UNIT-I

WIND ENERGY FUNDAMENTALS & WIND MEASUREMENTS

1. Introduction

SUBJECT CODE: SME1602

SUBJECT NAME: WIND AND SOLAR ENERGY

The people of energy dependant countries like India are much aware of the importance of conversion, conservation and development of new energy sources. Today the Power Engineer are concerned with three "E‟s" namely Energy, Economics and Ecology (Environment). Thus the power engineer must try to develop systems that produce large quantities of energy with minimal cost and with low impact on environment. The proper balance of these 3 "E‟s" is a major technological challenge.

In any energy conversion process, the energy must be conserved as implied by First Law of Thermodynamics. (For discussion: Einstein Equation) open system, closed system, isolated system, energy transformation, energy transfer (involves shaft work) machines).

Energy types:

In general, energy is of two types namely,

Transitional energy: Energy in motion and as such can move across system boundary.

Stored energy: Energy that exists as mass, position in a force field etc., These stored forms can easily be converted into some form of transitional energy. (For discussion: open system, closed system, isolated system, energy transformation, energy transfer (involves shaft work) machines).

Energy Classifications:

The energy can be classified into six major groups namely,

1. Mechanical energy – Transitional energy

2. Electrical energy – Transitional energy

3. Electromagnetic energy – Transitional energy

4. Chemical energy – Stored energy

5. Nuclear energy – Stored energy

6. Thermal energy – Transitional energy

Thermal energy is the basic form of energy and all the other energy forms can be completely converted into thermal energy. Thermal energy can be stored as either sensible heat or latent heat.

Sensible heat storage is accomplished by increase in temperature while the latent heat storage is an isothermal process associated with change of phase.

Energy Sources:

It has been divided into three categories namely,

1. Conventional or Exhaustible: Fossil fuels such as crude oil, coal and natural gas.

2. Non-conventional or inexhaustible or continuing or renewable sources: solar, wind, hydroelectric, biomass, biogas, tidal, geothermal and OTEC.

3. Nuclear sources: nuclear fission and nuclear fusion.

Scope Of Wind Energy In India

Wind power is an affordable, efficient and abundant source of domestic electricity.

It's pollution-free and cost-competitive with energy from new coal- and gas-fired power plants in many regions. The wind industry has been growing rapidly in recent years. The Ministry of New and Renewable Energy (MNRE) has fixed a target of 10,500 MW between 2007–12, but an additional generation capacity of only about 6,000 MW might be available for commercial use by 2012.The MNRE has announced a revised estimation of the potential wind resource in India from 49,130 MW assessed at 50m Hub heights to 102,788 MW assessed at 80m Hub height. The wind resource at higher Hub heights that are now prevailing is possibly even more. India has set a target of achieving overall wind energy installed capacity of 27,300 MW by 2017 and 38,500 MW by 2022. As per NOVONOUS estimates, this creates an US$31.25 billion opportunity in the wind energy market in India till 2022.

The wind energy market in India has been growing since the last many years. The total installed capacity of the Indian Wind Energy market is 21136.20 MW. India stands at the 5th Rank in terms of the total installed wind power capacity just behind China,USA, Germany and Spain. But the potential is far from being utilized. It is estimated by the Indian Wind Energy Association that the Wind power potential for all the states of India put together would be in the order of 1.5 GW. It can sustain the growing needs of electricity of the Indian consumers in a sustainable way. The wind energy report aims at providing the reader a detailed view of the industry with the use of analysis frameworks which help in identifying the political, economical, social and technical factors that determine the scenario of the market and the market forces prevailing in the industry. The Key challenges faced by existing players and the barriers for a new player entering into the market, are also covered. It also identifies the role played by the central and the state governments by analyzing the incentives and subsidies offered by central and state governments.

It also provides details about risks associated with credit, policy and technical factors in Indian wind energy market.Detailed company profiles including their position in wind energy value chain, financial performance analysis, product and service wise business strategy, SWOT analysis and key customer details for eleven companies namely Suzlon Energy Limited, Gamesa Wind Turbines Private Limited, Vestas Wind Technology India Private Limited, Wind World India Limited, Global Wind Power Limited, Inox Wind Limited, Kenersys India Private Limited, Regen Power tech Private Limited, GE India Industrial Private Limited, RRB Energy Limited and LM Wind Power Technologies (India) Pvt. Ltd.

Importance of Energy conservation

The earth provides enough to satisfy every man"s needs but not every man"s greed said Gandhiji. Hard facts on why energy conservation is a must are outlined below.

- We use energy faster than it can be produced - Coal, oil and natural gas - the most utilised sources take thousands of years for formation.
- Energy resources are limited - India has approximately 1% of world"s energy resources but it has 16% of world population.

- Most of the energy sources we use cannot be reused and renewed - Non renewable energy sources constitute 80% of the fuel use. It is said that our energy resources may last only for another 40 years or so.
- We save the country a lot of money when we save energy - About 75 per cent of our crude oil needs are met from imports which would cost about Rs.1, 50,000 crore a year
- We save our money when we save energy - Imagine your savings if your LPG cylinder comes for an extra week or there is a cut in your electricity bills
- We save our energy when we save energy - When we use fuel wood efficiently, our fuel wood requirements are lower and so is our drudgery for its collection
- Energy saved is energy generated - When we save one unit of energy, it is equivalent to 2 units of energy produced
- Save energy to reduce pollution - Energy production and use account to large proportion of air pollution and more than 83 percent of greenhouse gas emissions

An old Indian saying describes it this way - The earth, water and the air are not a gift to us from our parents but a loan from our children. Hence we need to make energy conservation a habit.

How wind is caused?

Wind is basically caused by the solar energy irradiating the earth. So wind energy is an indirect manifestation of solar energy. Wind results from air in motion. Air in motion arises from a pressure gradient. Winds are caused because of two factors namely:

1. the absorption of solar energy on the earth‟s surface and in the atmosphere.
2. the rotation of the earth about its axis and its motion around the sun.

Because of these factors alternate heating and cooling cycles occur, differences in pressure are created and the air is caused to move.

Wind, being the commercially viable and economically competitive renewable source is going to play an important role in the future meeting the energy demand.

Global leaders *in wind energy generation*

untry	Installed capacity, MW
Germany	14609
USA	6352
Spain	6202
Denmark	3115

India	2120

Application of wind power: water pumping wind mill.

Advantages:

- Its potential as a source of power is reasonably good and its capture produces no pollution.

Disadvantages:

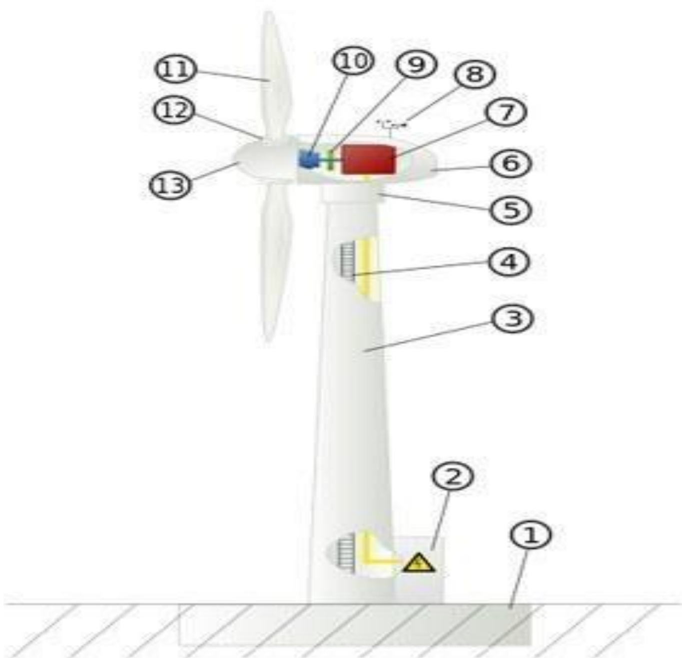
- Energy is available in dilute form.
- Availability of the energy varies considerably over a day with seasons. For these reasons, the face areas of the machines, which extract energy from the wind have to be necessarily large and a continuous supply of mechanical or electrical power cannot be obtained from them.

Principle of wind energy conversion: Energy available in the wind is basically the KE of large masses of air moving over the earth"s surface. Blades of the wind turbine receive this KE, which is then transformed to mechanical or electrical forms. The efficiency of converting wind to other useful energy forms greatly depends on the efficiency with which the rotor interacts with the wind stream.

Drawing of the rotor and blades of a wind turbine, courtesy of ESN

Fundamentals of Wind Energy

1. *Wind Energy:* Wind is caused by flow of air from high pressure area to low pressure area and this difference in pressure is result of heating of the uneven earth's surface by sun. So we can say that wind energy is a form of solar energy.
2. *Wind power:*Wind power is the conversion of wind energy into a useful form of energy, such as using wind turbines to make electrical power, windmills for mechanical power and wind pumps for water pumping.
3. *Wind Turbine:*A turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. A turbine is a turbo-machine with at least one moving part called a rotor assembly, which is a shaft with blades attached. Moving fluid acts on the blades so that they move and impart rotational energy to the rotor. A wind turbine is a device that converts kinetic energy from the wind into electrical power.



1. *Foundation:* Its the basement of a wind turbine on which the whole self weight of wind turbine's will come. It is normally under the surface and it cannot be seen.
2. *To Electric Grid:* This is the connection from which the generated power is sent to electric grid with the help of electric wires.

3. *Tower:* It is the supporting structure for nacelle and rotor. The nacelle is placed above this tower. Tower is a assembly of number of cylindrical hallow structure which are assembled at the site (wind farm).
4. *Access Ladder:* There will be a ladder inside the tower from basement to the top so that one can get access to the nacelle for any kind of repair or inspection work.
5. *Yaw Control:* Since the direction of wind keeps on changing with respect to time and the rotor should be placed in the direction of wind to get the maxim power output, this yaw control helps in o changing the direction of the rotor and will place it in the direction of the wind.
6. *Nacelle:* It is a rectangle like structure that contains generator, controller system, cooler etc. When yaw controls activates the whole nacelle is rotated in the direction of wind.
7. *Generator:* It is the unit responsible for power generation.
8. *Anemometer:* It is a device that is used for wind speed measurement. This data is sent to control system.
9. *Brake:* It is used to stop the rotor that is rotating. Usually brakes are applied when weather conditions are not good to generate power or the rpm of the rotor is above normal speed which may not suite to generator.
10. *Gear Box:* It consist of gears that increases the rpm of the rotor to suite to the rpm of generator.
11. *Rotor Blade:* Blades are the rotating member of wind turbine that makes the shaft to rotate which is connected to gearbox and then to generator. Blades are of aerofoil shape and length will vary from 30 m to 80m (approx.) depending on the rated power of wind turbine.
12. *Pitch Control:* It is used to change the angle of inclination, pitch angle which are responsible for getting maximum efficiency.
13. *Rotor Hub:* It is the one which holds the rotor blade and it will also rotate along with blades.

Site Selection

Anemometers are small and simple devices. A number of the newer units are digital hand held recorders which allow you to easily check wind conditions in different parts of your property. The anemometers aren't hard to set up and many can record not only wind speed but temperature and humidity as well. If your schedule allows you may wish to take recordings at different times of the year in order to get a complete picture of how the wind changes at your location by season.

Another major consideration when selecting a site is the proximity of the wind tower to your home or business. In most cases you don't want the wind tower attached to the building itself because of both noise and structural vibration considerations. However, if the tower is too far away then you could incur significant costs in running a power line from the tower to your house where the electric meter is or, if you are off the grid, to where your batteries are stored. That tower on the hill may sound nice but if the hill is two miles away you might find that it will cost you more to run the line then to have put up the tower in the first place.

Terrain is another consideration. If we live in a hilly area it is good to take advantage of hills in order to gain additional height for your tower. In particular, take care to avoid locations where you are on the leeward (sheltered) side of a hill since it would cut off the wind. Don't just consider existing obstacles. If you are putting up the tower prior to building a residence, consider the impact the home itself will have on wind patterns. Also take into consideration any locations where you may be planning to put up trees which could block the wind.

The impact even a small reduction in wind velocity will have on your ability to generate power. Wind power increases exponentially relative to speed (V^3). A site with an annual average wind speed of about 12.6 miles per hour (5.6 meters per second), has twice the energy available as a site with a 10 mile per hour (4.5 meter per second) average.

Even if have to be a perfect site for wind power, you should always check state and local regulations before investing money in a wind energy solution. Take the time to research local zoning requirements. Many communities have put up strong restrictions on the height of structures. Wind turbines perform better the higher they are placed but you may find that a 75 or 100 foot tower may violate local zoning requirements. For more information on the impact of regulations check out the *Government Regulations* section on our menu.

Also be considerate of our neighbors, particularly if they live close to where you are thinking of placing your wind tower. People can get awfully fussy about having their views block and what might seem like a trivial view to you may be a very big issue for them. Talk to your neighbors before proceeding, and if there is a local community group for your housing area make sure you get their input as well. Your neighbors might object to a wind machine that blocks their view, or they might be concerned about noise.

UNIT-II

WIND MACHINES

WINDMACHINES

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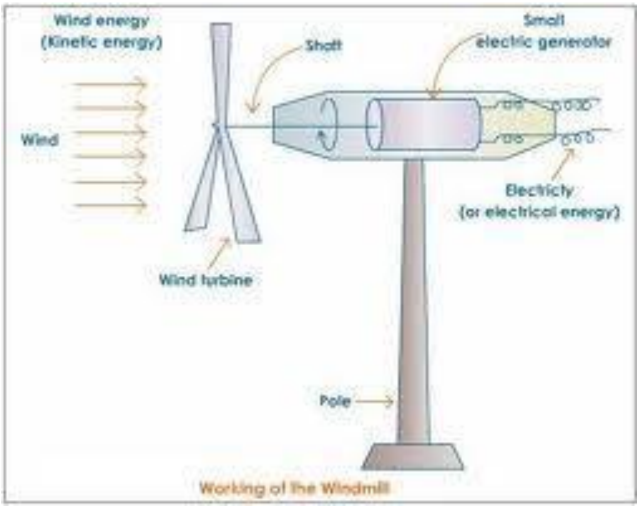
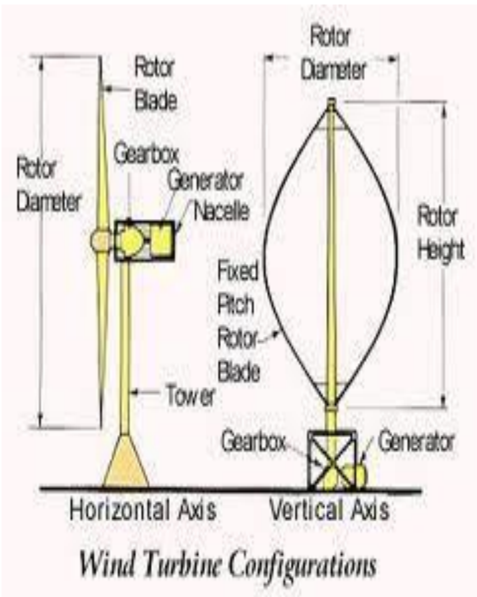
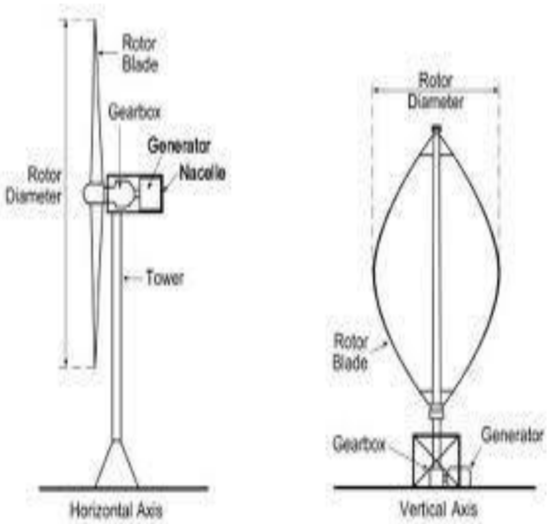
Classification of wind machines:

Wind energy is an indirect source of solar energy conversion and can be utilized to run wind mill, which in turn drives a generator to produce electricity.

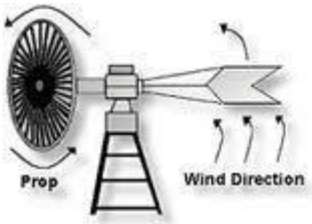


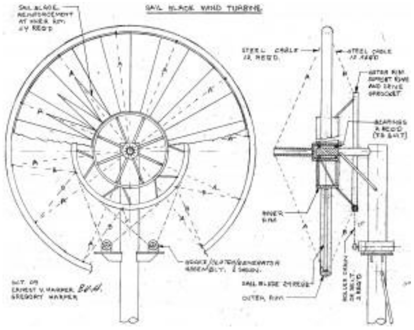
Wind machines are generally classified in terms of the orientation of the axis of rotation of their rotors as ***horizontal axis machines*** & ***vertical axis machines.***





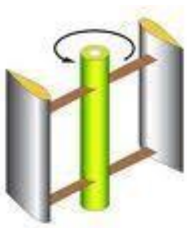
In a ***horizontal axis machine***, the rotor axis is horizontal and is continuously adjusted in a horizontal plane so that it is parallel to the direction of the wind stream. These machines have to face the direction of the wind in order to generate power. Eg: - Multi blade type, Propeller type & Sail type wind mills.

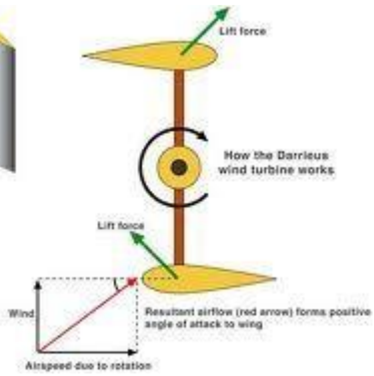




Multi blade type Propeller type Sail type

In a ***vertical axis machine***, the rotor axis is vertical and fixed, and it is ⊥ r to both the surface of the earth and the wind stream. These machines run independently of the direction of the wind because they rotate about a vertical axis. Eg:- Savonius type & Darrieus type wind mills(Designed in 1920 and patented in 1931).

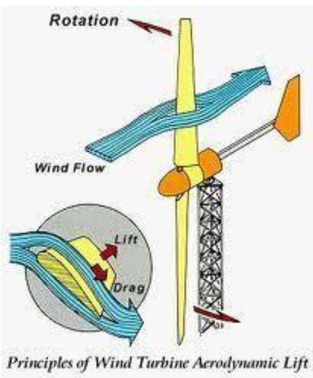


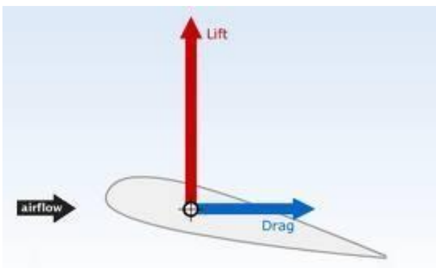


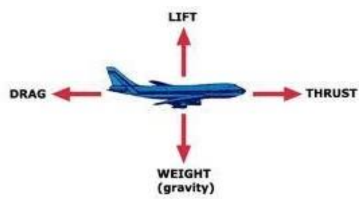
Savonius type Darrieus type

Lift Force and Drag Force:

- The extraction of power and hence energy from the wind depends on creating certain forces and applying them to rotate or to translate a mechanism.
- There are two primary mechanisms for producing forces from the wind namely *lift force* and *drag force.*







- Lift force act perpendicular to the air flow while drag force act parallel to the direction of air flow.
- Lift force is produced by changing the velocity of the air stream flowing over either side of the lifting surface (aerofoil): *speeding up of the air flow causes the pressure to drop while slowing the air flow down leads to increase in pressure.*
- In other words, any change in velocity generates a pressure difference across the lifting surface. This pressure difference produces a force that begins to act on a high pressure side and moves towards the low pressure side of the aerofoil.
- A good aerofoil should have more lift/drag ratio. For efficient operation, a wind turbine blade needs to function with as much lift and as little drag as possible because the drag force dissipates the energy..
- The design of each wind turbine blade specifies the angle at which the air foil should be set to achieve the maximum lift to drag ratio. Wind speeds for a wind machine:

Cut-in Speed: It is the wind speed below which the machine does not rotate and no power is produced.

Design Speed: It is the wind speed at which the machine produces its rated output. Usually the output is held constant at the rated value for wind speeds greater than the design speed. This is achieved by some form of governing mechanism.

Cut-out Speed: It is the wind speed at which it is advisable to shut down the wind machine in order to avoid mechanical damage.

Performance Calculations:

Power available in the wind stream = $\frac{1}{2}\rho A V^3$ ----- Eqn. 1

2 ∞

- The equation implies that the factors influencing the power available in the wind stream are air density, area of the wind rotor and the wind velocity. Effect of wind velocity is more prominent as shown. The density of air decreases with the increase in site elevation and temperature. The air density may be taken as 1.225 for most of the practical cases. Due to this relatively low density, wind is rather a diffused source of energy. Hence large sized systems are often required for substantial power production.
- The prominent factor deciding the power available in the wind is its velocity. When the wind velocity is doubled, the available power increases by 8 times. In other words, for the same power, rotor area can be reduced by a factor of 8, if the system is placed at a site with double the wind velocity. Hence selecting the right site play a vital role in the success of a wind power projects.

A = swept frontal area of the machine; V_∞ = Free stream wind speed.

Wind turbine power and torque:

Theoretical power available in the wind stream is given by eqn. 1. However, a turbine cannot extract this power completely from the wind. When the wind stream passes the turbine, a part of its KE is transferred to the rotor and the air leaving the turbine carries the rest away. Actual power produced by a rotor would thus be decided by the efficiency with which this energy transfer from the wind to the rotor takes place. This efficiency is usually termed as the power coefficient. Thus, the power coefficient of the rotor can be defined as the ratio of actual power developed by the rotor to the theoretical power available in the wind.

1. Power Coefficient, $C_p = \dfrac{P_e}{\frac{1}{2}\rho A V_\infty^3}$; P_e = Power extracted by the rotor

C_p or ideal or maximum theoretical efficiency, $\eta_{\max} = \dfrac{power extracted by the rotor}{power available in the wind stream}$

The power coefficient of a turbine depends on profile of the rotor blades, blade arrangement and setting etc., These parameters should be at its optimum so as to attain maximum C_p at a wide range of wind velocities.

2. Lift Coefficient = $C_L = \dfrac{F_L}{\frac{1}{2}\rho A_b V_\infty^2}$; A_b = Projected area of the blade facing the wind.

$C_L = \dfrac{Lift force on the blade}{Force of the free stream wind}$; F_L, Lift Force is ⊥ r to the direction of the incoming air flow and arises due to the unequal pressure on the two surfaces of the blade.

ρ

3. Drag Coefficient = $C_D = \frac{F_D}{\frac{1}{2} A_b V_\infty^2}$; F_D, Drag Force is parallel to the direction of the incoming air flow and arises due to the viscous friction forces at the surface of the blade as well as the unequal pressure on the blade surfaces.

4. Tip speed ratio, $\lambda = \frac{Speedofthebla \det ip}{Freestreamwindspeed} = \frac{\omega R}{V_\infty}$; ω = angular velocity of the rotor

and R = tip radius

This definition holds good for a horizontal axis wind machine. Blade should have high tip speed ratio.

For a vertical axis m/c, $\lambda = \frac{PeripheralSpeedatthemiddleofthebladelength}{Freestreamofthewindspeed}$

5. Solidity of a wind m/c, $\gamma = \frac{BladeArea}{SweptFrontalArea(\ facearea)ofthemachine} = \frac{Nc}{\pi R}$ (This definition holds good for a horizontal axis machine). Blades should have low solidity.

For a vertical axis machine:- $\gamma = \frac{Nc}{R}$...for Darrieus type and $\gamma = \frac{Nc}{2R}$ ...for other types

N = No. of blades; R = mean radius & c = mean chord of the blades

6. Maximum Power, $P_{max} = \frac{8}{27 g_c}\rho A V_i^3 = \frac{16}{27}\cdot\frac{1}{2}\frac{\rho A V_i^3}{g_c}$

$$P_{max} = 0.593\left(\frac{1}{2}\frac{\rho A V_i^3}{g_c}\right) = 0.593\, P_{total}$$

0.593 is known as the *Betz Coefficient*. C_p cannot exceed 0.593 for a horizontal axis m/c.

$$\eta_{max} = \frac{P_{max}}{P_{total}} = 0.593 = \frac{16}{27}$$

Forces on the blades & Thrust on the turbines for propeller type wind machines: There are 2 types forces are acting on the blades namely,

1. The ***circumferential force*** or *torque* acting in the direction of wheel rotation.

2. The ***axial force*** acting in the direction of wind stream.

The torque T can be obtained from T = $\frac{P}{\omega} = \frac{P}{\pi D N}$ in Newton;

N = wheel revolution per unit time, (1/S); D = diameter of the turbine wheel = $\sqrt{\frac{4}{\pi}.A}$ (in meters); ω = angular velocity of the turbine wheel in m/s.

Actual efficiency, $\eta = \frac{P}{P_{total}} \Rightarrow P = \eta \, . \, P_{total} = \eta \, . \left(\frac{1}{2}\frac{\rho A V_i^3}{g_c}\right)$

$\therefore$ Torque, T = $\eta \frac{1}{2g_c}\frac{\rho A V_i^3}{\pi D N} = \eta \frac{1}{8g_c}\frac{\rho D V_i^3}{N}$. At maximum efficiency, $\eta_{max}\left(=\frac{16}{27}\right)$, the torque has maximum value of T_{max} which is equal to: $T_{max} = \frac{2}{27 g_c}\cdot\frac{\rho D V_i^3}{N}$

g_c = gravitational conversion constant = 1 (kg m / s^2) / N

The axial force or thrust is given by the equation:

$$F_x = \frac{1}{2g_c}\rho A(V_i^2 - V_e^2) = \frac{\pi}{8g_c}\rho D^2(V_i^2 - V_e^2) .$$

The above equation implies that the axial forces are proportional to the square of the diameter of the turbine wheel. This limits the turbine wheel diameter of the large size.

Power Density:

The *power density* is the K.E flowing per unit area and is given by

$$\text{Power Density} = \frac{Power}{Area} = \frac{1}{2}(\rho V)V^2 = \frac{1}{2}\rho V^3 ;$$

ρ = air density in Kg / m^3 and V = wind speed in m / s.

Ideal power required to pump the water = $\rho g Q H$ watts

ρ = density of water; g = acceleration due to gravity; Q = discharge; H = differential head.

Expression for the maximum power developed by a horizontal axis wind machine.

