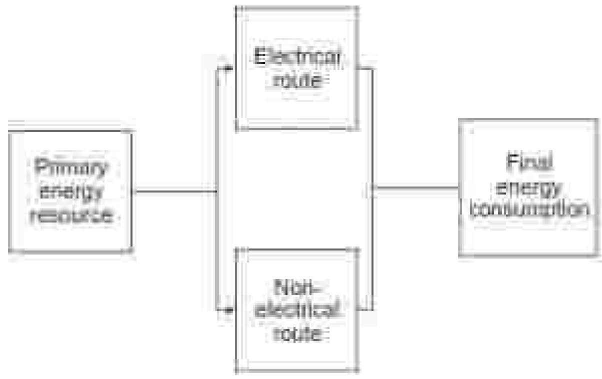


Figure 1.3 Energy routes

Common forms of Energy

1. Electrical Energy
2. Mechanical Energy
3. Thermal Energy
4. Chemical Energy

Advantages and disadvantages of Conventional Energy Sources

Advantages

1. Cost : At present these are cheaper than non-conventional sources.
2. Security : As storage is easy and convenient, by storing certain quantity, the energy availability can be ensured for certain period.
3. Convenience: These sources are very convenient to use as technology for their conversion and use is universally available.

Disadvantages

1. Fossil fuels generate pollutants. Main pollutants generated in the use of these sources are CO, CO_2, NO_x, SO_2, particulate matter and heat. These pollutants degrade the environment, pose health hazards and cause various other problems. CO_x is mainly responsible for global warming also.
2. Coal is also a valuable petro-chemical and is used as raw material for various chemical, pharmaceuticals and paints, etc. industries. From long-term point of view it is desirable to conserve coal for future needs.
3. There are safety and technical issues with nuclear energy. Major problems associated with nuclear energy are as follows:

(a) The waste material generated in nuclear plants has radioactivity of dangerous level; it remains above safe limit for a long period of time and thus is a health hazard. Its safe disposal, which is essential to prevent radioactive pollution, is a challenging task. Also the disposed radioactive waste is required to be guarded for a long period (till its radioactivity level comes down to a safe limit) in order to prevent against going in wrong hands.
(b) Possibility of accidental leakage of radioactive material from reactor (as happened in Chernobyl, former USSR in April 1986)
(c) Uranium resource, for which the technology presently exists, has limited availability.
(d) Sophisticated technology is required for using nuclear resources. Only few countries possess the required expertise to use nuclear energy.

4. Hydroelectric plants are cleanest but large hydro-reservoirs cause following problems:

(a) As large land area submerges into water, it leads to deforestation
(b) Causes ecological disturbances such as earthquakes

(c) Affects wild life

(d) Causes dislocation of large population and their rehabilitation problems

Salient Features of Non-Conventional Energy Sources

Merits

1. Non-conventional sources are available in nature free of cost.
2. They produce no or very little pollution. Thus by and large they are environment friendly.
3. They are inexhaustible(unlimited).

Demerits

1. In general the energy is available in dilute form from these sources.
2. Though available freely in nature the cost of harnessing energy from non-conventional sources is generally high.
3. Uncertainty of availability: the energy flow depends on various natural phenomena beyond human control.
4. Difficulty in transporting this form of energy.
5. Difficulty in storage.

Environmental Aspect of Energy

Greenhouse effect:- Carbon dioxide (CO_2) envelope present around the globe in the atmosphere behaves similar to a glass pane and forms a big global green house. This tends to prevent the escape of heat from earth, which leads to global warming. This phenomenon is known as greenhouse effect.

Apart from CO_2, other gases behaving similar to CO_2 include methane, nitrous oxide (NO),hydro fluorocarbons (HFCs), chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFC), sulphur hexafluoride, ozone and water vapor. These gases are known as greenhouse gases (GHG). Their average concentrations in atmosphere along with Global Warming Potentials (GWPs) relative to CO_2 and atmospheric lifetimes are listed in Table 1.3.

S. N.	Name of the Gas	Concentration in ppm	GWP (100 yr time horizon)	Atmospheric lifetime (yrs)
1.	Carbon dioxide (CO_2)	400	1	100-300
2.	Methane (CH_4)	1.893	28	12
3.	Nitrous oxide (N_2O), commonly known as laughing gas	0.326	265	121
4.	Sulfur hexafluoride (SF_6)	negligible	23,500	3,200

Ex-

A chemical industry produces 5 Tg (teragrams) of NO per day. How much pollution is added into the atmosphere per day in terms of carbon equivalent?

Solution:-The Global Warming Potential (GWP) of NO is 265.

The daily pollution of NO = 5 Tg

The daily pollution in terms of equivalent CO_2 (ref. Table 1.3) = 5 × 265 = 1,325 Tg = 1,325 Million Tons of CO_2

As (12/44) is the carbon to CO_2molecular weight ratio, the pollution in terms of Million Metric Tons of Carbon Equivalent (MMTCE) = 1,325 × (12/44)= 361.36 MMTCE

Global Warming:- 'Global warming is the continuing rise in the average temperature of the earth's atmosphere and ocean's surface due to greenhouse effect'.

World Energy Status

World total primary energy consumption by fuel in 2018

Coal (27%)

Natural Gas (24%)
Hydro (renewables) (7%)
Nuclear (4%)
Oil (34%)
Others (renewables) (4%)

World energy consumption is the total energy produced and used by the entire human civilization.

Closely related to energy consumption is the concept of total primary energy supply (TPES), which – on a global level – is the sum of energy production minus storage changes.

Energy supply, consumption and electricity

Key figures (TWh)

Year	Primary energy supply (TPES) (MTOE)	Final energy consumption (MTOE)	Electricity generation (TWH)
1973	71,013 (Mtoe 6,106)	54,335 (Mtoe 4,672)	6,129
1990	102,569	–	11,821
2000	117,687	–	15,395
2010	147,899 (Mtoe 12,717)	100,914 (Mtoe 8,677)	21,431
2011	152,504 (Mtoe 13,113)	103,716 (Mtoe 8,918)	22,126
2012	155,505 (Mtoe 13,371)	104,426 (Mtoe 8,979)	22,668
2013	157,482 (Mtoe 13,541)	108,171 (Mtoe 9,301)	23,322
2014	155,481 (Mtoe 13,369)	109,613 (Mtoe 9,425)	23,816
2015	158,715 (Mtoe 13,647)	109,136 (Mtoe 9,384)	
2017	162,494 (Mtoe 13,972)	113,009 (Mtoe 9,717)	25,606

[1] converted from Mtoe into TWh (1 Mtoe = 11.63 TWh) and from Quad BTU into TWh (1 Quad BTU = 293.07 TWh)

World total primary energy supply (TPES), or "primary energy" differs from the world final energy consumption because much of the energy that is acquired by humans is lost as other forms of energy during the process of its refinement into usable forms of energy and its transport from its initial place of supply to consumers. For instance, when oil is extracted from the ground it must be refined into gasoline, so that it can be used in a car, and transported over long distances to gas stations where it can be used by consumers. World final energy consumption refers to the fraction of the world's primary energy that is used in its final form by humanity.

In 2014, world primary energy supply amounted to 155,481 terawatt-hour (TWh) or 13,541 million tonne of oil equivalent (Mtoe), while the world final energy consumption was 109,613 TWh or about 29.5% less than the total supply.[11] World final energy consumption includes products as lubricants, asphalt and petrochemicals which have chemical energy content but are not used as fuel. This non-energy use amounted to 9,723 TWh (836 Mtoe) in 2015.[12]

2018 World electricity generation (26,700 TWh) by source (IEA, 2019)[

Coal (38%)
Gas (23%)
Hydro and other (19%)
Nuclear (10%)
Solar PV and wind (7%)
Oil (3%)

Electricity Consumption

The total amount of electricity consumed worldwide was 19,504 TWh in 2013, 16,503 TWh in 2008, 15,105 TWh in 2005, and 12,116 TWh in 2000. By the end of 2014, the total installed electricity generating capacity worldwide was nearly 6.14 TW (million MW) which only includes generation connected to local electricity grids.[16] In addition there is an unknown amount of heat and electricity consumed off-grid by isolated villages and industries. In 2014, the share of world energy consumption for electricity generation by source was coal at 41%, natural gas at 22%, nuclear at 11%, hydro at 16%, other sources (solar, wind, geothermal, biomass, etc.) at 6% and oil at 4%. Coal and natural gas were the most used energy fuels for generating electricity. The world's electricity consumption was 18,608 TWh in 2012.[*citation needed*] This figure is about 18% smaller than the generated electricity, due to grid losses, storage losses, and self-consumption from power plants (gross generation). Cogeneration (CHP) power stations use some of the heat that is otherwise wasted for use in buildings or in industrial processes.

In 2016 the total world energy came from 80% fossil fuels, 10% biofuels, 5% nuclear and 5% renewable (hydro, wind, solar, geothermal). Only 18% of that total world energy was in the form of electricity.[17] Most of the other 82% was used for heat and transportation.

World total primary energy consumption by fuel in 2018[2]

Coal (27%)
Natural Gas (24%)
Hydro (renewables) (7%)

Nuclear (4%)
Oil (34%)
Others (renewables) (4%)

By source

Total primary energy supply of 13,972 Mtoe by source in 2017 (IEA, 2019)[14]

Oil (32.0%)
Coal/peat/shale (27.1%)
Natural gas (22.2%)
Biofuels and waste (9.5%)
Hydro electricity (2.5%)
Others (renewables) (1.8%)
Nuclear (4.9%)

Availability of resources and future trend

The energy sources like coal and petroleum products take million years for production. These energy sources are going to be exhausted after few years. These energy sources are termed as *non-renewable energy sources*.

Energy sources like solar, wind, hydro, various forms of biomass and marine energy (wave & tidal) are never exhaustible. These are termed as *renewable energy sources.* Geothermal and ocean thermal energy sources are also renewable energy sources.

* The global primary energy supply and consumption is in table below.

Table: Annual primary energy consumption by fuel (2012) in Mtoe*

Country	Oil	Natural Gas	Coal	Nuclear Energy	Hydro-Electric	Renewable & Waste	Total
USA	884	594	615.7	83.8	28.2	77.3	2,283
Canada	152	83	31	9.4	68.6	NA	344
France	83	45	12.4	43.9	14.8	67.4	266.5
Russian Federation	494	438	153	16.3	35.6	NA	1136.9
United Kingdom	76.8	71.2	39.1	20.1	1.3	NA	208.5
China*	436	98.1	2500	12.3	58.5	103.1	3208
India*	205.5	47.1	352	4.1	11.4	98.4	718.5
Japan	199	93	71.6	25.8	8.3	98.1	495.8
Others	1807.3	1276.6	114.5	501.4	70.0	524.1	4293.9
Total	4337.6	2746	3889.3	717.1	296.7	968.4	12995.1

Mtoe- Million tons of oil equivalent.

Renewable Energy Sources:-

The capacity addition in renewable energy was about 27,300 MW in 2012.

Technology	Capacity Installed in MW by 2012.
Coal	11,202
Hydro	38,990
Renewable	27,300
Gas	18,381
Nuclear	4,780
Total	201,473

Table: India's Installed power generation capacity.

So, total renewable energy's contribution becomes almost 33% (includes Hydro power), plan wise grid connected renewable energy contribution is given in Table below.

Table: Power densities of *renewable energy sources* and *the conventional energy forms.*

Renewable Energy Sources	in KW/m^2
Wave	< 100
Extra terrestrial solar radiation	< 1.35
Wind	< 3
Solar radiation	0.2
Tidal	0.002
Biomass Production	0.002
Geothermal heat	0.00006

Conventional Energy	in KWh/m^2
Hot Plate	100
Coal	500
Nuclear	650
Power Cable	1000,000

Onshore wind energy potential is estimated to be around 49,130 MW at a height of 50 m. It is estimated that around 17% of wind energy is utilized whereas 25,000 MW Has been connected to the grid. Wind energy is considered to be a viable source to tackle the energy problems.

About 1/4th of energy used in India is in the form of biomass that consists of firewood, cattle dung, agriculture waste etc. This sector is managed by rural people without any technology, management and investment. Indian Govt. is promoting to use biomass to make deficit of energy. Studies have estimated that the biomass has potential of generating 17,000MW from agro and forest residues alone.

Biogas is a three decade old program across India which covers estimated 5 million installations.

India has put a national policy to replace the diesel and petrol by the production of biodiesel from *Jatropha, Karanja* and *Mahua* which has been tried for last two decades; and ethanol was considered to be successful replacement of petrol in transportation sector. The technology has been developed by Brazil in 1976 for successful of petrol and diesel. About 95% of cars sold in Brazil are flexible to run in both ethanol and petrol but this is not successful in India.

* Solar energy is distributed over the entire geographical region at the rate of 5-6 kwh/m^2/day. This can be utilized for the purpose of energy utilization in many thermal applications such as cooking or heating or in photovoltaic cells that convert sunlight to electricity.

India has launched a solar mission with an aim to install 20,000MW grid solar power, 2000MW off grid system, 20 million solar lights and20 million m^2 solar thermal collector by 2020.

Origin of Renewable Energy Sources:-

All available energy sources in the world that come from three different primary energy sources.

(i) Isotropic dissociation in the core of the earth.
(ii) Movements of the planets
(iii) Thermonuclear reactions in the earth.
* The largest energy flow comes from solar radiation, which is also responsible for the development of fossil energy sources, namely oil, coal and gas due to bio conversion which has occurred million years ago. All available natural renewable energy sources are presented in the diagram and their conversion is also shown below.

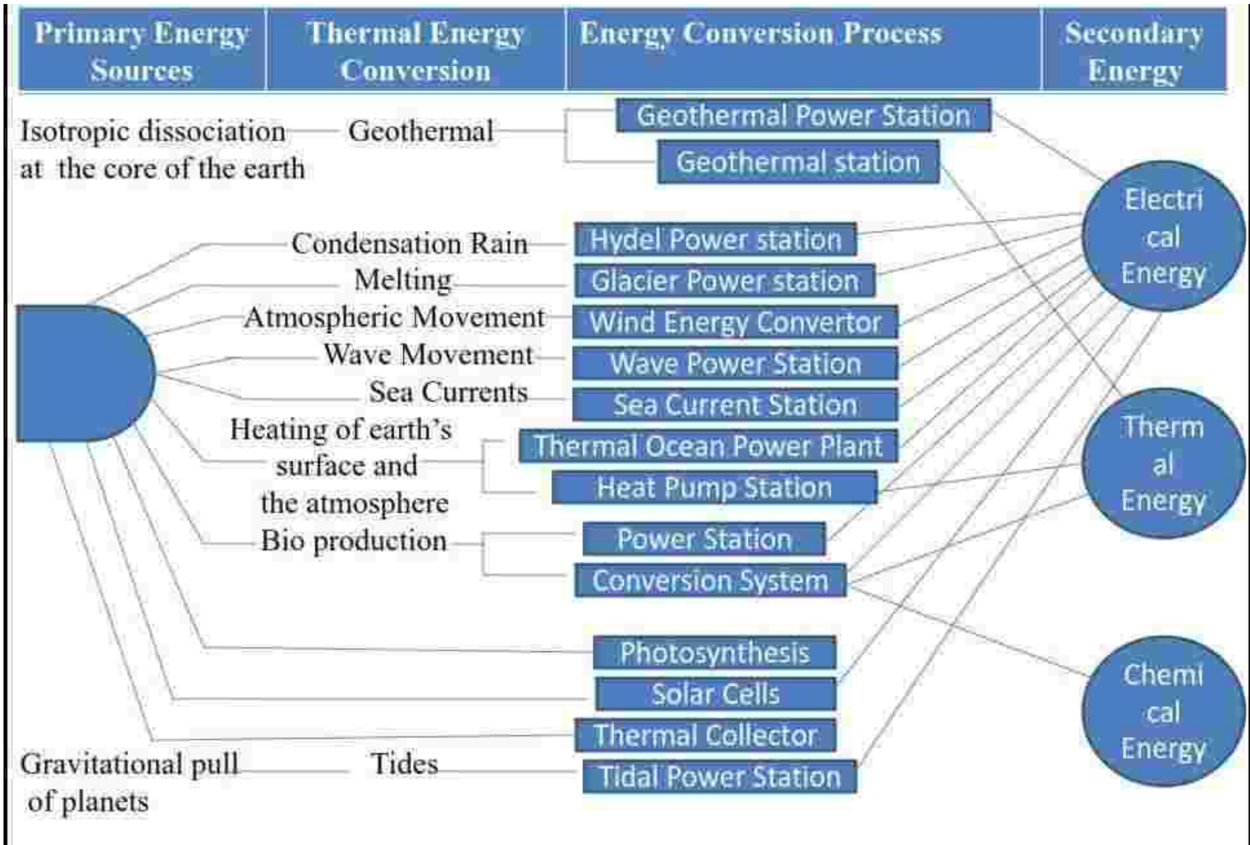


Fig: Use of renewable energy sources directly or indirectly through energy conversion process.

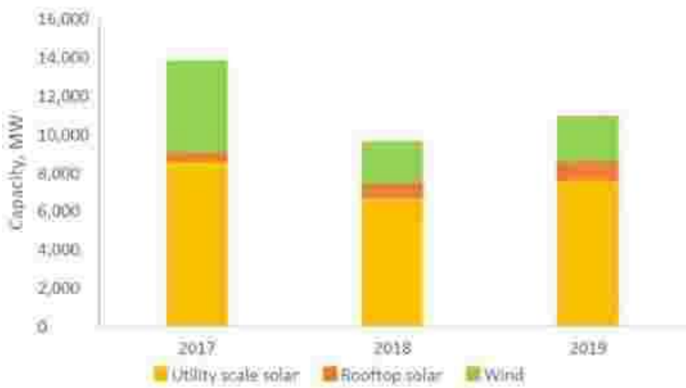
* Another source of energy is the geothermal energy originates from the earth's surface itself . The theoretical potential of geothermal energy is much lesser (less than by an order of 4) than the solar radiation.
* The third source of renewable energy is the movement of the planets . The force of attraction between planets and gravitational pull creates tide in the sea. This energy source magnitude is very less compared to geothermal energy.

Limitations:-

a) The real difficulty with the renewable energy sources are that the power density of those energies are very less in comparison to conventional energy sources.

b) Since the solar and wind energies fluctuate with respect to day and season; the surface area requirement will be large and so also storage device for heat and electricity. The thermal energy storage system (sensible heat storage systems) have low efficiency, while the phase change storage systems suffer density variations in two phases and stability over several cycles. Electrical storage device like batteries are heavy and not environment friendly.

New Delhi: India's renewable capacity installations reached 86 gigawatt (GW) as of 31 December, 2019, according to research firm JMK Research and Analytics. Wind energy became the biggest contributor with 44 per cent share in the total renewable energy mix followed by solar with 39 per cent share. Year wise installation trends in India



Sources: MNRE, JMK Research

"In 2019, about 7.5 GW of new utility scale solar capacity was added, which is about 14 per cent increase over the previous year. Another one GW was added in rooftop solar installations," it added.

About 2.4 GW of new wind capacity was added in 2019, which was a 10 per cent increase over 2018.

Gujarat led the installations with commissioning of 1.4 GW of new wind projects followed by Tamil Nadu with 650 MW and Maharashtra with 212 MW.

"Most of the wind projects allocated in 2018 and scheduled to commission in 2019 got delayed and are now likely to be commissioned in 2020. This delay in wind projects is primarily attributed to various land availability issues and lack of grid transmission availability," the research firm added.

Karnataka led the market with about 2 GW of new solar capacity additions followed by Rajasthan with 1.7 GW, Tamil Nadu with 1.5 GW, Gujarat with 936 MW, Andhra Pradesh with 917 MW, and Madhya Pradesh with 651 MW.

Distributed and Dispersed Generation

Distributed generation (DG) entails using many small generators, of 2-50 MW output, situated at numerous strategic points throughout cities and towns, so that each provides power to a small number of consumers nearby. While these small generators might be solar or wind turbine units, generating units in this category are most often highly efficient gas turbines in small combined cycle plants, because these are the most economical choices. Although small compared to traditional central station generators, such 2- 500 MW generating units are large, both physically and electrically compared to the needs of individual energy consumers., producing power for between 50 and 400 homes.

Dispersed generation refers to use of still smaller generating units, of less than 500 kW output and often sized to serve individual homes or businesses. These units are small enough to fit into garages or, like central air-conditioners, on a pad behind a house. Micro gas turbines, bel cells, diesel, and small wind and solar PV generators make up this category.

Basics of Distributed generation (DG)

Distributed generators include, but are not limited to synchronous generators, induction generators, reciprocating engines, micro-turbines (combustion turbines that run on high-energy fossil fuels such as oil, propane, natural gas, gasoline or diesel), combustion gas turbines, fuel cells, solar photo-voltaic, and wind turbines.

Applications of Distributed Generating Systems

There are many reasons a customer may choose to install a distributed generator.

- DG can be used to generate a customer’s entire electricity supply; for peak shaving (generating a portion of a customer’s electricity onsite to reduce the amount of electricity purchased during peak price periods); for standby or emergency generation (as a backup to Wires Owner's power supply); as a green power source (using renewable technology);or for increased reliability.
- In some remote locations, DG can be less costly as it eliminates the need for expensive construction of distribution and/or transmission lines.

Benefits of Distributed Generating Systems

Distributed Generation:

1. Has a lower capital cost because of the small size of the DG (although the investment cost per kVA of a DG can be much higher than that of a large power plant).

2.May reduce the need for large infrastructure construction or upgrades because the DG can be constructed at the load location.

3.If the DG provides power for local use, it may reduce pressure on distribution and transmission lines.
4. With some technologies, produces zero or near-zero pollutant emissions over its useful life (not taking into consideration pollutant emissions over the entire product lifecycle ie. pollution produced during the manufacturing, or after decommissioning of the DG system).
4. With some technologies such as solar or wind, it is a form of renewable energy. Can increase power reliability as back-up or stand-by power to customers. Offers customers a choice in meeting their energy needs.

Challenges associated with Distributed Generating Systems

- There are no uniform national interconnection standards addressing safety, power quality and reliability for small distributed generation systems.
- The current process for interconnection is not standardized among provinces.
- Interconnection may involve communication with several different organizations.
- The environmental regulations and permit process that have been developed for larger distributed generation projects make some DG projects uneconomical.
- Contractual barriers exist such as liability insurance requirements, fees and charges, and extensive paperwork.

Solar Energy: Solar processes and spectral composition of solar radiation.

- Solar energy is an important, clean, cheap and abundantly available renewable energy. It is received on Earth in cyclic, intermittent and dilute form with very low power density 0 to 1 kW/m^2.
- Solar energy received on the ground level is affected by atmospheric clarity, degree of latitude, etc.
- For design purpose, the variation of available solar power, the optimum tilt angle of solar flat plate collectors, the location and orientation of the heliostats should be calculated.

What is Solar Radiation?

Solar radiation is radiant (electromagnetic) energy from the sun. It provides light and heat for the Earth and energy for photosynthesis. This radiant energy is necessary for the metabolism of the environment and its inhabitants . The three relevant bands, or ranges, along the solar radiation spectrum are ultraviolet, visible (PAR), and infrared. Of the light that reaches Earth's surface, infrared radiation makes up 49.4% of while visible light provides 42.3% . Ultraviolet radiation makes up just over 8% of the total solar radiation. Each of these bands has a different impact on the environment.

- Solar radiation provides heat, light, and energy necessary for all living organisms. Infrared radiation supplies heat to all habitats, on land and in the water 24. Without solar radiation, Earth's surface would be about 32°C colder 25.

- Solar energy, received in the form of radiation, can be converted directly or indirectly in to other forms of energy, such as heat and electricity. The major draw backs of the extensive application of solar energy of

1. the intermittent and variable manner in which it arrives at the earth's surface and
2. the large area require to collect the energy at a useful rate.

Energy is radiated by the sun as electromagnetic waves of which 99% have wave lengths in the range of 0.2 to 4.0 micro meter (1 micro meter = 10-6 meter)

Solar constant

The sun is a large sphere of very hot gases, the heat being generated by various kinds of fusion reactions. Its diameter is 1.39×10^6 km while that of earth is 1.27×10^4km. the mean distance between the two is 1.5×10^8km. although the sun is large, its subtends angle of only 32 min. at the earth's surface.

- The brightness of the sun varies from its center to its edge. However the calculation purpose the brightness all over the solar disc is uniform.

The total radiation from the sun is 5762 degrees K(i.eK=Kelvin)

The rate at which solar energy arise at the top of the atmosphere is called the solar constant I_{sc} . This is the amount of energy received in unit time on a unit area perpendicular to the sun's direction at the mean distance of the earth from the sun.

The solar constant value varies up to 3 % throughout the year, because the distance between the sun and the earth varies little throughout the year.

- The earth is close set of the sun during the summer and farthest during the winter.
- This variation in distance produces sinusoidal variation in the intensity of solar radiation I that reaches the earth.

I_{sc} = 1367 watts/m²

$$\frac{I}{I_{sc}} = 1+0.033\cos\frac{360\,n}{365}$$ where n is the day of the year.

Spectral distribution of solar radiation intensity at the outer limit of the atmosphere .

- The luminosity of the Sun is about 3.86 x 1026 watts. This is the total power radiated out into space by the Sun. Most of this radiation is in the visible and infrared part of the electromagnetic spectrum, with less than 1 % emitted in the radio, UV and X-ray spectral bands.

- The sun's energy is radiated uniformly in all directions. Because the Sun is about 150 million kilometres from the Earth, and because the Earth is about 6300 km in radius, only 0.000000045% of this power is intercepted by our planet.

- The power of the sun at the earth, per square metre is called the solar constant and is approximately 1370 watts per square metre (W m-2).

- The solar constant actually varies by +/- 3% because of the Earth's slightly elliptical orbit around the Sun. The sun-earth distance is smaller when the Earth is at perihelion (first week in January) and larger when the Earth is at aphelion (first week in July). Some people, when talking about the solar constant, correct for this distance variation, and refer to the solar constant as the power per unit area received at the average Earth-solar distance of one “Astronomical Unit” or AU which is 149.59787066 million kilometres. There is also another small variation in the solar constant which is due to a variation in the total luminosity of the Sun itself. This variation has been measured by radiometers aboard several satellites since the late 1970's.

Solar Radiation Measuring Instruments (Radiometers)

A radiometer absorbs solar radiation at its sensor, transforms it into heat and measures the resulting amount of heat to ascertain the level of solar radiation. Methods of measuring heat include resulting amount of heat to ascertain the level of solar radiation.

- Methods of measuring heat include taking out heatflux as a temperature change (using a water flow pyrheliometer, a silver-disk pyrheliometer or a bimetallic pyranograph) or as a thermoelectromotive force (using a thermoelectric pyrheliometer or a thermo electric pyranometer).

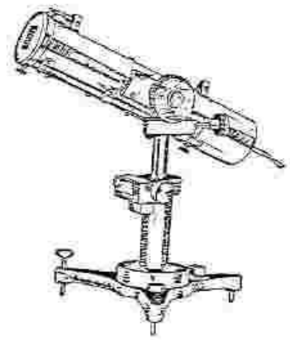
In current operation, types using a thermopile are generally used.

- The radiometers used for ordinary observation are pyrheliometers and pyranometers that measure direct solar radiation and global solar radiation, respectively.

Pyrheliometers

A pyrheliometer is used to measure direct solar radiation from the sun and its marginal periphery. To measure direct solar radiation correctly, its receiving surface must be arranged to be normal to the solar direction. For this reason, the instrument is usually mounted on a sun-tracking device called an equatorial mount.

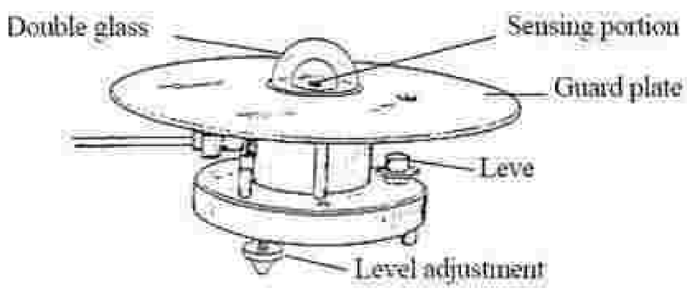
The structure of an Angstrom electrical compensation pyrheliometeris shown in Figure.2



This pyrheliometer has a rectangular aperture, two manganin-strip sensors (20.0 mm × 2.0 mm×0.02 mm) and several diaphragms to let only direct sunlight reach the sensor. The sensor surface is painted optical black and has uniform absorption characteristics for short-wave radiation. A copper constantan thermocouple is attached to the rear of each sensor strip, and the thermocouple is connected to a galvanometer. The sensor strips also work as electric resistors and generate heat when a current flows across them.

Pyranometers:

A pyranometer is used to measure global solar radiation falling on a horizontal surface. Its sensor has a horizontal radiation-sensing surface that absorbs solar radiation energy from the whole sky (i.e. a solid angle of 2p sr) and transforms this energy into heat. Global solar radiation can be ascertained by measuring thisheat energy. Most pyranometers in general use are now the thermopile type, although bimetallic pyranometers are occasionally found.



Sunshine recorder

The duration of bright sunshine in a day is measured by means of sun shine recorder. The sun’s rays are focused by a glass sphere to a point on a card strip held in a groove in spherical bowl mounted concentrically with the sphere. Whenever there is a bright sun shine the image formed is intensive enough to burn a part on the card strip. through out the day as sun moves across the sky, the image moves along the strip. Thus, a burnt trace whose length is proportional to the duration of sun shine is obtained on the strip.

Solar Radiation Data

Most radiation data is measured for horizontal surfaces. As shown in figure. It is seen a fairly, smooth variations with the maximum occurring around noon is obtained on a clear day. In contrast an irregular variation with many peaks and valleys may be obtained on a cloudy day.

- Peak values are generally measured in April or may with parts of Rajasthan or Gujarat receiving over 600 Langley's per day.
- During the monsoon and winter months, the daily global radiation decreases to about 300- 400 longley per day.
- Annual average daily diffuse radiation received over the whole country is around 175 longleys per day.
- The maximum value is about 300 langleys in Gujarat in July, while the minimum values between 75 and 100 langleys per day, are measured over many parts of the country during November and December as winter sets in.

Solar radiation on tilted surface:

The rate of receipt of solar energy on a given surface on the ground depends on the orientation of the surface with reference to the sun. A fully sun – tracking surface that always faces the sun receives the maximum possible solar energy at the particular location.

A surface of the same area oriented in any other direction will receive a smaller amount of radiation because solar radiation is such a dilute form of energy, it is desirable to capture as much as possible on a ground area. Most of the solar collectors or solar radiation collecting devices are tilted at an angle to horizontal surface with Y=0 facing south for tilted surface.

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

For horizontal surfaces $\cos\theta_z = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega$

Tilt factor for beam radiation

$$\Upsilon_b = \frac{\cos\theta}{\cos\theta z}$$

$$\Upsilon_d = \left[\frac{1+\cos s}{2}\right]$$

Solar Radiation through atmosphere:

For estimating efficiencies of the solar systems, one usually takes sky conditions of AM =1.5 i.e. the radiation has to travel 1.5 times more through the atmosphere in comparison to the normal incidence.

Solar radiation without any scattering suffers considerable losses at all wavelength regions while passing through earth's atmosphere. For certain wavelengths, the atmosphere is completely opaque and it is not allowed to reach earth.

The solar radiation received on the earth without any scattering in the atmosphere is known as beam or direct radiation. *The solar radiation received on earth from the sun with multiple scattering is known as diffused or sky radiation.* Summation of both these components yields global solar radiation. The atmosphere also radiates energy to the earth and its intensity is higher than that of global radiation. This radiation is included in the region of long-wavelength radiation to the atmosphere. The earth also radiates back long-wavelength radiation to the atmosphere and part of which gets absorbed.

Table: Radiation balance on a receiving surface on earth.

No.	Incident radiation components	Symbol	No	Reflected radiation components	Symbol
1.	Direct solar radiation	I_D	5.	Reflected direct solar radiation	I_{DR}
2.	Sky radiation	I_d	6.	Reflected diffused sky radiation	I_{dr}
3.	$\sum 1+2$: Global radiation	I_G	7.	$\sum 5+6$: Reflected total radiation	I_{GR}
4.	Atmosphere radiation	I_g	8.	Reflected atmospheric radiation	I_{AR}
			9.	Radiation from the receiving surface	I_E
			10.	$\sum 8+9$:Total re-radiation from the receiving surface	I_R

Rate of useful energy, $Q = (I_D) + I_d + I_g - (I_{DR} + I_{dr} + I_{AR} + I_E)$

The Generalized Transmission Law:

The radiation balance of earth's system fluctuates w.r.t. time and location. The global radiation is affected by the wavelength of the scattering and absorptive radiation phenomena in the atmosphere. These are termed as extinction in meteorology. The radiation reaching the earth's surface can be calculated as:

$$dI_{\lambda} = -I_{0\lambda} a\, d_s \qquad \text{W/m}^2$$

where

dI_{λ} is the radiation of the remaining wavelength after the incident radiation of the same wavelength $I_{0\lambda}$ has travelled through distance d_s of the atmosphere (w/m^2),

d_s is the distance travelled by the solar radiation in the atmosphere (m),

a is extinction coefficient (m^{-1}).

Integrating the above equation over the entire length of the atmosphere (m) yields the general transmission law for radiation passage through the atmosphere, i.e.

$$I = I_0 \exp(-a\, m) \qquad \text{W/m}^2$$

Where

I = radiation received on the earth, I_0 = extra-terrestrial radiation, m = air mass.

The transmission factor of the atmosphere

$$\tau_G = \frac{I}{I_G} = \exp(-a\, m)$$

The extinction coefficient (a) depends upon the transmission coefficient which consists of three factors.

$$\tau_G = \tau_{RS} \tau_{MS} \tau_{AB}$$

Where

τ_{RS} = transmission factor corresponding to Rayleigh scattering.

τ_{MS} = transmission factor due to Mie scattering

τ_{AB} = transmission factor due to absorption.

From the figure given below, the optical path length (m) can be calculated as:

$$m = \frac{H}{\sin \alpha_s} = \frac{H}{\cos Z}(m)$$

H = height of the atmosphere
α_s = solar altitude

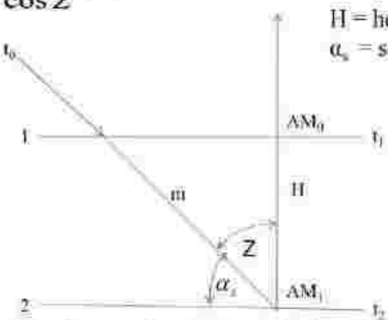


Fig: Penetration of solar radiation through an ideal plane atmosphere of constant density.

Instead of H, one can use only, $m = \frac{1}{\sin \alpha_s} = \frac{1}{\cos Z}$

Scattering by the atmosphere:-

The scattering of radiation by the atmosphere can be divided into two categories:

(i) Rayleigh scattering in molecules (f)

(ii) Mie scattering in aerosols.

The Rayleigh scattering takes place in particles, whose diameter is much smaller than the wavelength of the incident radiation. These particles scatter the *short wavelength of radiation* strongly. The scattered radiation is given by the expression:

$$I_{RS} = \frac{2\pi^2}{N\lambda^4}\left(n^2 - I\right)^2\left(\frac{1}{\cos^2 \varphi}\right)I_0 \ \text{W/m}^3$$

Where

I_{RS} = scattered radiation from a scattering volume (W/m^3).

N = number of molecules in the irradiated volume of air (1/m^3).

λ = wavelength (m), φ = angle of scattering (degree), n = refractive index,

I_0 = extra-terrestrial radiation (solar constant).

The solar radiation reaches on the earth surface depends upon the following factors:

(1) Reflection of the extra terrestrial atmosphere and on the earth's surface

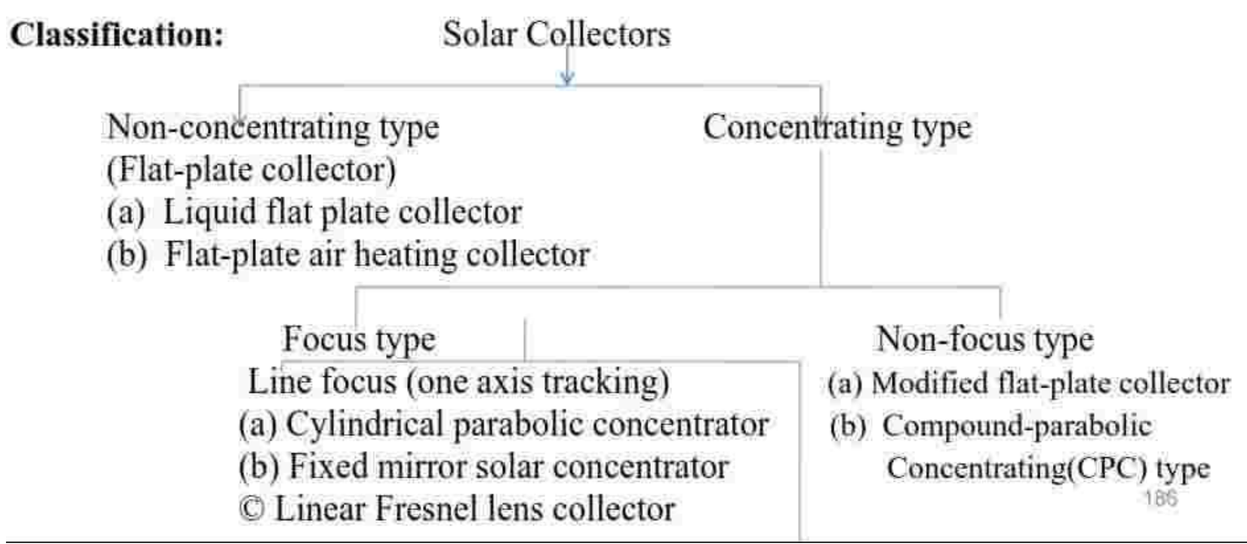
(2) Scattering on the earth's atmosphere.

(3) Absorption in the atmosphere.

Solar Collectors:-

Solar power has low density (1kW/m^2 to 0.1kW/m^2) per unit area. Hence large amount of solar power collection needs larger area. The solar collector being the first unit in the solar thermal system, collects heat from solar radiation then transfers to the transport fluid efficiently. The transport fluid utilizes the heat for necessary purposes.

Classification:



Point focus (two-axis tracking)
(a) Pentaboloidal dish collector.
(b) Hemispherical bowl mirror conc.
(c) Circular Fresnel lens cone.
(d) Central Tower receiver.

(**Fig:** Types of Solar Collector)

Concentrating type	Non-concentrating type (Flat Plate Type)
(1) In concentrating type solar collectors, solar radiation is converged from a large area into smaller area using optical means. Beam radiation has a unique direction which travels in a straight line, can be converged by reflection or refraction techniques. On the other hand diffused radiation does not have unique direction, can not obey optical principles. Thus diffused radiation does not converge to a single point. Thus concentrating type solar collectors utilizes beam radiation and partly diffused radiation coming directly over the observer.	(1) Non-concentrating (flat plate) type solar collectors absorb both beam type and diffused radiation. 187
(2) Complex in construction.	(2) The flat plate collector is simple in construction and does not require sun tracking.
(3) It does not sustain harsh atmospheric conditions.	(3) Since it requires outdoor installation, the outside atmospheric harsh conditions are likely to sustain.
(4) It requires high maintenance.	(4) It requires little maintenance.
(5) It attains high temperature due to presence of optical concentration.	(5) Due to absence of optical concentration, the heat loss is more. So it attains low temperature.

Performance Indices: The following performance indices are measured in a Solar collector.

(1)Collector efficiency:- It is defined as the ratio of the energy actually absorbed and transferred to the heat-transport fluid by the collector (useful energy) to the energy incident on the collector.

(2) Concentration ratio:- It is defined as the ratio of the area of the aperture of the system to the area of the receiver. The aperture of the system is the projected area of the collector facing (normal) to the beam.

(3) *Temperature range*: It is the range of temperature to which the heat transport fluid is heated up by the collector.

There are three types of solar collectors based on the temperature ranges.

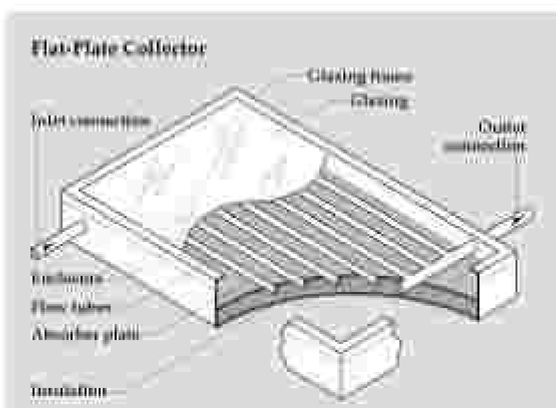
(i) Low temperature Systems($<150^0$ C):

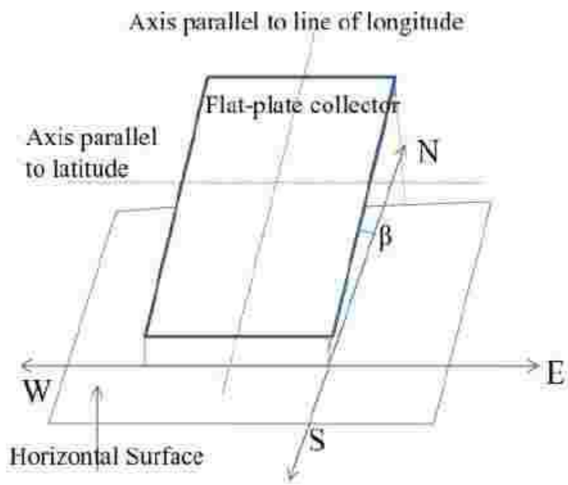
(ii) Medium-temperature Systems($150-400^0$C):

(iii) High-temperature Systems($400-1000^0$C):

FLAT-PLATE COLLECTORS:

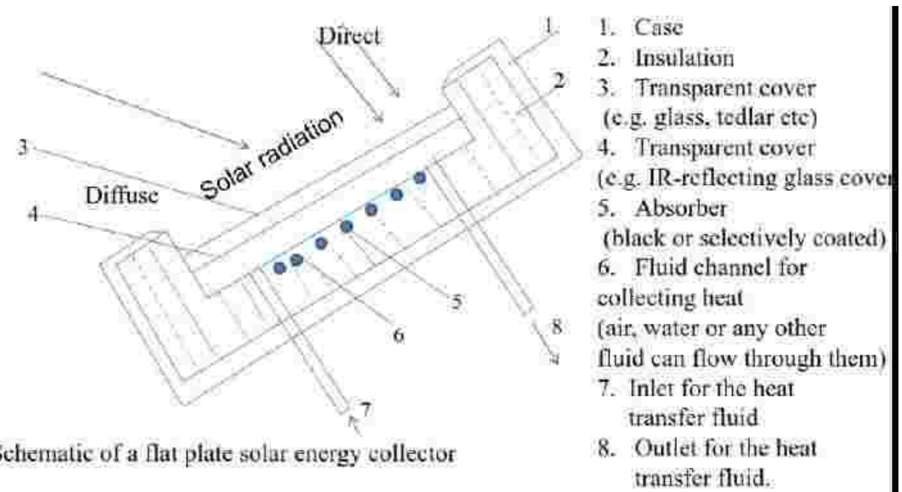
- Flat-plate collectors are the most common solar collector for solar water-heating systems in homes and solar space heating. A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark-colored absorber plate. These collectors heat liquid or air at temperatures less than 180°F.Flat-plate collectors are used for residential water heating and hydronic space-heating installations.
- The flat-plate collector is located in a position such that its length is aligned with longitude and is suitably tilted towards south to have maximum collection.
- Liquid Flat plate collectors:-The schematics of flat plate collectors are shown in the figure (a) and (b). It consists of a black coated plate made of metal or plastic, which absorbs all the solar radiation incident on it and converts into heat. This plate is known as the absorber. Fluid channels are welded below the absorber for carrying a heat transfer fluid generally water. This transport fluid transports the heat from the absorber into the utilisation purposes.
- Liquid flat plate collectors heat liquid as it flows through tubes in or adjacent to the absorber plate. The simplest liquid systems use potable household water, which is heated as it passes directly through the collector and then flows to the house.