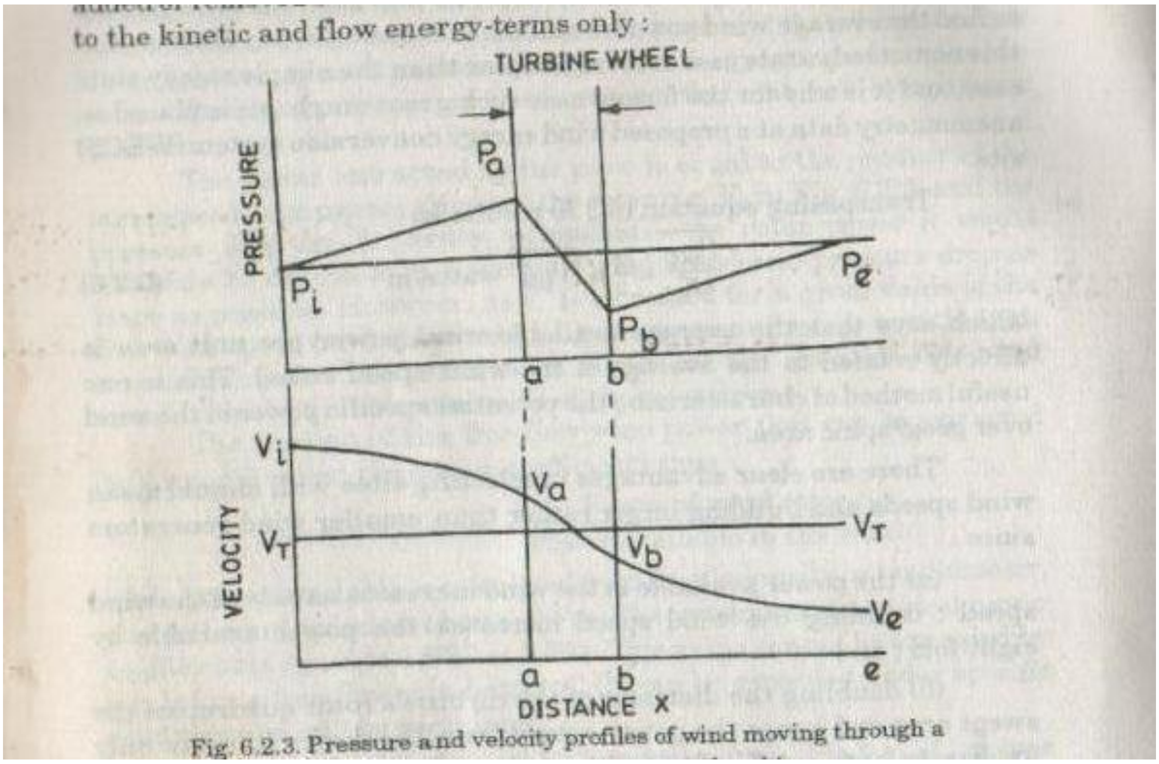


Fig. 6.2.3. Pressure and velocity profiles of wind moving through a

The wheel thickness of a horizontal axis wind machine is assumed to be ab.

Let p_i and v_i are the wind pressure and velocity at the upstream of the turbine.

p_e and v_e are the wind pressure and velocity at the downstream of the turbine.

v_e is less than v_i because kinetic energy is extracted by the turbine.

Considering the incoming air between *i* and *a* as a thermodynamic system and assuming the air density remains constant (since changes in p and T are very small compared to ambient), that the potential energy is zero and no heat or work is added or removed between *i* and *a*, the general energy equation reduces to the kinetic and flow energy terms only. Thus,

For inlet:

$$p_i v + \frac{v_i^2}{2g_c} = p_a v + \frac{v_a^2}{2g_c} \quad \cdots\cdots\cdots\cdots 1.a$$

$$p_i + \rho\frac{v_i^2}{2g_c} = p_a + \rho\frac{v_a^2}{2g_c} \quad \cdots\cdots\cdots\cdots 1.b$$

Similarly for exit:

$$p_e + \rho\frac{v_e^2}{2g_c} = p_b + \rho\frac{v_b^2}{2g_c} \quad \cdots\cdots\cdots\cdots 2$$

The wind velocity across the turbine decreases from *a* to *b* since kinetic energy is converted to mechanical work there. The incoming velocity v_i does not decrease abruptly but gradually as it approaches the turbine to v_a and as it leaves it to v_e. Thus $v_i > v_a$ and $v_b > v_e$ and therefore from equations 1 and 2: we have $p_a > p_i$ and $p_b < p_e$; that is, the wind pressure rises as it approaches, then as it leaves the wheel..

Combining equations 1 and 2, we get

$$p_a - p_b = \left(p_i + \rho\frac{v_i^2 - v_a^2}{2g_c}\right) - \left(p_e + \rho\frac{v_e^2 - v_b^2}{2g_c}\right) \quad 3$$

It can be assumed that wind pressure at *e* can be assumed to be ambient,

i.e.,

$$p_e = p_i \quad \cdots\cdots\cdots\cdots 4$$

As the blade width *a.b* is very small as compared to total distance considered, it can be assumed that velocity within the turbine does not change much and therefore

$$v_a \cong v_t \cong v_b \quad \cdots\cdots\cdots\cdots 5$$

Combining equations 3 to 5 gives,

$$p_a - p_b = \rho\left(\frac{v_i^2 - v_e^2}{2g_c}\right) \quad 6$$

The axial force F_x in the direction of wind stream on a turbine wheel with the projected area perpendicular to the stream is given by

$$F_x = (p_a - p_b)A = \rho A\left(\frac{v_i^2 - v_e^2}{2g_c}\right) \quad 7$$

This force is also equal to change in momentum of the wind (from Newton‟s II law), hence

$F_x = \nabla(mv) / g_c$ where $\dot{m}$ = mass flow rate = $\rho A v_t$

Thus $F_x = \dfrac{1}{g_c}\rho A v_t (v_i - v_e)$…………………8

Equating equations 7 and 8

$$\rho A\left(\frac{v_i^2 - v_e^2}{2g_c}\right) = \frac{1}{g_c}\rho A v_t (v_i - v_e) \text{ and therefore}$$

$$v_t = \frac{1}{2}(v_i + v_e) \text{ …………………………9}$$

Considering the total thermodynamic system bounded by *i* and *e*, there is no changes in potential energy, the internal energy is there from T_i and T_e, and flow energy is there from $p_i v$ and $p_e v$. In the system, no heat is added or rejected, i.e., adiabatic flow.

The general equation now reduces to the steady flow work W and kinetic energy terms,

$$W = kE_i - kE_e = \frac{v_i^2 - v_e^2}{2g_c} \text{……………………10}$$

The power P is defined as the rate of work, and from mass flow rate equation

$$P = \dot{m}\frac{v_i^2 - v_e^2}{2g_c} = \frac{1}{2g_c}\rho A v_t \left(v_i^2 - v_e^2\right) \text{……..11}$$

Combining this with equation 9, we get

$$P = \frac{1}{4g_c}\rho A(v_i + v_e)(v_i^2 - v_e^2)$$

$$P = \frac{1}{4g_c}\rho A(v_i + v_e)(v_i + v_e)(v_i - v_e) = \frac{\rho A}{4g_c}\left[\left(v_i^2 + v_e^2 + 2v_i v_e\right)(v_i - v_e)\right]$$

$$= \frac{\rho A}{4g_c}\left(v_i^3 - v_i^2 v_e + v_i v_e^2 - v_e^3 + 2v_i^2 v_e - 2v_i v_e^2\right)$$

$$= \frac{\rho A}{4g_c}\left(v_i^3 + v_i^2 v_e - v_i v_e^2 - v_e^3\right) \quad 12$$

It can be seen from equation 12, where v_e is positive in one term and negative in other, that too low or too high a value for v_e results in reduced power. There, thus is an optimum exit velocity v_e opt, thus results in maximum power P_{max}, which can be obtained by differentiating P, and equating the derivative to zero.

i.e., $$\frac{d_p}{dv_e} = 0$$

or $$\frac{d_p}{dv_e} = 3v_e^2 + 2v_i v_e - v_i^2 = 0$$

The above equation is solved for a positive v_e to give v_e opt. The above quadratic has two solutions, i.e., $v_e = v_i$ and $v_e = \frac{1}{3} v_i$, only second solution is physically acceptable. Thus,

$$v_e \text{opt} = \frac{1}{3} v_i \text{.. } 13$$

Using eqn.13 in eqn.12, for an ideal horizontal axis wind machine, we get

$$P_{max} = \frac{8}{27 g_c} \rho A v_i^3 \text{ .... } 14$$

$$P_{max} = \frac{16}{27 g_c} \frac{1}{2} \rho A v_i^3 = 0.593 \frac{1}{2} \frac{\rho A v_i^3}{g_c} = 0.593\, P_{total}$$

$$\therefore P_{max} = \mathbf{0.593}\ P_{total}$$

Wind is basically caused by the solar energy irradiating the earth. So wind energy is an indirect manifestation of solar energy. Wind results from air in motion. Air in motion arises from a pressure gradient. Winds are caused because of two factors namely:

1. the absorption of solar energy on the earth‟s surface and in the atmosphere.

2. the rotation of the earth about its axis and its motion around the sun.

Because of these factors alternate heating and cooling cycles occur, differences in pressure are created and the air is caused to move.

Advantages:

Its potential as a source of power is reasonably good and its capture produces no pollution.

Disadvantages:

1.Energy is available in dilute form. 2. Availability of the energy varies considerably over a day with seasons. For these reasons, the face areas of the machines, which extract energy from the wind have to be necessarily large and a continuous supply of mechanical or electrical power cannot be obtained from them.

Classification of wind machines:

Wind energy is an indirect source of solar energy conversion can be utilized to run wind mill, which in turn drives a generator to produce electricity. Wind machines are generally classified in terms of the orientation of the axis of rotation of their rotors as ***horizontal axis machines*** & ***vertical axis machines.***

In a ***horizontal axis machine***, the rotor axis is horizontal and is continuously adjusted in a horizontal plane so that it is parallel to the direction of the wind stream. These machines have to face the direction of the wind in order to generate power. Eg: - Multi blade type, Propeller type & Sail type wind mills.

In a ***vertical axis machine***, the rotor axis is vertical and fixed, and it is ⊥ r to both the surface of the earth and the wind stream. These machines run independently of the direction of the wind because they rotate about a vertical axis. Eg:- Savonius type & Darrieus type wind mills.

Performance Calculations:

1. Power Coefficient, $C_p = \dfrac{P_e}{\frac{1}{2}\rho A V_\infty^3}$; P_e = Power extracted by the rotor

C_p or ideal or maximum theoretical efficiency, $\eta_{\max} = \dfrac{power\,extracted\,by\,the\,rotor}{power\,available\,in\,the\,wind\,stream}$

A = swept frontal area of the machine; V_∞ = Free stream wind speed.

2. Lift Coefficient = $C_L = \dfrac{F_L}{\frac{1}{2}\rho A_b V_\infty^2}$; A_b = Projected area of the blade facing the wind.

$C_L = \dfrac{Lift\,force\,on\,the\,blade}{Force\,of\,the\,free\,stream\,wind}$; F_L, Lift Force is ⊥ r to the direction of the incoming air flow and arises due to the unequal pressure on the two surfaces of the blade.

3. Drag Coefficient = $C_D = \dfrac{F_D}{\frac{1}{2}\rho A_b V_\infty^2}$; F_D, Drag Force is parallel to the direction of the incoming air flow and arises due to the viscous friction forces at the surface of the blade as well as the unequal pressure on the blade surfaces.

4. Tip speed ratio, $\lambda = \dfrac{Speed\,of\,the\,blade\,tip}{Free\,stream\,wind\,speed} = \dfrac{\omega R}{V_\infty}$; ω = angular velocity of the rotor

and R = tip radius

This definition holds good for a horizontal axis wind machine.

For a vertical axis m/c, $\lambda = \dfrac{Peripheral\,Speed\,at\,the\,middle\,of\,the\,blade\,length}{Free\,stream\,of\,the\,wind\,speed}$

5. Solidity of a wind m/c, $\gamma = \dfrac{Blade\,Area}{Swept\,Frontal\,Area\,(face\,area)\,of\,the\,machine} = \dfrac{Nc}{\pi R}$ (This definition holds good for a horizontal axis machine).

For a vertical axis machine:- $\gamma = \dfrac{Nc}{R}$ ...for Darrieus type and $\gamma = \dfrac{Nc}{2R}$ ...for other types

N = No. of blades; R = mean radius & c = mean chord of the blades

6. Maximum Power, $P_{max} = \dfrac{8}{27}\dfrac{\rho A V_i^3}{g_c} = \dfrac{16}{27}\cdot\dfrac{1}{2}\dfrac{\rho A V_i^3}{g_c}$

$$P_{max} = 0.593\left(\frac{1}{2}\frac{\rho A V_i^3}{g_c}\right) = 0.593\ P_{total}$$

0.593 is known as the *Betz Coefficient*. C_p cannot exceed 0.593 for a horizontal axis m/c.

$$\eta_{max} = \frac{P_{max}}{P_{total}} = 0.593 = \frac{16}{27}$$

Forces on the blades and Thrust on the turbines for propeller type wind machines:

There are 2 types forces are acting on the blades namely,

1. The **circumferential force** or torque acting in the direction of wheel rotation.

2. The **axial force** acting in the direction of wind stream.

The torque T can be obtained from T = $\dfrac{P}{\omega} = \dfrac{P}{\pi DN}$ in Newton;

N = wheel revolution per unit time, (1/S); D = diameter of the turbine wheel = $\sqrt{\frac{4}{\pi}.A}$ (in meters); ω = angular velocity of the turbine wheel in m/s.

Actual efficiency, $\eta = \frac{P}{P_{total}} \Rightarrow P = \eta\ .\ P_{total} = \eta\ .\left(\frac{1}{2}\frac{\rho A V_i^3}{g_c}\right)$

$\therefore$ Torque, T = $\eta \frac{1}{2g_c}\frac{\rho A V_i^3}{\pi D N} = \eta \frac{1}{8g_c}\frac{\rho D V_i^3}{N}$. At maximum efficiency, $\left(\eta_{max} = \frac{16}{27}\right)$, the torque has maximum value of T_{max} which is equal to: $T_{max} = \frac{2}{27 g_c}.\frac{\rho D V_i^3}{N}$

The axial force or thrust is given by the equation:

$$F_x = \frac{1}{2g_c}\rho A(V_i^2 - V_e^2) = \frac{\pi}{8g_c}\rho D^2(V_i^2 - V_e^2).$$

The axial force on a turbine wheel operating at maximum efficiency is given by

$(F_x)_{max} = \frac{\pi}{9g_c}\rho D^2 V_i^2$; where V_i = Velocity at the upstream of the turbine.

V_e = Velocity at the downstream of the turbine.

The above equation implies that the axial forces are proportional to the square of the diameter of the turbine wheel. This limits the turbine wheel diameter of the large size.

Some more formulae: 1. The power density (i.e., the power per unit area normal to the wind) is the K.E flowing per unit area and is given by

Power Density = $\frac{Power}{Area} = \frac{1}{2}(\rho V)V^2 = \frac{1}{2}\rho V^3$; ρ = air density and V = wind speed

2. Ideal power required to pump the water = $\rho g Q H$ watt

UNIT 3

SOLAR RADIATION AND COLLECTORS

SOLAR RADIATION AND COLLECTORS

SUBJECT CODE SME1602

SUBJECT NAME WIND AND SOLAR ENERGY

Solar geometry :

Solstice: Either of the two occasions in a year when the sun is directly above either the furthest point north or the furthest point south on the equator that it ever reaches. These are the times in the year in the middle of summer or winter, when there are the longest hours of the day or night (summer solstice [longest day] / winter solstice [longest night]).

Equinox: Either of the two occasions in a year, when the day and night are of equal length and the sun is directly above the equator.

Equator: Equator is an imaginary line on the Earth's surface equidistant from the North Pole and South Pole that divides the Earth into a Northern Hemisphere and a Southern Hemisphere. The latitude of the Equator is 0°.

Longitude (λ)**:-** It is a geographic coordinate that specifies the east-west position of a point on the Earth's surface. It is an angular measurement, usually expressed in degrees, minutes and seconds, and denoted by the Greek letter lambda (λ). The longitude of Mumbai is 72˚51‟.

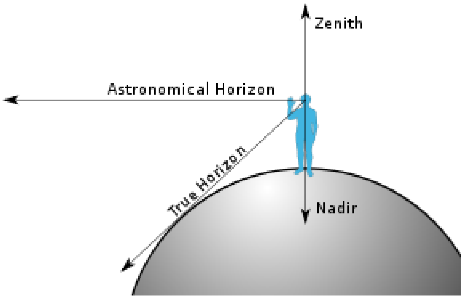
Latitude (ϕ):-The latitude of a location on the Earth is the angular distance of that location south or north of the equator. The latitude is usually measured in degrees. The equator has a latitude of 0°, the North pole has a latitude of 90° north (written 90° N or +90°), and the South pole has a latitude of 90° south (written 90° S or −90°). Together, latitude and longitude can be used as a geographic coordinate system to specify any location on the globe. For example, the Eiffel Tower has latitude of 48° 51′ 29″ N-- that is, 48 degrees plus 51 minutes plus 29 seconds. Alternatively, latitude may be measured entirely in degrees, e.g. 48.8583° N.

Diurnal: - Specialized happening over the period of the day or being active or happening during the day rather than at night.

Zenith: - It is a point on the celestial sphere directly over the head. It would change with respect to the location.

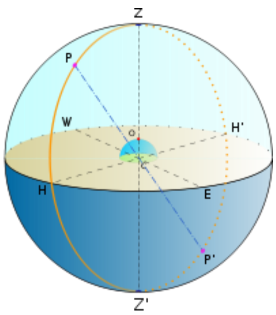
Nadir: - It is a point on the celestial sphere diametrically opposite to the zenith. This would also change w.r.to the location. Unlike zenith, nadir is not visible.

Celestial sphere: - The sky may conveniently be assumed to be a large sphere and this imaginary sphere is called celestial sphere.



Note that the Zenith is opposite the Nadir.

Meridian:- Some reference location on the earth will aid in locating a particular position. The location of Royal Observatory, Greenwich in southeast London has been universally accepted as a reference point. Prime Meridian passes through this observatory is known as the **International Meridian** or **Greenwich Meridian.** The meridian is the outer orange circle which Z, the zenith, lies on. O is the observer.



In the sky, a **meridian** is an imaginary great circle on the celestial sphere. It passes through the north point on the horizon, through the celestial pole, up to the zenith, through the south point on the horizon, and through the nadir, and is perpendicular to the local horizon. [***ante meridiem*** (***a.m.***, "before midday") and ***post meridiem*** (***p.m.***, English: "after midday")]

Solar Constant (G_{sc}): This is the amount of energy received in a unit time on unit area perpendicular to the sun‟s direction at the mean distance of the earth from the sun. Its currently accepted value is 1367 W/m^2, though other values, 1353 W/m^2, 1367 W/m^2 are also found in the literature.

The intensity of extra terrestrial solar flux (ET – outside the earth‟s atmosphere) on any day of the year (G) measured on the plane normal to radiation would be somewhat different from G as actual sun-earth distance varies during the year.

Thus, $G_{on} = G_{sc}\left(1 + 0.033\cos\left(360\, n / 365\right)\right)$

Where n is the number of the day of the year. For e.g. n = 1 for January 1 and n = 32 for February 1. **Sun's radius = 696,342 km with an uncertainty of only 65 km.** (from the report on March 22, 2012, The Hindu)

Solar Declination angle (δ): The earth-sun vector moves in an ecliptic plane. The angle b/w the earth-sun vector and the equatorial plane is called the solar declination angle. δ **v**aries from - 23.45° on December 21 (winter solstice) to + 23.45° on June 21 (summer solstice). It is zero on the two equinox days of March 21 and September 22.

δ can be calculated using the relation

$$\delta \text{ (in degrees)} = 23.45 \sin\left[\frac{360}{365}(284 + n)\right] \text{ where n = no. of the day.}$$

Solar azimuth angle (γ_s), Solar altitude angle (α_a), Solar zenith angle (θ_z):

The sun‟s position is usually specified in terms of solar azimuth angle and solar altitude angle.

The solar altitude angle (α_a) measures sun‟s angular distance from the horizon.

The solar azimuth angle (γ_s **)** measures the sun‟s angular distance in the horizontal plane from the south. (γ_s) is + ve to the east of south and – ve to the west of south.

Solar zenith angle (θ_z) is the sun‟s angular distance from the zenith. Thus α_a and θ_z are complimentary angles. i.e., $\alpha_a + \theta_z = 90°$.

Local Solar Time (LST) or Local Apparent Time (LAT) and standard time:

- The rotation of the earth about its axis causes the day and night cycle and is also responsible for the apparent diurnal motion of the sun.
- Solar time is based on the apparent angular motion of the sun across the sky.
- Solar noon is the time when the sun crosses the local meridian.
- Solar day is defined as the time interval between two successive occasions when the sun crosses the local meridian. The solar day varies in length throughout the year.
- Because of the earth"s forward movement in its orbit, during this time interval the time required for one full rotation of the earth is less than a solar day by about 4 minutes.
- Hence the standard time (which is a uniform time and is observed from a clock) and solar time differ.
- The time used for calculating the hour angle ω is the local solar time or local apparent time. This can be obtained from the standard time observed on a clock by applying two corrections:

  1. The first correction arises because of the difference between the longitude of the location and the meridian on which the standard time is based. The correction has a magnitude of 4 minutes for every degree difference in longitude.

  2. The second correction called the equation of time correction is due to the fact that the earth"s orbit and rate of rotation are subject to small variations. This correction is based on experimental observations and is plotted in the graph.

- Solar time is related to standard time by the following relation,

$$\text{LAT} = \text{Standard time} \pm 4\,(\text{standard time longitude} - \text{longitude of location}) + \text{Equation of time correction.}$$

The – ve sign in the first correction is applicable for the eastern hemisphere, while the positive sign is applicable for the western hemisphere.

In India, standard time is based on 82.5˚ E.

The Equation of time correction E (in minutes) can also be calculated from the following empirical relation:

$$E = 229.18\,(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B)$$

where, B = (n -1) 360 / 365 and *n* is the day of the year.

Solar hour angle (ω):- It is an angular measure of time and is equivalent to 15° per hour. It is used extensively to express solar time as it is directly related to the sun‟s position in the sky. It varies from - 180° to + 180°. Solar hour angle is measured from noon based on LAT. ω is positive before solar noon (in the morning) and negative after solar noon (in the afternoon). For e.g. For 8 a.m. solar time, ω = +60° & for 5 p.m. solar time, ω = -75°.

Monthly Average Daily Diffuse Radiation:

Either of the two equations or both can be used for India to calculate the Monthly Average Daily Diffuse Radiation.

$$\frac{\overline{H}_d}{\overline{H}_g} = 1.411 - 1.696 \left[\frac{\overline{H}_g}{\overline{H}_o} \right]$$ by Modi and Sukhatme

$$\frac{\overline{H}_d}{\overline{H}_g} = 0.8677 - 0.7365\left[\frac{\overline{S}}{\overline{S}_{\max}}\right] \quad \text{by Garg and Garg}$$

$$\frac{\overline{Hg}}{\overline{Ho}} = \overline{K}_T = \text{Monthly Average Clearness Index}$$

Monthly Average Hourly Global Radiation:

$$\frac{\overline{I}_g}{\overline{H}_g} = \frac{\overline{I}_o}{\overline{H}_o}\left(a + b\cos\omega\right)/f_c \text{.............................. by Gueymard}$$

Where: $a = 0.409 + 0.5016 \sin(\omega_s - 60^\circ)$

$b = 0.6609 - 0.4767 \sin(\omega_s - 60^\circ)$

Normalizing factor, $$f_c = a + 0.5b\left[\frac{\frac{\pi\omega_s}{180} - \sin\omega_s\cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s}\right]$$

$\overline{I}_g$ = Monthly Average of the hourly global radiation on a horizontal surface (kJ / m^2-h)

$\overline{I}_o$ = Monthly Average of the ET radiation on a horizontal surface (kJ / m^2-h)

Note: Wherever needed, an hourly value (kJ / m^2-h) can be calculated from an instantaneous value by taking the instantaneous value (kW / m^2) at the mid-point of the hour and multiplying by 3600.

Monthly Average Hourly Diffuse Radiation:

$$\frac{\overline{I}_d}{\overline{H}_d} = \frac{\overline{I}_o}{\overline{H}_o} \text{ .... by Liu and Jordan}$$

$$\frac{\overline{I}_d}{\overline{H}_d} = (a' + b'\cos\omega)\frac{\overline{I}_0}{\overline{H}_0} \text{ ....by Satyamurthy and Lahiri}$$

Where: $a' = 0.4922 + \left\{0.27/(\overline{H}_d/\overline{H}_g)\right\}$ for $0.1 \le \left(\frac{\overline{H}_d}{\overline{H}_g}\right) \le 0.7$

$$\text{or} \quad a' = 0.76 + \left\{0.113/(H_d / H_g)\right\} \text{ for } 0.7 < \left(\frac{H_d}{H_g}\right) \le 0.9$$

$$b' = 2(1 - a')(\sin \omega_s - \omega_s \cos\omega_s) / (\omega_s - 0.5\sin 2\omega_s)$$

Solar Radiation on Tilted Surfaces:

Most solar equipment like flat-plate collector, for absorbing solar radiation, is tilted at an angle to the horizontal. It therefore becomes necessary to calculate the flux which falls on a tilted surface. This flux is the sum of the beam and diffuse radiation falling directly on the surface and the radiation reflected onto the surface from the surroundings.

Beam Radiation

Beam radiation flux falling on a tilted surface (cos θ)

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

Beam radiation flux falling on a horizontal surface ($\cos\theta_z$)

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

Hence tilt factor for beam radiation, r_b is given as

$$r_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta\sin(\phi-\beta)+\cos\delta\cos\omega\cos(\phi-\beta)}{\sin\phi\sin\delta+\cos\phi\cos\delta\cos\omega}$$ Valid only for a tilted surface with $\gamma = 0°$

Diffuse Radiation

$r_d = (1+\cos\beta)/2$ valid for any tilted surface with a slope β and

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

Reflected Radiation

$r_r = \rho(1-\cos\beta)/2$ valid for any tilted surface with a slope β and

$(1-\cos\beta)/2$ is the radiation shape factor for a tilted surface w.r.to the surrounding ground and ρ (is the diffuse reflectivity) = 0.2, for concrete or grass surface.

Flux on Tilted Surface:

The flux I_T falling on a tilted surface at any instant is given by

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

To calculate hourly radiation falling on a tilted surface for the value of ω taken at the mid-point of the hour:

$$\frac{I_T}{I_g} = \left(1 - \frac{I_d}{I_g}\right) r_b + \frac{I_d}{I_g} r_d + r_r$$

To calculate monthly average hourly value $\left(\overline{I_T}\right)$ if the calculations are done for the representative day of the month:

$$\frac{\overline{I_T}}{\overline{I_g}} = \left(1 - \frac{\overline{I_d}}{\overline{I_g}}\right) \overline{r_b} + \frac{\overline{I_d}}{\overline{I_g}} \overline{r_d} + \overline{r_r}$$

Where $\overline{r_b} = r_b$ on the representative day

$\overline{r_d} = r_d$ and $\overline{r_r} = r_r$

To calculate the daily radiation falling on a tilted surface:

$$\frac{H_T}{H_g} = \left(1 - \frac{H_d}{H_g}\right) R_b + \frac{H_d}{H_g} R_d + R_r$$

For a south facing surface ($\gamma = 0^{o}$),

$$R_b = \frac{\omega_{st} \sin\delta \sin(\phi - \beta) + \cos\delta \sin\omega_{st} \cos(\phi - \beta)}{\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s}$$

$R_d = r_d$ and $R_r = r_r$

ω_{st} and ω_s are the sunrise or sunset hour angles (in radians) for the tilted surface and a horizontal surface respectively.