Fig(a): Positioning of flat-plate collector.

To reduce the heat losses, the back side and sides of the collector (below the absorber)are covered with insulation. The front above of the absorber is covered with one or two transparent glass sheets. The whole thing is sealed in a box or some sort of casing. The working of the collector basically depends upon the greenhouse effects. Flat plate collectors can convert solar radiation into heat upto maximum 100^0C.



Fig(b): Schematic of a flat plate solar energy collector

- ❖ **Air flat-plate collectors** are used primarily for solar space heating. The absorber plates in air collectors can be metal sheets, layers of screen, or non-metallic materials. The air flows past the absorber by using natural convection or a fan. Because air conducts heat much less readily than liquid does, less heat is transferred from an air collector's absorber than from a liquid collector's absorber, and air collectors are typically less efficient than liquid collectors.

❖ Air heating solar collectors are mostly used for agricultural drying and space heating applications. The basic advantages are low sensitivity to leakage, less corrosion and no need for additional heat exchanger. The main disadvantage is the requirement of larger surface area for heat transfer and higher flow rate.

Flat Plate Collector Efficiency:-

The instantaneous collection efficiency of a flat plate solar collector is defined as:

$$\eta_i = \frac{\text{Useful heat gain}}{\text{Solar Radiation incident on the Collector}} = \frac{Q_u}{I_{G\beta}}$$

Where $I_{G\beta} = Q_u + Q_c + Q_R + Q_e$

If A_c, τ and ρ are the collector area in m^2, transmissivity and reflectivity; the useful energy is given by: $Q_u = \tau I_{G\beta}\ (1-\rho) A_c - Q_L$ (W)

For an absorber, $(1-\rho) = \alpha$. So, $Q_u = \tau I_{G\beta} \alpha A_c - Q_L$ (W).

The heat losses Q_L are composed of convection and radiation parts. So Q_L can be represented as: $Q_L = Q_c + Q_R = U\ A_c\ (t_c - t_s)$ (W)

Where U = Overall heat transfer coefficient of the observer ($W/m^2\ {}^0C$).

t_c = Temperature of the collector's absorber (${}^0C$).

t_s = Temperature of the ambient (${}^0C$).

The reflected radiation from the absorber is given by: $Q_R = \tau I_{G\beta} A_c\ \rho$ (W).

So, $Q_u = \tau I_{G\beta} \alpha A_c - U\ A_c (t_c - t_s)$ (W). 193

Concentrating collectors

- Unlike solar (photovoltaic) cells, which use light to produce electricity, concentrating solar power systems generate electricity with heat. Concentrating solar collectors use mirrors and lenses to concentrate and focus sunlight onto a thermal receiver, similar to a boiler tube. The receiver absorbs and converts sunlight into heat. The heat is then transported to a steam generator or engine where it is converted into electricity.
- There are three main types of concentrating solar power systems: parabolic troughs, dish/engine systems, and central receiver systems.
- These technologies can be used to generate electricity for a variety of applications, ranging from remote power systems as small as a few kilowatts (kW) upto grid-connected applications of 200-350megawatts (MW) or more.
- A concentrating solar power system that produces 350MW of electricity displaces the energy equivalent of 2.3 million barrels of oil.

Parabolic Trough Systems

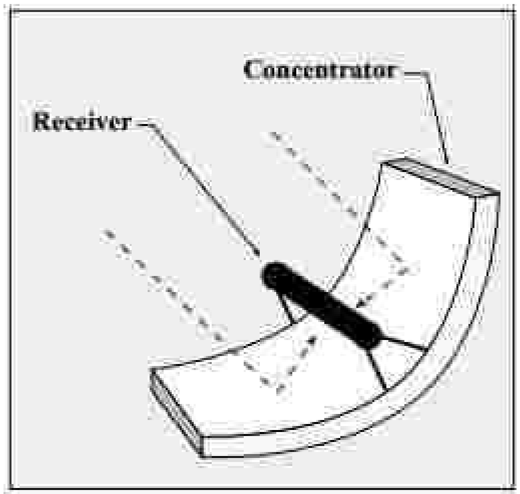
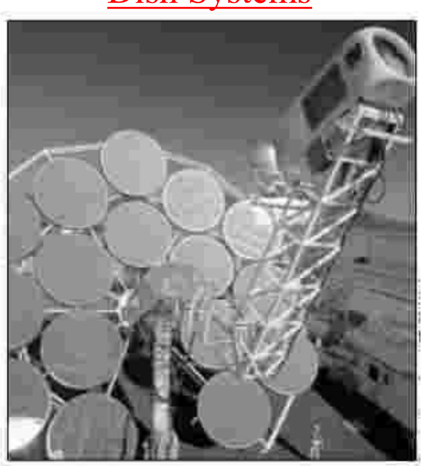


Fig. 1 A parabolic trough

These solar collectors use mirrored parabolic troughs to focus the sun's energy to a fluid-carrying receiver tube located at the focal point of a parabolically curved trough reflector (see Fig.1 above). The energy from the sun sent to the tube heats oil flowing through the tube, and the heat energy is then used to generate electricity in a conventional steam generator. Many troughs placed in parallel rows are called a "collector field." The troughs in the field are all aligned along a north south axis so they can track the sun from east to west during the day, ensuring that the sun is continuously focused on the receiver pipes. Individual trough systems currently can generate about 80 MW of electricity. Trough designs can in corporate thermal storage—setting aside the heat transfer fluid in its hot phase—allowing for electricity generation several hours into the evening. Currently, all parabolic trough plants are "hybrids," meaning they use fossil fuels to supplement the solar output during periods of low solar radiation.

Dish Systems



Each dish produces 5 to 50 kW of electricity and can be used independently or linked together to increase generating capacity.

Central Receiver Systems

Central receivers (or power towers) use thousands of individual sun-tracking mirrors called "heliostats" to reflect solar energy onto a receiver located on top of at all tower. The receiver collects the sun's heat in a heat-transfer fluid (molten salt) that flows through the receiver. The salt's heat energy is then used to make steam to generate electricity in a conventional steam generator, located at the foot of the tower. The molten salt storage system retains heat efficiently, so it can be stored for hours or even days before being used to generate electricity. Therefore, a central receiver system is composed of five main components: heliostats, receiver, heat transport and exchange, thermal storage, and controls (see Fig. 3).

Receiver and generator Concentrator individual dish/engine systems currently can generate about 25 kW of electricity.

Solar Two—a demonstration power tower located in the Mojave Desert—can generate about 10 MW of electricity. In this central receiver system, thousands of sun-tracking mirrors called heliostats reflect sunlight onto the receiver. Molten salt at 554ºF (290ºC) is pumped from a cold storage tank through the receiver where it is heated to about 1,050ºF (565ºC). The heated salt then moves on to the hot storage tank. When power is needed from the plant, the hot salt is pumped to a generator that produces steam. The steam activates a turbine/generator system that creates electricity. From the steam generator, the salt is returned to the cold storage tank, where it stored is and can be eventually reheated in the receiver. By using thermal storage, power tower plants can potentially operate for 65percent of the year without the need for a back-up fuel source. Without energy storage, solar technologies like this are limited to annual capacity factors near25 percent. The power tower's ability to operate for extended periods of time on stored solar energy separates it from other renewable energy technologies. Hot salt storage tank Steam generator 1,050˚F Cold salt storage tank Condenser cooling tower554˚FSystem boundary Substation Steam turbine and electric generator.

Solar Two Power Tower

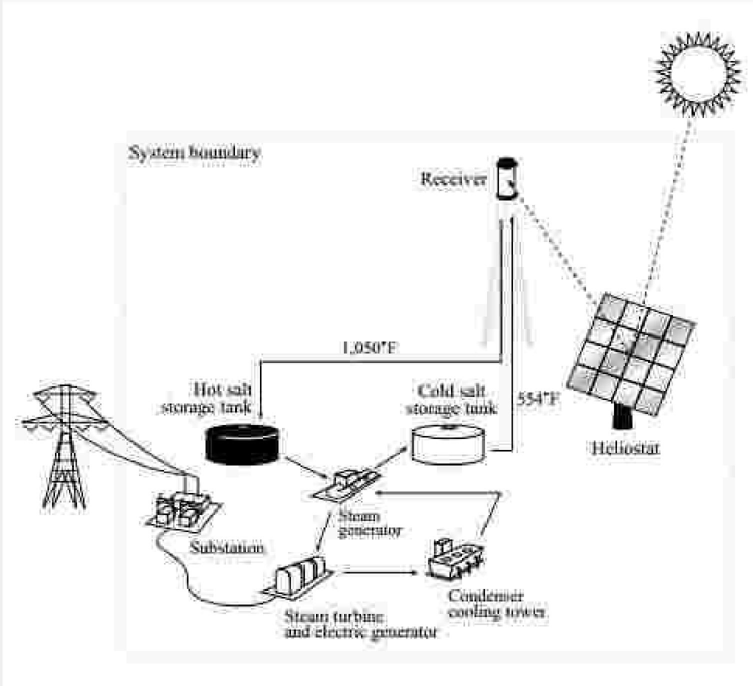


Fig. 3 Solar Two power tower system

Applications of Solar Energy

- Crop And Grain Drying
- Space And Water Heating
- Solar Energy Applications for Agriculture
- Greenhouse Heating
- Remote Electricity Supply (Photovoltaic)
- Water Pumping

Solar Space And Water Heating

- Livestock and diary operations often have substantial air and water heating requirements. Modern pig and poultry farms raise animals in enclosed buildings, where it is necessary to carefully control temperature and air quality to maximize the health and growth of the animals. These facilities need to replace the indoor air regularly to remove moisture, toxic gases odors, and dust. Heating this air, when necessary, requires large amount of energy. With proper planning and design solar air/space heaters can be incorporated into farm buildings to preheat incoming fresh air. These systems can also be used to supplement.
- SOLAR WATER HEATER

The details of most common type of solar water heater are shown in schematic diagram of Fig. 5.17. A tilted flat plate solar collector with water as heat transfer fluid is used. A thermally insulated hot water storage tank is mounted above the collector.The heated water of the collector rises up to the hot water tank and replaces an equal quantity of cold water, which enters the collector. The cycle repeats, resulting in all the water of the hot water tank getting heated up. When hot water is taken out from hot water outlet, the same is replaced by cold water from cold-water make up tank fixed above the hot water tank. The scheme is known as passive heating scheme, as water is circulated in the loop naturally due to thermos-siphon action. When the collector is fixed above the level of hot water tank, a pump is required to induce circulation of water in the loop and the scheme will be known as active (or forced) solar thermal system. An auxiliary electrical emersion heater may be used as back up for use during cloudy periods. In average Indian climatic conditions solar water heater can be used for about 300 days in a year. A typical 100 liters per day (LPD) rooftop, solar water heater costs approximately ` 15,000–21,900 (year 2015) and delivers water at 60–80 °C. It has a life span of 10–12 years and payback period of 2-6 years. Figure 5.18 shows the photograph of an installed and operating solar water heater.

In other schemes the hot water from collector delivers heat to service water through a heat exchanger. In this scheme an anti-freeze solution may be used as heat transport medium to avoid freezing during cold nights.

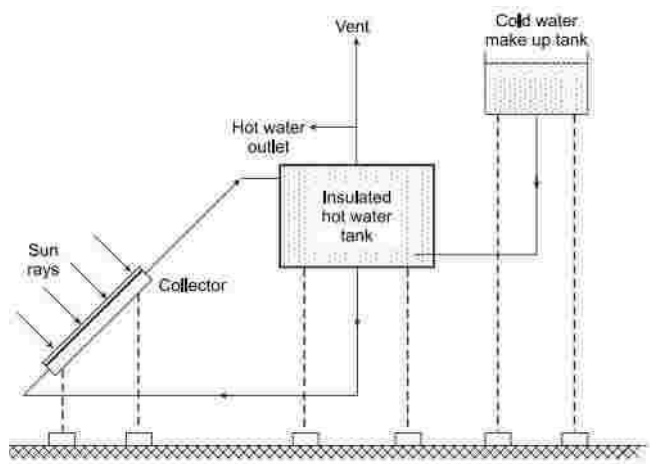


Figure 5.17 Solar water heater

Figure 5.18 Solar water heater

SOLAR PASSIVE SPACE HEATING AND COOLING SYSTEMS

Solar energy is also used for heating or cooling a building to maintain comfortable temperature inside. Passive systems do not require any mechanical device and make use of natural process of convection, radiation and conduction for transport of heat.

Use of passive heating/cooling systems put restrictions on the building design to make possible the flow of heat naturally. Such a specially designed building is called "solar house". The state of the art for passive cooling is much less developed than for passive space heating. Natural passive cooling may not always be sufficient to meet the requirement and at peak load, auxiliary means may also be needed, but it greatly reduces the load on the air conditioner plant.

Active heating/cooling systems employ mechanical devices, e.g. pump, blower, etc.to circulate the working fluid for transportation of heat and therefore special building design is not necessary as required in the case of passive heating. Nevertheless, careful building design and insulation is desirable and will be less expensive than additional heating/cooling load due to poor design.

A solar passive space heating system is shown in Fig. 5.19. The south facing thick wall, called 'Trombe Wall' is made of concrete, adobe, stone or composites of brick blocks and sand, designed for thermal storage. In order to increase the absorption, the outer surface is painted black. The entire south wall is covered by one or two sheets of glass or plastic sheet with some air gap (usually 10–15 cm) between the wall and inner glazing. Solar radiation after penetration through the glazing is absorbed by the thermal storage wall. The air in the air gap between the glazing and the wall thus gets heated, rises up and enters the room through the upper vent

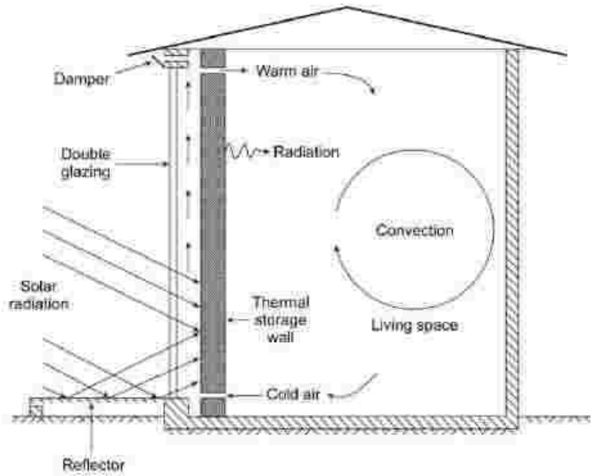


Figure 5.19 Solar space heating

while cool air from the room replaces it from the bottom vent. The circulation of air continues till the wall goes on heating the air. Thus the thermal wall collects stores and transfers the heat to the room. Heating can be adjusted by controlling the airflow through the inlet and outlet vents by shutters. Opening the damper at the top of the glazing allows the excess heat to escape outside, when heating is not required.
Sometimes a reflective horizontal surface is also provided to make available the additional radiation for thermal storage. A movable insulation cover (not shown in figure) also sometimes used to cover the glaze to reduce the heat loss from the storage wall to outside during night. In some models the thermal storage wall is made up of water drums stacked over one another to increase the thermal storage capacity. In another variation the thermal storage mass is provided above a metallic roof of the building instead of a wall.

Solar desalination is a technique to produce water with a low salt concentration from sea-water or brine (i.e Water with salt in it) using solar energy. There are two common methods of solar desalination. Either using the direct heat from the sun or using electricity generated by solar cells to power a membrane process.

- In the direct method, a solar collector is coupled with a distilling mechanism and the process is carried out in one simple cycle.
- Water production by direct method solar distillation is proportional to the area of the solar surface and incidence angle and has an average estimated value of 3–4 litres per square metre (0.074–0.098 US gal/sq ft).

(A solar still distills water with substances dissolved in it by using the heat of the Sun to evaporate water so that it may be cooled and collected, thereby purifying it. They are used in areas where drinking water is unavailable, so that clean water is obtained from dirty water or from plants by exposing them to sunlight.)

(Distillation is the process of separating the components or substances from a liquid mixture by using selective boiling and condensation.)

Indirect solar desalination employs two separate systems; a solar collection array, consisting of photovoltaic and/or fluid-based thermal collectors, and a separate conventional desalination plant. Production by indirect method is dependent on the efficiency of the plant and the cost per unit produced is generally reduced by an increase in scale.

Solar stills

The solar still is one of the oldest and by far the simplest water desalination method. A solar still consists of a structural element called a basin covered with a transparent material to allow the incident solar radiation to pass through to the basin saline water for thermal absorption and evaporation. Solar energy absorption, saline water evaporation, and fresh water condensation occur within a single enclosure for a solar still. Solar stills are inherently direct collection systems. Solar distillation using solar stills is considered to be a mature technology. Because it has a low maintenance requirement, it is used worldwide to produce fresh water. Typically, the basin is colored in dark or black to enhance solar flux absorption. The water is heated by the solar rays absorbed by the basin, which increases the water vapor pressure until some portion of the saline water evaporates as shown in Figure 1. The water vapor moves upward and typically condenses on the cool glass cover and run downs through a guiding channel to the collection reservoir. There exist many types of solar stills, including single slope, double slope, single and double basin, inverted, tubular, spherical, double effect multi wick, and greenhouse integrated solar stills as shown in Figure 2.

Solar stills can be passive or active, depending on whether water circulation is needed.

The main advantages of passive solar stills are that they do not require electrical energy for pumping (passive solar collector), it is simple, and it is easy to operate.

However, the main drawback of the solar still is that it typically has low water production due to the loss of latent heat of condensation through the solar still transparent.

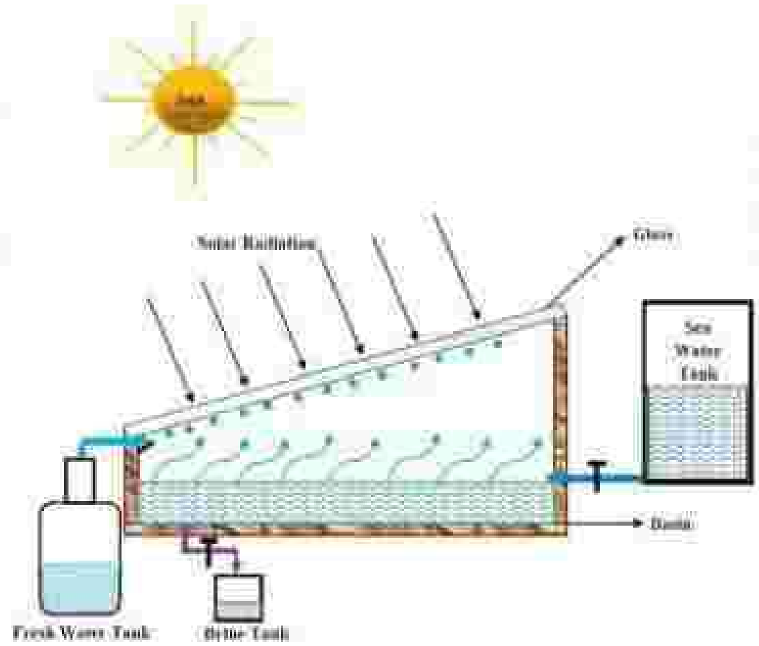


Figure 1. Solar still [47].

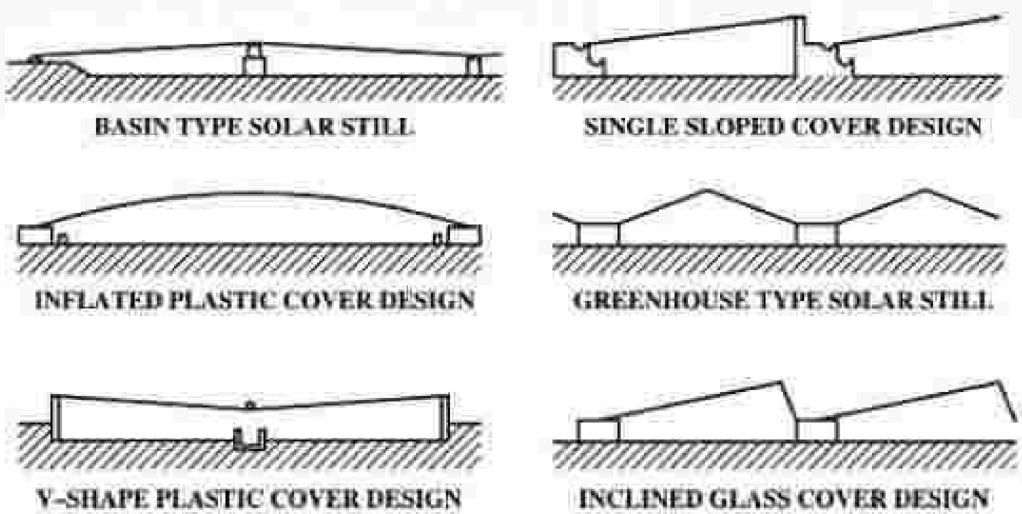


Figure 2. Common designs of solar stills [2].

Transmissivity based on Reflection-Refraction

The direction of incident and refracted beams are related to each other by Snell's law as
follows:

As shown in Fig. 5.43, I_{bn} is the intensity of the incoming beam radiation striking the interface of two medium at an angle of incidence of q. The reflected beam has reduced intensity of Ir1 making an angle of reflection which is equal to angle of incidence. The direction of incident and refracted beams are related to each other by Snell's law as follows:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

where, θ_1 = angle of incidence,

θ_2 = angle of refraction, and

n_1, n_2 = refractive indices of the two media

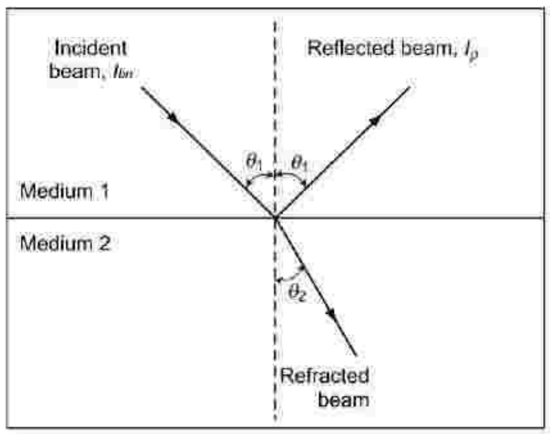


Figure 5.43 Reflection and refraction of the incident beam

The reflectivity ρ (= I_ρ/I_{bn}) is related to the angle of incidence and refraction as follows:

$$\rho = \frac{I_\rho}{I_{bn}} = \frac{1}{2}(\rho_I + \rho_{II}) \quad (5.7)$$

SOLAR COOKERS-

-By using Soar cooker, Solar energy can be used for cooking purposes.

Thermal energy requirements for cooking purpose forms a major share of total energy consumed, especially in rural areas. Variety of fuels like coal, kerosene, cooking gas, firewood, dung cakes and agricultural wastes are being used to meet the requirement. Fossil fuel is a fast depleting resource and need to be conserved, firewood for cooking causes deforestation and cow dung, agricultural waste, etc., may be better used as a good fertilizer. Harnessing solar energy for cooking purpose is an attractive and relevant option. A variety of solar cookers have been developed, which can be clubbed in four types of basic designs: (i) box type solar cooker, (ii) dish type solar cooker,(iii) community solar cooker, and (iv) advance solar cooker.

1. Box Type Solar Cooker

The construction of a most common, box type solar cooker is schematically shown in Fig. 5.27. The external dimensions of a typical family size (4 dishes) box type cooker are 60 × 60 × 20 cm. This cooker is simple in construction and operation. An insulated box of blackened aluminum contains the utensils with food material. The box receives direct radiation and also reflected radiation from a reflector mirror fixed on inner side of the box cover hinged to one side of the box. The angle of reflector can be adjusted as required. A glass cover consisting of two layers of clear window glass sheets serves as the box door. The glass cover traps heat due to greenhouse effect. Maximum air temperature obtained inside the box is around 140–160 °C. This is enough for cooking the boiling type food slowly in about 2–3 hours. It is capable of cooking 2 kg of food and can save 3–4 LPG cylinder fuel in a year. Electrical backup is also provided in some designs for use during non-sunshine hours. Its cost varies from Rs.5,000 to Rs.6,290 (year 2016) depending on the type, size, quality and electrical backup facility etc. A more affordable, folding type model of solar cooker, made of cardboard material is also developed.

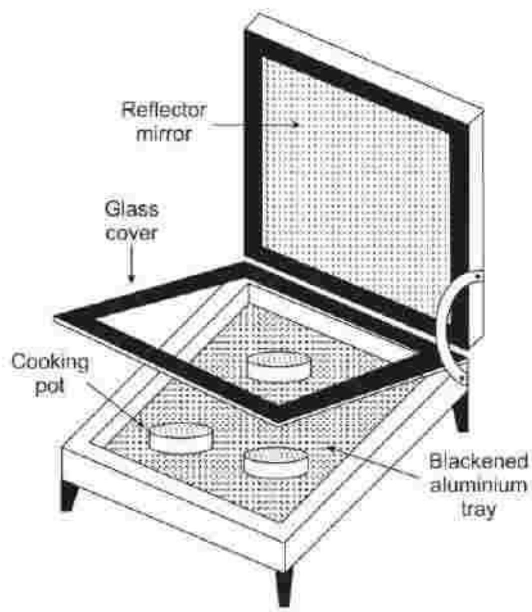


Figure 5.27 Box type solar cooker

2. Paraboloidal Dish Type (Direct Type) Solar Cooker

A specially designed paraboloidal reflector surface concentrates the beam radiation at its focus, where a cylindrical brass vessel containing food material is placed. A commercial dish type solar cooker, SK 14, developed by EG solar, an NGO of Germany, and being manufactured in India is shown in Fig. 5.28. The vessel directly receives the concentrated solar radiation. The reflector is periodically adjusted to track the sun. A fairly high temperature of about 450 °C can be obtained and a variety of food requiring boiling, baking and frying can be cooked for 10–15 persons. It can save on fuel up to 10 LPG cylinders annually on full use. Cooking time is approximately 20–30 minutes. The approximate cost of the cooker is Rs.8,500 (year 2016).

3. Community Solar Cooker

Community solar cooker has been developed for indoor cooking. It has a large automatically tracked paraboloidal reflector standing outside the kitchen. Solar Thermal Systems The reflector reflects the sunrays into the kitchen through an opening in its north wall.

A secondary reflector further concentrates the rays on to the bottom of the cooking pot, which is painted black. It can cook all types of food for about 40–50 people and can save up to 30 LPG cylinders in a year with optimum use.

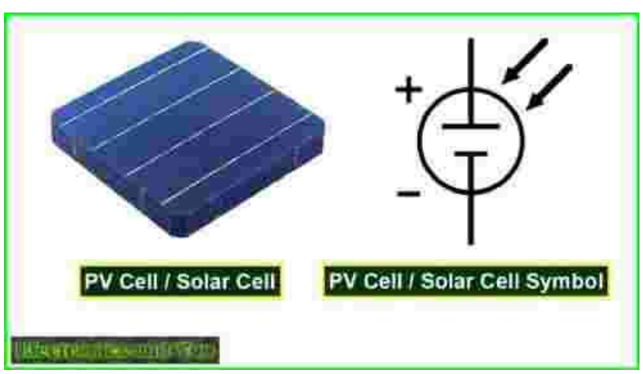
In another design of community solar cooker, large numbers of automatically tracked paraboloidal reflectors are installed in series and parallel combinations and generate steam for cooking in community kitchen. It can cook food for thousands of people in a short time depending upon its capacity. It is normally installed in conjunction with a boiler that may also use conventional fuel when necessary.

Photovoltaic effect

Conversion of light energy in electrical energy is based on a phenomenon called photovoltaic effect. When semiconductor materials are exposed to light, the some of the photons of light ray are absorbed by the semiconductor crystal which causes a significant number of free electrons in the crystal. This is the basic reason for producing electricity due to photovoltaic effect. **Photovoltaic cell** is the basic unit of the system where the photovoltaic effect is utilised to produce electricity from light energy. Silicon is the most widely used semiconductor material for constructing the photovoltaic cell. The silicon atom has four valence electrons. In a solid crystal, each silicon atom shares each of its four valence electrons with another nearest silicon atom hence creating covalent bonds between them. In this way, silicon crystal gets a tetrahedral lattice structure. While light ray strikes on any materials some portion of the light is reflected, some portion is transmitted through the materials and rest is absorbed by the materials.

The same thing happens when light falls on a silicon crystal. If the intensity of incident light is high enough, sufficient numbers of photons are absorbed by the crystal and these photons, in turn, excite some of the electrons of covalent bonds. These excited electrons then get sufficient energy to migrate from valence band to conduction band. As the energy level of these electrons is in the conduction band, they leave from the covalent bond leaving a hole in the bond behind each removed electron. These are called free electrons move randomly inside the crystal structure of the silicon. These free electrons and holes have a vital role in creating electricity in photovoltaic cell. These electrons and holes are hence called light-generated electrons and holes respectively. These light generated electrons and holes cannot produce electricity in the silicon crystal alone. There should be some additional mechanism to do that.

When a pentavalent impurity such as phosphorus is added to silicon, the four valence electrons of each pentavalent phosphorous atom are shared through covalent bonds with four neighbour silicon atoms, and fifth valence electron does not get any chance to create a covalent bond.



A PV Cell or Solar Cell or Photovoltaic Cell is the smallest and basic building block of a Photovoltaic System (*Solar Module and a Solar Panel*). These cells vary in size ranging from about 0.5 inches to 4 inches. These are made up of solar photovoltaic material that converts solar radiation into direct current (*DC*) electricity.

Materials used for photovoltaic include mono crystalline silicon, polycrystalline silicon, microcrystalline silicon, cadmium telluride, and copper indium selenide /sulfide.

Different Types of PV Cells

Many new styles of PV cells are being developed today but mainly two distinct material:

1. Crystalline Silicon PV Cells (Mono crystalline)

These Solar Cells are manufactured from crystalline silicon. Many of you must be knowing that silicon is the second most common material on Earth and is abundantly found in sand. To make solar cells out of silicon, manufactured silicon crystals are sliced to about 300 micrometers thick and coated to work as a semiconductor to capture solar energy.

2. Thin-film or Polycrystalline PV Cells

Thin-film PV cells use amorphous silicon or an alternative to silicon as a semiconductor. These solar cells are relatively flexible and can be directly installed with building materials. They work great even during clouds when there is low sun light. Here, the disadvantage is that thin-film PV Cells comparatively generate less electricity than crystalline silicon cells.

Solar PV Module

A bare single cell cannot be used for outdoor energy generation by itself. It is because (i) the output of a single cell is very small and (ii) it requires protection (encapsulation) against dust, moisture, mechanical shocks and outdoor harsh conditions. Workable voltage and reasonable power is obtained by interconnecting an appropriate number of cells. Cells from same batch are used to make PV module. This is done to ensure that mismatch losses are minimal in the module. The electrically connected cells are encapsulated, typically by using two sheets of ethylene vinyl acetate (EVA) at either side. EVA is a good electrical insulator, transparent material and has very low water absorption. The encapsulant cannot provide rigidity to the module, for which glass is provided at the front side of the module. At the rear side of the module a hard polymer material, typically, polyvinyl fluoride (PVF, also known as tedlar) is used. Theses layers are arranged as shown in Fig. 6.29 and hermetically sealed to make it suitable for outside applications for 20-30 years without environmental degradation. This assembly is known as solar module a basic building block of a PV system. Most common commercial modules have a series connection of 32 or 36 silicon cells to make it capable of charging a 12 V storage battery. However, larger and smaller capacity modules are also available in international market.

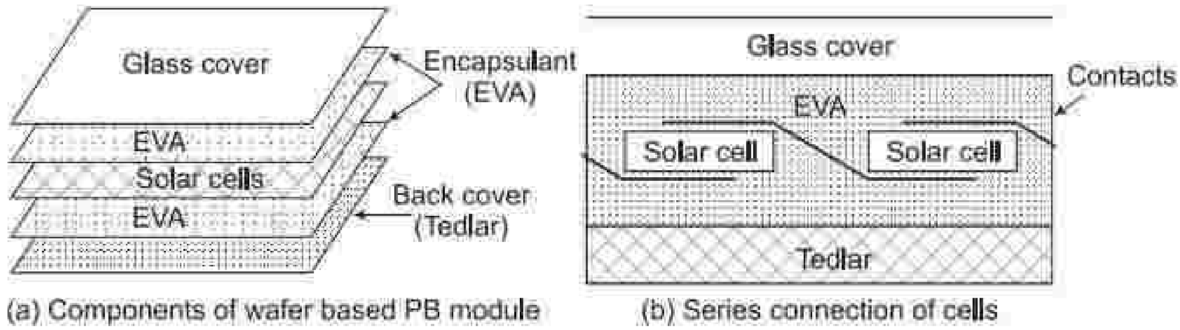


Fig 6.29 PV Module details

Cell Mismatch in a Module

In a module, a number of cells are interconnected, it is very important that these cells should match as closely as possible. That means Voc , Isc, Vm and Im (or fill factor) for all cells must be exactly same. Any mismatch in the characteristics of these cells leads to additional mismatch loss. Therefore, peak power of the combination is always less than the sum of individual peak power of the cells. Only under ideal case when all cells are exactly identical that the resultant peak power would be equal to arithmetic sum of that of its constituents. This is elaborated as follows.

When two cells with mismatched characteristics are connected in series and load is applied, both cells are bound to carry same current.

The composite characteristics of the combination can be obtained by adding the individual output voltage of the cell corresponding to a common current, for all operating points, as shown in Fig. 6.30. At a particular operating point, while one cell may be operating at peak power, the other may not. Thus peak power of the combination is always less than the sum of individual peak power of each cell. This is also clear from the shape of composite characteristics, which has lower fill factor. Also if such a combination is short circuited, equal and opposite voltages V_1', and V_2' are produced by individual cells and therefore, one cell will be generating power while the other will be dissipating it. Had the two cells been perfectly matched no power would be generated or dissipated.

Similar conclusion may be drawn by considering a parallel combination of two mismatched cells. Here the voltages of the cells are bound to be equal, but the currents will be different and hence the maximum power points. The conclusion may be generalized for more than two cells connected in series or in parallel. It can also be shown that larger the number of cells in a module more would be the possibility and quantum of mismatch loss.

To reduce mismatch losses, modules are fabricated from cells belonging to same batch. Also cell sorting is carried out to categorize cells having matched parameters with specified tolerance.

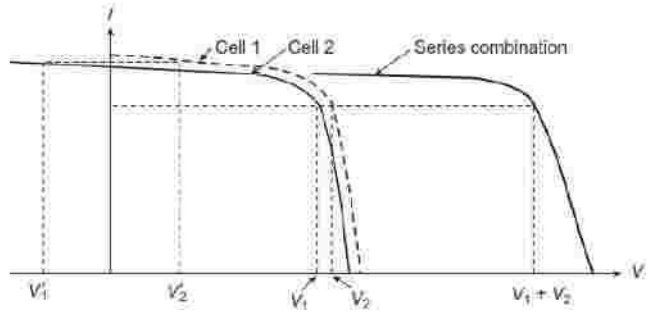


Figure 6.30 Composite characteristic of two cells in series

Effect of Shadowing

Partial shadowing may have serious consequences and may completely damage a module due to creation of hot spot. Let us examine the operation of a module under the conditions of: (i) partial shadowing of a cell in an open circuited, series string of cells and (ii) complete shadowing of one cell in a short circuited, series string of cells.

When a cell is partially shadowed, the shadowed portion will not produce any power but the remaining portion will remain active and produce power. The generated voltage by illuminated portion will forward bias the parallel rectifier corresponding to shadowed portion as shown in Fig. 6.31. If shadowed area is relatively small, the large circulating current through it will result in excessive heating of the shadowed portion. The phenomenon is known as hot spot effect and may completely damage the module for prolonged partial shadowing.

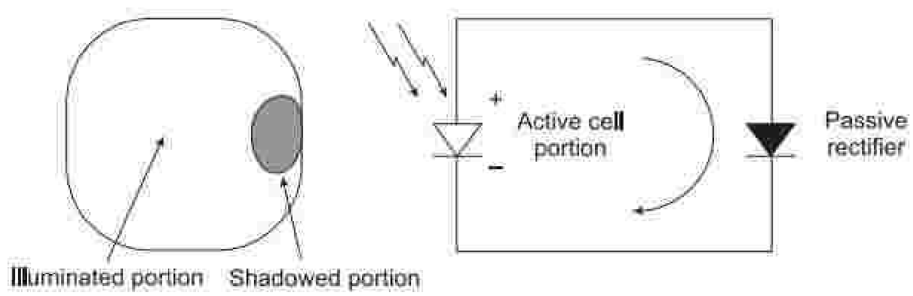


Figure 6.31 Partial shadowing of a cell

A short-circuited, series string of (n + 1) cells with one cell completely shadowed is shown in Fig. 6.32. Here the voltages produced by n illuminated cells add up and appears as reverse bias voltage of nV volts across the shadowed cell. As long as peak inverse voltage (PIV) of the shadowed cell is more than the reverse bias, no current will flow. If, however, the PIV is less than total reverse voltage appearing across the shadowed cell, current will flow through the string, dissipating large power in the shadowed cell, leading to possible damage of the module. The chances of damage to the shadowed cell, due to excessive heating, increase with the number of cells in the string. If the string supplies a load instead of being short-circuited, the chances of damage still persist through to a lesser extent. The damage due to shadowing can be avoided by connecting a bypass diode across the affected cell as shown in Fig. 6.32. This bypass diode would allow an alternative path for the load current. During healthy operation, the bypass diode has no role as the cell voltage would keep it reverse biased. Even so, its use would result some loss because of finite reverse leakage current through it. It is neither practical, nor required to incorporate a bypass diode across each cell in a module. It has been the international practice to provide a bypass diode for every 18 crystalline silicon solar cells in a series string. Thus, the internationally standard module with 34–36 cells would contain two bypass diodes placed inside its terminal box.

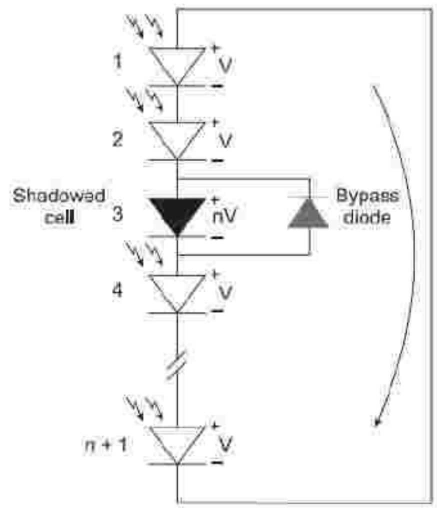
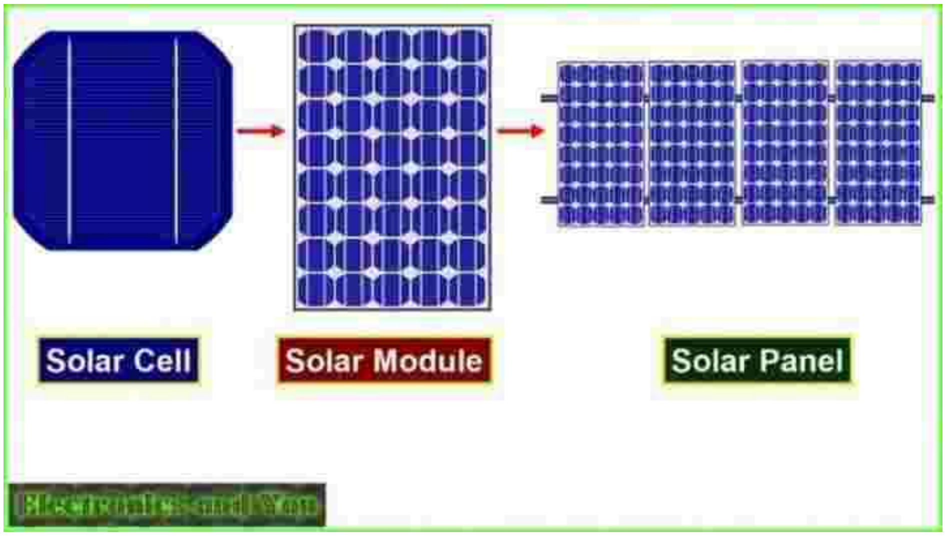


Figure 6.32 Shadowed cell and bypass diode connection

Solar Photovoltaic Panels

An array or Solar PV Cells are electrically connected together to form a PV Module and an Array of such Modules are again electrically connected together to form a Solar Panel. This connection is done by soldering using flux cored solder wire and PV Ribbon.



Solar PV Panel

Several solar modules are connected in series/parallel to increase the voltage/current ratings. When modules are connected in series, it is desirable to have each module's maximum power production occur at the same current. When modules are connected in parallel, it is desirable to have each module's maximum power production occur at the same voltage. Thus while interconnecting the modules; the installer should have this information available for each module. Solar panel is a group of several Solar Photovoltaic Systems modules connected in series-parallel combination in a frame that can be mounted on a structure. Fig. 6.33 shows the construction of module and panel.

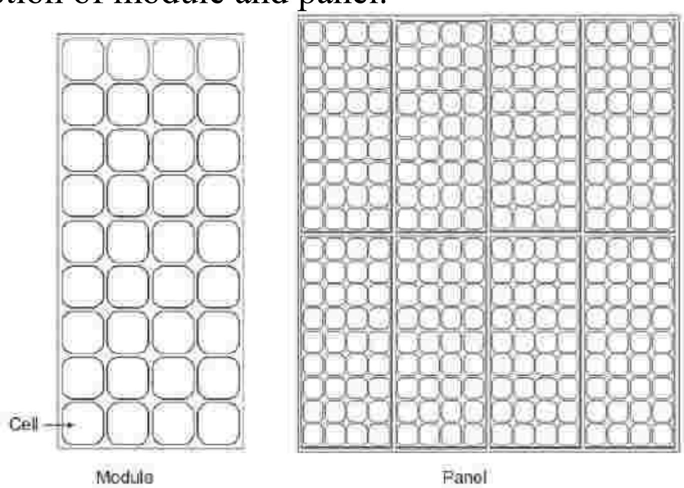


Figure 6.33 Cell, module and panel

Figure 6.34 shows a series-parallel connection of modules in a panel. In parallel connection, blocking diodes are connected in series with each series string of modules, so that if any string should fail, the power output of the remaining series strings will not be absorbed by the failed string. Also bypass diodes are installed across each module, so that if one module should fail, the output of the remaining modules in a string will bypass the failed module. Some modern PV modules come with such internally embedded bypass diodes.

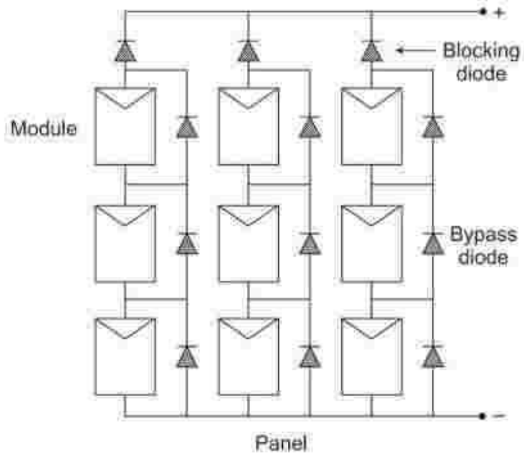


Figure 6.34 A typical panel: Series-parallel connection of modules

Solar PV Array

In general, a large number of interconnected solar panels, known as solar PV array, are installed in an array field. These panels may be installed as stationary or with sun tracking mechanism. It is important to ensure that an installed panel does not cast its shadow on the surface of its neighboring panels during a whole year. The layout and mechanical design of the array such as tilt angle of panels, height of panels, clearance among the panels, etc., are carried out taking into consideration the local climatic conditions, ease of maintenance, etc.