To calculate monthly average daily radiation falling on a tilted surface if the values are calculated for the representative day of the month:

$$\frac{\overline{H_T}}{\overline{H_g}} = \left(1 - \frac{\overline{H_d}}{\overline{H_g}}\right) \overline{R_b} + \frac{\overline{H_d}}{\overline{H_g}} \overline{R_d} + \overline{R_r}$$

Where $\overline{R_b} = R_b$ on the representative day

$\overline{R_d} = R_d$ and $\overline{R_r} = R_r$

Terrestrial Radiation: - Long-wave electromagnetic radiation origination from earth & its atmosphere. It is the radiation emitted by naturally radioactive materials on earth including uranium, thorium and radon.

Extraterrestrial Radiation: - Electromagnetic radiation which originates outside the earth or its atmosphere, as in the sun or stars.

Solar Radiation at the Earth's Surface:-

Solar radiation is received at the earth"s surface in an attenuated form (reduced in strength) because it is subjected to the mechanisms of absorption and scattering as it passes through the earth"s atmosphere.

Mechanism of absorption:- It occurs primarily because of the presence of ozone and water vapor in the atmosphere, and to a lesser extent due to other gases like CO_2, NO_2, CO, O_2, CH_4 and particulate matter(- are tiny subdivisions of solid matter suspended in a gas). Absorption results in an increase in the internal energy of the atmosphere.

Mechanism of scattering: - It occurs due to all gaseous molecules as well as particulate matter in the atmosphere. This scattered radiation is redistributed in all directions, some going back into space and some reaching the earth"s atmosphere.

Solar radiation received at the earth"s surface are of two types namely beam (or direct) and diffuse radiation.

Beam or Direct Radiation: - The radiation received at the earth"s surface without change of direction, i.e., in line with the sun is called beam or direct radiation. Instrument used: Pyrheliometer.

Diffuse Radiation: - The radiation received at the earth"s surface after its direction has been changed by scattering and reflection is called diffuse radiation.

Instrument used: Pyranometer using shading ring arrangement.

Total Radiation: - The sum of the beam *and* diffuse radiation *is called as* total *or* global radiation.

Instrument used:- Pyranometer.

Thermopile: - A thermopile is an electronic device that converts thermal energy into electrical energy. It is composed of several thermocouples connected usually in series or, less commonly, in parallel. Thermopiles do not respond to absolute temperature, but generate an output voltage proportional to a local temperature difference or temperature gradient. The output of a thermopile is usually in the range of tens or hundreds of millivolts.

Working Principle of Pyrheliometer: -

A **pyrheliometer** is an instrument for direct measurement of solar irradiance. Sunlight enters the instrument through a window and is directed onto a thermopile which converts heat to an electrical signal that can be recorded. The signal voltage is converted via a formula to measure watts per square meter. It is used with a solar tracking system to keep the instrument aimed at the sun. ("Irradiance" is used when the electromagnetic radiation is incident on the surface).

A **pyrheliometer** is an instrument which measures beam radiation falling on a surface normal to the sun‟s rays. In contrast to a pyranometer, the black absorber plate (with the hot junctions of the thermopile attached to it) is located at the base of the collimating tube. The tube is aligned with the direction of the sun‟s rays with the help of a two-axis tracking mechanism and an alignment indicator. Thus the black plate receives only beam radiation and a small amount of diffuse radiation falling with the „acceptance angle‟ of the instrument.

Pyrheliometer on a solar tracker which keeps the instrument pointed at the sun.

Working principle of Pyranometer to measure global or total radiation:

It consists of a „black" surface which heats up when exposed to solar radiation. Its temperature increases until the rate of heat gain by solar radiation equals the rate of heat loss by convection, conduction and reradiation. The hot junctions of a thermopile are attached to a black surface, while the cold junctions are located under a guard plate so that they do not receive the radiation directly. As a result, an emf is generated. This emf which is usually in the range of 0 to 10 mV can be read, recorded or integrated over a period of time and is a measure of solar radiation.

The pyranometer shown is used commonly in India. It has its hot junction arranged in the form of a horizontal circular disc of diameter 25 mm and coated with a special lacquer having a high absorptivity in the solar wavelength region. The disc is placed on a large diameter guard plate which may be horizontal or sloping. Two concentric hemispheres 30 and 50 mm in diameter respectively, made of optical glass having excellent transmission characteristics are used to protect the disc surface from the weather. An accuracy of ± 2 % can be obtained with the instrument.

Pyranometer to measure diffuse radiation using shading ring: -

This is done by mounting the pyranometer at the centre of a semicircular shading ring. The shading ring is fixed in such a way that its plane is parallel to the plane of the path of the sun"s daily movement across the sky and it shades the thermopile element and the two glass domes of the pyranometer at all times from direct sunshine. Consequently, the pyranometer only the diffuse radiation received from the sky.

Shading ring:-

1. ABCD is a horizontal rectangular frame 35 cm x 80 cm with its long sides in an E-W direction.

2. Two angle-iron arms EF and GH, 70 cm long, are with slots along their length. The angle-iron arms are pivoted to the sides AB and CD respectively.

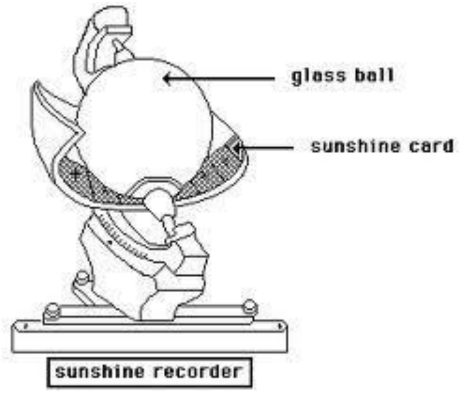
3. The arms are pivoted about a horizontal axis which passes through the center of the rectangular frame and can be adjusted at an angle to the horizontal equal to the latitude of the station.

4. The movement of the ring up and down the arms allows for changes in the sun"s declination..

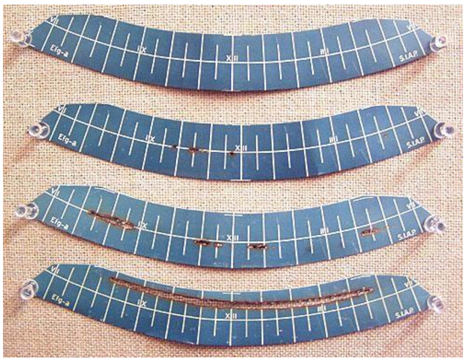
5. EF and GH carry sliders, SS, on which the semicircular shading ring R is mounted. The shading ring R is made of Al, 50 mm width, and is bent to a radius of 450 mm. The

inner surface of the ring is painted dull black, while the rest of the shading ring is painted dull matt white. A thick metal plate P is fixed to the bottom of the frame ABCD. This plate P has a circular slot so that the frame when fixed on a masonry platform with nuts and bolts can be adjusted in its proper position by rotation about a vertical axis. Another thick metal plate P‟‟ is fitted to the top of the frame, on which the pyranometer is fitted.

Sunshine recorder: -



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



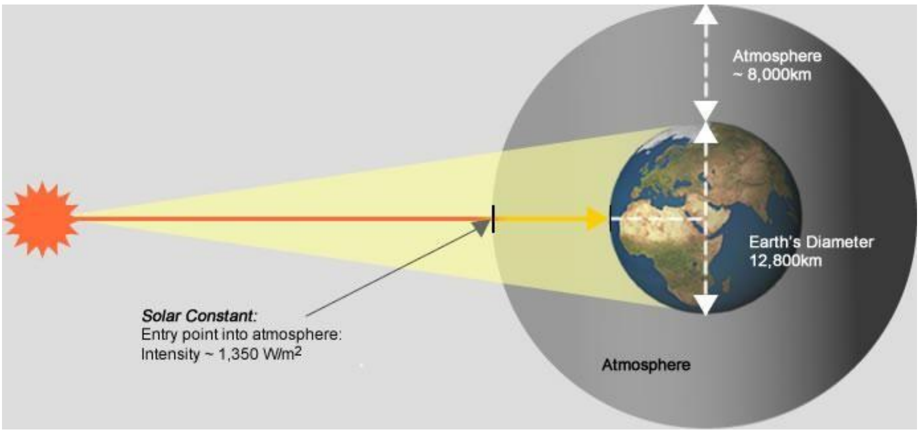
Air Mass (AM): -

AM is used as a measure of the distance traveled by beam radiation through the atmosphere before it reaches a location on the earth‟s surface.

It is defined as the ratio of the mass of the atmosphere through which the beam radiation passes to the mass it would pass through if the sun is directly overhead (i.e. at its zenith). The zenith angle θ_z is the angle made by the sun‟s rays with the normal to a horizontal surface.

Since AM = sec θ_z , AM 0 $\Rightarrow$ Extraterrestrial radiation, AM 1 $\Rightarrow$ the sun at its zenith &

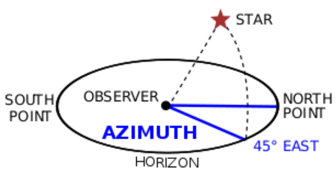
AM 2 $\Rightarrow$ zenith angle of 60°.



The intensity of solar radiation directly outside the earth‟s atmosphere on a horizontal surface is almost constant and is equal to 1367 W/m^2 and this is called solar constant. This entry point into the atmosphere is called Air Mass -0 or AM-0, where 0 points out that there is no air mass.

Azimuth: - An azimuth is an angular measurement in a spherical coordinate system. The vector from an observer (origin) to a point of interest is projected perpendicularly onto a reference plane; the angle between the projected vector and a reference vector on the reference plane is called the azimuth. Azimuth is usually measured in degrees.

An example of an azimuth is the measurement of the position of a star in the sky. The star is the point of interest, the reference plane is the horizon or the surface of the sea, and the reference vector points to the north. The azimuth is the angle between the north point and the perpendicular projection of the star down onto the horizon.



Measuring Instruments

Solar Radiation Data:-

1 Wh = 3600 J

I_g = Hourly global radiation in kJ/m^2-h.

I_d = Hourly diffuse radiation in kJ/m^2-h.

H_d = Daily diffuse radiation in kJ/m^2-day.

Solar Radiation Geometry:-

Aim: - To find the beam energy falling on a surface having any orientation (horizontal / inclined). For this, convert the value of beam flux coming from the sun (I_{bn}) to an equivalent value corresponding to the normal direction to the surface ($I_{bn}\cos\theta$). Relationships for making this conversion is presented hereunder.

If θ is the angle between an incident beam of flux I_{bn} and the normal to a plane surface, then the equivalent flux falling normal to the surface is given by $I_{bn}\cos\theta$.

The angle θ can be related by a general equation to $\phi, \beta, \gamma, \delta, \omega$ (latitude, slope, surface azimuth angle, declination and hour angle).

1. δ (in degrees) = $23.45 \sin\left[\frac{360}{365}(284+n)\right]$ $(Eqn.1)$

where - n is the day of the year.

It can be shown that

2. $\cos\theta = \sin\varphi(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) + \cos\varphi(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta$ -----------------$(Eqn.2)$

Special cases of $(Eqn.2)$ are normally required. Some of these are:-

Case 1:- For a vertical surface, slope $\beta = 90^\circ$

$\cos\theta = \sin\varphi\cos\delta\cos\gamma\cos\omega - \cos\varphi\sin\delta\cos\gamma + \cos\delta\sin\gamma\sin\omega$---------- $(Eqn.3)$

Case 2:- For a horizontal surface, slope $\beta = 0^\circ$

$\cos\theta = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega$ -----------------$(Eqn.4)$

The angle θ in this case is the *zenith angle* θ_z .

$\therefore \cos\theta_z = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega$

The compliment of the zenith angle is also used quite often in calculations. It is called *solar altitude angle* (α_a).

$$\alpha_a = \frac{\pi}{2} - \theta_z$$

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

$$= \sin\delta\sin(\varphi - \beta) + \cos\delta\cos\omega\cos(\varphi - \beta) \text{-----------------} (Eqn.5)$$

Case 4:- For a vertical surface facing due south, slope $\beta = 90^\circ$;

surface azimuth angle $\gamma = 0^\circ$

$$\cos\theta = \sin\varphi\cos\delta\cos\omega - \cos\varphi\sin\delta \text{-----------------} (Eqn.6)$$

Case 5:- For an inclined surface facing due north, surface azimuth angle $\gamma = 180^\circ$

$$\cos\theta = \sin\delta\sin(\varphi + \beta) + \cos\delta\cos\omega\cos(\varphi + \beta) \text{-----------------} (Eqn.7)$$

The angle of incidence θ can also be expressed in terms of *zenith angle* θ_z , slope β , surface azimuth angle γ and solar azimuth angle γ_s. Braun and Mitchell have shown that

$$\cos\theta = \cos\theta_z\cos\beta + \sin\theta_z\sin\beta\cos(\gamma_s - \gamma) \text{-----------------} (Eqn.8)$$

Solar azimuth angle γ_s:- It is the angle made in the horizontal plane between the horizontal line due south and the projection of the line of sight of the sun on the horizontal plane. Thus it gives the direction of the shadow cast in the horizontal plane by a vertical rod.

Solar azimuth angle γ_s = + ve if the projection of the line of sight is east of south

= - ve if the projection of the line of sight is west of south

In order to use Eqn. 8, it is necessary to first calculate θ_z and γ_s. θ_z is obtained from Eqn. 4, while γ_s is obtained from the expression 8.

$$\cos\gamma_z = (\cos\theta_z\sin\varphi - \sin\delta) / \sin\theta_z\cos\varphi$$

Also, $\sin\alpha_a = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$

$$\text{Incident angle} = \frac{\pi}{2} - \alpha_a$$

where, δ – declination, φ – latitude, θ – angle of incidence,

γ – surface azimuth angle, β – slope, ω – hour angle, θ_z – zenith angle

γ_z – solar azimuth angle, α_a – solar altitude angle.

Sunrise, Sunset and Day length:

$$\cos\omega_s = -\tan\varphi\tan\delta$$

ω_s = hour angle corresponding to sunrise or sunset (in degrees)

For inclined surface facing due south, $\gamma = 0^o$

$$\omega_{st} = \cos^{-1} [-\tan (\varphi - \beta) \tan \delta]$$

$$|\omega_{st}| = \min [|\cos^{-1} (-\tan \varphi \tan \delta)|, | \cos^{-1} \{ - \tan (\varphi - \beta) \tan \delta\} |]$$

For inclined surface facing due north,

$$|\omega_{st}| = \min [|\cos^{-1} (-\tan \varphi \tan \delta)|, | \cos^{-1} \{ - \tan (\varphi + \beta) \tan \delta\} |]$$

Sunrise, Sunset and Day Length

For Horizontal Surface: The hour angle corresponding to sunrise or sunset (ω_s) on a horizontal surface can be found from eqn. 4 if we substitute the value of 90° for the zenith angle. Thus we obtain

$$\cos \omega_s = -\tan \varphi \tan \delta$$

ω_s = hour angle corresponding to

sunrise or sunset (in degrees) = $\cos^{-1} (-\tan \varphi \tan \delta)$ -------- Eqn. 10

The above equation yields a positive and negative value for ω_s , the **positive** value corresponding to **sunrise** and **negative** to **sunset.** Since 15° of the hour angle is equivalent to 1 hour, the corresponding *day length* (in hours)

$$\text{Day length, } S_{max} = \frac{2}{15}\omega_s = \frac{2}{15} \cos^{-1} (-\tan \varphi \tan \delta) \text{-------- Eqn. 11}$$

where, ω_s is in degrees.

For inclined surface facing due South (γ = 0):

*The above **eqn.11** can be used if the day lies **between September 22 and March 21*** and the location is in the northern hemisphere.

Between ***March 21 and September 22***, the hour angle at sunrise or sunset would be ***smaller*** in ***magnitude*** than the value given by eqn. 10 and is given as

$$\omega_{st} = \cos^{-1} [-\tan (\varphi - \beta) \tan \delta] \text{ ---------- Eqn. 12}$$

$$|\omega_{st}| = \min [|\cos^{-1} (-\tan \varphi \tan \delta)|, | \cos^{-1} \{- \tan (\varphi - \beta) \tan \delta\} |] \text{ ---- Eqn. 13}$$

For inclined surface facing due North

$$|\omega_{st}| = \min [|\cos^{-1} (-\tan \varphi \tan \delta)|, | \cos^{-1} \{- \tan (\varphi + \beta) \tan \delta\} |] \text{ ---- Eqn. 14}$$

Empirical Equations for Predicting the Availability of Solar Radiation:

The best approach for estimating average solar radiation for a place: - Measure solar radiation over a period of time at that place.

If this is not possible, data from nearby locations having a similar geography and climate can be used.

In case, if both these approaches are not possible, one can use empirical relationships linking the values of radiation, global or diffuse, with meteorological parameters like sunshine hours, cloud cover and precipitation.

Sometimes, even if measurements of radiation are available, the data may not be in the desired form. For e.g., the daily global radiation may be measured whereas hourly data may be needed for some specific purposes. Again we may require the beam and diffuse components explicitly out of the daily global radiation.

Attempts have been made by many researchers to develop empirical relationships for such situations and these are

1. Monthly average daily global radiation

2. Monthly average daily diffuse radiation

3. Monthly average hourly global radiation

4. Monthly average hourly diffuse radiation

Monthly average daily global radiation:

Angstrom suggested that

$$\frac{\bar{H}g}{\bar{H}c} = a + b\left[\frac{\bar{S}}{\bar{S}_{msx}}\right] \quad \text{………….. Eqn. A}$$

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

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

$\bar{S}_{msx}$ = monthly average of the maximum possible sunshine hours per day at the location, i.e., the day length on a horizontal surface (h)

a,b = constants

Because of difficulties in deciding what constitutes a clear day, Page suggested that $\bar{Hc}$ in eqn. A be replaced by $\bar{Ho}$, the monthly average of the daily extraterrestrial radiation which would fall on a horizontal surface at the location under consideration.

$$\frac{\bar{Hg}}{\bar{Ho}} = a + b\left[\frac{\bar{S}}{\bar{S}_{msx}}\right] \quad \text{Eqn. B}$$

In the above computation, the quantity $\bar{Ho}$ is the mean value (H_0) for each day of the month. H_0 is obtained by integrating over the day length as follows:

$$H_o = I_{sc}\left[1 + 0.033\cos\frac{360n}{365}\right]\int\left(\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega\right)dt \quad \ldots\ldots\text{Eqn. C}$$

$I_{sc} = 1367\ W/m^2$

Where, $t = \dfrac{180\omega}{15\pi}$ t is in hours and ω is in radians

Hence, $dt = \dfrac{180}{15}d\omega$

$$Ho = \frac{12}{\pi}Isc\left(1 + 0.033\cos\frac{360n}{365}\right)\int_{-\omega_s}^{+\omega_s}\left(\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega\right)d\omega$$

$$Ho = \frac{24}{\pi}Isc\left(1 + 0.033\cos\frac{360n}{365}\right)\left(\omega_s\sin\phi\sin\delta + \cos\phi\cos\delta\sin\omega_s\right) \quad \ldots\ldots\text{Eqn. D}$$

The dates on which the value of $Ho = \bar{Ho}$ are as follows:

January 17	February 16	March 16
April 15	May 15	June 11
July 17	August 16	September 15

Correlation: For predicting the daily global radiation at locations all over the world including locations in India.

$$\frac{\bar{H}g}{\bar{H}o} = a_1 + b_1\left[\frac{\bar{S}}{S_{msx}}\right]$$

where

$$a_1 = -0.309 + 0.539\cos\phi - 0.0693\,E_L + 0.290\left[\frac{\bar{S}}{S_{max}}\right]$$

$$b_1 = 1.527 - 1.027\cos\phi + 0.0926\,E_L - 0.359\left[\frac{\bar{S}}{S_{max}}\right]$$

E_L = Elevation of location above MSL (in kilometers).

Monthly Average Daily Diffuse Radiation:

The equation shown below shows that the daily diffuse-to-global radiation ratio can be correlated against the daily global-to-extraterrestrial radiation ratio.

Either of the two equations or both can be used for India to calculate the Monthly Average Daily Diffuse Radiation.

$$\frac{\bar{H}_d}{\bar{H}_g} = 1.411 - 1.696\left[\frac{\bar{H}_g}{\bar{H}_o}\right] \quad \text{by Modi and Sukhatme}$$

$$\frac{\bar{H}_d}{\bar{H}_g} = 0.8677 - 0.7365\left[\frac{\bar{S}}{S_{max}}\right] \quad \text{by Garg and Garg}$$

$$\frac{\bar{H}g}{\bar{H}o} = \overline{K_T} = \text{Monthly Average Clearness Index}$$

Monthly Average Hourly Global Radiation:

$$\frac{\bar{I}_g}{\bar{H}_g} = \frac{\bar{I}_o}{\bar{H}_o}\left(a + b\cos\omega\right)/f_c \text{.................................by Gueymard}$$

Where: a = 0.409 + 0.5016 sin (ω_s - 60˚)

b = 0.6609 – 0.4767 sin (ω_s - 60˚)

Normalizing factor, $f_c = a + 0.5b\left[\dfrac{\dfrac{\pi\omega_s}{180} - \sin\omega_s\cos\omega_s}{\sin\omega_s - \dfrac{\pi\omega_s}{180}\cos\omega_s}\right]$

$\overline{I_g}$ = Monthly Average of the hourly global radiation on a horizontal surface (kJ / m^2-h)

$\overline{I_o}$ = Monthly Average of the ET radiation on a horizontal surface (kJ / m^2-h)

Note: Wherever needed, an hourly value (kJ / m^2-h) can be calculated from an instantaneous value by taking the instantaneous value (kW / m^2) at the mid-point of the hour and multiplying by 3600.

Monthly Average Hourly Diffuse Radiation:

$$\frac{\overline{I_d}}{\overline{H_d}} = \frac{\overline{I_o}}{\overline{H_o}} \quad \text{.......... by Liu and Jordan}$$

$$\frac{\overline{I_d}}{\overline{H_d}} = (a' + b'\cos\omega)\frac{\overline{I_0}}{\overline{H_0}} \quad \text{..........by Satyamurthy and Lahiri}$$

Where: $a' = 0.4922 + \left\{0.27/(\overline{H_d}/\overline{H_g})\right\}$ for $0.1 \le \left(\dfrac{\overline{H_d}}{\overline{H_g}}\right) \le 0.7$

or $a' = 0.76 + \left\{0.113/(\overline{H_d}/\overline{H_g})\right\}$ for $0.7 < \left(\dfrac{\overline{H_d}}{\overline{H_g}}\right) \le 0.9$

$$b' = 2(1 - a')(\sin\omega_s - \omega_s\cos\omega_s)/(\omega_s - 0.5\sin 2\omega_s)$$

Also,

$$I_O = I_{SC}\left(1 + 0.033\cos\frac{360n}{365}\right)(\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega) = \text{Hourly ET radiation.}$$

Solar Radiation on Tilted Surfaces:

Most solar equipment like flat-plate collector (which is used for absorbing solar radiation) is tilted at an angle to the horizontal. It therefore becomes necessary to calculate the flux which falls on a tilted surface. This flux is the sum of the beam and diffuse radiation falling directly on the surface and the radiation reflected onto the surface from the surroundings.

Beam Radiation

Beam radiation flux falling on a tilted surface (cos θ)

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

Beam radiation flux falling on a horizontal surface ($\cos\theta_z$)

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

Hence tilt factor for beam radiation, r_b is given as

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

Valid only for a tilted surface with $\gamma = 0^{\circ}$

Diffuse Radiation

$r_d = (1+\cos\beta)/2$ valid for any tilted surface with a slope β and

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

Reflected Radiation

$r_r = \rho(1-\cos\beta)/2$ valid for any tilted surface with a slope β and

$(1-\cos\beta)/2$ is the radiation shape factor for a tilted surface w.r.to the surrounding ground and ρ (is the diffuse reflectivity) = 0.2, for concrete or grass surface.

Flux on Tilted Surface:

The flux I_T falling on a tilted surface at any instant is given by

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

To calculate hourly radiation falling on a tilted surface for the value of ω taken at the mid-point of the hour:

$$\frac{I_T}{I_g} = \left(1 - \frac{I_d}{I_g}\right) r_b + \frac{I_d}{I_g} r_d + r_r$$

To calculate monthly average hourly value $\left(\overline{I_T}\right)$ if the calculations are done for the representative day of the month:

$$\frac{\overline{I_T}}{\overline{I_g}} = \left(1 - \frac{\overline{I_d}}{\overline{I_g}}\right) \overline{r_b} + \frac{\overline{I_d}}{\overline{I_g}} \overline{r_d} + \overline{r_r}$$

Where $\bar{r}_b = r_b$ on the representative day

$\bar{r}_d = r_d$ and $\bar{r}_r = r_r$

To calculate the daily radiation falling on a tilted surface:

$$\frac{H_T}{H_g} = \left(1 - \frac{H_d}{H_g}\right) R_b + \frac{H_d}{H_g} R_d + R_r$$

For a south facing surface ($\gamma = 0^{\circ}$),

$$R_b = \frac{\omega_{st} \sin\delta \sin(\phi - \beta) + \cos\delta \sin\omega_{st} \cos(\phi - \beta)}{\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s}$$

$R_d = r_d$ and $R_r = r_r$

ω_{st} and ω_s are the sunrise or sunset hour angles (in radians) for the tilted surface and a horizontal surface respectively.

To calculate monthly average daily radiation falling on a tilted surface if the values are calculated for the representative day of the month:

$$\frac{\bar{H}_T}{\bar{H}_g} = \left(1 - \frac{\bar{H}_d}{\bar{H}_g}\right) \bar{R}_b + \frac{\bar{H}_d}{\bar{H}_g} \bar{R}_d + \bar{R}_r$$

where $\bar{R}_b = R_b$ on the representative day; $\bar{R}_d = R_d$ and $\bar{R}_r = R_r$

SOLAR COLLECTORS

Introduction

A solar collector is a device for collecting solar radiation and transfers the energy to a fluid passing in contact with it.

Utilization of solar energy requires solar collectors. They are broadly classified into:

1. Non concentrating or flat plate type solar collector

- Collector area is the same as the absorber area.
- Simple in design.
- Has no moving part.
- Requires less maintenance.
- Used for both beam and diffuse solar radiation.
- Temperature range 40˚ C - 100˚ C.

2. Concentrating or focusing type solar collector

- Collector area is greater than the absorber area.
- Here higher temperature can be obtained.
- For generation of medium pressure steam.
- Better efficiency than the flat plate type.

Principle of operation of a collector

Expose a dark surface to solar radiation so that the radiation is absorbed. The part of the absorbed radiation is then transferred to a fluid like air or water.

Flat plate collector

It consists of an absorber plate on which the solar radiation falls after coming through a transparent cover, made of glass. The absorbed radiation is partly transferred to a liquid flowing through tubes which are fixed to the absorber plate. This energy transfer is the useful heat gain. The remaining part of the radiation absorbed in the absorbed plate is lost by convection and re-radiation to the surroundings from the top surface, and by conduction through the back and the edges. The transparent cover helps in reducing the losses by convection and re-radiation, while thermal insulation on the back and the edges helps in reducing the conduction heat loss. A liquid flat-plate collector is usually held tilted in a fixed position on a supporting structure, facing south if located in the northern hemisphere.

In order to reduce the heat lost by re-radiation from the top of the absorber plate of a flat-plate collector, it is usual to put a selective coating on the plate. The selective coating exhibits the characteristic of a high value of absorptivity for incoming solar radiation and a low value of emissivity for out-going re-radiation. As a result, the collection efficiency of the flat-plate collector is improved.

Based on the type of heat transfer fluid used, FPC may be classified as Liquid Heating Collector and Air Heating Collector(solar air heater).

Applications of solar air heaters

- For heating buildings.
- For drying agricultural produce.
- Heating green houses.
- Using air heaters as the heat source for a heat engine such as a Brayton cycle.

Flat plate collector

The basis parts of a liquid flat plate collector are

(a) the absorber plate (made of thin metal(Cu) sheet of thickness from 0.2 to 0.7 mm).

(b) the tubes fixed to the absorber plate through which the liquid to be heated flows (made of metal(Cu) with ϕ = 1 to 1.5 cm / liquid used – water. Sometimes mixtures of water and ethylene glycol are used if ambient temperatures below 0˚ C are likely to be encountered / pitch of the tubes = 5 to 12 cm).

(c) the transparent cover (Property of the cover – highly transparent to incoming solar radiation and at the same time, opaque to the long wavelength re-radiation emitted by the absorber plate / made of toughened glass with low ferric oxide / 4 or 5 mm thickness).

(d) the collector box (made of Al with an epoxy coating on the outside for protection / the bottom and sides are usually insulated by mineral wool, rock wool or glass wool with a covering of Al foil and has a thickness ranging from 2.5 to 8 cm).

Advantages:- Utilizes both beam and diffuse components of solar radiation, simple stationary design, less maintenance.

Disadvantages:- Because of the absence of optical concentration, the area from which heat is lost is large. As a result, the collection efficiency is low.

Principle of operation:- It consists of an absorber plate on which the solar radiation falls after coming through a transparent cover, made of glass. The absorbed radiation is partly transferred to a liquid flowing through tubes which are fixed to the absorber plate. This energy transfer is the useful heat gain. The remaining part of the radiation absorbed in the absorbed plate is lost by convection and re-radiation to the surroundings from the top surface, and by conduction through the back and the edges. The transparent cover helps in reducing the losses by convection and re-radiation, while thermal insulation on the back and the edges helps in reducing the conduction heat loss. A liquid flat-plate collector is usually held tilted in a fixed position on a supporting structure, facing south if located in the northern hemisphere. In order to reduce the heat lost by re-radiation from the top of the absorber plate of a flat-plate collector, it is usual to put a selective coating on the plate. The selective coating exhibits the characteristic of a high value of absorptivity for incoming solar radiation and a low value of emissivity for out-going re-radiation. As a result, the collection efficiency of the flat-plate collector is improved. Based on the type of heat transfer fluid used, FPC may be classified as Liquid Heating Collector and Air Heating Collector (solar air heater).

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Performance Analysis of Flat Plate Collector

The analysis is done for steady state condition in which the liquid is flowing through tubes bonded on the under-side of the absorber plate.

$q_u = A_p S - q_l$, where q_u = useful heat gain (i.e., rate of heat transfer to the working fluid)

S = incident solar flux absorbed in the absorber plate

$S = I_b r_b (\tau\alpha)_b + \{I_d r_d + (I_b + I_d) r_r\} (\tau\alpha)_d$

τ = transmissivity; α = absorptivity; A_p = area of the absorber plate

$(\tau\alpha)_b$ = Transmissivity-absorptivity product for beam radiation falling on the collector. The transmissivity-absorptivity product is defined as the ratio of the flux absorbed in the absorber plate to the flux incident on the cover system.

q_l = rate at which heat is lost by convection and re-radiation from the top and by conduction and convection from the bottom and sides.

Instantaneous Collection Efficiency, $\eta_i = \dfrac{q_u}{A_c I_T}$ **;** where $A_c =$ Collector Gross Area.

Stagnation efficiency:- If the liquid flow rate through the collector is stopped, then there is no useful heat gain and the efficiency is zero. In this case, the absorber plate attains a temperature such that $A_p S = q_l$. This temperature is the highest that the absorber that the plate can attain. Knowledge of the stagnation temperature is useful as an indicator for comparing different collector designs.

Effective transmittance absorptance product $((\tau\alpha) = \dfrac{\square\tau\alpha}{1-(1-\alpha)\rho_d}$

ρ_d = diffuser reflectivity of the cover system = 0.16 for one glass cover system.

= 0.24 for two glass cover system.

= 0.29 for three glass cover system.

Overall loss coefficient and heat transfer correlations

Heat lost from the collector, $q_l = U_l A_p (T_{pm} - T_a)$

U_l = overall loss coefficient $= U_t + U_b + U_s$; (= top loss coefficient + bottom loss coefficient + side loss coefficient)

A_p = Area of the absorber plate

T_{pm} = Average temp. of the absorber plate; T_a = Temp. of the surrounding air

$$q_l = q_t + q_b + q_s$$

q_t = rate at which heat is lost from the top = $U_t A_p (T_{pm} - T_a)$

q_b = rate at which heat is lost from the bottom = $U_b A_p (T_{pm} - T_a)$

q_s = rate at which heat is lost from the sides = $U_s A_p (T_{pm} - T_a)$

U_l is an important parameter since it is a measure of all the losses and typical values range

Top loss coefficient (U_t):

The top loss coefficient is evaluated by considering convection and re-radiation losses from the absorber plate in the upward direction. Assumption: one-dimensional, steady, temp. drop across the thickness of the covers is negligible.

In a steady state, the heat transferred by convection and radiation between (i) the absorber plate and the first cover (ii) the first cover and the second cover (iii) the second cover and the surrounding must be equal. Hence,

$$\frac{q_t}{A_p} = h_{p-c1}(T_{pm} - T_{c1}) + \frac{\sigma(T_{pm}^4 - T_{c1}^4)}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1\right)} = h_{c1-c2}(T_{c1} - T_{c2}) + \frac{\sigma(T_{c1}^4 - T_{c2}^4)}{\left(\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_c} - 1\right)} = h_w(T_{c2} - T_a) + \sigma\varepsilon_c(T_{c2}^4 - T_{sky}^4)$$

h_{p-c1} = convective heat transfer coefficient between the absorber plate & the first cover

h_{c1-c2} = convective heat transfer coefficient between the first and second covers.

h_w = convective heat transfer coefficient between the top cover and surrounding air

T_{c1}, T_{c2} = temperatures attained by two covers

$T_{sky} = T_a - 6$

ε_p = emissivity of the absorber plate for long wavelength radiation

ε_c = emissivity of the covers for long wavelength radiation.

The above equations constitute a set of three non-linear equations which have to be solved for the unknowns q_l, T_{c1} and T_{c2}. However, before this can be done it will be necessary to have some correlations for calculating the convective heat transfer coefficients h_{p-c1}, h_{c1-c2} and h_w, and the sky temperature T_{sky}.

Heat Transfer Coefficient between Inclined Parallel Surfaces:

The natural convection heat transfer coefficient for the enclosed space between the absorber plate and the first cover or between two covers is calculated by using one of the following correlations:

$Nu_L = 1$; $Ra_L \cos\beta < 1708$

$\left(1708 \right)$

$$Nu_L = 0.229\,(Ra_L \cos\beta)^{0.252}\ ;\ 5900 < Ra_L \cos\beta < 9.23 \times 10^4$$

$$Nu_L = 0.157\,(Ra_L \cos\beta)^{0.285}\ ;\ 9.23 \times 10^4 < Ra_L \cos\beta < 10^6$$

The characteristic dimension L is the spacing between the surfaces, while properties are evaluated at the arithmetic mean of the surface temperatures.

Heat Transfer Coefficient at the top cover:

The convective heat transfer coefficient (h_w) at the top cover is often referred to as the ***wind heat transfer coefficient***. It is calculated using the relation,

$$h_w = 8.55 + 2.56\,V_\infty\ ; \qquad h_w \text{ is in W/m}^2 - \text{K and } V_\infty \text{ is in m/s.}$$

Bottom loss coefficient (U_b):

The bottom loss coefficient is evaluated by considering conduction and convection losses from the absorber plate in the downward direction through the bottom of the collector.

Assumption: one-dimensional, steady. In most cases, the thickness of insulation provided is such that the thermal resistance associated with conduction dominates. Thus neglecting convective resistances, we have

$$U_b = \frac{k_i}{\delta_b} \quad \text{where} \quad k_i = \text{thermal conductivity of the insulation}$$

$\delta_b =$ thickness of insulation

Side loss coefficient (U_s):

Side loss coefficient is always much smaller than the top loss coefficient.

Assumption: one-dimensional, steady, conduction resistance dominates.

If the dimensions of the absorber plate is $L_1 x L_2$ and the height of the collector casing is L_3, then the area across which heat flows sideways is $2(L_1 + L_2)L_3$. The temperature drop across which the heat flow occurs varies from $(T_{pm} - T_a)$ at the absorber plate level to zero both at the top and bottom. Assuming, therefore, that the average temperature drop across the side insulation is $(T_{pm} - T_a)/2$ and that the thickness of the side insulation is δ_s, we have,

$$q_s = 2L_3(L_1 + L_2)k_i \frac{(T_{pm} - T_a)}{2\delta_s}$$

Useful heat gain for the flat plate collector (q_u):

$$q_u = F_R\, A_p\, [\, S - U_L\, (\, T_{fi} - T_a\,)]$$

F_R = Collector heat removal factor ; A_p = Area of the collector plate

S = Flux absorbed in the absorber plate = $I_b\, r_b\, (\tau\alpha)_b$; U_L = Top loss coefficient

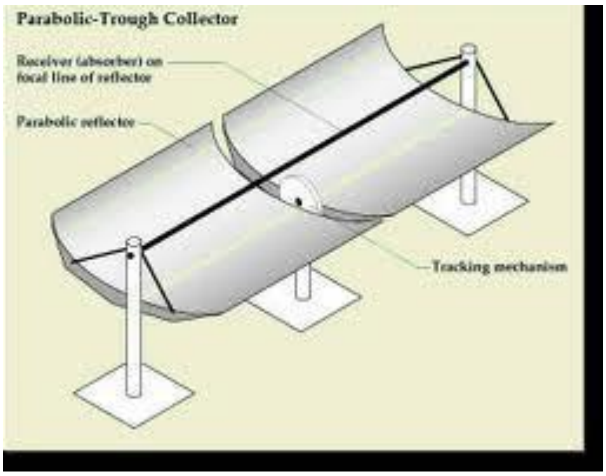
T_{fi} = Collector fluid temperature ; T_a = Ambient temperature

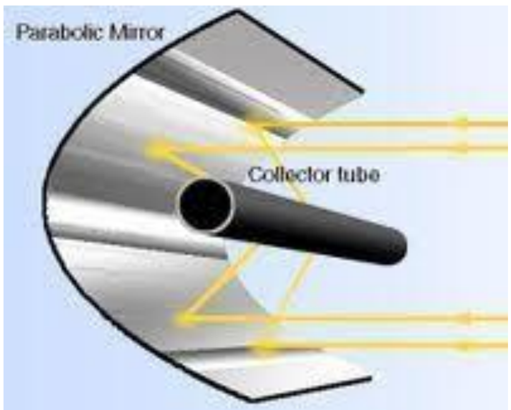
Collector efficiency (η_i):

$$\eta_i = \frac{q_u}{I_b r_b}$$

Focusing or Concentrating Collectors

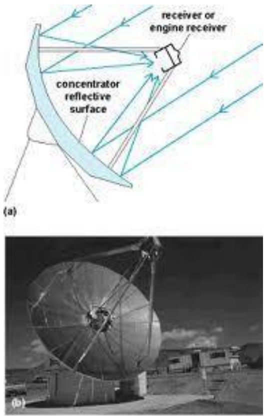
- Used for higher temperatures, from 100 - 400˚ C or above 400˚ C.
- It consists of a concentrator and receiver. The concentrator is a mirror reflector (optical system) having the shape of a cylindrical parabola. It focuses the sunlight on to its axis, where it is absorbed on the surface of the absorber tube and transferred to the fluid flowing through it.
- A concentric glass cover around the absorber tube helps in reducing the convective and radiative losses to the surroundings.
- In order that the sun‟s rays should always be focused on to the absorber tube, the concentrator has to be rotated. This movement is called ***tracking***.
- **One axis tracking:** In the case of cylindrical parabolic concentrators (CPC), rotation about a single axis is generally required. In CPC, fluid temperatures up to 400˚ C can be achieved.





- **Two axis tracking:** Temperatures more than 400˚ C is obtained using Paraboloid

Concentrating Collectors (PCC) which has a point focus. These PCC require 2-axis tracking so that the sun is in line with the focus and the vertex of the paraboloid.



Disadvantages:

- Because of the presence of an optical system, a concentrating collector has to track the sun so that the beam radiation is directed on to the absorber surface. The need for *tracking* introduces a certain amount of complexity in the design.
- Maintenance requirements are also increased. All these factors add to the cost.
- Much of the diffuse radiation is lost because it does not get focused.

Definitions:

Concentrator: Optical system which directs the solar radiation on to the absorber

Receiver: Consists of the absorber, its cover and the accessories.

Aperture (W): It is the plane opening of the concentrator through which the solar radiation passes.

Area concentration ratio(C) / Geometric concentration ratio / Concentration ratio: It is the ratio of the effective area of the aperture to the surface area of the absorber. C = 1 (is the limiting case for a flat-plate collector) to a few thousand for a paraboloid dish.

Intercept factor (γ): It is the fraction of radiation which is reflected or refracted from the concentrator and is incident on the absorber. γ is generally close to unity.

Acceptance angle ($2\theta_a$): It is the angle which beam radiation may deviate from the normal to the aperture plane and yet reach the absorber. Collectors with large acceptance angles require only occasional adjustments, while collectors with small acceptance angles have to be adjusted continuously.

Absorber area (A_{abs}): It is the total area that receives the concentrated solar radiation. It is the area from which the useful energy can be removed.

Optical efficiency (η_o): It is defined as the ratio of energy absorbed by the absorber to the energy incident on the concentrator‟s aperture.

Thermal efficiency (η_t): It is defined as the ratio of useful energy delivered to the energy incident on the aperture.

Types of concentrating collectors:

1. Flat-plate collector with plane reflectors

2. Compound parabolic collector

3. Cylindrical parabolic collector

4. Collector with fixed circular concentrator and moving receiver

5. Fresnel lens concentrating collector 6. Paraboloid dish collector.

Thermal and Performance Analysis of Concentrating Collectors: Under steady-state condition,

$q_u =$ $A_a S - q_l$ (assumption: diffuse radiation is negligible) …..Eqn. 1

where $q_l = U_l A_p \left(T_{pm} - T_a\right) \Rightarrow q_l = U_l \pi D_o L(T_{pm} - T_a)$ …..Eqn. 2

$q_u =$ $A_a \left[S - \frac{U_l}{C}(T_{pm} - T_a) \right]$ …..Eqn. 3

q_u = rate of useful heat gain ; q_l = rate of heat loss from the absorber.

A_a = effective aperture area of the concentrator = (W- D_o)L

(Also:- A_a = aperture area of the concentrator = (W- D_{co})L)

D_{c0} = outer diameter of the transparent cover

D_{ci} = inner diameter of the transparent cover

A_p = area of the absorber surface or receiver = $\pi D_o L$

S = solar beam radiation per unit effective aperture area absorbed in the absorber

U_l = overall loss coefficient

C = concentration ratio = $\frac{A_a}{A_p} = \frac{(W - D_o)}{\pi D_o}$

$D_o =$ outer diameter of absorber tube ; D_i = inner diameter of absorber tube

T_{pm} = average temperature of the absorber tube

T_a = temperature of the surrounding air ;

T_c = temperature attained by the cover

I_b = instantaneous beam radiation on a horizontal surface

r_b = tilt factor for instantaneous beam radiation

I_d = instantaneous diffuse radiation on a horizontal surface

r_d = tilt factor for instantaneous diffuse radiation

ϕ_r = rim angle ; m = fluid mass flow rate in kg/hr ; C_p = sp. heat at constant pressure ;

T_{fi} = inlet fluid temperature ; T_{fo} = outlet fluid temperature

h_{p-c} = convective ht. tr. coeff. betn. the absorber tube and the glass cover

Collector efficiency factor:

$$F' = \frac{\frac{1}{U_l}}{\left[\frac{1}{U_l} + \frac{D_o}{D_i h_f}\right]} \qquad \text{.....Eqn. 4}$$

h_f = ht. tr. coeff. on the inside surface of the tube

Useful heat gain rate:

$$q_u = F_R \left(W - D_o\right) L \left[S - \frac{U_l}{C}\left(T_{fi} - T_a\right)\right] \qquad \text{.....Eqn. 5}$$

$$S = I_b r_b \rho \gamma (\tau.\alpha)_b + I_b r_b (\tau\alpha)_b \left(\frac{D_o}{W - D_o}\right) \qquad \text{.....Eqn. 6}$$

$I_b r_b$ = beam radiation on the plane of the aperture per unit time per unit area

ρ = specular reflectivity of the concentrator surface ; γ = intercept factor

Instantaneous collection efficiency, $\eta_i = \dfrac{q_u}{(I_b r_b + I_d r_d)WL}$ …..Eqn. 8

The instantaneous collection efficiency can also be calculated on the basis of beam radiation alone, in which case

$$\eta_{ib} = \frac{q_u}{I_b r_b WL} \quad \text{…..Eqn. 9}$$

Overall Loss Coefficient (U_l) and Heat Transfer Correlations:

The calculation of U_l is based on convection and reradiation losses. The absorber tube and the glass cover around it constitute a system and hence we have

Heat loss rate per unit length, $\dfrac{q_l}{L} = h_{p-c}\left(T_{pm} - T_c\right)\pi D_o + \dfrac{\sigma\pi D_0\left(T_{pm}^4 - T_c^4\right)}{\left\{\dfrac{1}{\varepsilon_p} + \dfrac{D_0}{D_{ci}}\left(\dfrac{1}{\varepsilon_c} - 1\right)\right\}}$ …..Eqn. 10

$$= h_w\left(T_c - T_a\right)\pi D_{co} + \sigma\pi D_{co}\,\varepsilon_c\left(T_c^4 - T_{sky}^4\right) \quad \text{…..Eqn. 11}$$

Eqns. 10 and 11 are a set of two non-linear equations which have to be solved for the unknowns q_l/L and T_c after substituting the values of h_{p-c} and h_w.

σ = Stefan Boltzmann Constant = 5.67 x 10^{-8} W/m^2-K^4.

Heat Transfer Coefficient between the absorber tube and the cover:

The natural convective heat transfer coefficient h_{p-c} for the enclosed annular space between a horizontal absorber tube and a concentric cover is calculated using

$$\frac{k_{eff}}{k} = 0.317\left(Ra^*\right)^{1/4} \quad \text{…..Eqn. 12}$$

where k_{eff} = Effective thermal conductivity – It is defined as the thermal conductivity that the motionless air in the gap must have to transmit the same amount of heat as the moving air.

Ra^* = modified Rayleigh number related to the usual Rayleigh number by

$$\left(Ra^*\right)^{1/4} = \frac{\ln\left(D_{ci}/D_o\right)}{b^{3/4}\left(1 + 1\right)^{5/4}}Ra^{1/4} \quad \text{…..Eqn. 13}$$

$$\left(\frac{}{D_o^{3/5}} \quad \frac{}{D_{ci}^{3/5}} \right)$$

The characteristic dimension used for the calculation of the Rayleigh number is the radial gap $b = \left(D_{ci} - D_o\right)/\,2$. Properties are evaluated at the mean temperature $\left(T_{pm} + T_c\right)/\,2$.

Note:- k_{eff} cannot be less than k. Hence $\left(k_{eff}/k\right)$ is put equal to unity if the use of eqn. 13 yields a value less than unity.

$$h_{p-c} = \frac{2k_{eff}}{D_o \ln\left(D_{ci}/D_0\right)}$$

…..Eqn. 14. The limitations on using eqn. 12 are that Ra^* should be less than 10^7 and b should be less than 0.3 D_o.

Heat Transfer Coefficient on the outside surface of the cover:

The convective heat transfer coefficient h_w on the outside surface of the cover (*wind heat transfer coefficient*) is calculated using the equation

$Nu = C_1 \operatorname{Re}^n$ …..Eqn. 15 (Assumption: wind velocity is at ⊥ angles to the axis of the collector.

Where C_1 and n are constants having the following values:

For 40 < Re < 4000, C_1=0.615, n=0.466

For 4000 < Re < 40000, C_1=0.174, n=0.618

For 40000 < Re < 400000, C_1=0.0239, n=0.805

Characteristic dimension used in eqn. 15 is D_{co}. Properties are to be evaluated at the mean temperature $\left(T_c + T_a\right)/\,2$. $\operatorname{Re} = 4D_{co}/\nu$ and $Nu = h_w.L/K$.

Performance Analysis of Liquid Flat-Plate Collectors

The performance analysis is done for a steady state condition in which the liquid is flowing through tubes bonded on the under-side of the absorber plate.

An energy balance on the absorber plate yields the following equation for a steady state

$q_u = A_p S - q_l$ -------------- ***Eqn 1***

Where q_u = useful heat gain (i.e., rate of heat transfer to the working fluid)

α = absorptivity of the absorber plate

$\tau\alpha$ = transmissivity- absorptivity product

A_p = area of the absorber plate; b = beam radiation; d = diffuse radiation

q_l = rate at which heat is lost by convection and re-radiation from the top, and by conduction and convection from the bottom and sides.

In order to find q_u, it is necessary to derive expressions to calculate $(\tau\alpha)_b$, $(\tau\alpha)_d$ and q_l.

Instantaneous Collection Efficiency:

$$\eta_i = \frac{q_u}{A_c I_T} = \frac{\textit{usefulheatgain}}{\textit{radiationincidentonthecollector}} \quad \text{-------------- } \textbf{\textit{Eqn 3}}$$

$A_c =$ Collector Gross Area (the area of the topmost cover including the frame).

Stagnation Temperature: If the liquid flow rate through the collector is stopped, there is no useful heat gain and the efficiency is zero. In this case, the absorber plate attains a temperature such that $A_p S = q_l$. This temperature is the highest temperature that the absorber plate can attain and is called as the *stagnation temperature.* Knowledge of the stagnation temperature is useful as an indicator for comparing different collector designs. It also helps in choosing proper materials for construction of the collector.

Transmissivity of the cover system:

$$\tau = \tau_r \tau_a$$

Where τ_r = **transmissivity obtained by considering only reflection and refraction**

$$= \frac{1}{2}(\tau_{rI} + \tau_{rII})$$

$$\tau_{rI} = \frac{1-\rho_I}{1+\rho_I} \quad \text{and} \quad \tau_{rII} = \frac{1-\rho_{II}}{1+\rho_{II}}$$

$$\rho_I = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} \quad \text{and} \quad \rho_{II} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)}$$

θ_1 = angle of incidence; θ_2 = angle of refraction

ρ_I and ρ_{II} are the reflectivities of the two components of polarization.

If there are M covers, the exponent is multiplied by M; δ_c = thickness of the transparent cover; K = extinction coefficient = 4 to 25 m^{-1} for different quality of glass. A low value is desirable.

Effective transmittance absorptance product $((\tau\alpha) = \dfrac{\square\tau\alpha}{1-(1-\alpha)\rho_d}$

Diffuse reflectivity of the cover system = ρ_d = 0.16 for one glass cover system

= 0.24 for two glass cover system

= 0.29 for three glass cover system

<u>Overall loss coefficient and heat transfer correlations:</u> Overall loss coefficient is the sum of top loss coefficient U_t, bottom loss coefficient U_b and side loss coefficient U_s.

Heat lost from the collector, $q_l = U_l A_p (T_{pm} - T_a)$

U_l = overall loss coefficient = $U_t + U_b + U_s$

A_p = Area of the absorber plate

T_{pm} = Average temperature of the absorber plate

T_a = Temperature of the surrounding air

$$q_l = q_t + q_b + q_s$$

$$q_t = U_t A_p (T_{pm} - T_a);\ q_b = U_b A_p (T_{pm} - T_a);\ q_s = U_s A_p (T_{pm} - T_a)$$

$$U_l = U_t + U_b + U_s$$

The overall loss coefficient is an important parameter since it is a measure of all the losses. Typical values range from 2 to 10 W/m^2-K.

<u>Top loss coefficient:</u>

The top loss coefficient U_t is evaluated by considering convection and re-radiation losses from the absorber plate in the upward direction. A schematic diagram for a two cover system is shown.

In a steady state, the heat transferred by convection and radiation between (i) the absorber plate and the first cover (ii) the first cover and the second cover (iii) the second cover and the surroundings must be equal.

Hence,

$$\frac{q_t}{A_p} = h_{p-c1}(T_{pm} - T_{c1}) + \frac{\sigma(T_{pm}^4 - T_{c1}^4)}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1\right)} = h_{c1-c2}(T_{c1} - T_{c2}) + \frac{\sigma(T_{c1}^4 - T_{c2}^4)}{\left(\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_c} - 1\right)} = h_w(T_{c2} - T_a) + \sigma\varepsilon_c(T_{c2}^4 - T_{sky}^4)$$

h_{p-c1} = convective heat transfer coefficient between the absorber plate and the I cover

h_{c1-c2} = convective heat transfer coefficient between the I and II covers.

h_w = convective heat transfer coefficient between the top cover and surrounding air

T_{c1}, T_{c2} = temperatures attained by two covers

$T_{sky} = T_a - 6$ in Kelvin.

ε_p = emissivity of the absorber plate for long wavelength radiation

ε_c = emissivity of the covers for long wavelength radiation.

The above equation constitute a set of three non-linear equations (A nonlinear equation does not produce a straight line and the exponent is to the second power or more), which have to be solved for the unknowns q_l, T_{c1} & T_{c2}. However, before this can be done it will be necessary to have some correlations for calculating the convective heat transfer coefficients h_{p-c1}, h_{p-c2}, h_w & T_{sky}.

Heat Transfer Coefficient between Inclined Parallel Surfaces:

The natural convective heat transfer coefficient for the enclosed space between the absorber plate and the first cover or between two covers is calculated by using one of the following correlations:-

$$Nu_L = 1 \; ; \; Ra_L \cos\beta < 1708$$

$$Nu_L = 1 + 1.446\left(1 - \frac{1708}{Ra_L \cos\beta}\right) \; ; \; 1708 < Ra_L \cos\beta < 5900$$

$$Nu_L = 0.229\,(Ra_L \cos\beta)^{0.252} \; ; \; 5900 < Ra_L \cos\beta < 9.23 \times 10^4$$

$$Nu_L = 0.157\,(Ra_L \cos\beta)^{0.285} \; ; \; 9.23 \times 10^4 < Ra_L \cos\beta < 10^6$$

Nu and Ra are the Nusselt & Rayleigh Nos. respectively. The characteristic dimension L is the spacing between the surfaces, while properties are evaluated at the arithmetic mean of the surface temperatures.