Example 6.4

A PV system feeds a dc motor to produce 1 hp power at the shaft. The motor efficiency is 85%. Each module has 36 multicrystalline silicon solar cells arranged in 9×4 matrix. The cell size is 125mm × 125mm and cell efficiency is 12%. Calculate the number of modules required in the PV array. Assume global radiation incident normally to the panel as 1 kW/m^2.

Solution

Motor output power = 1 hp = 746 W

Electrical power required by the motor = 746/0.85 = 877.65 W

Cell area in one module = $9 \times 4 \times 125 \times 125 \times 10^{-6} = 0.5625$ m^2

Let n number of modules is required

Solar radiation incident on panel = 1 kW/m^2 = 1000 kW/m^2

Cell efficiency = 0.12

Output of solar array = $1000 \times 0.5625 \times n \times 0.12 = 67.5 \times n$

The output of solar array is the input to the motor;

$$67.5 \times n = 877.65$$

$$n = 13$$

Therefore 13 modules are required in the panel.

MAXIMISING THE SOLAR PV OUTPUT AND LOAD MATCHING

To make best use of solar PV system, the output is maximized in two ways. The first is mechanically tracking the sun and always orienting the panel in such a direction as to receive maximum solar radiation under changing positions of the sun. That means adjusting the panel such that the sun rays always fall normal to its surface. The second is electrically tracking the operating point by manipulating the load to maximize the power output under changing conditions of insolation and temperature.

The operating point of an electrical system is determined by the intersection of source characteristics (source line) and load characteristics (load line). The operation for a solar PV system connected to a resistive load is shown in Fig. 6.35. For a low value of resistance, R_1 the system operates at Q_1. As the resistance is increased to R_2 and subsequently to R_3, the operating point moves respectively to Q_2 and Q_3. Maximum power is available from the PV system for load resistance of R_2. Such load matching is required for extracting maximum power from PV system.

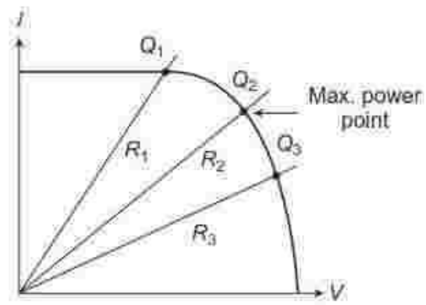


Figure 6.35 Load matching with resistive load

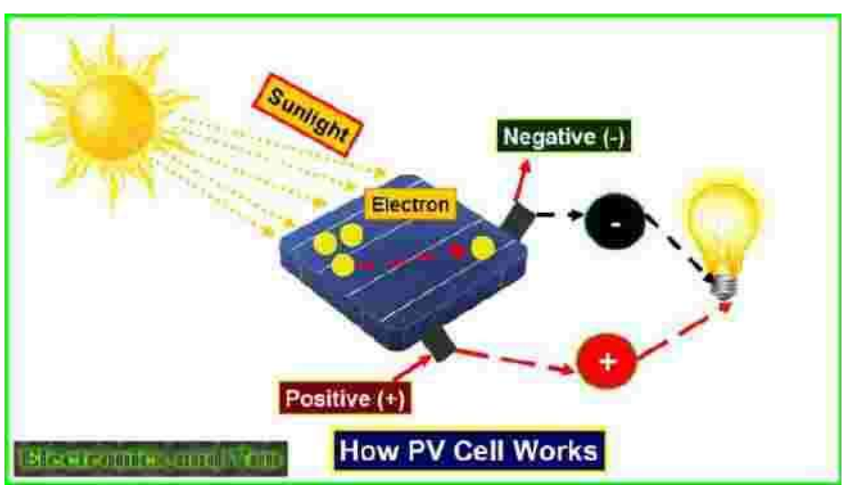
PV Cell or Solar Cell Characteristics

Do you know that the sunlight we receive on Earth particles of solar energy called photons. When these particles hit the semiconductor material (*Silicon*) of a solar cell, the free electrons get loose and move toward the treated front surface of the cell thereby creating holes. This mechanism happens again and again and more and more electrons (*Negative Charge*) flows towards toward the front surface of the cell and creates an imbalance of electrons. Now, when the front (–) and back (+) surface of the photovoltaic cell are joined by a conductor such as a copper wire then electricity is generated.

PV Cell Working Principle to Generate Electricity

Solar cells convert the energy in sunlight to electrical energy. Solar cells contain a material such as silicon that absorbs light energy. The energy knocks electrons loose so they can flow freely and produce a difference in electric potential energy, or voltage. The flow of electrons or negative charge creates electric current.

Solar cells have positive and negative contacts, like the terminals in a Battery. If the contacts are connected with a conductive wire, current flows from the negative to positive contact. The Figure below shows how a PV cell works to generate electricity.



How much Electricity can a PV Cell Generate

A single photovoltaic cell can produce about 1 to 2 watts of electricity. This energy is too less for use in any household or for a commercial purpose.

In order to increase the output of electricity, several photovoltaic cells are electrically connected together to form a photovoltaic module and these modules are further electrically connected to form a photovoltaic panel / photovoltaic array. The number of modules connected to form an array depends on the amount of solar electrical energy needed.

Converting DC to AC Electricity

The PV cells generate DC or direct current. This DC electricity has to be converted to AC or alternating current so that it can be used in a home lighting system or running appliances. An inverter is used to convert DC to AC. This is same as converting DC from a battery to AC.

Storing Electricity Generated by Solar Cells

The electricity generated by solar cells by using solar energy has to be stored so that it can be used later as when required. This is done by running the current into a bank of Solar Batteries.

Solar photovoltaic (PV) systems convert solar energy directly into electrical energy.
Basic conversion device used is known as a solar photovoltaic cell or a solar cell. Solar cells were first produced in 1954 and were rapidly developed to provide power for space satellites based on semiconductor electronics technology. Commercial photocells may have efficiencies in the range of 10–20 per cent and can approximately produce an electrical energy of about 1 kWh per sq. m per day in ordinary sunshine. Typically, it produces a potential difference of about 0.5 V and a current density of about 200 A per sq. m. of cell area in full solar radiation of 1 kW per sq. m. A typical commercial cell of 100 sq-cm area–thus produces a current of 2A. It has a life span in excess of about 20 years. As a PV system has no moving parts it gives almost maintenance free service for long periods and can be used unattended at inaccessible locations.
Major uses of photovoltaics have been in space satellites, remote radio communication booster stations and marine warning lights. These are also increasingly being used for lighting, water pumping and medical refrigeration in remote areas especially in developing countries. Solar powered vehicles and battery charging are some of the recent interesting application of solar PV power.
Major advantages of solar PV systems over conventional power systems are:

(i) It converts solar energy directly into electrical energy without going through thermal-mechanical link. It has no moving parts.
(ii) Solar PV systems are reliable, modular, durable and generally maintenance free.
(iii) These systems are quiet, compatible with almost all environments, respond instantaneously to solar radiation and have an expected life span of 20 years or more.
(iv) It can be located at the place of use and hence no or minimum distribution network is required, as it is universally available.
It also suffers from some disadvantages such as:
(i) At present the costs of solar cells are high, making them economically uncompetitive with other conventional power sources.
(ii) The efficiency of solar cells is low. As solar radiation density is also low, large area of solar cell modules are required to generate sufficient useful power.
(iii) As solar energy is intermittent, some kind of electrical energy storage is required, to ensure the availability of power in absence of sun. This makes the whole system more expensive.

Energy Losses and Efficiency

The conversion efficiency of a solar cell is the ratio of electrical power output to incident solar power. The optimum possible theoretical efficiency of 31 per cent for an ideal solar cell under ideal conditions is obtained at band gap of 1.45 eV. In laboratory studies, the highest reported conversion efficiency of a single crystal silicon solar cell is about 24 per cent. Conversion efficiencies of commercially produced single crystal solar cells are in the range 12–18 per cent.
Various loss mechanisms lead to limit the conversion efficiency of the cell. Some of these losses are due to inherent nature of internal physical processes and available input. These cannot be influenced by external means. The other category of losses can be influenced by suitable selection of material, processing technology and other parameters of the cell.

1. Loss of Low Energy Photons

The photons having energy, E less than the band gap energy, E do not get absorbed in the material and, therefore, do not contribute to the generation of electron-hole pairs. This is referred as transmission loss, and is almost equal to 23 per cent for a single junction solar cell.

2. Loss Due to Excess Energy Photons

When the photon energy E is higher than the band gap energy EG, the excess energy(E – EGG) is given off as heat to the material. For a single junction solar cell, this is equal to about 33 per cent.

3. Voltage Loss

A fraction of developed voltage is lost due to Auger recombination. The Auger recombination occurs at high level of carrier concentration (>1017). In this process, an electron recombining with hole gives its energy to another electron in the conduction band, pushing it into higher energy level. The second electron then goes through several scattering steps before coming back to conduction band edge.

4. Fill Factor Loss

This type of loss arises due to parasitic resistance (series and shunt resistance) of the cell. In best case FF could be 0.89.

5. Loss by Reflection

There are losses due to reflection from the active surface of the cell. As a result, a fraction of incident photons will not enter the bulk material. To minimize these losses, the active surface must be properly treated, by suitable anti-reflective coating and/or by having a pyramidal or textured structure as shown in Fig. 6.17.

6. Loss Due to Incomplete Absorption

It refers to loss of photons which have enough energy (i.e., E > E) to get absorbed in the solar cell, but do not get absorbed due to limited solar cell thickness. As discussed earlier, silicon is an indirect band gap material. Photons of adequate energy require traveling some distance in bulk material in order to get absorbed. If the thickness of the cell is not sufficient (approx. 100 micron) some photons will pass through full thickness of the material without ever getting absorbed. In order to utilize these photons, appropriate light-trapping schemes should be utilized such as; a reflecting G back ohmic contact should be used on the backside, to enhance photon absorption in thinner cells, as shown in Fig. 6.17.

7. Loss Due to Metal Coverage

In wafer-based solar cells, the contact to the front side of the cell is made in the form of finger and bus bar. This metal contact shadows some light which can be up to 10 per cent. Several approaches are adopted to minimize this loss, which include one side contact cell, buried contact solar cell or transparent contacts as used in thin film solar cells.

8. Recombination Losses

Not all the generated electron hole-pairs contribute to photocurrent because some are killed due to recombination. The recombination could occur in the bulk of material or more predominantly at the surface. This type of recombination can be minimized by appropriate surface and bulk passivation techniques in order to obtain high I_L.

MAXIMUM POWER POINT TRACKER

When a solar PV system is deployed for practical applications, the I-V characteristic keeps on changing with insolation and temperature. In order to receive maximum power the load must adjust itself accordingly to track the maximum power point.

The I-V characteristics of PV system, along with some common loads, are shown in Fig. 6.36. An ideal load is one that tracks the maximum power point.

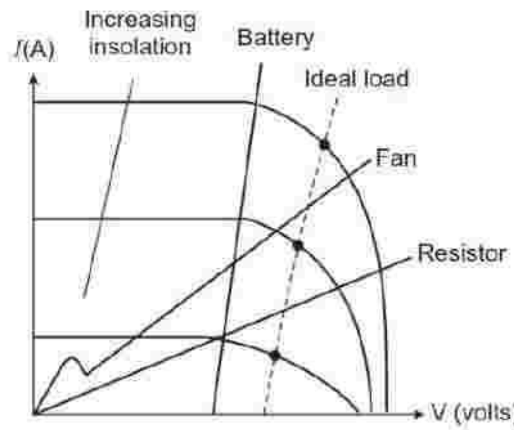


Figure 6.36 Characteristics of PV and some loads

If the operating point departs significantly from maximum power point, it may be desirable to interpose an electronic maximum power point tracker (MPPT) between PV system and load. Generally MPPT is an adaptation of dc-dc switching voltage regulator. Coupling to the load for maximum power transfer may require either providing higher voltage at a lower current or lower voltage for higher current. A buck-boost scheme is commonly used with voltage and current sensors tied into a feedback loop using a controller to vary the switching times. Basic elements of a buck boost converter that may be used in an MPPT are shown in Fig. 6.37. The output voltage of the buck-boost converter is given by:

$$V_{out} = \frac{D}{1-D} V_{in}$$

Where, D is the duty cycle of the MOSFET, expressed as fraction ($0 < D < 1$). Details of operation and design of the converter may be found in any standard book of power electronics.

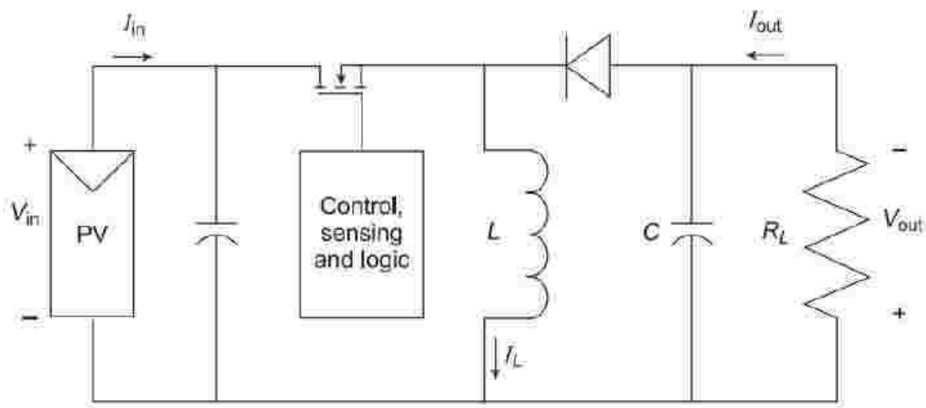


Figure 6.37 Maximum point tracker using buck-boost converter

The power output of a PV system is given by:

$$\Delta P = \Delta V.I + \Delta I.V \quad (6.41)$$

ΔP must be zero at peak point. Therefore, at peak point the above expression in the limit becomes:

$$\frac{dV}{dI} = -\frac{V}{I} \quad (6.42)$$

It may be noted here that $\frac{dV}{dI}$ is the dynamic impedance of the source, which is required to be equal to negative of static impedance, $\frac{V}{I}$.

There are three possible strategies for operation of an MPPT:

(a) By Monitoring Dynamic and Static Impedances A small signal current is being periodically injected into an array bus and the dynamic as well as static bus impedances (Z_d and Z_s respectively) are being measured. The operating voltage is then adjusted until the condition $Z_d = -Z_s$ is achieved.

(b) By Monitoring Power Output From the shape of *P-V* characteristics given in Fig. 6.14(c) it is clear that the slope, d*P*/d*V* is zero at maximum power point. This property is utilized to track the maximum power point. Voltage is adjusted and power output is sensed. The operating voltage is increased as long as d*P*/d*V* is positive. That is, voltage is increased as long as we get increased output. If d*P*/d*V* is sensed negative, the operating voltage is decreased. The voltage is held unaltered if d*P*/d*V* is near zero within a preset dead band.

(c) By Fixing the Output Voltage as a Fraction of V_{oc} This method makes use of the fact that for most PV cells the ratio of the voltage at maximum power point to the open circuit voltage, is approximately constant (say k). This is also evident from Fig. 6.14. For high quality crystalline silicon cell $k = 0.72$. In order to implement this principle, an additional identical unloaded cell is installed on the array to face same environment as the module in use and its open circuit voltage V_{oc} is continuously measured. The operating voltage of the array is then set at $k.V_{oc}$. The implementation of this scheme is simplest among all the available schemes.

Example 6.5

A PV source having IV characteristics as shown in Fig. 6.38 is supplying power to a load whose load line intersects the characteristics at (10 V, 8 A). Determine the additional power gained if an MPPT is interposed between the source and the load. If the cost of the MPPT is Rs. 4000.00, for how long the system needs to operate in order to recover the cost of MPPT. The cost of electricity may be assumed as Rs 7.00 per kWh. The efficiency of MPPT may be assumed as 95%.

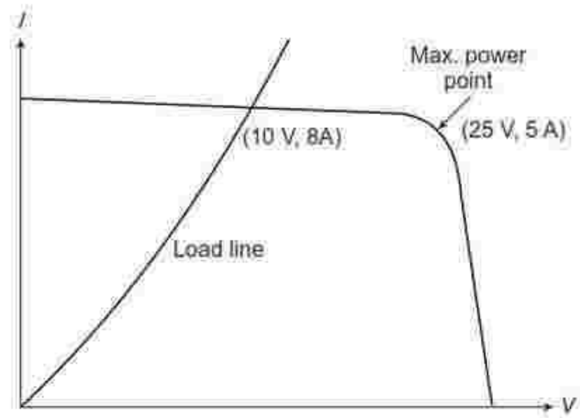


Figure 6.38 PV system – load characteristics

Solution

Power produced without MPPT = $10 \times 8 = 80$ W

Maximum power production capability of the PV module = $25 \times 5 = 125$ W

As the efficiency of the MPPT is 95%, actual power produced with MPPT = $125 \times 0.95 = 118.75$ W

Surplus power produced by use of MPPT = $118.75 - 80 = 38.75$ W

Surplus energy produce in t hours = $\dfrac{38.75 \times t}{1000} = 0.03875 \times t$ kWh

Cost of surplus energy = $7 \times 0.03875 \times t = 0.27125 \times t$

Cost of MPPT = Rs 4000

Time, t (in hours) required to recover the cost of MPPT = $\dfrac{4000}{0.27125} = 14746.54$ hours

Batteries

As solar energy is not available continuously and steadily, some form of energy storage is normally required in most PV systems. Lead acid battery, Nickle cadmium battery and Lithium ion storage batteries are commonly used in PV applications for this purpose. The principles of operation of these batteries are already covered in Section 3.4.2. Some general parameters of batteries are discussed here.

(a) Battery Voltage Three types of voltage available across its terminals are specified: (a) open circuit voltage (maximum voltage); (b) nominal or working voltage (available operating voltage during use), (c) cut-off voltage (minimum voltage after which the battery should be disconnected from the load for recharging). Rechargeable batteries are available with nominal voltages of 3 V, 6 V, 12 V, 24 V, etc.

(b) Battery Capacity It is the maximum charge storage capacity of a battery expressed in Ah. (Ampere-hour). Higher Ah requires more active material. Therefore, as the Ah capacity of a battery increases, the size of the battery also increases. Multiplying Ah with voltage gives energy storage of the battery in Wh (Watt-hours).

(c) Battery Life Cycle It is defined as the number of complete charge/discharge cycles that a battery can perform before its storage capacity falls below 80 per cent of its rated capacity. The aging process (for instance shedding of active material from plates) results in gradual reduction in storage capacity over time. The battery can still be used but its available storage capacity will be lower.

(d) State of Charge (SoC) The SoC at a particular instant indicates the amount of charge available with the battery at that instant. In lead acid battery, the electrolyte's specific gravity provides a convenient indication of the state of charge of the battery.

(e) Depth of Discharge (DoD) This is a measure of energy withdrawn from the battery expressed as percentage of its full capacity. If a battery has a state of charge as 60 per cent, it indicates that its DoD is 40 per cent. The DoD increases as the battery is discharged more and more. Large DoD adversely affects the life cycle of the battery.

(f) Discharge Rate or C-rating C-rating is defined as the charge or discharge current given in terms of capacity of the battery divided by number of hours for full Solar Photovoltaic Systems charge or discharge. For instance a 120 Ah capacity battery with C-rating of C/10(or 0.1C), will have a charge or discharge current of 120/10 = 12 A. Similarly, a 180 Ah capacity battery with C-rating of C/20 (or 0.05C) will have a charge or discharge current of 180/20 = 9 A.

(g) Self-discharge Self-discharge is the loss of stored charge (or energy) when the battery is not in use. It is caused due to internal electrochemical processes and may be considered as equivalent to having a small external load. The self-discharge capacity increases with increase in temperature. Therefore, in order to reduce self-discharge, batteries must be stored at lower temperatures. In SIL batteries some antimony is alloyed with lead to improve mechanical strength. But it also results in increased self-discharge of the battery.

Deep Discharge Batteries

Ordinary batteries are not allowed to discharge beyond 50 per cent DoD. Batteries allowed discharging up to 80 per cent or more are known as deep discharge batteries.

In traction applications where batteries are used to supply the load for longer duration, deep discharge batteries are used. Normal SLI (starting, lighting and ignition) batteries are shallow discharge batteries. They cannot be used in such applications as battery life cycle is significantly reduced due to deep discharge. In deep discharge batteries, the electrode plates are made thicker and stronger to avoid possible wrap of plates. In case of lead acid batteries, tubular batteries are used for such applications.

SLI batteries remain at float charging most of the time. They are normally subjected to only 2–5 per cent depth of discharge during starting of a vehicle. Therefore, these batteries use thin plates with large surface area to supply large current during starting process.

Battery Temperature During Discharge

Both battery capacity and battery voltage decrease, if used at lower temperature. At high temperature also, its capacity may decrease due to deterioration in chemical reaction. Normally, the best battery performance is obtained in temperature range of 20 to 40 ˚C.

Battery Charging

Different methods of charging are suggested for different type of batteries. A lead acid battery may be charged by constant current, constant voltage or a combination of the two. A typical charging cycle for a lead acid battery is shown in Fig. 6.39. The lead acid battery is charged in three stages: (i) constant-current charge, (ii) topping charge and (iii) float charge (or trickle charge). The battery is first charged with a constant current (specified in data sheet) until its terminal voltage reaches the float potential value, $V_{B, float}$ (typically 2.3 V to 2.45 V per cell). The constant current charge applies the bulk of the charge (about 70 per cent) and takes up roughly half of the required charge time. Thereafter the battery is charged by constant voltage $V_{B, float}$ as the current into the battery tappers off. This phase is known as topping charge phase and continues for few hours to fill the remaining 30 per cent. The battery is fully charged when the Non-Conventional Energy Resources current drops to a set low level. Subsequently the applied voltage across the battery is reduced so that small amount of charge keeps trickling into the battery. The float charge compensates for the loss caused by self-discharge. Lead acid battery charging is sluggish and cannot be charged as quickly as other battery systems. current drops to a set low level. Subsequently the applied voltage across the battery is reduced so that small amount of charge keeps trickling into the battery. The float charge compensates for the loss caused by self-discharge. Lead acid battery charging is sluggish and cannot be charged as quickly as other battery systems.

SOLAR PV APPLICATIONS

Batteries used in PV Applications

The most commonly used batteries in PV applications are the lead acid and nickel cadmium batteries. Lithium-ion and nickel-metal hydride are also used, but to a much lesser extent. Lead acid batteries are most popular. These batteries perform well in deep discharging mode than any other battery.

Grid Interactive PV Power Generation

The first large sized (1 MW_p) grid interactive PV plant was installed in Lugo, in California, USA. The second and largest (6.5 MW_p) plant was installed in Carissa Plains, California, USA. Also some other large sized plants are operating in various countries and many others are proposed in Italy, Switzerland, Germany, Austria,Spain and Japan. Presently, the biggest solar PV plant of 579 MW capacity, solar star project, is located at Antelope valley, Los Angeles County, California. This is followed by a 550 MW Desert Sunlight Star at Riverside County, and 550 MW Topaz Solar farm at San Louis, Obispo County, California.

In India, a 221 MW solar PV plant at Chankara, Gujarat is the biggest plant.

Another 750 MW plant is underway at Rewa, MP.

A large number of small rooftop grid interactive systems are successfully being operated in various parts of the world.

Water Pumping

Pumping of water for the purpose of drinking or for minor irrigation, during sunshine hours, is very successful application of stand-alone PV system without storage. Water pumping appears to be most suited for Solar PV applications as water demand increases during dry days when plenty of sunshine is available. There would be less need of water during rainy season when the availability of solar energy is also low.

SPV water pumping systems have been successfully used in many parts of the world in the range of few hundred W_p to 5 kW.

An SPV water pumping system is expected to deliver a minimum of 15,000 liters per day for 200 W_p panel and 1, 70,000 liters per day for 2,250 W_p panel from suction of 7 meters and / or a total head of 10 meters on a clear sunny day. Three types of motors have generally been used: (i) permanent magnet dc motor (in low capacity pumping systems), (ii) brush-less dc motors and (iii) variable voltage and variable frequency ac motors, with appropriate electronic control and conversion system. An SPV water pumping system for a fishing farm is shown in Fig. 6.53.

Figure 6.53 An SPV water pumping system for fishing form

Lighting

Next to water pumping, lighting is the second most important and extensive application of stand-alone solar PV system.

As lighting is required when sun is not available battery storage is essential. Energy efficient compact fluorescent lamps (CFL) or low-pressure sodium vapour lamps(LPSVL) are used at 25–35 kHz frequencies, as SPV is an expensive power source. Pole mounted out-door lighting, shown in Fig. 6.54, is designed for 3–6 hours an evening. A typical system has two 35 W modules connected in parallel, an 11W (900 lumens) CFL, a 90 or 120 Ah, 12 V storage battery and associated electronics including inverter, battery charger and timer to switch on and off the light. The approximate cost of one pole mounted streetlight is Rs 30,000.

Figure 6.54 Pole mounted SPV lighting

Medical Refrigeration

In many developing countries where such life-saving vaccines are in great demand, electricity is not available to operate conventional refrigerators. WHO has specified technical details for PV based refrigerators using solar energy for such applications. This has resulted in success of WHO sponsored immunization program in these countries. The volume of refrigerator chamber varies from 20-100 liters with freezer volume ranging from 10–35 liters. The PV module size ranges from 100 W_p to over 600 W with 12 V /24 V battery, of 150 to over 600 Ah capacities. An SPV powered portable medical refrigerator is shown in Fig. 6.56.

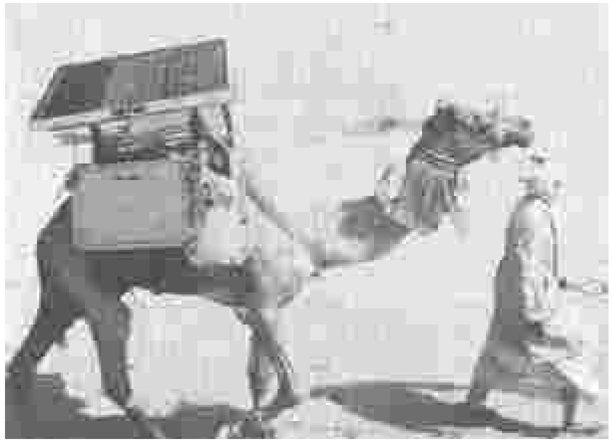


Figure 6.56 An SPV powered portable medical refrigerator

Village Power

Solar PV power can be used to meet low energy demands of many remote, small, isolated and generally unapproachable villages in most developing countries. Two approaches have generally been used:

(i) Individual SPV system for every household

(ii) A centralized SPV plant to meet combined load demand of the whole village

Telecommunication and Signaling

Solar PV power is ideally suited for telecommunication applications such as, local telephone exchange, radio and TV broadcasting, microwave and other forms of electronic communication links. This is because, in most telecommunication applications, storage batteries are already in use and the electrical systems are basically dc. An SPV for satellite earth station is shown in Fig. 6.57.

Figure 6.57 SPV for satellite earth station

Link for Solar cell working

https://youtu.be/X0OZ6tpZ3Mc

SOLAR CELL || PRINCIPLE, CONSTRUCTION, WORKING, VI CHARACTERISTICS AND APPLICATIONS OF SOLAR CELL

https://youtu.be/c58uWGY66Z0

Link for SOLAR CELL,Module,Panel,Array

https://youtu.be/FNQzj98x_pA

Theory of solar cells|Solar cell materials|solar cell array|solar cell power plant

https://youtu.be/Moovzsy15aw

Solar cell losses

https://youtu.be/LMoE7uIeR18

Solar cell losses, Advantages, Disadvantages and Applications

https://youtu.be/roiNF6_kGFM

Effect of shadowing on Solar PV panels

https://youtu.be/JTDSPjDSrS8

https://youtu.be/Be5eZcLY7FQ

Solar Cell mismatching

https://youtu.be/vj_VyVmCSQU

MPPT

https://youtu.be/61KOruxxxiU

https://youtu.be/5Us5mM87PU8

PV Cell modelling

https://youtu.be/rjLd6eJYMsI

https://youtu.be/RRebGefCFps

Module-II
Wind Energy

Wind power or **wind energy** is the use of wind to provide mechanical power through wind turbines to turn electric generators and traditionally to do other work, like milling or pumping.

- Wind power is a sustainable, renewable energy source that has a much smaller impact on the environment compared to burning fossil fuels.
- Wind turbines convert the kinetic energy in the wind into mechanical power.
- Wind turbines convert the energy in wind to electricity by rotating propeller-like blades around a rotor. The rotor turns the drive shaft, which turns an electric generator. Three key factors affect the amount of energy a turbine can harness from the wind: wind speed, air density, and swept area.

Equation for Wind Power

$$P = \frac{1}{2}\rho A V^3$$

V=Wind speed, $\rho =$ Density of the air, A=Swept area of the turbine

A wind energy conversion system (WECS) is powered by wind energy and generates mechanical energy that sends energy to the electrical generator for making electricity. Fig. 1.3 shows the interconnection of a WECS. The generator of the wind turbine can be a permanent magnet synchronous generator (PMSG), doubly fed induction generator, induction generator, synchronous generator, etc. Wind energy acquired from the wind turbine is sent to the generator. To achieve maximum power from the WECS, the rotational speed of the generator is controlled by a pulse width modulation converter. The output power of the generator is supplied to the grid through a generator-side converter and a grid-side inverter. A wind farm can be distributed in onshore, offshore, seashore, or hilly areas. The WECS might be the most promising DG for future SG.

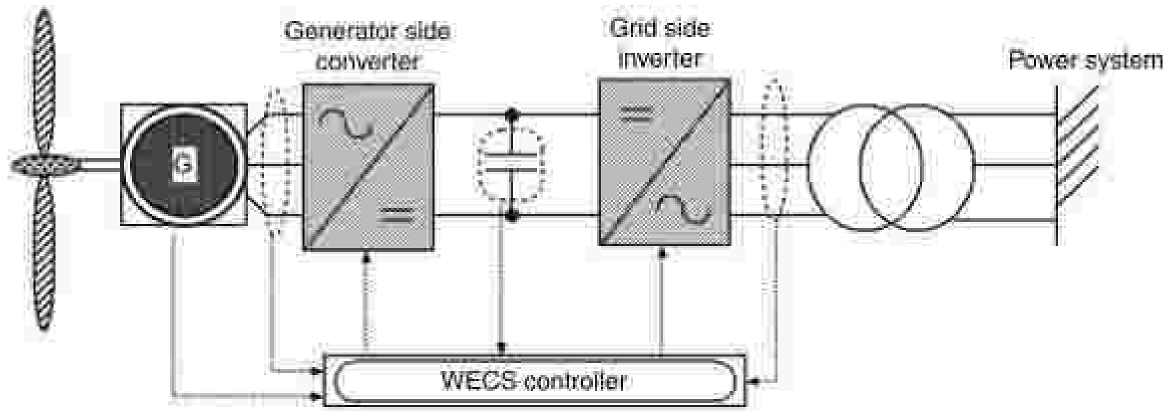
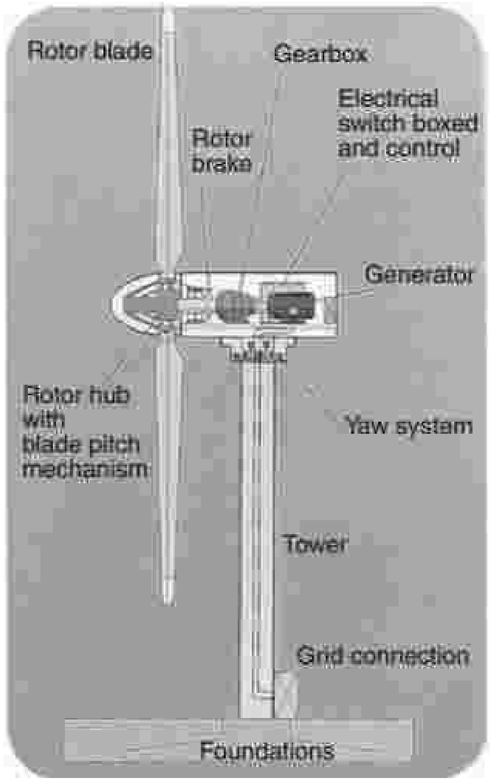


Figure 1.3. Wind energy conversion system.

Wind energy is an alternative to fossil fuels, it is plentiful, renewable, widely distributed, clean, low cost, produces no emissions during operation, and uses a tiny land area [14]. The effects on the environment are generally less problematic than those from other conventional power sources. Due to the variable wind speed, the output power of the WECS fluctuates and may create a frequency deviation of the power grid. To solve this problem, much research has already been conducted.

The world wind energy association (WWEA) published the key statistics of the World Wind Energy Report 2013.

The world wind energy capacity reached 318.5 GW by end of 2013 (this was 282.2 GW in 2012). In total, 103 countries are today using wind power on commercial basis. China was still by far the leading wind market with a new capacity of 16 GW and a total capacity of 91.3 GW. Wind power contributes close to 4% of the global electricity demand. For the year 2020, the WWEA predicts a wind capacity of more than 700 GW [15].



Horizontal-axis wind turbine showing major components.

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:

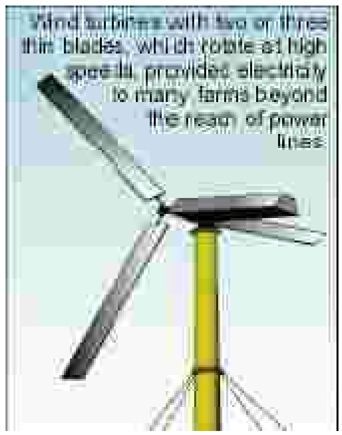
$$\text{specific power of the site} = \frac{1}{2}\rho V^3$$

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.

History of Wind-Mills:

The wind is a by-product of solar energy. Approximately 2% of the sun's energy reaching the earth is converted into wind energy. The surface of the earth heats and cools unevenly, creating atmospheric pressure zones that make air flow from high- to low pressure areas. The wind has played an important role in the history of human civilization. The first known use of wind dates back 5,000 years to Egypt, where boats used sails to travel from shore to shore. The first true windmill, a machine with vanes attached to an axis to produce circular motion, may have been built as early as 2000 B.C. in ancient Babylon. By the 10th century

A.D., windmills with wind-catching surfaces having 16 feet length and 30 feet height were grinding grain in the areas in eastern Iran and Afghanistan. The earliest written references to working wind machines in western world date from the12th century. These too were used for milling grain. It was not until a few hundred years later that windmills were modified to pump water and reclaim much of Holland from the sea.
A typical modern windmill looks as shown in the following figure. The wind-mill contains three blades about a horizontal axis installed on a tower. A turbine connected to a generator is fixed about the horizontal axis.



Like the weather in general, the wind can be unpredictable. It varies from place to place, and from moment to moment. Because it is invisible, it is not easily measured without special instruments. Wind velocity is affected by the trees, buildings, hills and valleys around us. Wind is a diffuse energy source that cannot be contained or stored for use else where or at another time.

Classification of Wind-mills:

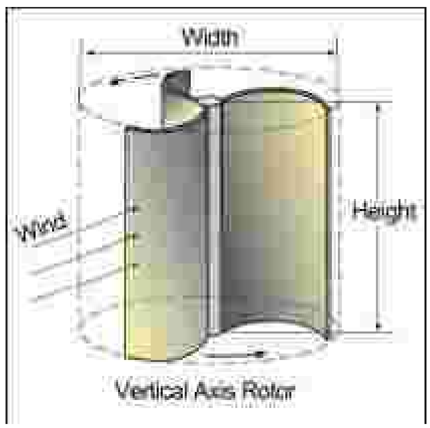
Wind turbines are classified into two general types: Horizontal axis and Vertical axis.
A horizontal axis machine has its blades rotating on an axis parallel to the ground as shown in the above figure. A vertical axis machine has its blades rotating on an axis per pendicular to the ground. There are a number of available designs for both and each type has certain advantages and disadvantages. However, compared with the horizontal axis type, very few vertical axis machines are available commercially.

Horizontal Axis:

This is the most common wind turbine design. In addition to being parallel to the ground, the axis of blade rotation is parallel to the wind flow. Some machines are designed to operate in an upwind mode, with the blades upwind of the tower. In this case, a tail vane is usually used to keep the blades facing into the wind. Other designs operate in a downwind mode so that the wind passes the tower before striking the blades. Without a tail vane, the machine rotor naturally tracks the wind in a downwind mode. Some very large wind turbines use a motor-driven mechanism that turns the machine in response to a wind direction sensor mounted on the tower. Commonly found horizontal axis wind mills are aero-turbine mill with 35% efficiency and farm mills with 15% efficiency.

Vertical Axis:

Although vertical axis wind turbines have existed for centuries, they are not as common as their horizontal counterparts. The main reason for this is that they do not take advantage of the higher wind speeds at higher elevations above the ground as well as horizontal axis turbines.
The basic vertical axis designs are the Darrieus, which has curved blades and efficiency of 35%,the Giromill, which has straight blades, and efficiency of 35%, and the Savonius, which uses Renewable Energy Sources scoops to catch the wind and the efficiency of 30%. A vertical axis machine need not be oriented with respect to wind direction. Because the shaft is vertical, the transmission and generator can be mounted at ground level allowing easier servicing and a lighter weight, lower cost tower. Although vertical axis wind turbines have these advantages, their designs are not as efficient at collecting energy from the wind as are the horizontal machine designs. The following figures show all the above mentioned mills.



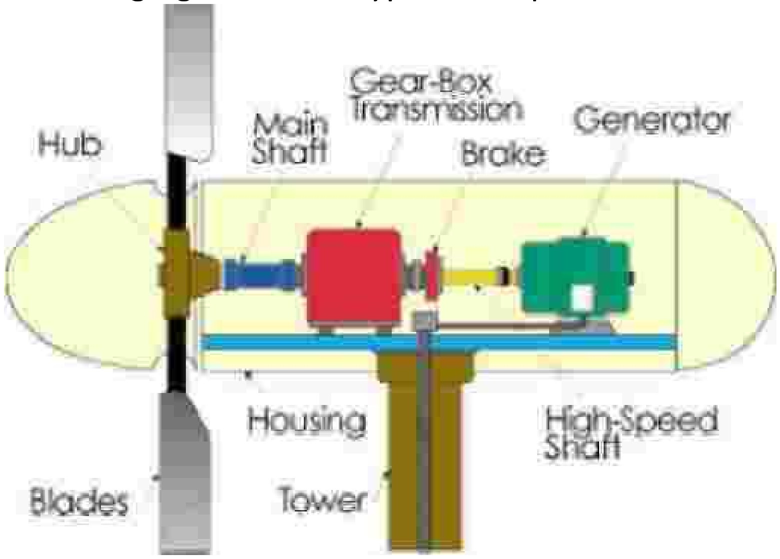
There is one more type of wind-mill called Cyclo-gyro wind-mill with very high efficiency of about 60%. However, it is not very stable and is very sensitive to wind direction. It is also very complex to build.

Link for Videos
Wind Energy
https://youtu.be/vfxX4HMBj6o

https://youtu.be/qSWm_nprfqE
Wind Energy Conversion
https://youtu.be/Q1uedC-1gko
https://youtu.be/Ac8NMoN-vCo
https://youtu.be/eywdMIb2FqE

Main Components of a wind-mill :

Following figure shows typical components of a horizontal axis wind mill.



Rotor:

The portion of the wind turbine that collects energy from the wind is called the rotor.
The rotor usually consists of two or more wooden, fiberglass or metal blades which rotate about an axis (horizontal or vertical) at a rate determined by the wind speed and the shape of the blades. The blades are attached to the hub, which in turn is attached to the main shaft.

Drag Design:

Blade designs operate on either the principle of drag or lift. For the drag design, the Wind literally pushes the blades out of the way. Drag powered wind turbines are characterized by slower rotational speeds and high torque capabilities. They are useful for the pumping, sawing or grinding work. For example, a farm-type windmill must develop high torque at start-up in order to pump, or lift, water from a deep well.

Lift Design:

The lift blade design employs the same principle that enables airplanes, kites and birds to fly. The blade is essentially an airfoil, or wing. When air flows past the blade, a wind speed and pressure differential is created between the upper and lower blade surfaces. The pressure at the lower surface is greater and thus acts to "lift" the blade. When blades are attached to a central axis, like a wind turbine rotor, the lift is translated into rotational motion. Lift-powered wind turbines have much higher rotational speeds than drag types and therefore well suited for electricity generation.

Tip Speed Ratio:

The tip-speed is the ratio of the rotational speed of the blade to the wind speed. The Larger this ratio, the faster the rotation of the wind turbine rotor at a given wind speed. Electricity generation requires high rotational speeds. Lift-type wind turbines have maximum tip-speed ratios of around 10, while drag-type ratios are approximately 1.

Given the high rotational speed requirements of electrical generators, it is clear that the lift-type wind turbine is most practical for this application.

The number of blades that make up a rotor and the total area they cover affect wind turbine performance. For a lift-type rotor to function effectively, the wind must flow smoothly over the blades. To avoid turbulence, spacing between blades should be great enough so that one blade will not encounter the disturbed, weaker air flow caused by the blade which passed before it. It is because of this requirement that most wind turbines have only two or three blades on their rotors.

Generator:

The generator is what converts the turning motion of a wind turbine's blades into electricity. Inside this component, coils of wire are rotated in a magnetic field to produce electricity. Different generator designs produce either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings.

The generator's rating, or size, is dependent on the length of the wind turbine's blades because more energy is captured by longer blades.

It is important to select the right type of generator to match intended use. Most home and office appliances operate on 240 volt, 50 cycles AC. Some appliances can operate on either AC or DC, such as light bulbs and resistance heaters, and many others can be adapted to run on DC. Storage systems using batteries store DC and usually are configured at voltages of between 12 volts and 120 volts.

Generators that produce AC are generally equipped with features to produce the Correct voltage of 240 V and constant frequency 50 cycles of electricity, even when the Wind speed is fluctuating.

DC generators are normally used in battery charging applications and for operating DC appliances and machinery. They also can be used to produce AC electricity with the use of an inverter, which converts DC to AC.

Transmission:

The number of revolutions per minute (rpm) of a wind turbine rotor can range between 40 rpm and 400 rpm, depending on the model and the wind speed. Generators typically require rpm's of 1,200 to 1,800. As a result, most wind turbines require a gear-box transmission to increase the rotation of the generator to the speeds necessary for efficient electricity production. Some DC-type wind turbines do not use transmissions. Instead, they have a direct link between the rotor and generator. These are known as direct drive systems. Without a transmission, wind turbine complexity and maintenance requirements are reduced, but a much larger generator is required to deliver the same power output as the AC-type wind turbines.

Tower:

The tower on which a wind turbine is mounted is not just a support structure. It also raises the wind turbine so that its blades safely clear the ground and so it can reach the stronger winds at higher elevations. Maximum tower height is optional in most cases, except where zoning restrictions apply. The decision of what height tower to use will be based on the cost of taller towers versus the value of the increase in energy production resulting from their use. Studies have shown that the added cost of increasing tower height is often justified by the added power generated from the stronger winds. Larger wind turbines are usually mounted on towers ranging from 40 to 70 meters tall.

Towers for small wind systems are generally "guyed" designs. This means that there are guy wires anchored to the ground on three or four sides of the tower to

hold it erect. These towers cost less than freestanding towers, but require more land area to anchor the guy wires.
Some of these guyed towers are erected by tilting them up. This operation can be quickly accomplished using only a winch, with the turbine already mounted to the tower top. This simplifies not only installation, but maintenance as well. Towers can be constructed of a simple tube, a wooden pole or a lattice of tubes, rods, and angle iron. Large wind turbines may be mounted on lattice towers, tube towers or guyed tilt-up towers.

Towers must be strong enough to support the wind turbine and to sustain vibration,wind loading and the overall weather elements for the lifetime of the wind turbine. Their costs will vary widely as a function of design and height.