Heat Transfer Coefficient at the top cover:

The convective heat transfer coefficient (h_w) at the top cover is also known as the *wind heat transfer coefficient.* It is calculated using the following correlation:

$$h_w = 8.55 + 2.56\, V_\infty \; ; \quad h_w \text{ is in W/m}^2 - \text{K and } V_\infty \text{ is in m/s.}$$

Bottom loss coefficient:

The bottom loss coefficient U_b is calculated by considering conduction and convection losses from the absorber plate in the downstream direction through the bottom of the collector.

In most cases, the thickness of the insulation provided is such that the thermal resistance associated with conduction dominates. Thus neglecting the convective resistances, we have

$U_b = \dfrac{k_i}{\delta_b}$ Where k_i = thermal conductivity of the insulation; δ_b = thickness of the insulation.

Side loss coefficient:

Here also, it is assumed that the conduction resistance dominates and the flow of heat is 1-Dimensional and steady. The side loss coefficient is always much smaller than the top loss coefficient.

If the dimensions of the absorber plate are L_1 x L_2 and the height of the collector casing is L_3, then the area across which the heat flows sideways is $2(L_1 \text{ x } L_2)L_3$. The temperature drop across which the heat flow occurs varies from ($T_{pm} - T_a$) at the absorber plate level to zero both at the top and bottom. Assuming, therefore, that the average temperature drop across the side insulation is ($T_{pm} - T_a$) / 2 and that the thickness of the side insulation is δ_s , we have

$$q_s = 2L_3 (L_1 + L_2) k_i \frac{(T_{pm} - T_a)}{2\delta_s}$$

Thus, from eqn., $q_s = U_s A_p (T_{pm} - T_a)$

$$U_s = \frac{(L_1 + L_2) L_3 k_i}{L_1 L_2 \delta_s}$$

Useful heat gain for the flat plate collector (q_u):

$$q_u = F_R\, A_p\, [\, S - U_L\, (\, T_{fi} - T_a\,)]$$

F_R = Collector heat removal factor

A_p = Area of the collector plate

S = Flux absorbed in the absorber plate = $I_b\, r_b\, (\tau\alpha)_b$

U_L = Top loss coefficient

T_a = Ambient temperature

Collector efficiency (η_i):

$$\eta_i = \frac{q_u}{I_b r_b}$$

Collector Heat Removal Factor and Concentrating Collector

Collector heat-removal factor (F_R): F_R is an important design parameter since it is a measure of the thermal resistance encountered by the absorbed solar radiation in reaching the collector fluid.

F_R represents the ratio of the actual heat gain rate to the gain which would occur if the collector absorber plate was at the temperature of collector fluid temperature (T_{fi}) everywhere. F_R value ranges between 0 and 1.

Useful heat gain for the flat plate collector (q_u):

$q_u = F_R A_p [S - U_l (T_{fi} - T_a)]$ …. *Hottel-Whiller-Bliss equation*

F_R = Collector heat removal factor

A_p = Area of the collector plate

U_l = Top loss coefficient

T_{fi} = Inlet fluid temperature

T_a = Ambient temperature

S = Flux absorbed in the absorber plate = $I_b r_b (\tau\alpha)_b$

Collector efficiency (η_i):

$$\eta_i = \frac{q_u}{I_b r_b}$$

Empirical Equation for Top Loss Coefficient:

$$U_t = \left[\frac{M}{\left(\frac{C}{T_{pm}}\right)\left(\frac{T_{pm} - T_a}{M + f}\right)^{0.252}} + \frac{1}{h_w} \right]^{-1} + \left[\frac{\sigma\left(T_{pm}^2 + T_a^2\right)\left(T_{pm} + T_a\right)}{\frac{1}{\varepsilon_p + 0.0425M\left(1 - \varepsilon_p\right)} + \frac{2M + f - 1}{\varepsilon_c} - M} \right]$$

M = Number of glass covers

C = $204.429(\cos\beta)^{0.252} / L^{0.24}$ and L = spacing in metre

$$f = \left(\frac{9}{h_w} - \frac{30}{h_w^2}\right)\left(\frac{T_a}{316.9}\right)(1 + 0.091M) \text{ and } h_w = 5.7 + 3.8V_\infty$$

Concentrating Collector: - *for temperatures up to 400˚C.*

1. Concentration of solar radiation is achieved using a reflecting arrangement of mirrors or a refracting arrangement of lenses.

2. The optical system directs the solar radiation on to an absorber of smaller area which is usually surrounded by a transparent cover.

3. Because of the presence of an optical system, a concentrating collector has to track the sun so that the beam radiation is directed on to the absorber surface. The need for some form of tracking introduces a certain amount of complexity in the design. Also the maintenance requirements are increased, which adds to the cost. An added disadvantage is the fact that much of the diffuse radiation is lost because it does not get focused.

Definitions:

Concentrator: optical subsystem which directs the solar radiation on to the absorber

Receiver: subsystem consisting of the absorber, its cover and other accessories.

Overall Loss Coefficient (U_l) & Heat Tr. Correlations for Concentrating Collectors:

Assumption: Absorber tube & the glass cover around it constitute a system of long, concentric tubes.

$$\frac{q_l}{L} = h_{p-c}\left(T_{pm} - T_c\right)\pi D_o + \frac{\sigma\pi D_o\left(T_{pm}^4 - T_c^4\right)}{\left\{\frac{1}{\varepsilon_p} + \frac{D_o}{D_{ci}}\left(\frac{1}{\varepsilon_c} - 1\right)\right\}} \text{ ----------C.1}$$

$$= \left(h_w\left(T_c - T_a\right)\pi D_o\right) + \sigma\pi D_{co}\varepsilon_c\left(T_c^4 - T_{sky}^4\right) \text{ -------------C.2}$$

$\frac{q_l}{L}$ = heat loss rate per unit length; ε_p = emissivity of the absorber tube surface

h_{p-c} = convective heat transfer coefficient between the absorber tube and the glass cover

T_{pm} = average temperature of the absorber tube; T_c = temperature attained by the cover

D_o = outer φ of the absorber tube; D_{ci} = inner φ of the glass cover; T_a = ambient temp.

ε_c = emissivity of the glass cover; h_w = wind heat transfer coefficient in W/m^2-K.

UNIT 4

SOLAR THERMAL TECHNOLOGIES

SOLAR THERMAL TECHNOLOGIES

SUBJECT CODE: SME1602

SUBJECT NAME: WIND AND SOLAR ENERGY

Energy can be **stored** as potential, kinetic, chemical, electromagnetic, thermal, etc. ... Examples of chemical **energy storage systems** include batteries, flow batteries, and fuel cells. Mechanical (kinetic and potential) **energy storage systems** include pumped **storage** hydropower, flywheels, and pressurized gas **storage systems**.

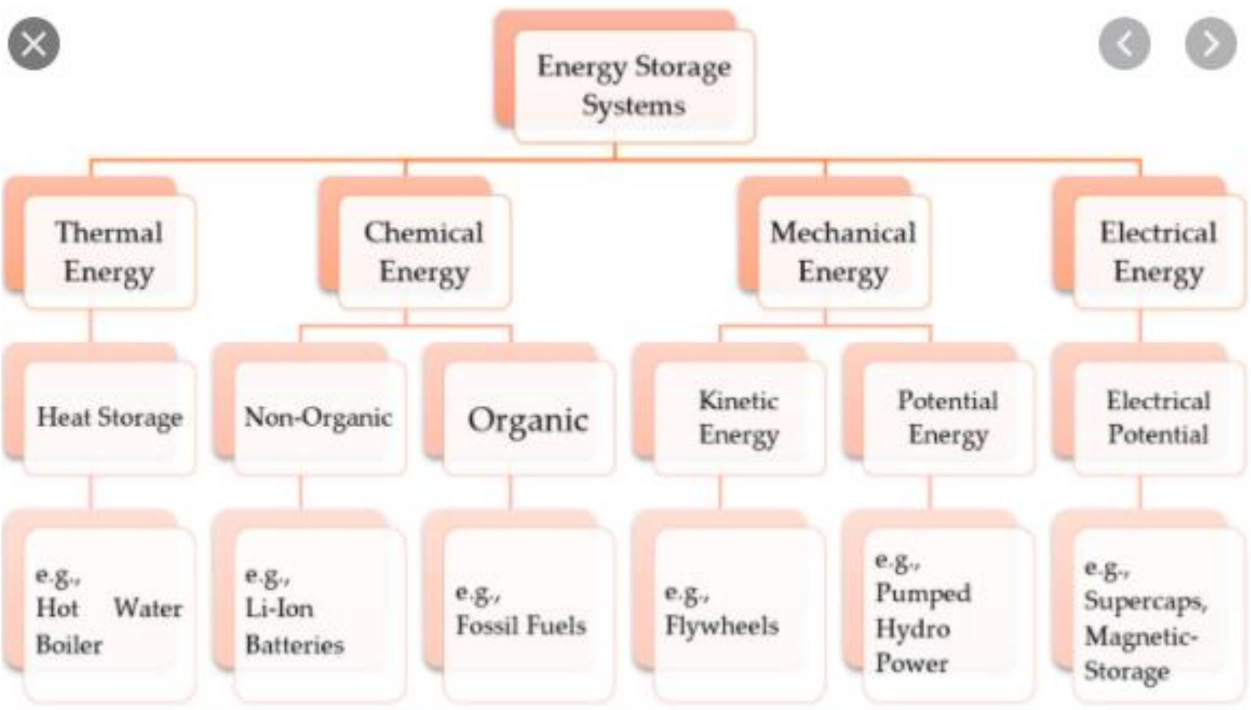
Thermal energy storage (TES) is a technology that stocks **thermal energy** by heating or cooling a **storage** medium so that the **stored energy** can be used at a later time for heating and cooling applications for power generation. TES **systems** are used particularly in buildings and in industrial processes.

Major problem associated with the utilization of solar energy is its availability.

Most applications require 'energy storage' system.

The purpose of 'energy storage' system is to store energy when it is in excess of the requirement of an application and to make it available for extraction when the supply of solar energy is absent or inadequate.

Energy storage can be in the following forms



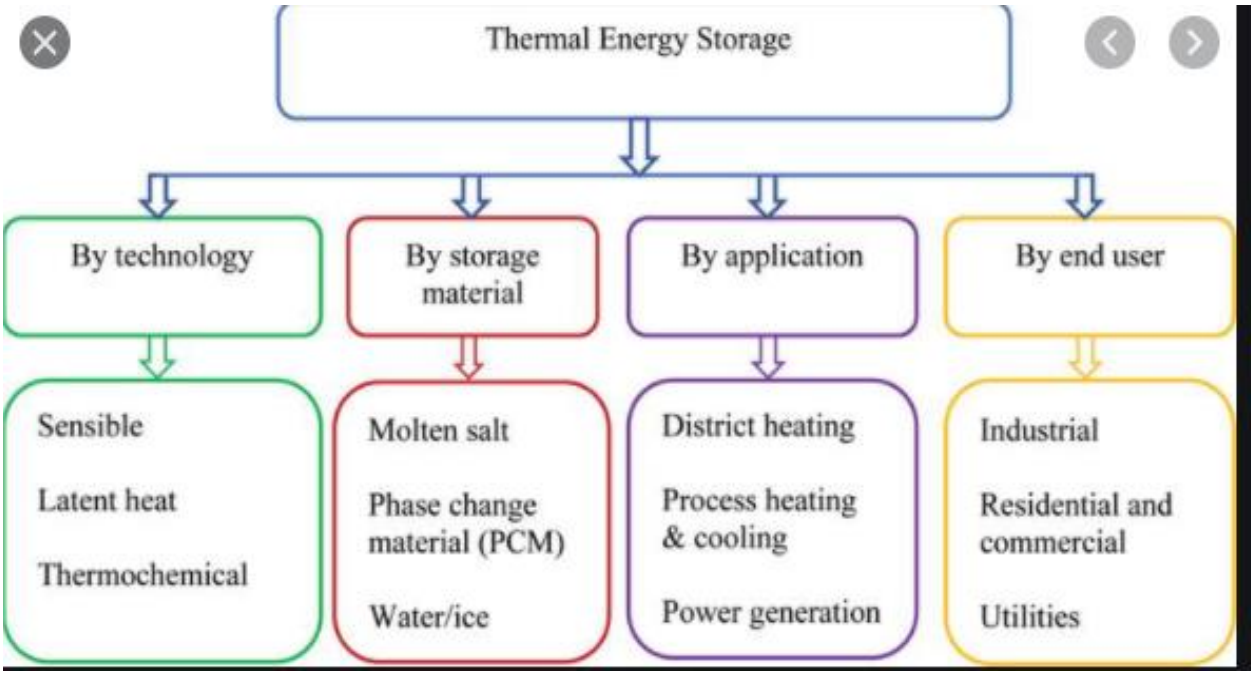
- Thermal energy – can be stored as ***sensible heat*** *or as* ***latent heat****.*
- Electrical energy

- Mechanical energy
- Chemical energy

SENSIBLE HEAT STORAGE

- It is usually done in an insulated container containing a liquid like water or a porous solid in the form of pebbles or rocks.
- The first type is used for liquid collectors while the second type is compatible with air heaters.
- Sensible heat storage systems operate over a range of temperatures.

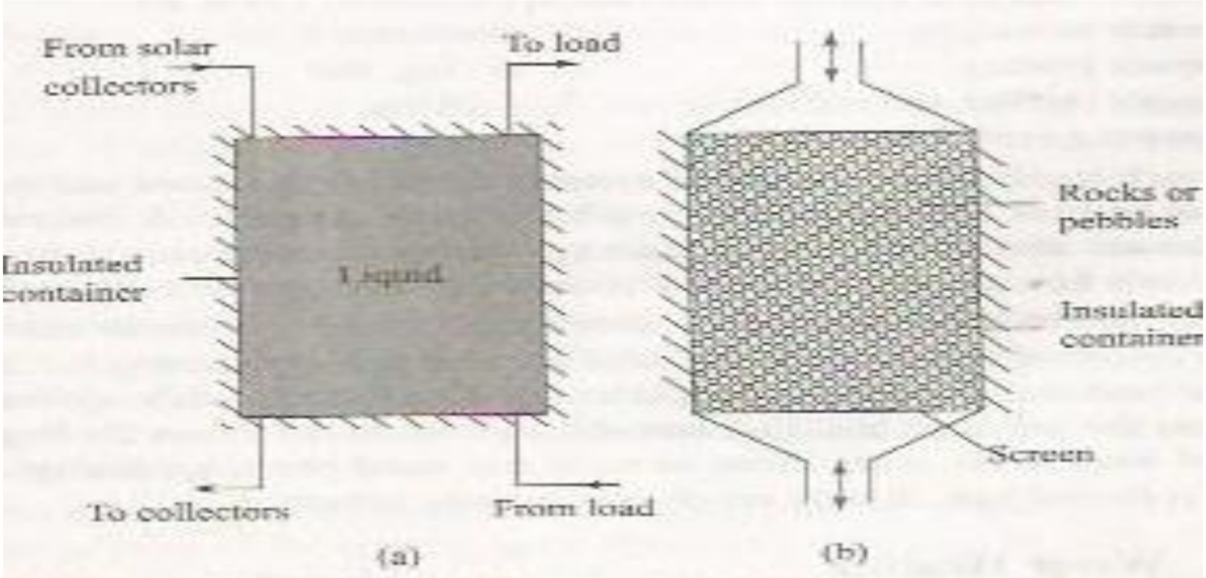
Classification of Thermal energy storage systems (TES)



Sensible heat storage: Heating a liquid or solid which does not change phase. The quantity of heat stored is proportional to the temperature rise of the material. If T_1 and T_2 represent the lower and higher temperature, V the volume and ρ the density of the storage material, and C_p the specific heat, then the energy stored Q is given by:

$$Q = V\rho \int_{T1}^{T2} Cp \, dT$$

- **Latent heat storage (Phase change heat storage):** In this system, heat is stored in a material when it melts, and heat is extracted from the material when it freezes. Heat can also be stored when a liquid changes to gaseous state, but as the volume change is large, such a system is not economic.
- The amount of energy stored in this case depends upon the mass and the latent heat of fusion of the material. Thus, $E = m.\lambda$; λ = latent heat of fusion.
- Latent heat storage systems operate essentially at the temperature at which the phase change takes place.



Schematics of two forms of sensible heat storage: (a) liquid, (b) porous solid

- **Mechanical Energy Storage:** Storage is done in large sized flywheels or in compressed air. Compressed air is stored in large underground chambers.
- **Electrical Energy Storage:** Storage is in the form of electric batteries (lead – acid battery storage).
- **Chemical Energy Storage:** Using heat to induce a certain chemical reaction and then storing the products. The heat is released when the reverse reaction is made to occur.
- **Solar pond:** A novel device which combines the functions of both ***collection*** and ***storage*** is the ***solar pond***.
    - It consists of an span of water about a meter or two in depth, in which salts like sodium or magnesium chloride are dissolved.
    - The concentration of the salt is more at the bottom and less at the top.
    - Because of this, the bottom layers of water are denser than the surface layers even if they are hotter and natural convection does not occur.
    - Thus, the heat from the sun's rays absorbed at the bottom of the pond is retained in the lower depths, and the upper layers of water act like a thermal insulation.

SENSIBLE HEAT STORAGE

In sensible heat storage systems, energy is stored or extracted by heating or cooling a liquid or solid which does not change its phase during the process.

Liquids used: water, heat transfer oils, inorganic molten salts

Solids used: rocks, pebbles, refractories – material is invariably in porous form. Heat is stored or extracted by the flow of a gas or liquid through the pores or voids.

Choice of the substance depends on the temperature level of the application.

For temperatures below 100℃ – water is used.

For temperatures around1000℃ – refractory bricks are used.

Advantage of sensible heat storage: simpler in design than latent heat or thermo- chemical storage.

Disadvantage: 1. Bigger in size. 2. They cannot store or deliver energy at a constant temperature.

SENSIBLE HEAT STORAGE – LIQUIDS

Water is the most commonly used medium in a sensible heat storage systems.

Most solar water heating and space heating systems use hot water storage tanks

located either inside or outside the buildings or underground.

Size of the tanks - few 100 litres to a few 1000 cubic meters.

General thumb rule: 75 -100 litres of storage per square meter of collector area.

Storage tanks are made of steel, concrete and fibreglass.

Tanks should be suitably insulated with glass wool, mineral wool or polyurethane.

Thickness of insulation: 10 – 20 cm.

Because of the above, the cost of the insulation represents a significant part of the total cost of the sensible heat storage.

It is possible to store water at temperatures a little above 100℃ by using pressurized tanks.

In order to reduce the cost of water storage systems, naturally occurring underground aquifers which already contain water is used.

In such systems, the need for building a storage tank is eliminated.

For storing energy, hot water is pumped into the aquifer through an injection well.

At the same time, cold ground water is displaced through another well.

For withdrawing energy, the reverse procedure is followed.

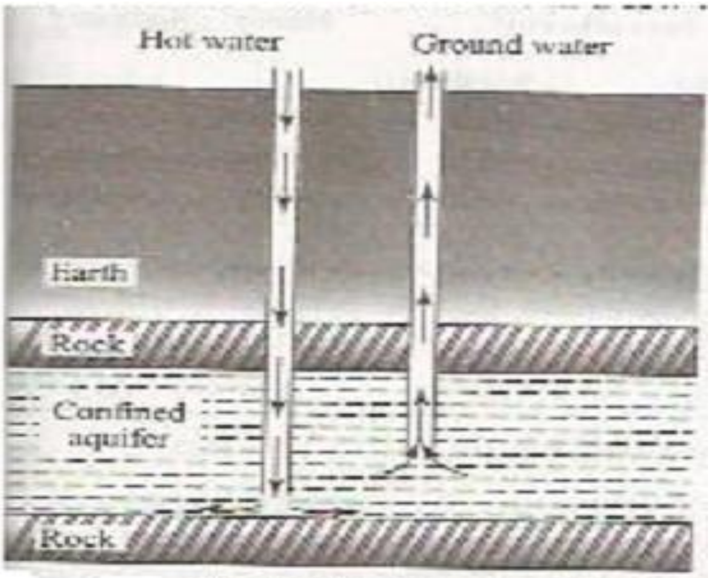
Heat transfer oils: Used for intermediate temperatures ranging from 100 – 300℃.

Eg: Servotherm is used in India.

Disadvantages: 1. The main problem associated with the use of heat transfer oils is that they tend to degrade with time.The degradation is particularly serious if they are used above their recommended temperature limit.

- 2. The use of oils also presents safety problems since there is a possibility of ignition above their flash point. For this reason, it is recommended to use the systems with inert gas cover.

1. Cost of the heat transfer oil, which ranges from 60 – 120 per litre (of Indian brands). Hence these are used in small storage systems



Schematic diagram of the underground aquifer storage concept

SOLAR COOKER

An important domestic thermal application is that of cooking.

SOLAR COOKER

Box type cooker (for domestic purpose)	Dish type cooker (for community purpose)

A slow cooking device suitable for domestic purposes.

It consists of a rectangular enclosure

Insulated at the bottom and sides with one or two glass covers on the top. Solar radiation enters through the top and heats up the enclosure in which the food to be cooked is placed in shallow vessels.

Temperatures around 100 ˚C can be obtained in these cookers on sunny days and pulses, rice, vegetables etc., can be readily cooked.

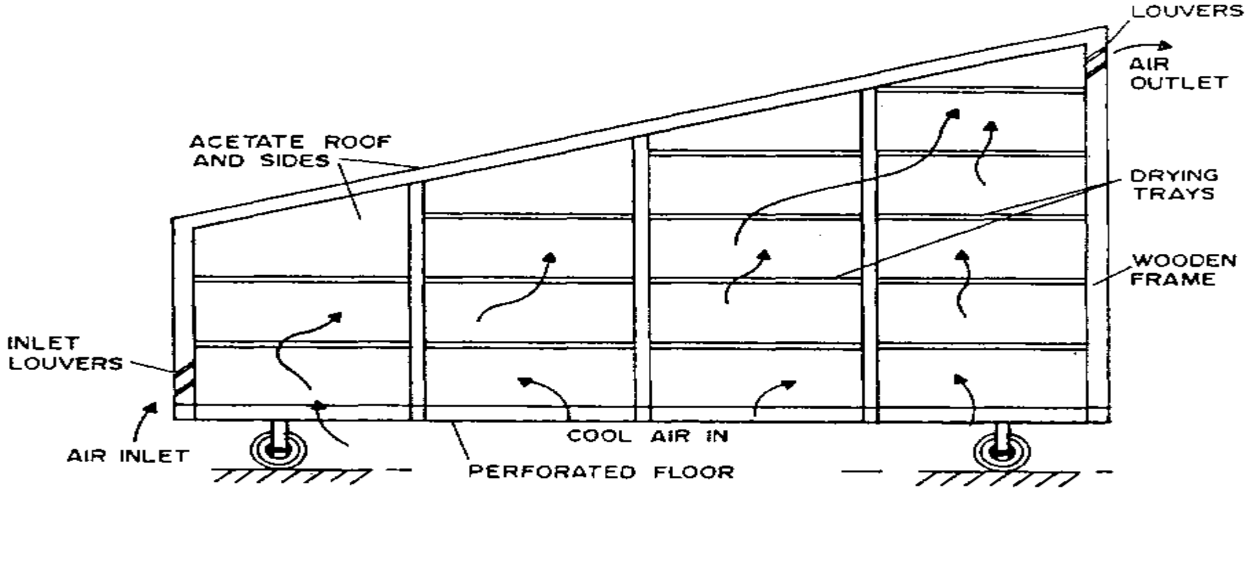
The time taken for cooking depends upon the solar radiation and varies from half an hour two and a half hours.

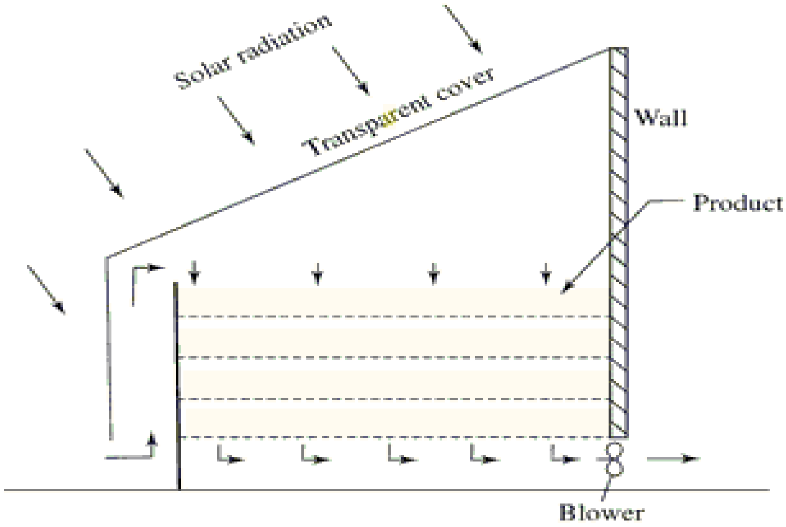
A single class reflector (mirror) whose inclination can be varied is usually attached to the box type cooker. The reflector helps in achieving enclosure temperatures which are higher by about 15 – 20 ˚C. As a result, cooking time is reduced.

Box-type solar cooker

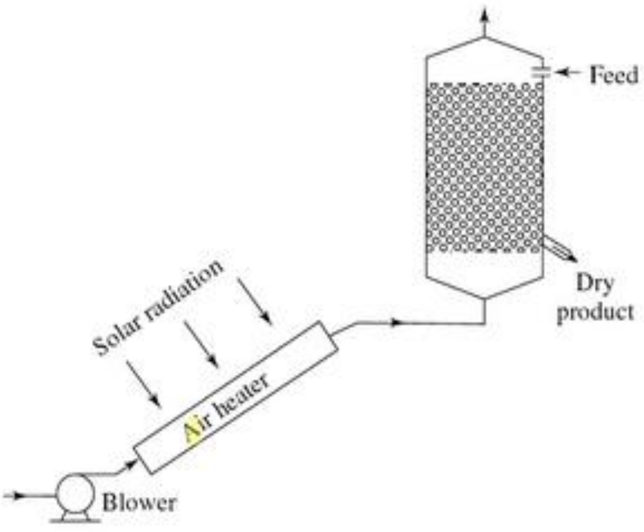
SOLAR DRYING

- One of the traditional uses of solar energy has been drying of agricultural products.
- The drying process removes moisture and helps in the preservation of the product.
- A cabinet type solar dryer consists of an enclosure with a transparent cover.
- The material to be dried is placed on perforated drying trays.
- Solar radiation entering the enclosure is absorbed in the product itself and the surrounding internal surfaces of the enclosure.
- As a result, moisture is removed from the product and the air inside is heated.
- Suitable openings at the bottom and the top ensure a natural circulation.
- Temperatures ranging from 50 - 80℃ are usually attained and drying time ranges from 2 – 4 days. Products dried are: dates, apricots, chillies and grapes.