Wind Energy Conversion
https://youtu.be/Ac8NMoN-vCo

Horizontal and Vertical Axis Turbine
https://youtu.be/NNBFpkNrhbY

https://youtu.be/65k2Nh8YHFI

Vertical Axis Wind Turbine
https://youtu.be/jdtDG0n2MSw

https://youtu.be/QgYYrvAa0Jw

https://youtu.be/qx_M0nvDIGU

Operating Characteristics of wind mills:

All wind machines share certain operating characteristics, such as cut-in, rated and cutout wind speeds.

Cut-in Speed:

Cut-in speed is the minimum wind speed at which the blades will turn and generate usable power. This wind speed is typically between 10 and 16 kmph.

Rated Speed:

The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power. For example, a "10 kilowatt" wind turbine may not generate 10kilowatts until wind speeds reach 40 kmph. Rated speed for most machines is in the range of 40 to 55 kmph. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases. The output of most machines levels off above the rated speed.
Most manufacturers provide graphs, called "power curves, "showing how their wind turbine output varies with wind speed.

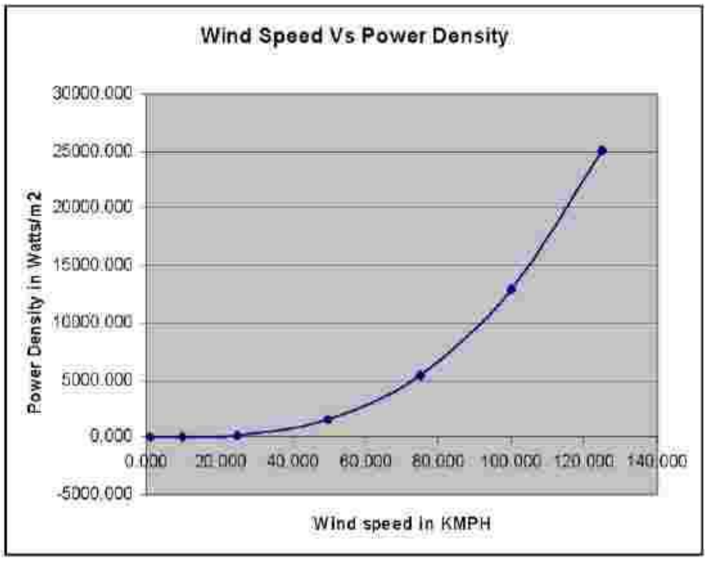
Cut-out Speed:

At very high wind speeds, typically between 72 and 128 kmph, most wind turbines cease power generation and shut down. The wind speed at which shut down occurs is called the cut out speed. Having a cut-out speed is a safety feature which protects the wind turbine from damage. Shut down may occur in one of several ways. In some machines an automatic brake is activated by a wind speed sensor. Some machines twist or "pitch" the blades to spill the wind.
Still others use "spoilers," drag flaps mounted on the blades or the hub which are automatically activated by high rotor rpm's, or mechanically activated by a spring loaded device which turns the machine sideways to the wind stream. Normal wind turbine operation usually resumes when the wind drops back to a safe level.

Betz Limit:

It is the flow of air over the blades and through the rotor area that makes a wind turbine function. The wind turbine extracts energy by slowing the wind down. The theoretical maximum amount of energy in the wind that can be collected by a wind turbine's rotor is approximately
59%. This value is known as the Betz limit. If the blades were 100%efficient, a wind turbine would not work because the air, having given up all its energy, would entirely stop. In practice, the collection efficiency of a rotor is not as high as 59%.A more typical efficiency is 35% to 45%.
A complete wind energy system, including rotor, transmission, generator, storage and other devices, which all have less than perfect efficiencies, will deliver between 10% and 30% of the original energy available in the wind.

The following plot gives the relationship between wind speed in KMPH and the power density.



In the last column of the table, we have calculated the output of the turbine assuming that the efficiency of the turbine is 30%. However, we need to remember that the efficiency of the turbine is a function of wind speed. *It varies with wind speed*.

Now, let us try to calculate the wind speed required to generate power equivalent to 1square meter PV panel with 12% efficiency. We know that solar insolation available at the PV panel is 1000 watts/m^2at standard condition. Hence the output of the PV panel with 12% efficiency would be 120 watts. Now the speed required to generate this power by the turbine with 30% efficiency can be calculated as follows:

Turbine output required = 120 Watts/m^2

Power Density at the blades = 120/ (0.3) = 400 watts/m^2

Wind Power:-

Wind power is generated on account of flow of wind. The blow of wind takes place due to density difference at two places on the surface of the earth. The density difference occurs when the solar radiation differs on earth's surface. Most of the energy stored in wind is found in high altitudes, over flat areas. But most of the potential is close to the coastal areas, approximately equivalent to

72 TW, or 54,000 Mtoe per year. *The power of the wind is proportional to the cubic power of the velocity.* To assess the frequency of wind speeds at a particular location, a probability distribution function is often fit to the observed data. Different locations will have different wind speed distributions. The worldwide wind generation capacity is 1,94,400 MW. India's present installed capacity is 2,000 MW.

Off-shore Wind Power:-

Offshore wind power refers to the installation of wind power plant in the water. Better wind speeds are obtained if the installation is made in the water than the land. Induction generators are often used for power generation. The power generators behave differently due to fluctuation of wind speed during power generation. So, the installation of advanced electromechanical generators are highly essential.

The capacity factor of wind generator is the ratio of actual productivity in a year to the theoretical maximum. The capacity factor of a wind generator varies from 20-40%. The capacity factor arises due to the variation of wind speed at the site and the generator size. The smaller generator would be cheaper and achieve higher capacity factor. Conversely the larger generator would cost more and produce smaller capacity factor.

* The wind power has low operating cost but it carries high capital cost.

Origin of Wind:

The flow of air starts when there is pressure difference between two places. The region where solar radiation is less the atmospheric air gets low temperature and hence low pressure region. On the contrary where the solar radiation is high the atmospheric air gets heated and pressure is high. These differences in atmospheric air pressure (*pressure gradient*) cause acceleration of the air particles which is called wind.

The rotation of earth about its own axis creates Coriolis force which superimposes on the pressure gradient. The direction of wind motion is affected by this *Coriolis force*. In the Northern hemisphere, the moving object turns towards right due to the effect of the Coriolis force if the observer moves in the direction of wind movement. Similarly, the moving object turns towards left in the southern hemisphere.

* In a friction free, rectilinear and stationary wind movement, the force due to pressure gradient and Coriolis force are of same magnitude but in opposite direction. *The wind motion due to Coriolis force is known as geostropic wind*.

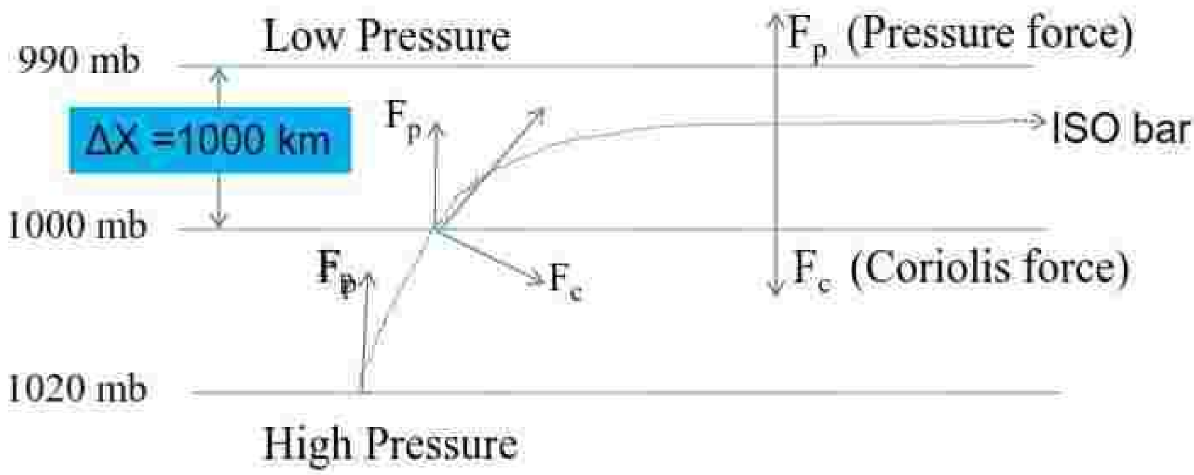


Fig: Geostropic wind on the northern hemisphere

As a result of pressure difference, the air first moves towards low pressure region. It then follows inclined movement towards right due to Coriolis force. This inclination towards right continues till the magnitude of Coriolis force is exactly equal to the pressure gradient force. At this point the wind moves in the direction of isobars whose motion is in the same direction as that of geotropic winds.

Consider a small air element whose Coriolis force is equal to the product of the Coriolis acceleration and mass of the air, i.e. $F_c = 2\omega \sin\phi \times v_g \times (\Delta X \Delta Y \Delta Z) \times \rho_a$

Where

F_c = Coriolis force in newton

$\omega \sin \phi$ = angular velocity of earth at the latitude ϕ (1/sec)

ϕ = latitude

$\Delta X \Delta Y \Delta Z$ = Volume of the considered small air element in (m^3)

ρ_a = density of air (m/sec)

v_g = geostropic wind velocity (m/sec)

The pressure force (F_p) on the air element can be written as: $F_p = \Delta p \Delta Y \Delta Z$

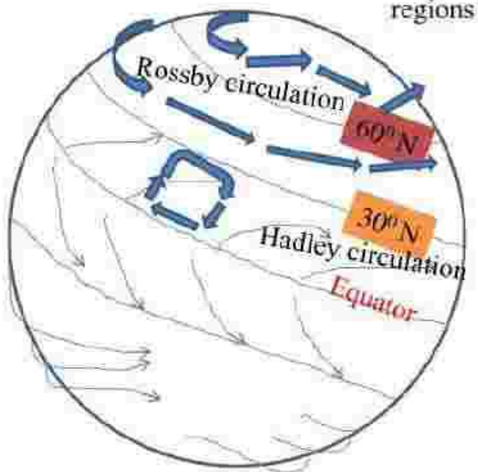
Where Δp = pressure difference on the air element (N/m^2)

$\Delta Y \Delta Z$ = area of air element (m^2).

By equating, $F_c = F_p \Rightarrow 2\omega \sin\phi \, v_g \Delta X \rho_a = \Delta p \Rightarrow v_g = \dfrac{\Delta p}{\Delta X} \dfrac{1}{2\omega (\sin\phi)\, \rho_a}$

* *It is seen that the pressure gradient is directly proportional to the velocity of the geostropic wind.*

Fig(a): Wind stream flow patterns near the surface of the earth in high and low pressure regions in the northern hemisphere.



Fig(b): Simplified circulation system of the earth **(WMO 1981)**

If the path of the wind is curved, then the centrifugal force of the wind particle are also affected by the pressure force and Coriolis forces. The air particles close to the earth's surface are affected by the frictional forces. There is a formation of boundary layer over the surface due to these frictional forces. These collective forces creates a mechanism up to the range of heights *300m to 600m*. The wind velocity within this boundary layer is much smaller than that at higher altitudes. The air flow motion in the form of parallel isobars deviate with decreasing altitude.

In figure (a), the wind flow patterns near the surface of the earth at high and low pressure region have been shown in the hemisphere region.

In figure (b), the circulation system of the earth has been shown. It consists of two components: (i) *Hadley circulation* in the equator region and (ii) *Rossby circulation* in the upper and lower region of the earth.

The operating power of Hadley circulation is the strong solar radiation at the equator. The air gets heated, rises high and moves towards north and south, where it is deviated towards east as result of Coriolis force. The air gets cooled and sinks down in the latitude region ±30^0 (+ North, – South) and flows back towards the equator, where it is deviated towards west due to the Coriolis force. These are the regions where local storms overlap and wind-flows are not always predictable. In the northern and southern region around latitudes ±60^0 the westerly winds of Rossby circulation dominate the region. These winds have wave-form character and vary strongly in the flow patterns.

Wind Flow and Wind Direction:-

Wind speed is classified on representative scale of 12. The order of wind classification is in m/sec or knots (1 nautical miles = 1.852km/hr). The direction of wind are normally divided into eight segments: North, North-East, East, South-East, South, South-West, West and North-West.

Power Density of the Wind:-

Power density of the wind is calculated based on the normal area (A) to the direction of flow of wind stream. The kinetic energy (dE) contained within the mass of the element (dM) is: $dE = \frac{1}{2} dmv^2$ ....(i)

Where

dE = Kinetic energy (joule)

dm = Elemental mass (kg)

$v = dx/dt$ = wind velocity (m/sec). (Here dx is the path travelled in the direction of wind in time dt).

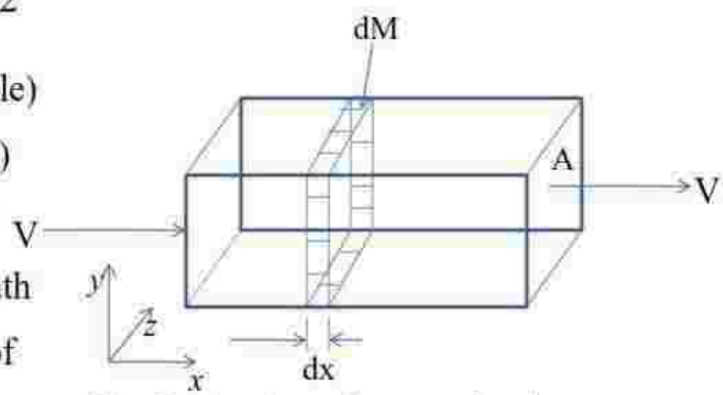


Fig: Derivation of power density

If the density of air is ρ_a and dv is the elemental volume in m^3

then $dv = A.dx$ and $dm = \rho_a \, dv$ …………..(ii)

The mass element dm can be expressed as:

$$dm = A\rho_a .v.dt \text{ (kg)............(iii)}$$

So the K.E. is: $dE = (1/2)\, \rho_a A v^3 dt$

The power, P is: $P = \frac{dE}{dt}$ *and power density in (w/m²) is:* $P = \frac{P}{A} = \frac{1}{2}\rho_a v^3$

It is seen that the wind power density (Pressure) depends upon the cube of wind velocity.

Wind Measurement: -

Wind pressure Measurement:- $P_t = P_s(\text{Static Pressure}) + (1/2)\rho_a v^2 \text{........}(iv)$

Applying Bernoulli's equation the total pressure (P_t) can be calculated as:

and the velocity can be calculated as: $v = \sqrt{\frac{2(P_t - P_s)}{\rho_a}} \text{..................}(v)$

The velocity can be calculated if both the pressures are known. The Prandtl tube is used for pressure measurement.

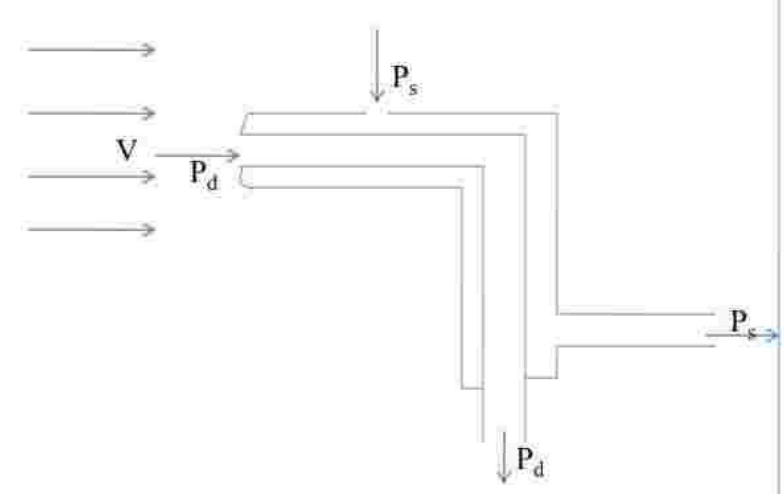


Fig: Prandtl tube for Pressure measurement

The Prandtl's pressure tube contains two tubes. Both are concentric tubes. The inner tube converts the dynamic pressure ($(1/2)\rho_a V^2$) to the stagnation condition. This converts the kinetic energy to pressure energy. At the downstream end the inner tube the pressure head is measured with the manometer. The outer tube measures the static pressure head (P_s) using a manometer.

Annual Average Wind Speed:

The annual average wind velocity at a particular plate can be calculated (in m/sec) by the formula:

$$\bar{v}_i = \frac{\int_{t_1}^{t_2} v\,dt}{t_2 - t_1}$$

Where,

v = Daily average wind velocity (m/sec),

t = time

$t_2 - t_1$ = time duration of one year (sec).

Such annual average values can be obtained for many years by taking average of values for total number of years, i.e.

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} \bar{v}_i$$

Where

n = number of years,

$\bar{v}_i$ = annual average value for the year i in m/sec.

Altitude Dependence of Wind Speed:

The maximum velocity of jet stream occurs at a height of 10 km. The velocity there is nearly five times more than its magnitude at a height of 10 m. In the boundary layer the velocity of flow varies linearly on a log-log representation. It indicates the variation of wind velocity is exponential. The wind velocity at a height H is obtained as:

$$\bar{v}_H = \bar{v}_{10}\left[\frac{H}{10}\right]^{g^*} \quad \text{m/sec.}$$

Where

$\bar{v}_H$ = average annual velocity (in m/sec) at a height H (in m).

$\bar{v}_{10}$ = annual average velocity (in m/sec) at a height of 10 m.

H = height (m)

g^* = exponent.

The above equation is accurate up to height of 200m. The values of the exponent are given in table below.

Recording of wind data:

The wind speed is measured by an anemometer and wind direction is measured by a wind vane attached to a direction indicator. Anemometer works on one of the following principles.

(i) The oldest and simplest anemometer is a swinging plate hung vertically and hinged along its top edge. Wind speed is indicated by the angle of deflection of the plate with respect to the vertical.

(ii) A cup anemometer consists of three or four cups mounted symmetrically about a vertical axis. The speed of rotation indicates wind speed.

(iii) A hot-wire anemometer measures the wind speed by recording cooling effect of the wind on a hot-wire. The heat is produced by passing an electric current through the wire.

(iv) An anemometer can also be on sonic effect. Sound travels through still air at a known speed. However, if the air is moving, the speed decreases or increases accordingly.

(v) Wind speed can be recorded by measuring the wind pressure on a flat plate.

(vi) The other methods include the laser drop anemometer, the anemometer and the SODAR Doppler anemometer.

Applications of Wind Power: Mechanical Power:-

(i) Wind Pumps

(ii) Heating

(iii) Sea Transport

Off-grid Electrical Power Source:(i) Machines of lower power with rotor diameter of about 3m to 40-1000 Watt rating can generate sufficient electrical energy for space heating and cooling of homes, water heating, battery charging and for operating domestic appliances

such as fans, lights and small tools.

(ii) Applications of somewhat more powerful turbines of about 50 KW are producing electrical power for navigation signals, remote communication, weather stations and off-shore oil drilling platforms.

(iii) Intermediate power range, roughly 100 to 250 KW aero-generators can power to isolated populations, farm cooperatives, commercial refrigerators and to small industries.

(iii) For lifting water to hill, aero-generator is installed on the top of hill and electrical energy is transmitted to a pump fixed at lower level.

Grid-Connected Electrical Power Source.

(i) Large aero-generators in the range of a few hundred KW to a few MW are planned for supplying power to a utility grid. Large arrays of aero-generators,known as wind farms are being deployed in open plains or off-shore in shallow water for this purpose.

Wind Energy Converters:-

The wind energy converters convert wind energy to electrical and mechanical energies.

Maximum Power Coefficient:*The maximum power coefficient of the wind energy can be defined as the ratio of the convertible power to the theoretically maximum power from the available wind energy.*

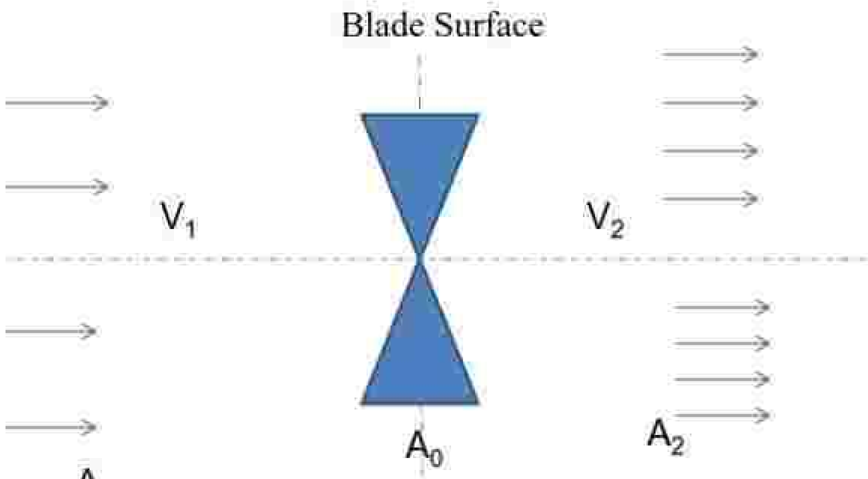


Fig: Wind stream profile in an external wind turbine

The *incompressible, friction free and one dimensional wave* is shown here. The flow is called *Rankine-Froude momentum* theory. The flow velocity (V_1 m/sec) and cross sectional area (A_1 m^2) enters into the surface of the wind blade and leaves out with velocity (V_2 m/sec) at a cross sectional area (A_2 m^2).

According to the equation of continuity: $\dot{m} = A_1 v_1 = A_2 v_2 \text{ m}^3\text{/sec}$............(vi)

At the surface of the rotor: $\dot{m} = \rho_a v_0 A_0 \text{ kg/sec}$........*(vii)*

Where ρ_a = air density (kg/m^3)

v_0 = Wind velocity at the surface of the rotor (m/sec)

A_0 = rotor disc area (m^2)

So v_0 can be written as: $v_0 = \frac{1}{2}(v_1 + v_2)$ m/sec..............*(viii)*

We know that the power density,

$$P_1 = \frac{1}{2}\rho_a v_1^3 A_1 \text{ (W) and } P_2 = \frac{1}{2}\rho_a v_2^3 A_2 (\text{W}).........(ix)$$

The power of the rotor is:

$$P = P_1 - P_2 \text{ (W)} \quad \text{or } P = \frac{1}{2}\rho_a\left(A_1 v_1^3 - v_2^3 A_2\right) \text{ (W)}..........(x)$$

Or $P = \rho_a v_1 A_1 \frac{v_1^2}{2} - \rho_a v_2 A_2 \frac{v_2^2}{2}$ (W)

Or $P = \frac{1}{2} \dot{m}\left(v_1^2 - v_2^2\right) \quad \left(\because \dot{m} = A v \rho\right)$

Or $P = \frac{1}{4} \rho_a A_0 \left(v_1 + v_2\right)\left(v_1^2 - v_2^2\right) \quad \left(\because v_0 = \frac{1}{2}\left(v_1 + v_2\right)\right)$

Or $P = \frac{1}{4} \rho_a A_0 v_1^3 \left(1 + \frac{v_2}{v_1}\right)\left(1 - \frac{v_2^2}{v_1^2}\right)$ (W)........................(xi)

The maximum power is obtained when the wind speed (v_2) is zero.

$$P_{max} = \frac{1}{4} \rho_a v_1^3 A_0 \text{ (W)} ....(xii)$$

The ideal power coefficient (C_p) of a wind machine is the ratio of the power P of the rotor to the maximum wind power, i.e.

$$C_p = \frac{P}{P_{max}} = \frac{1}{2}\left(1 + \frac{v_2}{v_1}\right)\left(1 - \left(\frac{v_2}{v_1}\right)^2\right) ....(xiii)$$

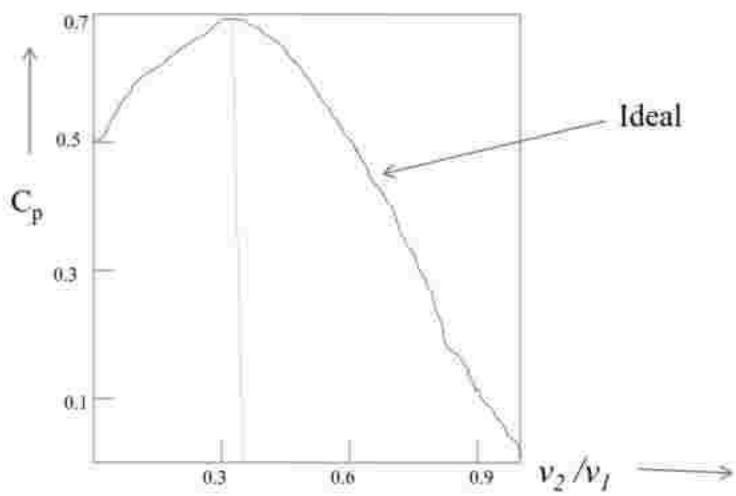
The maximum power coefficient (C_p) can be determined by differentiating Eq.(*xiii*) w.r.t. v_2/v_1. So,

$$\frac{\partial C_p}{\partial\left(v_2/v_1\right)} = 0 \Rightarrow \frac{v_2}{v_1} = \frac{1}{3} \ldots\ldots(xiv)$$

From Eq.(xiii) and (xiv), we get

$$C_{pmax} = 0.593\ldots\ldots\ldots\ldots(xv)$$

So, it is clear that the maximum usable power from an ideal wind energy converter is 59.3%.



Power Coefficient of a Drag or Resistive type Rotor:-

For an oblique surface, the drag force is:

$$F_R = (1/2)\, C_R\, \rho_a\, v^2 A \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (xvi)$$

Where F_R = Drag force (N),

ρ_a = density of air (kg/m³)

v = wind velocity (m/sec)

A = area of the resistance rotor (m²)

C_R = drag coefficient (which depends upon the value of the geometry of the body)

If the motion of the linear speed (u) of the rotor is taken into account, then

$$F_R = \frac{1}{2} C_R \rho_a (v-u)^2 A. \quad \text{newton} \ldots\ldots (xvii)$$

The power produced by the drag is: $P = \frac{1}{2} \rho_a C_R (v-u)^2 .u.A$ (W)....$(xviii)$

The maximum power of the rotor at the surface of the blade is; $P = \frac{1}{2} \rho_a v^3 A$ (W)..(xix)

The power coefficient for the drag type rotor is the ratio of rotor power to the maximum power.

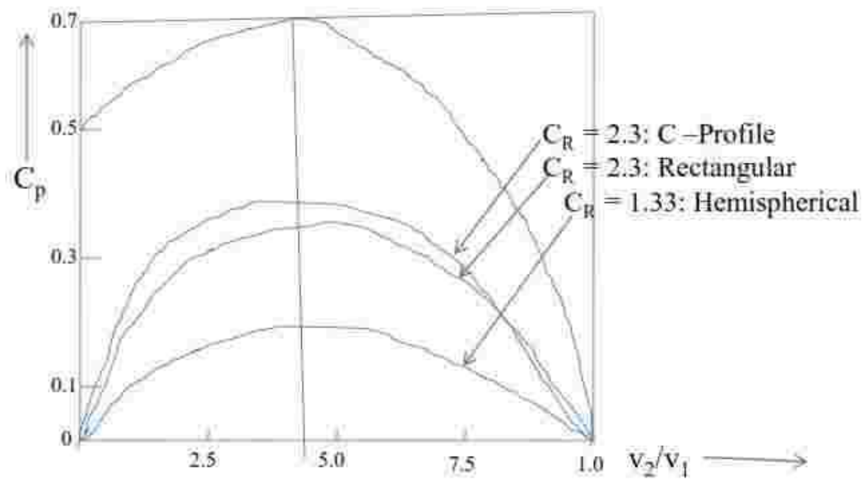
$$C_{PR} = \frac{P}{P_{max}} = \frac{(1/2)\rho_a C_R (v-u)^2 uA}{(1/2)\rho_a v^3 A} = C_R (1 - \frac{u^2}{v^2}) \frac{u}{v} ....(xx)$$

The maximum C_{PR} is obtained by setting $\frac{\partial C_{PR}}{\partial\left(\frac{u}{v}\right)} = 0..............(xxi)$

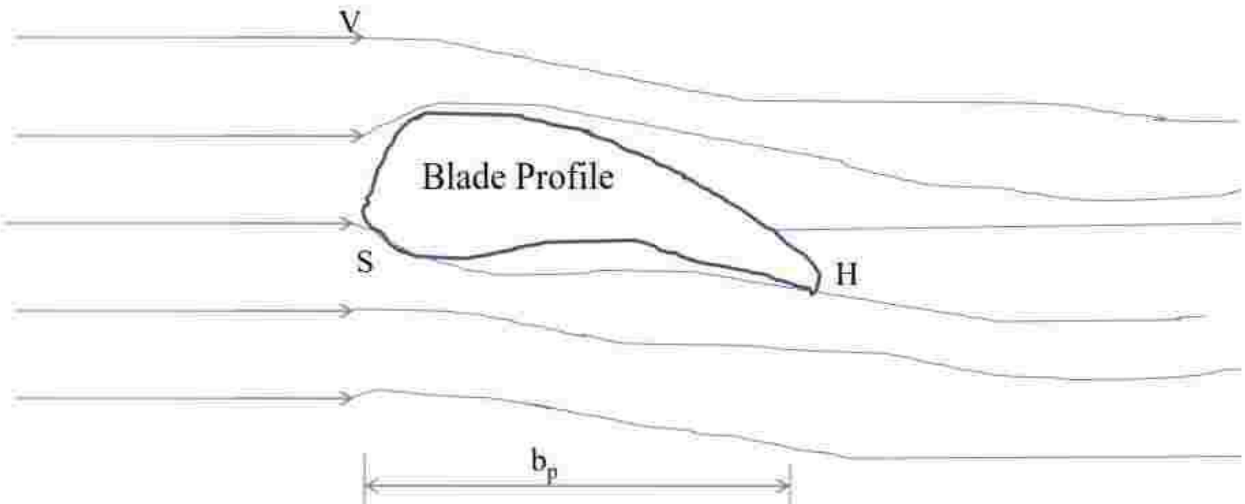
By solving we will get *u/v = 1/3.*

So the maximum value: C_{PR} max = (4/27) C_R ....*(xxii)*

Fig: Comparison of ideal power coefficient with maximum values of power coefficient of resistive rotors.



Wind Stream Profiles:-

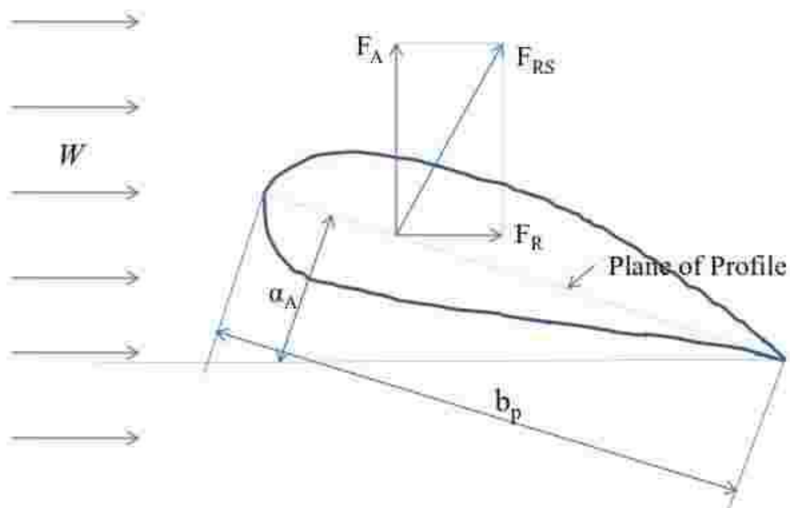


The lift force (F_A) is given by: $F_A = \int_0^{b_p} (P_L - P_u) L dx$.............(xxiii)

P_L = Pressure at the lower side of the profile (N/m^2) , P_u = Pressure at the upper side of the profile (N/m^2), L = Length (m), b_p = width of the profile (m).

* *The pressure is lower on the upper side than the lower side.*

Buoyancy Coefficient and the Drag Coefficient:-



For an asymmetrical profile, there exists two forces:

(1) The lift force (F_A) perpendicular to the direction of flow, and (2) the drag force (F_R) parallel in the direction of flow.

Let us assume: α_A = incident angle or angle of attack (angle between the profile and the flow direction).

w = apparent wind velocity (m/sec).

A = profile area (m^2) = $b_p L$.

P_a = air density (Kg/m^2).

L = length of the profile (m)

b_p = width of the profile (m)

C_R = drag coefficient (dimensionless).

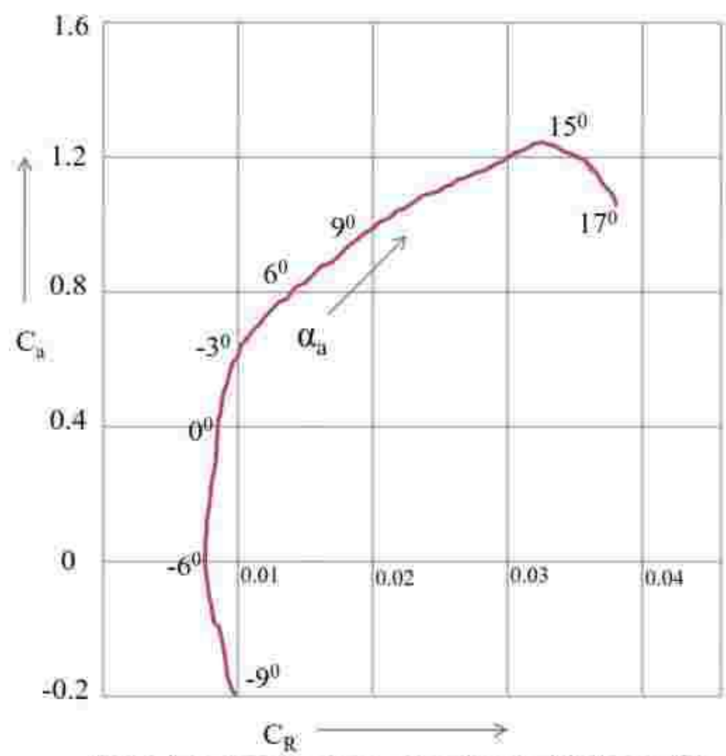
The horizontal drag force (F_R) developed due to friction with the surface of the profile is:

$$F_R = \frac{1}{2}\rho_a C_R w^2 A = \frac{1}{2}\rho_a C_R w^2 b_p L \quad \text{(N)}$$

The vertical force lift (F_L) can be calculated as:

$$F_R = \frac{1}{2}\rho_a C_a w^2 A = \frac{1}{2}\rho_a C_a w^2 b_p L \quad \text{(N)}$$

The drag coefficient C_R and the lift coefficient C_a are determined experimentally for a particular profile. The values of C_R and C_a are determined from the polar diagram with angle of attack as a parameter which is shown in the next slide.



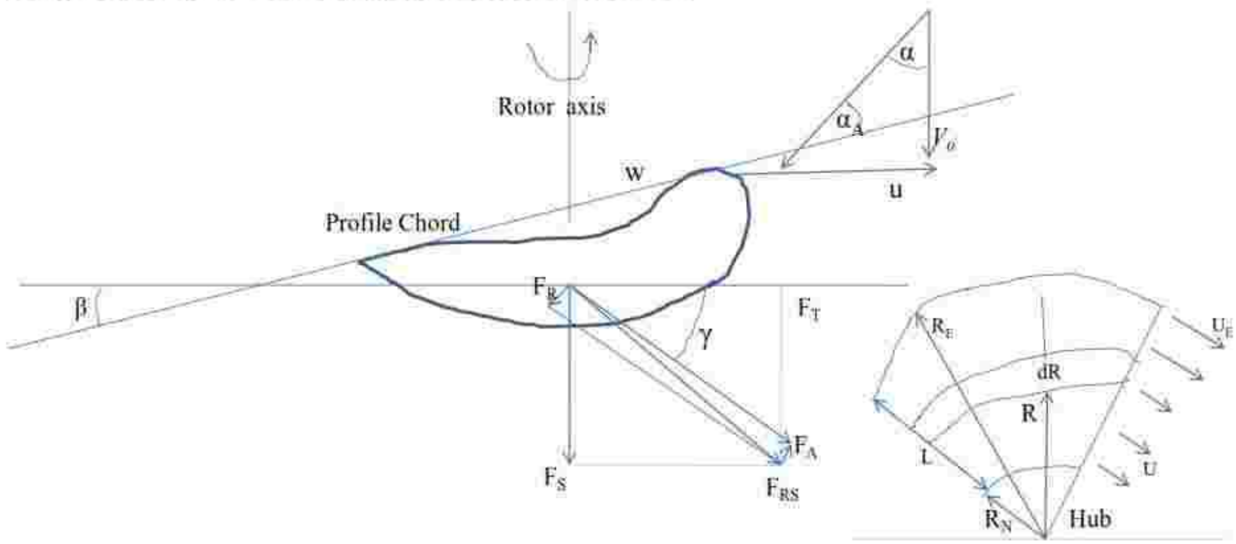
The diagram is shown for the Reynolds number of the flow (Re) as:

$$\mathrm{Re} = \frac{w b_p}{\nu}$$

Where ν is the kinematic viscosity (m^2/sec)

Fig: A Polar diagram of a simple blade profile (Re = 10^5).

Velocities and Forces at the Rotor Blade:-



u = Circumferential velocity of rotor blade (m/sec), v_0 = Velocity of wind (m/sec), w = Approach velocity of wind (m/sec), β = Blade angle (Angle between profile plane and rotor plane), F_{RS} = Resultant of the F_A and F_R . F_s = Axial component of F_{RS} , R_E= Outer rotor radius, R_N = radius of the hub, u_E = Peripheral velocity at the edge of the blade, α_A = angle of attack, γ = angle between wind velocity v_0 and relative 70
approach velocity, L = Rotor blade length, For an element which delivered power dP along the length dR of the rotor blade, one can write: $dP = u\,dF_T$ (W)

Where dF_T is an elemental tangential force. It is expressed as:

$$dF_T = dF_A \cos\gamma \quad \text{newton}$$

So the power produced is given by: $dP = u\cos\gamma\, dF_A$ (W)

Using the expression for dF_A we can write;

$$dP = u\cos\gamma \frac{C_A}{2}\rho_a w^2 dA \text{ (W)}$$

$$\text{Again,}\quad \cos\gamma = \frac{v_0}{w} = \frac{v_0}{\sqrt{u^2 + v_0^2}}$$

and for the area element: $dA = b_p N_R dR$

Where N_R is the number of rotor blades and dR is the length of the elemental rotor.

By substitution of dA in dP we can get power of an element,

$$dP = \frac{C_A}{2}\rho_a w^2 u\left(v_0 \Big/ \sqrt{u^2 + v_0^2} \right) b_p N_R dR \text{ (W)}$$ 71

The total power of the rotor can be calculated by integration of dP from R_N to R_E.

So, $$P = \int_{R_N}^{R_E} \frac{C_a}{2} \rho_a w^2 u \frac{v_0}{\sqrt{u^2 + v_0^2}} b_p N_R dR \qquad \text{(W)}$$

Similarly, thrust force can be calculated on the rotor blades along the vertical axis:

$$dF_s = dF_A \sin\gamma = \frac{C_a}{2} \rho_a w^2 dA \frac{u}{\sqrt{u^2 + v_0^2}} \qquad \text{(N)}$$

or $$dF_s = \frac{C_a}{2} \rho_a w^2 (b_p N_R dR) \frac{u}{\sqrt{u^2 + v_0^2}} \qquad \text{(N)}$$

or $$F_s = \int_{R_N}^{R_E} \frac{C_a}{2} \rho_a w^2 (b_p N_R) \frac{u}{\sqrt{u^2 + v_0^2}} dR \qquad \text{(N)}$$

Components of a Wind Power Plant:

The different components of a wind converter are described below.

Wind Turbine:-

The wind rotors are various types depending upon number of blades, speed, control system, gear box (or gear less), type of generator etc. All the machines are based upon four basic concepts of rotor dynamics. These are given in the table below.

Table: Classification of selected wind power converters (Hau 2002).

Lift principle horizontal axis	High speed system, one-blade, two-blade or three –blade rotor, Low speed system, Historical wind mill, multiple rotor, Flettner rotor, sail rotor
Lift principle vertical axis	High speed systems, Darrieus rotor, H-rotor, three-blade rotor, low speed systems, Savonius rotor with lift principle.
Concentrating wind mill	Shrouded windmill, tornado type wind mill, delta concentrator wind mill, Berwian windmill.
Drag principle	Savonius windmill, cup anemometer windmill, half shielded windmill 73

* After extensive field experience, horizontal-axis, three-blade wind rotor has become an established system for field applications.

* In 1980s and 1990s, one and two-blade rotors were also developed because of higher rotational speed. But due to instability experience in operation, these were not used further.
* Gearless rotors are generally low speed converters which requires a special generator.

Tower: -

A component that sustains the whole weight of the rotor and its components is the tower. The tower should have sufficient height to operate the rotor at desired speed. The tower should also be strong enough to sustain the static and dynamic load of the rotor and vibrations during high and gusty winds. Tower are constructed from concrete or steel. Off-shore wind machines are of lower height because the wind speed is larger. So the foundations built in those cases are costly.

Electric Generators:

Electrical generators convert the rotational energy into mechanical energy then to electrical energy. Commercially available generators with slight modification are used for converters with gear box. Specially designed three phase generators are used for gearless converters.

Synchronous Generator:-

These generators are equipped with a fixed stator at the outside and a rotor at the inside located on a pivoting shaft. Normally DC is supplied to the rotor to create a magnetic field. When the shaft drives the voltage is created in the stator whose frequency matches exactly the rotational speed of the rotor. This type of generators are used most of the places but the disadvantage is that it runs with constant speed of the rotor and fixed frequency. It is therefore not suitable for variable speed operations in the wind plants.

Asynchronous Generator:

The asynchronous generator is electromagnetic generator. The stator of this generator is made of numerous coils with three groups and is supplied with three phase current. The three coils are spread around the stator periphery and carry currents, which are not in phase with each other. This combination produces a rotating magnetic field, which is the key feature of the asynchronous generator. The angular speed of the rotating magnetic field is called the synchronous magnetic field and is given by:

$$N_s = 60\frac{f}{p} \text{ rpm}$$

Where f = frequency of the stator excitation, p = number of magnetic pole pairs.

The stator coils are embedded in slots of high permeability magnetic core to produce a required magnetic fields intensity with low exciting currents. The rotor in this generator is squirrel cage rotor with conducting bars embedded in the slots of the magnetic core. The bars are connected at ends by a conducting ring. The stator magnetic field rotates at the synchronous speed given above. The relative speed between the stator and the rotor induces a voltage in each rotor turn linking the stator flux $V = (-dF/dt)$, F being the magnetic flux linking the rotor turn.

Foundations:-

The type of foundations required to anchor towers and thus wind energy converters, into the ground depends upon the plant size, meteorological and operational stress and local soil conditions. Erection of wind converters on a coastal line is much more costly. Depending on the soil conditions, there types of foundations namely gravity foundation, monopole foundation and tripod foundations are used . All these foundations are discussed in the beginning.

Turbine Rating:-

The normal rating of a wind turbine has no standard global rating. The power output of a turbine is proportional to the square of the rotor diameter and also to the cube of the wind speed.

* The rotor of a given diameter will generate different power at different wind speed (like 300 KW at 7m/sec and 450 KW at 8 m/sec).

* Many manufacturers mention a combined rating specification like 300/30 means 300 KW generator and 30 m rotor diameter.

* Specific rated capacity (SRC) is often used as a comparative index defined as:

SRC = Generator Electrical Capacity/Rotor Swept Area.

Multiple Choice Questions and answers

1. What does Heating and cooling of the atmosphere generates?
   a)Thermo line circulation
   b) Radiation currents
   c) Convection currents
   d) Conduction currents
   Answer: c
   Explanation: Wind energy can be economically used for the generation of electrical energy. Heating and cooling of the atmosphere generates convection currents. Heating is caused by the absorption of solar energy on the earth surface.
2. How much is the energy available in the winds over the earth surface is estimated to be?
   a) 2.9 X 120 MW
   b) 1.6 X 107 MW