Forced circulation dryer (direct gain)



Forced circulation dryer (indirect gain)

- When the temperature of the product needs to be controlled or when the solar radiation falling on the product is not adequate, indirect gain forced circulation dryer is used.
- Here, the air is heated separately in an array of solar air heaters and then ducted to the chamber in which the product to be dried is stored.
- Suitable for food grains, tea, spices, leather and ceramics.

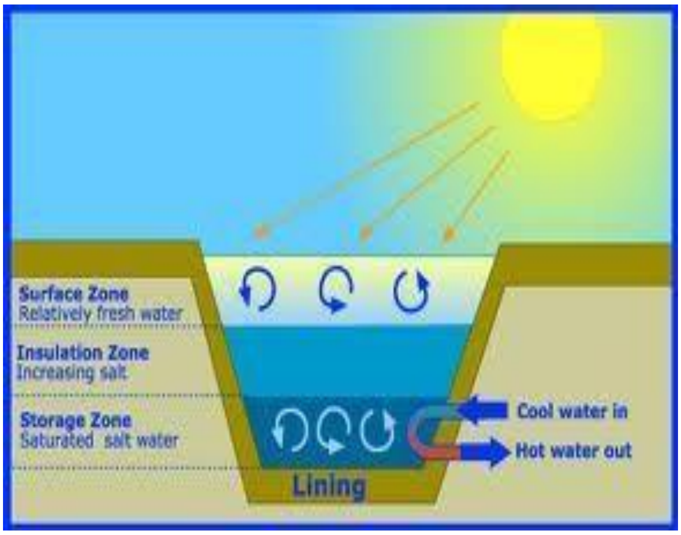
SOLAR POND

A solar pond is a body of water that collects and stores solar energy. Solar energy will warm a body of water (that is exposed to the sun), but the water loses its heat unless some method is used to trap it. Water warmed by the sun expands and rises as it becomes less dense. Once it reaches the surface, the water loses its heat to the airthrough convection, or evaporates, taking heat with it. The colder water, which is heavier, moves down to replace the warm water, creating a natural convective circulation that mixes the water and dissipates the heat. The design of solar ponds reduces either convection or evaporation in order to store the heat collected by the pond. They can operate in almost any climate.

A solar pond can store solar heat much more efficiently than a body of water of the same size because the salinity gradient prevents convection currents. Solar radiation entering the pond penetrates through to the lower layer, which contains concentrated salt solution. The temperature in this layer rises since the heat it absorbs from the sunlight is unable to move upwards to the surface by convection. Solar heat is thus stored in the lower layer of the pond.

WORKING PRINCIPLE

The solar pond works on a very simple principle. It is well-known that water or air is heated they become lighter and rise upward. Similarly, in an ordinary pond, the sun‟s rays heat the water and the heated water from within the pond rises and reaches the top but loses the heat into the atmosphere. The net result is that the pond water remains at the atmospheric temperature. The solar pond restricts this tendency by dissolving salt in the bottom layer ofthe pond making it too heavy to rise . You can see a shematic view of a solar pond in Figure



A solar pond is an artificially constructed water pond in which significant temperature rises are caused in the lower regions by preventing the occurrence of convection currents. The more specific terms salt-gradient solar pond or non-convecting solar pond are also used. The solar pond, which is actually a large area solar collector is a simple technology that uses water- a pond between one to four metres deep as a working material for three main functions

- Collection of radiant energy and its conversion into heat (upto 95° C)

- Storage of heat and transport of thermal energy out of the system

  The solar pond possesses a thermal storage capacity spanning the seasons. The surface area of the pond affects the amount of solar energy it can collect. The bottom of the pond is generally lined with a durable plastic liner made from material such as black polythene and hypalon reinforced with nylon mesh. This dark surface at the bottom of the pond increases the absorption of solar radiation. Salts like magnesium chloride, sodium chloride or sodium nitrate are dissolved in the water, the concentration being densest at the bottom (20% to 30%) and gradually decreasing to almost zero at the top. Typically, a salt gradient solar pond consists of three zones.

- An upper convective zone of clear fresh water that acts as solar collector/receiver and which is relatively the most shallow in depth and is generally close to ambient temperature,

- A gradient which serves as the non-convective zone which is much thicker and occupies more than half the depth of the pond. Salt concentration and temperature increase with depth, A lower convective zone with the densest salt concentration, serving as the heat storage zone. Almost as thick as the middle non-convective zone, salt concentration and temperatures are nearly constant in this zone,

When solar radiation strikes the pond, most of it is absorbed by the surface at the bottom of the pond. The temperature of the dense salt layer therefore increases. If the pond contained no salt, the bottom layer would be less dense than the top layer as the heated water expands. The less dense layer would then rise up and the layers would mix. But the salt density difference keeps the „layers‟ of the solar pond separate. The denser salt water at the bottom prevents the heat being transferred to the top layer of fresh water by natural convection, due to which the temperature of the lower layer may rise to as much as 95°C.

SOLAR DESALINATION

These are separation processes that rely on a technique or technology for transforming a mixture of substances into two or more distinct components. The purpose of this type of process is to purify the saline water of its impurities.

The principle of a separation process is to use a difference of properties between the interest compound and the remaining mixture. When the difference property will be greater, the separation is easy. So the choice of the separation process starts with a good knowledge of the mixture composition and properties of different components. The desalination processes are divided into two main categories: on the one hand, the distillation process (which requires a phase change, evaporation / condensation) and on the other hand the membrane processes (filtration).

The most current techniques of desalination are thermal distillation - for the treatment of great volumes of water (55 000 m3/jour) – and the membranes technology: electrodialysis and reverse osmosis. The ability of treatment with membrane technology can be adapted according to the intended use (the great plants have a capacity of more than 5000 m3/day, the averages plant between 500 and 5000 m3/day, while that small installations have a maximum capacity of 500 m3/day).

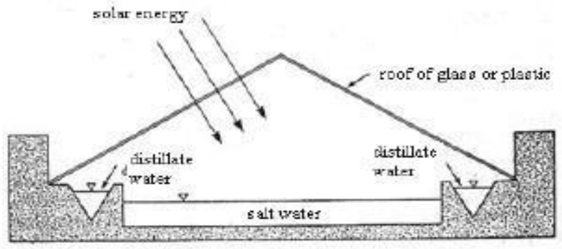
It is noticed that these processes use thermal energy and / or electrical energy and consequently are consumer‟s energy and pollutants. The energy, conventional methods commonly used, can be of solar origin either a partial or total depending on production capacity and in this way we minimize significantly the consumption of energy while protecting the environment. Future research in this area is oriented toward the maximum utilization of solar energy, which is free and clean, or through technological innovation and/or improvements on conventional methods.

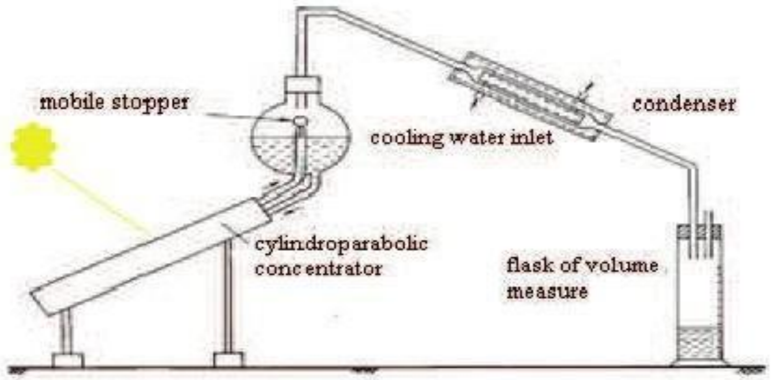
For their operation, the distillation processes require for much of the thermal energy for heating salt water. Furthermore, this thermal energy must be supplied at a relatively low temperature, between 60 and 120 ° C. Heat can be provided in the case of the use of solar energy by solar flat plate or concentrator collector according to working conditions.

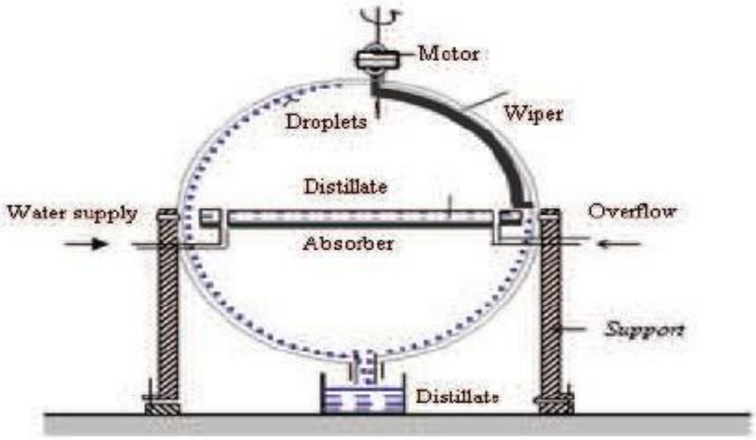
The processes most commonly used and which are likely to be coupled to a source of solar energy are:

-The direct solar greenhouse distillation is a properly solar process.

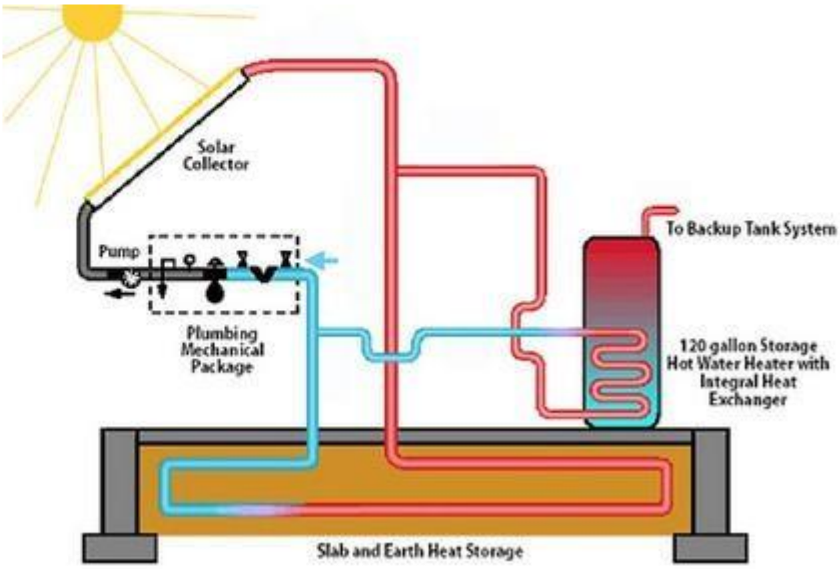
-The conventional distillation processes such as multi-stage flash, multi-effects, vapor compression







Solar energy is not available at night, making energy storage an important issue in order to provide the continuous availability of energy. Both wind power and solar power are intermittent energy sources, meaning that all available output must be taken when it is available and either stored for when it can be used, or transported, over transmission lines, to where it can be used. Wind power and solar power tend to be somewhat complementary, as there tends to be more wind in the winter and more sun in the summer, but on days with no sun and no wind the difference needs to be made up in some manner. The Institute for Solar Energy Supply Technology of the University of Kassel pilot-tested a combined power plant linking solar, wind, biogas and hydrostorage to provide load-following power around the clock, entirely from renewable sources.



Solar energy can be stored at high temperatures using molten salts. Salts are an effective storage medium because they are low-cost, have a high specific heat capacity and can deliver heat at temperatures compatible with conventional power systems. The Solar Two used this method of energy storage, allowing it to store 1.44 TJ in its 68 m^3 storage tank, enough to provide full output for close to 39 hours, with an efficiency of about 99%.

Artificial photosynthesis involves the use of nano technology to store solar electro magnetic energy in chemical bonds, by splitting water to produce hydrogen fuel or then combining with carbon dioxide to make bio polymers such as methanol. Many large national and regional researchprojects on artificial photosynthesis are now trying to develop techniques integrating improvedlight capture, quantum coherence methods of electron transfer and cheap catalytic materials thatoperate under a variety of atmospheric conditions.

Solar Heating and Cooling:

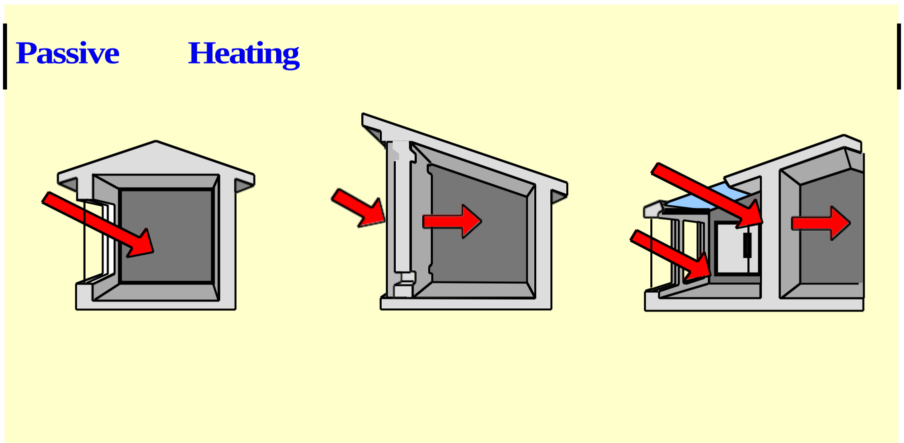
Solar thermal energy is appropriate for both heating and cooling. Key applications for solar technologies are those that require low temperature heat such as domestic water heating, space heating, pool heating, drying process and certain industrial processes. Solar applications can also meet cooling needs, with the advantage that the supply (sunny summer days) and the demand (desire for a cool indoor environment) are well matched. To generate synergy effects in climates with heating and cooling demand combined systems should be used.

Solar Heating:

Over 70% of the household‟s energy use goes into space and water heating. Covering a big part with a solar system leads to energy as well as financial savings. Solar heating is a well established renewable energy source and applied in numerous projects worldwide. Solar thermal systems consist of a solar collector, a heat exchanger, storage, a backup system and a load. This system may serve for both, space heating and tap water heating, known as combi system.

Passive Solar heating

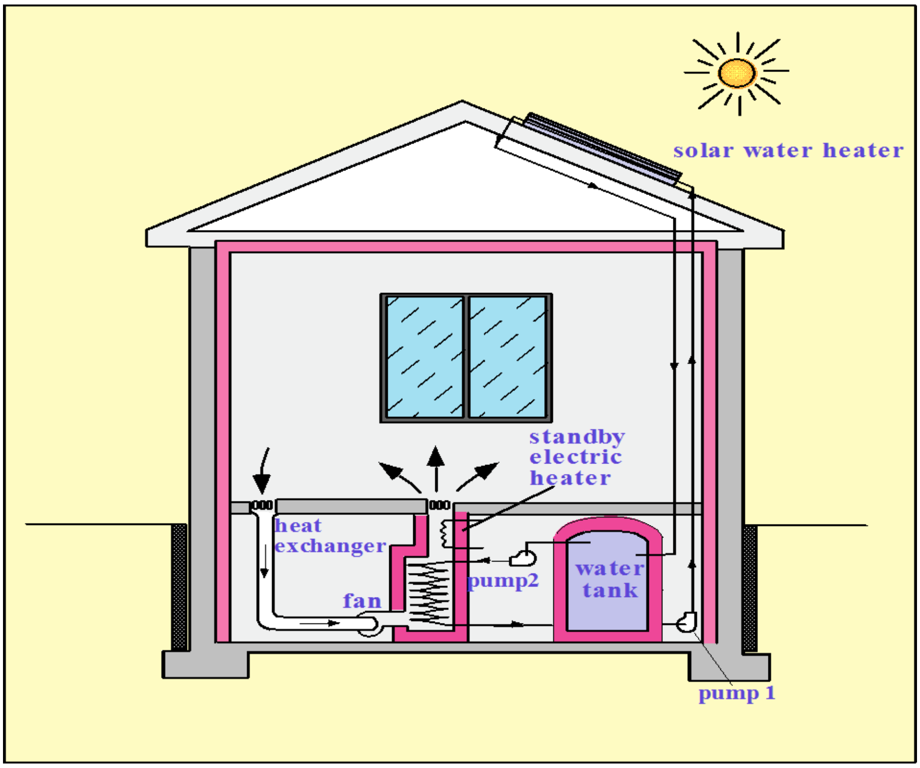
- A passive solar system uses no external energy, its key element is good design.
- House faces south.
- South facing side has maximum window area (double or triple glazed).
- Roof overhangs to reduce cooling costs.
- Thermal mass inside the house (brick, stones or dark tile).
- Deciduous trees on the south side to cool the house in summer, let light in the winter.
- Insulating drapes (closed at night and in the summer).
- Greenhouse addition.
- Indirect gain systems also such as large concrete walls to transfer heat inside.



Direct Gain	Thermal Storage W all	Sunspace
Passive Cooling		
Shading	Vent ilat ion	Earth Contact

Active Solar Heating

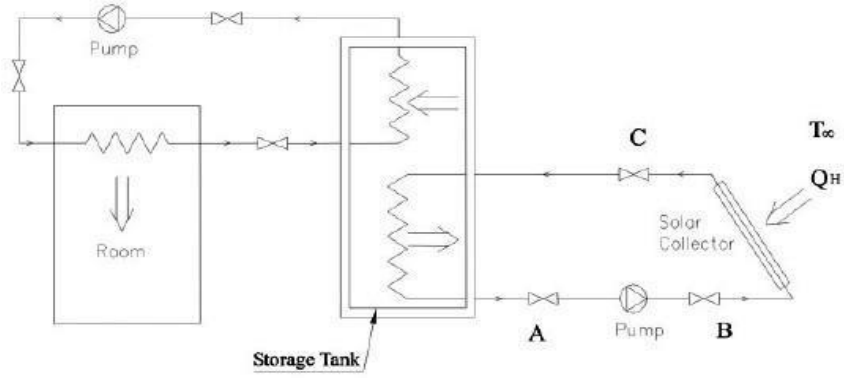
- Flat plate collectors are usually placed on the roof or ground in the sunlight.
- The sunny side has a glass or plastic cover.
- The inside space is a black absorbing material.
- Air or water is pumped (hence active) through the space to collect the heat.
- Fans or pumps deliver the heat to the house.



Solar Energy Storage Systems

Concrete is a relatively good medium for heat storage in passively heated or cooled houses. It is also considered for application in intermediate–temperature solar thermal plants.

Consider the thermal energy storage system shown schematically in the below Figure . The system consist of a large liquid bath of mass m and specific heat C placed in an insulated vessel. The system also includes a collector to give the collector fluid a heat gain and a room in which this heat gain is discharged.


Pump
Room
Storage Tank
C
T_∞
Q_H
Solar
Collector
A
Pump
B

Schematic Diagram of the Solar Energy Storage System.

Operation of the system takes place in three steps; charging, storage and removal processes. At the beginning of the storage process valves A, B, C are opened. Hot fluid from the collector at temperature Tis enters the system through valve C. This hot collector fluid is cooled while flowing through the heat exchanger 2 immersed in the bath and leaves at the bottom of the system at temperature Tes. The heat carrying liquid is then pumped to the collector with the help of pump 2. The fluid entering the collector takes QH from the sun and its temperature increases to Tis and the storage cycle is completed. While the hot gas flowing through the heat exchanger 2, the bath temperature Tb and fluid exit temperature of storage process Tes approach the hot fluid inlet temperature of storage process Tis. The heating process is allowed to continue up to the desired storage material (water) temperature. At that desired moment the valves A, B, C are closed. After the storage period D, E, F are opened, so the removal process begins. Cold fluid with constant mass flow rate flows through valve F and gets into the heat exchanger 1 and it receives energy from the liquid bath then leaves the system through valve D. This heated fluid is then pumped to the radiator to give heat to the medium (room) and the removal cycle is completed. other controlling unit is located at the radiator outlet. If the radiator outlet temperature is higher than the tank temperature it stops the pump 1 automatically.

Phase Change Energy Storage

In latent heat storage the principle is that when heat is applied to the material it changes its phase from solid to liquid by storing the heat as latent heat of fusion or from liquid to vapor as latent heat of vaporization. When the stored heat is extracted by the load, the material will again change its phase from liquid to solid or from vapor to liquid. The latent heat of transformation from one solid phase into another is small. Solid-vapor and liquid-vapor transitions have large amounts of heat of transformation, but large changes in volume make the system complex and impractical. The solid-liquid transformations involve relatively small changes in volume. Such materials are available in a range of transition temperatures.
Heat storage through phase change has the advantage of compactness, since the latent heat of fusion of most materials is very much larger than their enthalpy change for 1 K or even 0 K.. For example, the ratio of latent heat to specific heat of water is 80, which means that the energy required to melt one kilogram of ice is 80 times more than that required to raise the temperature of one kilogram of water one degree Celsius.

Any latent heat thermal energy storage system should have at least the following three components:a suitable phase change material (PCM) in the desired temperature range, a containment for the storage substance, and a suitable heat carrying fluid for transferring the heat effectively from the heat source to the heat storage.

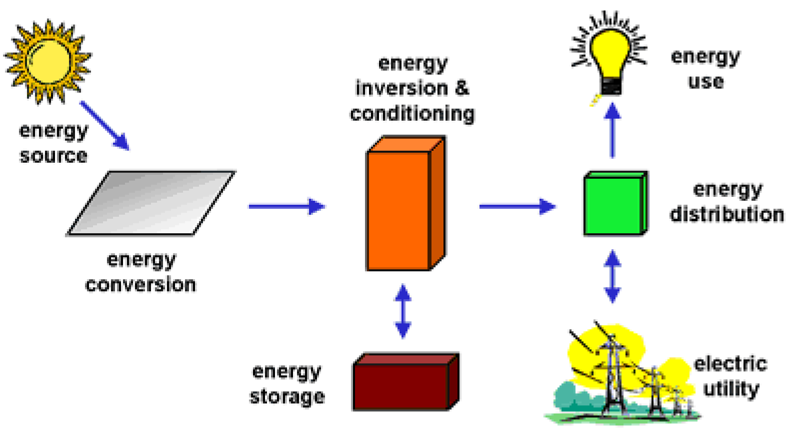
Furthermore, the PCMs undergo solidification and therefore cannot generally be used as heat transfer media in a solar collector or the load. Many PCMs have poor thermal conductivity and therefore require large heat exchange area. Others are corrosive and require special containers. Latent heat storage materials are more expensive than the sensible heat storage media generally employed, like water and rocks. These increase the system cost.

SOLAR ENERGY STORAGE SYSTEM

Solar Photovoltaic

PV systems are like any other electrical power generating systems, just the equipment used is different than that used for conventional electromechanical generating systems. However, the principles of operation and interfacing with other electrical systems remain the same, and are guided by a well-established body of electrical codes and standards. Although a PV array produces power when exposed to sunlight, a number of other componentsare required to properly conduct, control, convert, distribute, and store the energy produced by thearray.

Depending on the functional and operational requirements of the system, the specific components required may include major components such as a DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and sometimes the specified electrical load(appliances). In addition, an assortment of balance of system (BOS) hardware, including wiring,overcurrent, surge protection and disconnect devices, and other power processing equipment. Figure show a basic diagram of a photovoltaic system and the relationship of individual components.



Major photovoltaic system components.

Batteries are often used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed (during the night and periods of cloudy weather). Other reasons batteries are used in PV systems are to operate the PV array near its maximum power point, to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and over discharge.

UNIT-V

SOLAR PHOTOVOLTAICS

Photovoltaic Systems

A photovoltaic (PV) system is able to supply electric energy to a given load by directly converting solar energy through the photovoltaic effect. The system structure is very flexible. PV modules are the main building blocks; these can be arranged into arrays to increase electric energy production. Normally additional equipment is necessary in order to transform energy into a useful form or store energy for future use. The resulting system will therefore be determined by the energy needs (or loads) in a particular application.

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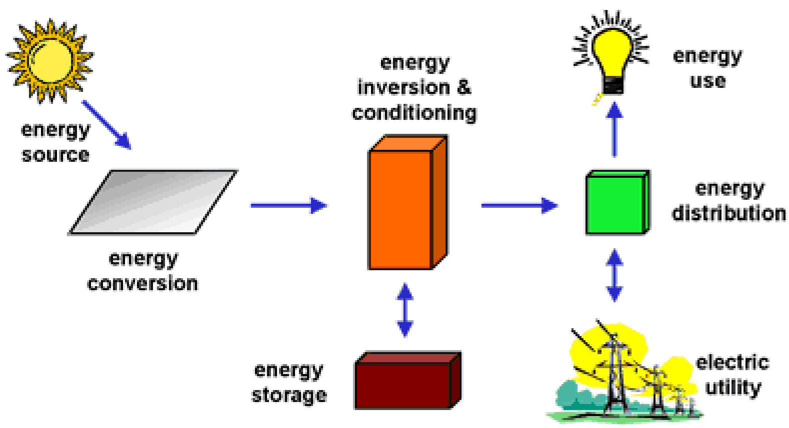

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Off-grid PV systems have traditionally used rechargeable batteries to store excesselectricity. With grid-tied systems, excess electricity can be sent to the transmission grid. Net metering programs give these systems a credit for the electricity they deliver to the grid. This credit offsets electricity provided from the grid when the system cannot meet demand, effectively using the grid as a storage mechanism. Credits are normally rolled over month to month and any remaining surplus settled annually.Pumped-storage hydroelectricity stores energy in the form of water pumped when surplus electricity is available, from a lower elevation reservoir to a higher elevation one. The energy is recovered when demand is high by releasing the water: the pump becomes a turbine, and the motor a hydroelectric power generator.

PV systems can be broadly classified in two major groups:

1) Stand-Alone: These systems are isolated from the electric distribution grid. Figure 5.1 describes the most common system configuration. The system described in Figure 5.1 is actually one of the most complex; and includes all the elements necessary to serve AC appliances in a common household or commercial application. An additional generator (e.g., bio-diesel or wind) could be considered to enhance the reliability but it is not necessary. The number of components in the system will depend on the type of load that is being served. The inverter could be eliminated or replaced by a DC to DC converter if only DC loads are to be fed by the PV modules. It is also possible to directly couple a PV array to a DC load when alternative storage methods are used or when operating schedules are not of importance. A good example may be water pumping applications were a PV module is directly coupled to a DC pump, water is stored in a tank through the day whenever energy is available.

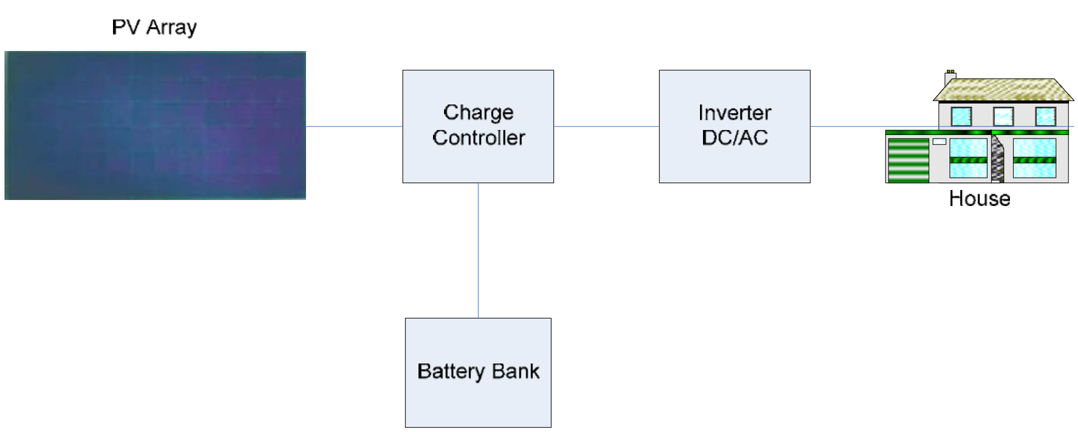


Figure 5.1 Stand-Alone Photovoltaic System

- Grid-Tied: These systems are directly coupled to the electric distribution network and do not require battery storage. Figure 5.2 describes the basic system configuration. Electric energy is either sold or bought from the local electric utility depending on the local energy load patterns and the solar resource variation during the day, this operation mode requires an inverter to convert DC currents to AC currents. There are many benefits that could be obtained from using grid-tied PV systems instead of the traditional stand-alone schemes.

- Smaller PV arrays can supply the same load reliably.
- Less balance of system components are needed.
- Comparable emission reduction potential taking advantage of existing infrastructure.
- Eliminates the need for energy storage and the costs associated to substituting and recycling batteries for individual clients. Storage can be included if desired to enhance reliability for the client.
- Takes advantage of the existing electrical infrastructure.
- Efficient use of available energy. Contributes to the required electrical grid generation while the client's demand is below PV output.

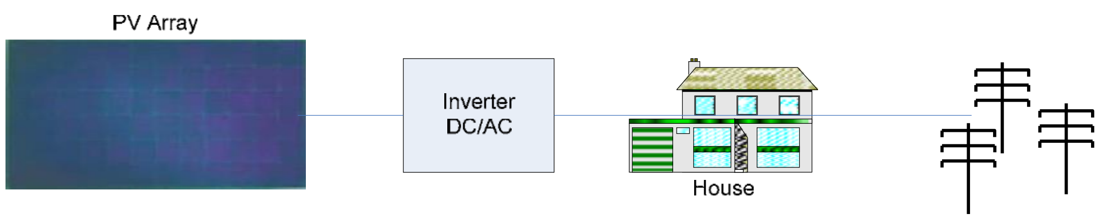


Figure 5.2 Grid-Tied Photovoltaic System

Hybrid systems may be possible were battery storage or a generator (or both) can be combined with a grid connection for additional reliability and scheduling flexibility (at additional cost). Most of the installed residential, commercial and central scale systems use pre-fabricated flat plate solar modules, because they are widely available. Most available reports on PV system costs are therefore related to this kind of technology and shall be our focus in this chapter. Other specialized technologies are available (e.g., concentrating PV systems), but not as commercially available as the traditional PV module.

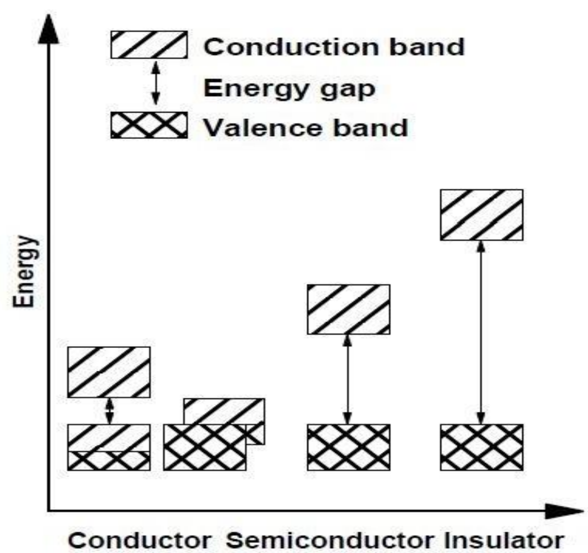
Electricity Generation with Solar Cells

The photovoltaic effect is the basic physical process through which a PV cell converts sunlight into electricity. Sunlight is composed of photons (like energy accumulations), or particles of solar energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons hit a PV cell, they may be reflected or absorbed. Only the absorbed photons generate electricity. When this happens, the energy of the photon is transferred to an electron in an atom of the cell (usually silicon atoms). The electron is able to escape from its normal position associated in the atom to become part of the current in an electrical circuit.

To produce the electric field within a PV cell, the manufacturers create a junction of two different semiconductors (types P and N). The most common way of making P or N type silicon material is adding an element that has an extra electron or has a deficit of an electron. Silicon is the most common material used in manufacturing process of photovoltaic cells. Silicon atoms have 14 electrons, where the four electrons in the last layer are called valence electrons. In a crystal solid, each silicon atom normally shares one of its four valence electrons in a covalent junction with another silicon atom. The silicon crystal molecule is formed of 5 silicon atoms in a covalent junction.

The process of doping introduces an atom of another element into the silicon crystal to alter its electrical properties. The element used for doping has three or five valence electrons. Usually Phosphorus is used to make the N type (Phosphorus has 5 valence electrons) and Boron the P type (Boron has 3 valence electrons). In a polycrystalline thin-film cell the top layer is made of a different semiconductor material than the bottom semiconductor layer .

Besides the positively charged protons and the uncharged neutrons inside the nucleus an atom is composed of the negatively charged electrons that assume discrete energy levels (such as "shells" or "orbitales") around the nucleus. There is a limited number of electrons that can occupy a certain energy level; according to the so-called Pauli exclusion principle any possible energy level may only be occupied by a maximum of two electrons. These two electrons are only allowed if they again differ from each other by their "spin" (i.e. self angular momentum).



Conductors: (metals and their alloys) two different conditions might occur:
The most energy-rich band (i.e. conduction band) occupied by electrons is not entirely occupied.The most energy-rich band fully occupied with electrons (i.e. valence band) and the conduction band located on top overlap, so that also a partly covered band (conduction band) is formed. electrical conductors are characterized by a low specific resistance.With rising temperature, the increasing thermal oscillation of the atomic cores impedes the movement of the electrons.This is why the specific resistance of metals increases with a rising temperature.

Insulators:

- (e.g. rubber, ceramics) are characterized by a valence band fully filled with electrons, a wide energy gap ($E_g > 3$ eV) and an empty conduction band.
- Hence, insulators possess virtually no freely moving electrons.
- Only at very high temperatures (strong "thermal excitation") are a small number of electrons able to overcome the energy gap.
- Thus, ceramics, for instance, show conductivity only at *very high temperatures*.

Semiconductors:
(e.g. silicon, germanium, galliumarsenide) are insulators with a relatively narrow energy gap (0.1 eV < E_g < *3* eV*)*.

Therefore, at low temperatures, a chemically pure semiconductor acts as an insulator.
Only by adding thermal energy, electrons are released from their chemical bond, and lifted to the conduction band.
This is the reason why semiconductors become conductive with increasing temperatures.
This is the other way round compared to metals, where conductivity decreases with rising temperatures.

Regarding specific resistance, semiconductors are in-between conductors and insulators.
Within the transition area between semiconductors and conductors, in case of very narrow energy gaps (0 eV < E_g < *0.1 eV), such elements are also referred to* as metalloids or semi-metals as they may show similar conductivity as metals.
However, unlike "real" metals they are characterized by a reduced conductivity with decreasing temperatures.

Crystalline silicon is such an indirect semiconductor, and silicon cells must thus be relatively thick and/or contain an appropriate light-trapping scheme to generate a prolonged optical path length.

Amorphous silicon, CdTe or CIS are in contrast direct semiconductors.
Solar cells made of these materials can thus have a thickness clearly below 10 μm, while the thickness of crystalline silicon solar cells typically stretches from 200 to 300 μm.
Thinner crystalline silicon cells are under development, but must be provided with the discussed optical properties, resulting in increased manufacturing expenditure.

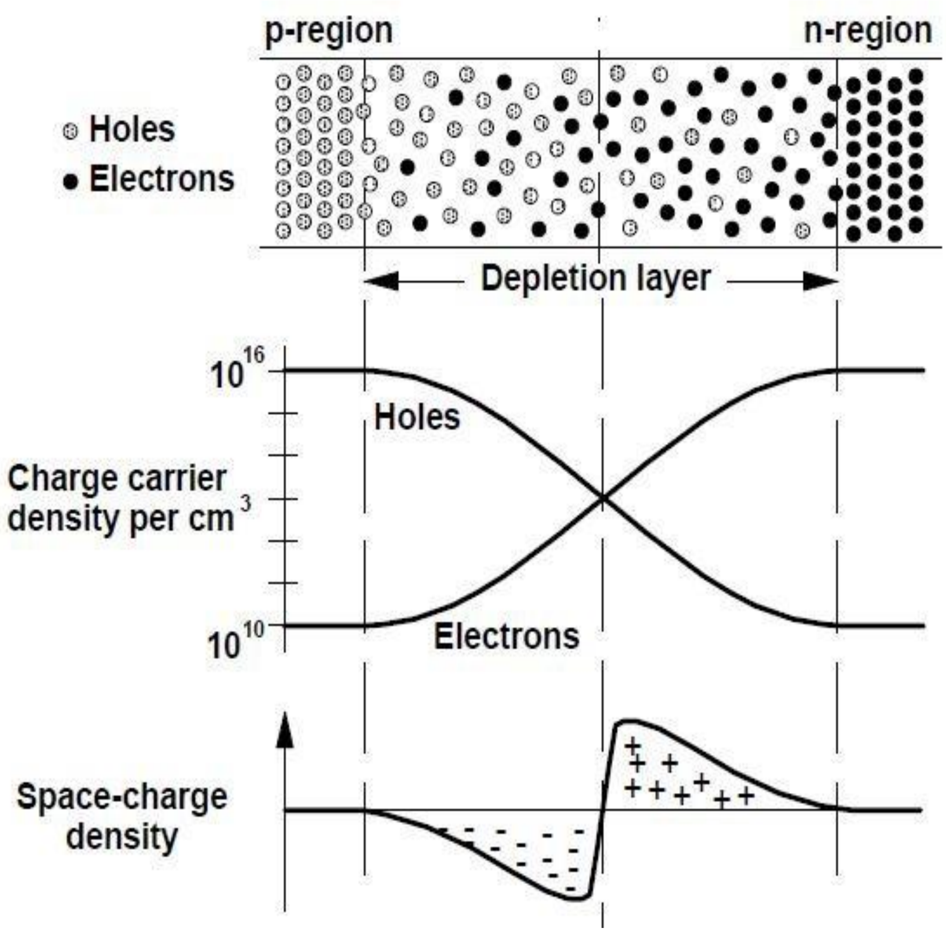
Photo Effect

The term "photo effect" refers to the energy transfer from photons (i.e. quantum of electromagnetic radiation) to electrons contained inside material.

Photon energy is thereby converted *into potential and kinetic energy of electrons*.
The electron absorbs the entire quantum energy of the photon defined as the product of Planck's quantum and the photon frequency.

PN Junction

- If p- and n-doped materials brought into contact*, holes from the p-doped side diffuse into* the n-type region and vice versa.
- First a strong concentration gradient is formed at the p-n- junction, consisting of electrons inside the conduction bandand holes inside the valence band.
- Due to this concentration, gradient holes from the p-region diffuse into the n-region while electrons diffuse from the n- to the p area.
- Due to the diffusion, the number of majority carriersare reduced on both sides of the p-n-junction.
- The charge attached to the stationary donors or acceptors then creates a negative space charge on the p-side of the transition area and a positive space charge on the n-side.



As a result of the equilibrated concentration of free charge carriers an electrical field is built up across the border interface (p-n-junction).

The described process creates a depletion layer in which diffusion flow and reverse current compensate each other.

The no longer compensated stationary charges of donors and acceptors define a depletion layer whose width is dependent on the doping concentration

Photovoltaic Effect

If photons, the quantum's of light energy, hit and penetrate into a semiconductor, they can transfer their energy to an electron from the valance band

- If such a photon is absorbed within the depletion layer, the region's electrical field directly separates the created charge carrier pair The electron moves towards the n-region, whereas the hole moves to the p-region.

- If, during such light absorption, electron-hole-pairs are created outside of the depletion region within the p- or n region (i.e. outside of the electrical field), they may also reach the space-charge region by diffusion due to thermal movements (i.e. without the direction being predetermined by an electrical field).
- At this point the respective minority carriers (i.e. the electrons within the p-region and the holes in the n-region) are collected by the electrical field of the space-charge region and are transferred to the opposite side.
- The potential barrier of the depletion layer, in contrast, reflects the respective majority carriers.

Photovoltaic Cell And Module

- The basic structure of a photovoltaic cell consisting of p-conducting base material and an n-conducting layer on the topside.
- The entire cell rear side is covered with a metallic contact while the irradiated side is
- equipped with a finger-type contact system to minimize shading losses.
- Also full cover, transparent conductive layers are used.
- To reduce reflection losses the cell surface may additionally be provided with an anti-reflecting coating.
- A silicon solar cell with such construction usually has a blue color. By the incorporation of inverse pyramids into the surface reflection losses are further reduced.
- The inclination of the pyramid surfaces is such that photons are reflected onto another pyramid surface, and thus considerably enhance the possibility of photon penetration into the crystal.
- Absorption of the solar light by these cells is almost complete, the cells appear black

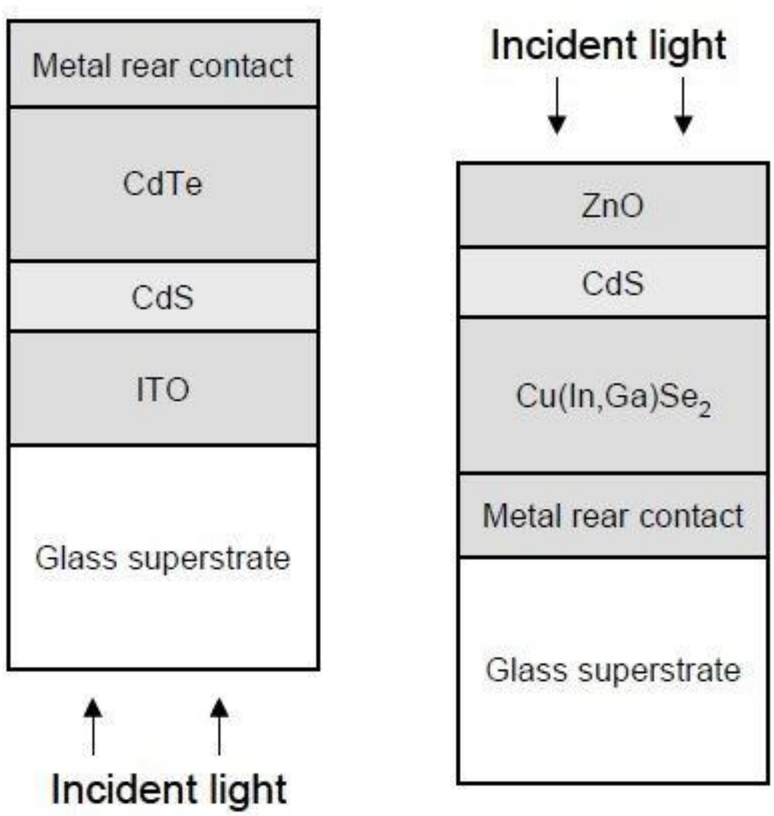
Solar cell

- Since solar cells are (still) relatively expensive, there is a tendency to concentrate solar radiation and thus to reduce the required surface of the photovoltaic cells.
- Furthermore, efficiencies of photovoltaic cells tend to increase with increased irradiance – if cell temperature remains constant.
- For concentrating systems, more expensive but more efficient solar cell technologies may be

applied cost-efficiently.

 For instance, mirror and lens systems are used to concentrate solar radiation.

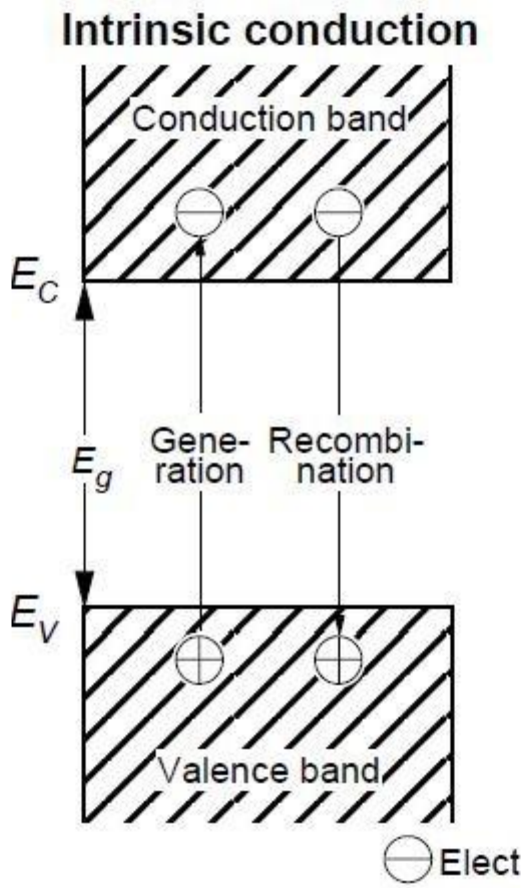
- But under these circumstances tracking systems are additionally needed, helping to enhance the energy yield per unit surface.
- Such concentrating systems are most suitable for direct radiation (only direct radiation can be focused) and thus for regions throughout the world where the solar radiation is determined by direct irradiance (like in deserts).



Intrinsic conductivity:

Semiconductors are conductive beyond a certain temperature level as valence electrons are released from their chemical bonds with increasing temperatures and thus reach the conduction band (intrinsic conductivity).
They become conduction electrons that are able to move freely through the crystal lattice (i.e. electron conduction).

On the other hand, also the resulting hole inside the valence band can move through the semiconductor material, since *a neighboring electron can advance to the hole*.
Holes thus contribute equally to conductivity (hole conduction).
Since every free electron creates a hole within undisturbed pure semiconductor crystals both types of charge carriers equally exists.



Energy gap model

- Intrinsic conductivity is counteracted by recombination, namely the recombination of a free electron and a positive hole.
- Despite this recombination *the number of holes and free electrons remains equal* since at a certain temperature level always the same number of electron-hole-pairs are formed as recombine.

For every temperature, there thus *exists an equilibrium state* with a certain number of free holes and free electrons.

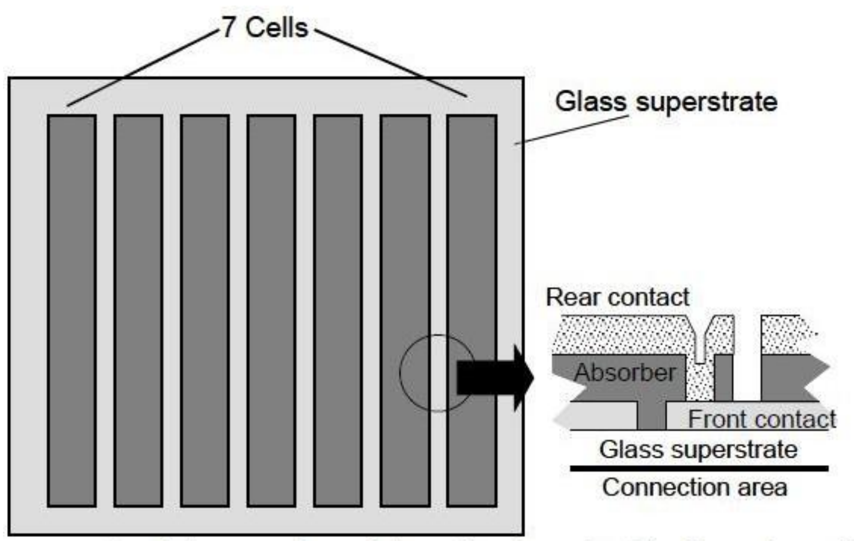
- The number of free electron-hole-pairs increases with rising temperature.

Solar cells for concentrating photovoltaic systems:

- Solar cells of concentrating photovoltaic systems are illuminated up to 500 times more at standard test conditions (STC) compared to fixed mounted cells.
- However, at higher radiation concentrations *the serial resistance constitutes a major problem due to the high currents*.
- This is why concentrator cells must be especially highly doped and be provided with low-loss contacts
- Terrestrial concentrating photovoltaic systems are almost exclusively provided with silicon-based solar cells, whose structure is similar to that of the highly efficient silicon solar cells mentioned above.
- On a laboratory scale, they reach electrical efficiencies of up to 29 % at 140- fold concentration of the radiation.

For such concentrator systems it is of particular importance to avoid high temperatures, which will cause power losses.
Further more it has to be taken into consideration that high concentration factors, in the range of several 100's, do need a two axis tracking system and only direct radiation can be used.

Polycrystalline Si Monocrystalline Si
**Thin film solar cells made of crystalline silicon (Different process)*



Solar Module

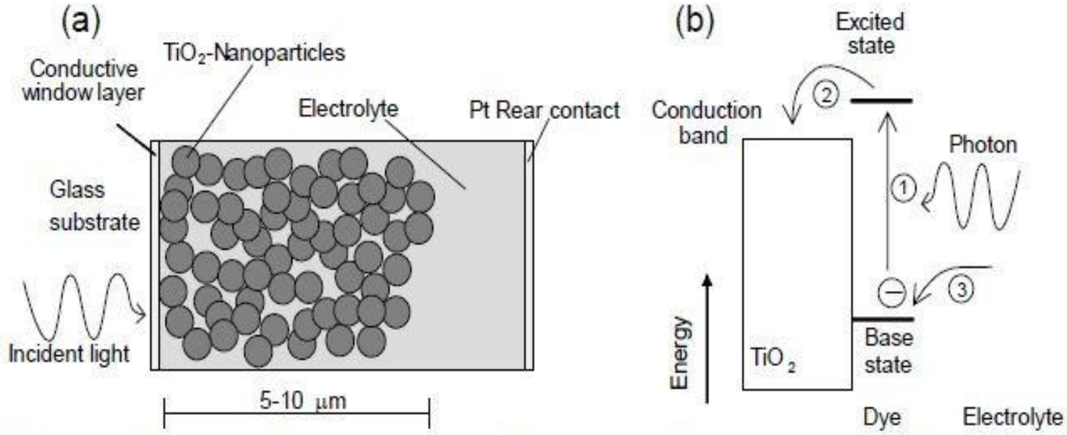


Fig. 6.14 (a) Schematic illustration of a dye solar cell of nano-porous TiO_2 (not shown: single-molecular dye layer adsorbed by TiO_2 nanoparticles of a thickness of approximately 20 nm); (b) simplified energy scheme illustrating the primary charge carrier separation by a three-step process: 1 excitation of dye; 2 injection of the electron from the excited status of the dye into the conduction band of TiO_2; 3 regeneration of dye from the electrolyte

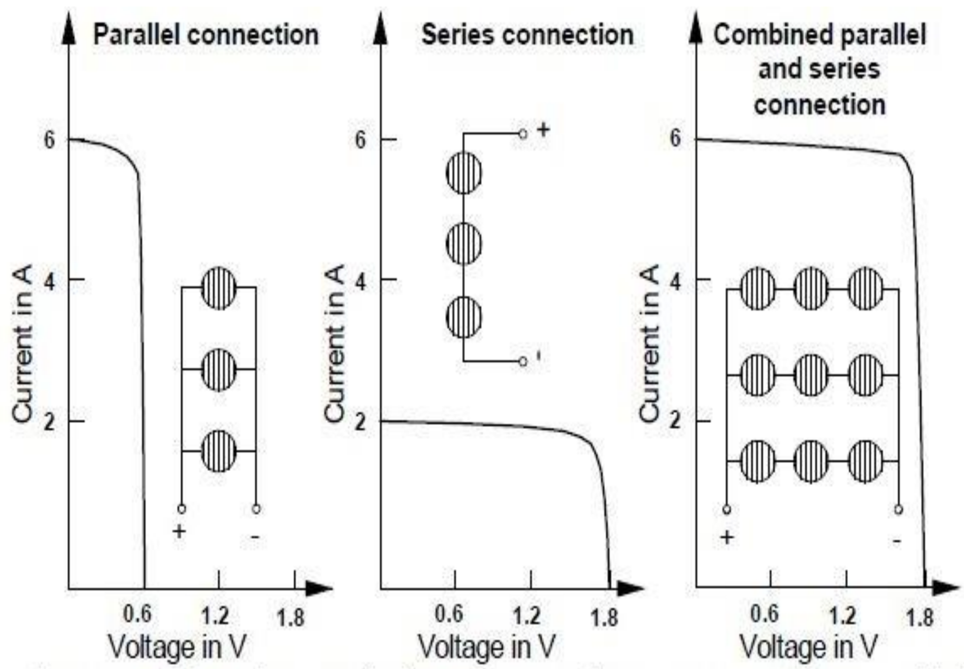


Fig. 6.15 Change of the characteristic current-voltage curve when combining various photovoltaic cells to a module exemplarily for cells of 2 A short-circuit current and 0.6 V open-circuit voltage (according to various sources)

Photovoltaic Systems Total Costs Overview

The PV industry is rapidly maturing because of worldwide environmental concerns and its energy production potential due to the widely available free solar resource. The industry is in a race to achieve grid parity (PV energy costs equal to conventional utility costs) and increase competitiveness in the energy markets. PV system installed costsrange from 4,600 to 19,500 $/kW (typically the size of the PV array is used to determine the kW or W rating of the system when complete system costs are considered). Common figures are 8,000 $/kW for grid-tied systems, and 14,000 $/kW for stand-alone systems. Energy production costs are typically estimated above 0.18
$/kWh in the United States, yet these energy costs are highly dependent on the available solar resource at the location under study and cannot be used as a general reference. Table 5.1 summarizes some of these factors.

Table 5.1 Summary of Factors Affecting PV System Costs and Feasibility

Factors	Facts
Grid connection	• Grid-connected systems do not need batteries which reduces considerably initial capital costs and energy costs. • For a comparable load, grid-tied systems use smaller PV arrays than stand-alone systems. • Grid-Tied systems are estimated to cost ~$4,800/kW less than stand-alone systems including inverters and batteries according to the study in systems built in the US between 1997-2000.
Distance to nearest	• Stand-alone systems tend to become feasible In

utility grid	locations which are far from electrical distribution networks. • Grid extensions can cost thousands of dollars per mile of transmission line.
Solar resource	• Solar resource will not affect capital costs but the availability of solar energy does affect the cost of producing energy, hence the payback period for the investment. • According to location is considered the second largest factor affecting PV system cost performance. • Location can have influence on shading patterns, soiling, operating temperature and solar resource variations.
BOS (tracking)	• Balance of system components is estimated to represent 30-50% of the total costs of a PV System. • Most cost reductions for PV systems over the last decade are in BOS components including inverters. • Local safety codes or regulations can require additional balance of system costs for the installation.

Type of installation , Mounting, size and Space	• When flat roofs are considered, 10^{o} tilt uses 30% more roof area when flat roofs are considered Commercial and industrial clients prefer horizontal installation to maximize flat roof utilization and to lower mounting expenses.
	• Retrofit installations tend to be more expensive than those planned for new buildings. According to :
	  ▪ Large residential projects are ~$1.2/W_{ac}$ less expensive.
	  ▪ Affordable Housing projects are ~$1.9/W_{ac}$ less expensive.
	  ▪ Custom New House ~$0.18/W_{ac}$ more expensive.
	• Large Scale systems tend to be less expensive on a per watt basis. Due to the volume or the purchases, developers take advantage of wholesale prices or discounts. This is also true for large residential projects as discussed above.
	• Due to capital cost restrictions, stand-alone systems tend to be smaller or used for smaller loads.
	• Grid-tied systems tend to be larger because they provide lower capital costs and energy costs for larger loads.

	• Typically larger systems tend to have lower cost per kW. According to costs diminish ~$40 for every additional kW.
Module technology	• Modules account for 40-50% of total system costs. • Module efficiency determines the total area needed to install the system. Less area per watt is desired to maximize roof or land use. • PV modules that require less material, energy and time to develop have lower costs (details below).
PV production	• Supply and demand laws have been slowing the cost of PV modules in the last years. Market shortage of PV modules has been particularly driven by high demand and silicon supply shortage. • US production of both silicon and PV modules is constantly increasing to satisfy the demand. • Many research efforts today seek to reduce the quantity of materials used per module, one example is thin-film cell technology. • A doubling in PV production results in ~20% module price reduction .
Time and Learning Curve	• According to next year cost reduction for systems built in the US between the years 1997 and 2000 is ~ $600/kW. • According to a 7.3% annual decline has been observed on small scale system costs since 1998. Large scale systems showed lower reductions, yet these tend to be less expensive for each watt of capacity. • Lower component costs are complemented by the acquired knowledge by system designers and installers who can perform their jobs more efficiently as they gain experience, reducing overall costs as well.
O&M	• Most PV systems do not have notable O&M costs especially grid-tied systems. • The study in suggests $11/kW/yr. for small residential and commercial systems and $27/kW/yr. • According to O&M costs may range between 0.4 to 9.5 cents/kWh although most tend to the lower limit. • Most small scale grid-tied systems do not have moving parts and therefore maintenance is minimal. • Large-scale systems may use tracking systems and therefore may require more work.

	• Battery assisted systems may require acid refills when valve regulated batteries are not used. • Some arrays will require regular cleaning. This could represent additional costs especially for large scale systems. • Tree branch trimming may be also considered O&M costs were applicable. • Batteries, inverters and charge controllers will probably require at least one replacement during project lifetime, it is therefore important to consider equipment lifetime and replacement cost as part of O&M costs during a projects lifetime. Insurance and inspection should also be considered.
Energy Use and Cost	• System size depends mostly on energy use, solar resource and component efficiency. • Reducing energy consumption greatly reduces the initial capital cost investment necessary. • The average energy use for the US is ~10W/ft^2. • Average residential energy use in Puerto Rico is ~800kWh/month. • PV systems can be cost competitive in locations with high energy prices and Net metering programs. The assumption that PV is expensive is therefore relative to the solar resource and utility energy prices in a location.
Indirect benefits (home value, GHG reduction, etc.)	• Home appraisal is estimated at ~$20 for every $1 reduction in annual utility bills . • Customers would pay 10% more for a solar equipped residence . • Emissions reductions provide a wide range of economical, environmental and health benefits. These are difficult to quantify, yet they cannot be ignored.
Available grants or Incentive Programs	• PV technology is considered very expensive in most applications; therefore several strategies have been implemented to jumpstart the widespread use of the technology. Some of these are: - Tax Deductions - Renewable Energy Credits - Emissions Reduction Credits - Net Metering Programs - Accelerated Depreciation - Grants • Not all have positive effects; therefore incentive programs should be carefully tailored.

Financing and economic variables	• Debt term, debt ratio, interest rate and project life have market effect on payback time and energy costs.
	• Small systems (residential or commercial) can be financed at 7-8.5% interest rates, these numbers coincide with local financing institutions.
	• Larger systems can be financed at lower rates.
	• Project specific financial parameters are not the only factors having effect on PV system economic performance. The economic performance is also affected by external parameters like inflation and energy escalation rates.
	• Energy costs in Puerto Rico are currently between $0.21 and $0.25, and rising due to the heavy dependence on petroleum derived fuels (June 2008).
	• In Puerto Rico inflation is 8%, energy cost escalation rate is 14% .
	• Utilities generally use MARR values between 3 and 18%. The 6 to 11% range is most common .
	• According to average MARR values for private investment (big money) or corporations are:
	  - 40% for high risk investments (new products, new business, acquisitions, joint ventures).
	  - 25% for medium risk investments (capacity increase to supply forecasted sales).
	  - 15% for low risk investments (Cost improvement, make v.s. buy, capacity increase to meet existing orders).
	• MARR values for individuals are not commonly available and are difficult to calculate.
	• 20 year debt terms are common for utilities.
	• 12 year debt terms are common for developers.
	• Residential systems can be financed with debt terms in the range of 5 to 15 years. Is systems are financed as part of residential mortages, debt terms would tend to the upper limit. Personal loans tens to the lower limits.
	• 5 year MACRS depreciation methods are common in many incentive programs.

Photovoltaic Energy Equipment: General Characteristics and Costs

Cost information on individual components and labor affecting the overall cost of grid- tied PV systems is compiled below along with a brief description of each item. The data for individual components represents the estimated average unit cost for an individual unit, not considering bulk or wholesale special prices. The information found agrees with the total costs information compiled in the previous section.

1) Photovoltaic (PV) Modules: The basic building block of a photovoltaic module is the photovoltaic cell; these convert solar energy into electricity. The power output will depend on the amount of energy incident on the surface of the cell and the operating temperature of the photovoltaic cell. The power output of a single cell can supply small loads like calculators or watches, but in order to be useful for high energy demand projects these cells must be arranged in series and parallel connections. A photovoltaic module is an array of photovoltaic cells pre-arranged in a single mounting mold. The type of module is therefore determined by the cells that compose the module itself. There are three dominating cell technologies:

   - Monocrystalline: As the name implies, these are cells that are grown from a single crystal. The production methods are difficult and expensive. These tend to be more efficient (more power in less area) and more expensive.
   - Multicrystalline: The production process allows multiple crystalline structures to develop within the cell. It is easier to implement in a production line. It is relatively cheaper than mono- crystalline at the expense of lower efficiency.
   - Thin-film: Uses less silicon to develop the cell (hence the name thin film) allowing for cheaper production costs (silicon is in high demand). It tends to be less expensive but has also lower efficiency.

   The overall efficiency of the module will depend on the cell efficiency and placement within the module, and on the laminating materials used. The standard testing condition (STC), defined as a total irradiance of $1000W/m^2$ and an ambient temperature of 25^oC, is used to define module ratings. Typical module efficiencies range between 11% and 17% for crystalline technologies at STC; most of the commercially available modules are in the lower bound of this range. Thin-film module efficiencies range between 6% and 12% . Since 2003 total PV production grew in average 50%, whereas the thin film segment grew almost 80% and reached 196 MW or 8% of total PV production in 2006. About 90% of the current production uses wafer-based crystalline silicon technology. The main advantage of this technology was that complete production lines could be bought, installed and manufactured within a relatively short time. This predictable production start-up scenario constitutes a low-risk placement with high expectations for return on investments.The technology is receiving much benefit from research that strives to make existing technologies cheaper and more accessible. The Energy Information Administration (EIA) reports that 26 companies were expected to introduce new photovoltaic products in the market in the year 2007. Recent years have presented new alternatives to the way solar modules are built and implemented.

Examples of creativity include shingles and windows that use photovoltaic cells as part of their design. Architects and engineers have developed ways to use PV modules in building facades substituting them for regular building materials, hence reducing the net cost of the PV generated energy. The approach is known as building integrated photovoltaic (BIPV) architecture.

2) Inverters: Inverters are used to transform DC current into AC currents. In the photovoltaic industry, inverters can be classified into two broad categories:

- Stand-Alone Inverters- These inverters are meant to operate isolated from the electrical distribution network and require batteries for proper operation. The batteries provide a constant voltage source at the DC input of the inverter. Inverters can be classified briefly as:
  - Square Wave Inverters
  - Modified Sine Wave Inverters
  - Sine wave inverters (quasi-sine wave).

  Voltage and current waveforms produced by inverters are never perfect sinusoids (even for sine wave inverters); therefore some harmonic currents are expected during normal system operation. Total harmonic distortion (THD) is a measure of the harmonic content in current and voltage waveform. The type of inverter used will depend on the load that it will serve. Resistive loads could tolerate square wave inverters which are cheaper and easier to develop. Motors and sensitive electronics will need inverters that are able to produce almost perfect sinusoidal voltage and current waveforms in order to operate correctly. These tend to be more expensive and difficult to design. The designer should choose inverters according to load types and power requirements. Modern stand-alone inverters have software applications embedded that monitor and control equipment operation.

- Grid-Tied Inverters- These inverters operate coupled to the electric distribution network and therefore must be able to produce almost perfect sinusoidal voltages and currents. The operating requirements for these types of inverters are in most cases determined by the local utilities, yet most utilities rely on existing standards to determine feasible technologies. The most referenced standards in the United States are the IEEE1547 and the UL 1741. These standards include the minimum requirements that manufacturers should include into their inverter designs in order to prevent adverse effects in the distribution grid [20]-[24]. Normally, embedded software applications monitor and control equipment operation to comply with standard requirements. There are two main categories of grid-tied inverters. Line-commutated inverters derive their switching signals directly from the grid line currents. The low switching frequencies produce harmonic currents that need to be filtered out. In the case of small single-phase inverters the bulky and expensive filtering networks are not practical. In the case of large three phase inverters, multiple units could be connected through a multi-phase isolation transformer at the utility output, filtering any unwanted currents . Self-commutated inverters derive their switching frequencies from internal control units as they monitor grid conditions, in particular frequency and voltage. High switching frequencies (3 – 20 kHz) are used and therefore lower current harmonic content is possible without the need of using large filtering networks. Self-commutated inverters can be either voltage source inverters or current source inverters. PV modules behave like voltage sources; therefore our interest will be in voltage source type inverters. Voltage source type inverters can yet again be subdivided into current control and voltage control types. In applications where there is no grid reference, voltage control schemes are used and the inverter behaves as a voltage source. Where a grid connection is used the current control scheme is used and the inverter behaves as a current source. These inverters use the utility voltage as reference to provide the current available from the PV, and are not able to operate as an island. The advantages of current control voltage source inverters are:

- Power Factor (PF) ~ 1 (employing a simple control scheme).
- Transient Current Suppression: The fault current is limited in the range of 100% to 200% rms rated current. The fault contributions of these inverters are limited by their control and protection system. The fast switching frequencies these inverters use, allow them to detect large currents that may exceed their semiconductor ratings and stop operation within 0.5 cycles .

Some stand-alone inverters can also be operated as grid-tied inverters or in combination with other renewable energy sources as part of hybrid power systems. Modern inverters can achieve efficiencies higher than 95% (especially grid-tied inverters) and are warranted for 5 to 10 years in most cases. Most inverters have efficiencies above 85%.

3) Batteries: These are most commonly used to store energy in stand-alone applications for use at times when no irradiance is available (e.g. night, rainy day). Batteries are also used for a diverse number of applications including stand-by power and utility interactive schemes. PV batteries require tolerance to deep discharges and irregular charging patterns. Some applications may require the batteries to remain at a random state of charge for a prolonged time. The most common technology used in PV systems is the lead-acid battery. These batteries are available in two major categories:

- Flooded (Vented)- This is the regular battery technology most people are used to. It tends to be the cheapest option when only initial costs are of interest. In this battery, overcharge results in the conversion of water into hydrogen and oxygen gases. The gases are released into the atmosphere; hence the batteries require that the water is replaced adding a maintenance cost to the system.
- Valve Regulated- The chemical characteristics of these batteries allow for maintenance free operation because the oxygen is allowed to recombine with the hydrogen within the battery. The recombination has a maximum rate which depends on the charging current. If excess pressure builds up, it

is vented through valves to the atmosphere, proper charge control can limit this effect. These batteries tend to allow deeper discharge cycles resulting in smaller battery banks and are expected to have longer life times. There are two main technologies available: Absorbed glass mat (AGM) and Gel. Another advantage of these sealed batteries is that most are spill proof.Nickel-Cadmium batteries can also be used in PV applications, especially where extreme temperatures are expected that could lower the battery life of lead-acid batteries. Some batteries of this technology allow discharges of 90% or more of rated capacity and tolerate prolonged periods at sub-optimal state of charge without damage or memory effect. Nickel-Cadmium batteries are 3 to 4 times more expensive per stored kWh and are highly difficult to dispose off due to their toxic potential. Battery technology is relatively old, and is often regarded as the weakest link in photovoltaic systems. Improper care of the batteries can seriously affect battery lifetime.

4) Balance of System Components (BOS) and Charge Controllers: BOS components typically constitute 30-50% of total system costs. They are all the additional elements necessary in order to properly install the PV system. The minimum requirements are regulated in the 2005 NEC (the 2008 version is now available as well) . A comprehensive overview can be found in BOS components may include:

- Conductors, conduits and boxes
- Overcurrent Protection (e.g. Fuses and Breakers)
- Ground Fault Protection
- Mounting Gear (support structure)
- Disconnects
- Metering Equipment
- Maximum Power Point Trackers
- Charge Controllers
- Battery Enclosures

The cost of the support structure could vary considerably depending on whether the system is to be mounted on the building wall, or roof, or whether it is to be ground mounted. For an array installed flush into a ceiling, support structure costs are negligible. More complicated structures may cost ~$200/m^2. Tracking system costs are in the $300 to $1,200 per m^2. Large or simple structures are in the lower boundary region of this range. Small complicated tracking systems are in the upper boundary region of this range.

System installation is in the $900 to $2,500 per kW . Installation costs depend on system size, location and complexity. Larger systems could require heavy machinery and larger crews. Land based systems could require terrain preparation and trench digging.

Electrical equipment could cost ~$700/kW for simple or residential systems and ~$1,500/kW for industrial systems . Costs are determined by system complexity and system size. Stand-alone systems generally have higher costs than grid-connected systems on a per watt basis.

Charge controllers are part of the electrical equipment costs. These control the current flow from the PV array to the battery in order to ensure proper charging. These controllers disconnect the PV array from the battery whenever produced energy exceeds battery storage capacity or the load whenever charge levels are dangerously low or reach a certain threshold. It is common for charge controllers to monitor battery voltage, temperature, or a combination of both to determine depth of discharge. The controllers extend battery life and are a safety requirement of the National Electrical Code (NEC) for residential and commercial installations. It is important to select a proper charge controller and controller settings for the battery type selected for the system. Some controllers can be adjusted to accommodate different battery types; some are built for specific battery technologies exclusively. Today, commercially available controllers can achieve efficiencies as high as 95%. Most charge controllers currently available rely on solid state technology to control current flowing into the battery bank; still some electromechanical relay versions available. Electromechanical relays can only perform classic on/off control (therefore little flexibility is possible), this control strategy can still be rough on the battery. Solid state controllers are more varied or flexible in terms of control strategies. Some of the possibilities are:

- On-off
- Constant Voltage
- PWM, constant voltage and with current regulation
- MPPT

The PV industry is relatively new. The industry has space for small companies which specialize in specific equipment, or large corporations which have expanded their product range to include PV related equipment. A list of component manufacturers has been compiled in Table 5.2.

PV Modules

A number of solar cells electrically connected to each other and mounted in a support structure are called a photovoltaic module. Modules are designed to supply electricity at a certain DC voltages such as 12, 24 or 48 volts. The current produced is directly dependent on how much light hits the module. Multiple modules can be wired together to form an array. A larger area of a module or array will produce more electricity. PV modules are rated on the basis of the power delivered under Standard Testing Conditions (STC) of 1 kW/m² of sunlight and a PV cell temperature of 25 degrees Celsius (°C). Their output measured under STC is expressed in terms of “peak Watt” or Wp nominal capacity]. A typical crystalline silicon module consists of a series circuit of 36 cells, encapsulated in a glass and plastic package for protection from the environment. Although PV modules are warranted for power output for periods from 10-25 years, they can be expected to deliver amounts of energy (voltage and current) for periods of 40 to 50 years . Typical electrical information supplied by the manufacturer includes:

- Polarity of output terminals or leads
- Maximum series fuse for module protection
- Rated open-circuit voltage
- Rated operating voltage
- Rated operating current
- Rated short-circuit current
- Rated maximum power
- Maximum permissible system voltage

Table 5.3 and Table 5.4 summarize characteristics of various PV cell technologies.

Table 5.3 Photovoltaic categories by semiconductor selection .

Crystalline silicon solar cells Market Share: 93%	• Monocrystalline, produced by slicing wafers (up to 150 mm diameter and 350 microns thick) from high-purity single crystal. • Multicrystalline
Thin Film Solar Cells Market Share: 7%	• Amorphous silicon • Pollycristalline materials: Cadmium Telluride (CdTe), Copper indium (gallium) Diselenide (CIS or CIGS).

Table 5.4 Advantages and Disadvantages by solar cell technologies .

Cell Type	Advantages	Disadvantages
Single Crystal Silicon	• Well established and tested technology • Stable • Relatively efficient	• Uses a lot of expensive material • Lots of waste in slicing wafers • Costly to manufacture • Round cells can’t be spaced in modules efficiently
Polycrystalline Silicon	• Well established and tested technology • Stable • Relatively efficient • Less expensive than single Crystalline Si • Square cells for more efficient spacing	• Uses a lot of expensive material • Lots of waste in slicing wafers • Fairly costly to manufacture • Slightly less efficient than Single Crystalline Si

Ribbon Silicon	• Does not require slicing • Less material waste than single and polycrystalline • Potential for high speed manufacturing • Relatively efficient	• Has not been scaled up to large-volume production • Complex manufacturing process
Amorphous Silicon	• Very low material use • Potential for highly automated and very rapid production • Potential for very low cost	• Pronounced degradation in power output • Low efficiency

Inverters

Inverters are electronic solid-state devices used to transform electric energy from DC to AC, as shown in Figure 5.7. The simplest inverter can be accomplished with a circuit similar to that shown in Figure 5.8. The ideal switches in the circuit may represent MOSFETs, IGBTs or bipolar transistors (depending on the power and voltage requirements). If the switches are turned on and off at the required AC frequency (S1&S3 and S2&S4), a square wave voltage can be obtained as shown in Figure 5.9. This is a simple control strategy, yet no control of load voltage is possible and high harmonic currents and voltages are present. High frequency pulse width modulation techniques are used to diminish harmonic distortion and provide load voltage control. Harmonic content may cause overheating in motor loads due to higher copper losses as well as uneven magnetic fields affecting overall operation. Sensitive electronic loads may also display erratic operation. Today, advanced control schemes and creative topologies allow the creation of AC with very low harmonic distortion; three phase designs are also possible by incorporating additional switches.

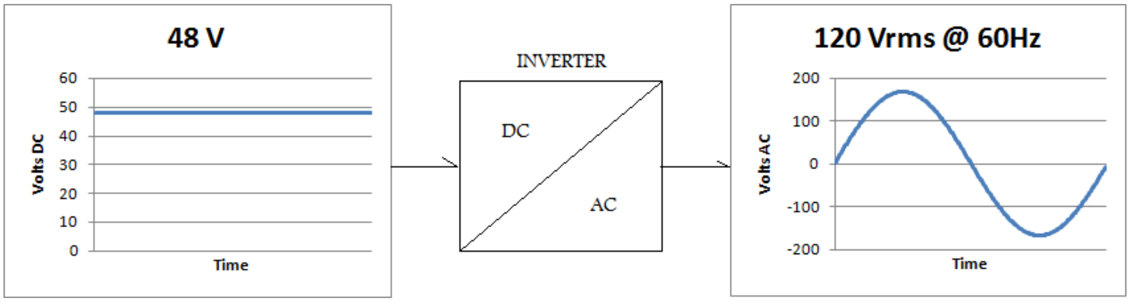
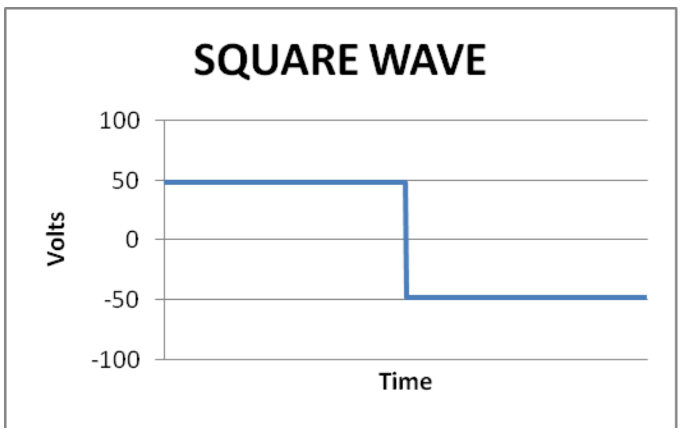


Figure 5.7 Representation of DC to AC conversion Process



Many industries have found applications for inverters; hence design requirements tend to be specific to the needs of a particular application. A whole new industry has evolved around the need of a proper inverter to accommodate the needs of the relatively new solar industry, with both big and small manufacturers entering the market. PV modules produce DC outputs which are dependent on the irradiance, temperature and load operation. Stand-alone inverters operating with energy storage or batteries need a small DC voltage operating range to allow for voltage differences due to battery state of charge, and surge capacity to allow for safe and uninterrupted transient event operation. Grid-tied systems do not normally incorporate energy storage; hence larger DC voltage operating ranges are needed to accommodate both the varying operating conditions and module configurations. Maximum power point tracking control algorithms are normally included to take full advantage of the PV module energy production capabilities. Advanced protection functions are normally also included in order to guarantee safe operation in parallel with the distribution grid. These are just examples of specific requirements for PV inverters in their specific applications. The following section shall summarize current PV inverter characteristics, industry status and trends, especially in the grid-tied market, which is currently of most public interest. The industry challenges attended include:

1. Reliability
2. Inverter lifetime improvements
3. Higher inverter efficiencies
4. Production cost reduction

5. System and installation cost reduction
6. Unreliable or inadequate components or parts
7. Safety
8. Grid connection issues
9. Optimal circuit topologies, etc.

Grid-Tied inverters operate coupled to the electric distribution network and therefore the operation requirements are quite different from those of stand-alone inverters. Figure 5.4 shows a simple block diagram of a grid-connected PV system. Energy Storage is not considered in most grid-connected applications, hence it is not included in the diagram, but it could be an option depending on the reliability needs of the owner. In general terms the system can be divided into the solar panels and the power conditioning equipment, which includes: the maximum power point tracker, the inverter, the galvanic isolation (optional), and protection and control features. These components are commonly integrated in the same enclosure or unit as a way to reduce production and installation costs; hence it has been customary in the PV industry to refer to the combination of all these elements as the inverter. We shall adopt this practice.

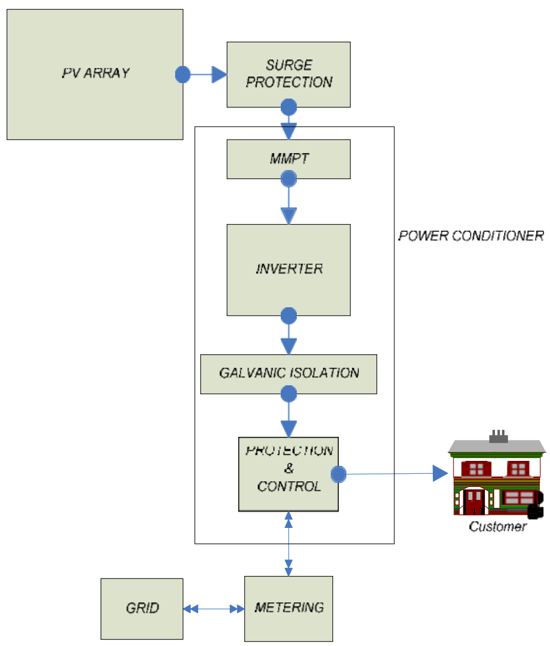


Figure 5.4-Grid-Connected PV System Block Diagram

It is commonly said that grid connected PV systems are as good as their interfaces between the DC and AC power segments. As an example, the best solar modules in the industry will not be of great use if the power is not transformed efficiently and safely to useful levels at the load side. For the utilities it is of no use to allow the integration of DG systems that could degrade the quality of the electric power in the distribution network. Inverter failure will prevent any useful energy being produced. Proper inverter systems should include or consider the following:

- Maximum Power Point Tracker (MPPT) - Nominal voltage and current conditions will not be available from the PV array at all times due to constant changes in solar irradiance. Figure 5.5 displays the I-V curves for a PV module at different operating characteristics. The MPPT guarantees optimum power is always obtained from the PV modules at any given operating condition. Different algorithms have been developed to achieve MPPT control, some achieving more than 98% of the PV array output capacity. The most popular is the Perturb and Observe (P&O) algorithm, this algorithm increases or decreases voltage in small steps and monitors the power output until maximum power point is found. A summary of available literature is available at .

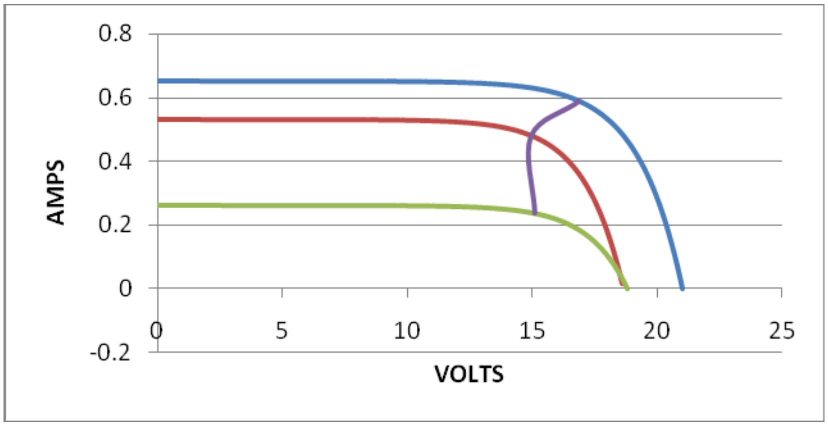


Figure 5.5- I-V Curves for a PV Module at different operating conditions

- Inverter- Inverters have the task of DC/AC conversion. There are two main categories of grid-tied inverters. Line-commutated inverters derive their switching signals directly from the grid line currents. The low switching frequencies produce harmonic currents that need to be filtered out. In the case of small single-phase inverters the bulky and expensive filtering networks are not practical. In the case of large three phase inverters, multiple units could be connected through a multi-phase isolation transformer at the utility output to filter any unwanted currents; the transformers should be rated to withstand additional heating due to harmonic current copper losses [20]. Self-commutated inverters derive their switching frequencies from internal control units as they monitor grid conditions, in particular frequency and voltage. Self-commutated inverters can be either voltage source inverters or current source inverters. PV modules behave like voltage sources; therefore our interest will be in voltage source type inverters. Voltage source type inverters can yet again be subdivided into current control and voltage control types. In applications where there is no grid reference, voltage control schemes are used and the inverter behaves as a voltage source. Where a grid connection is used the current control scheme is preferred and the inverter behaves as a current source. Operating the inverter under current control limits the possibility of active voltage regulation, a high power factor can be obtained with simpler control circuits (usually the power factor is kept as near to unity as possible), and transient current suppression is possible when disturbances as voltage fluctuations occur. Another advantage is that current related power quality disturbances related to inverter operation, like harmonics, can be controlled with ease and independence from voltage quality which then depends entirely on the utility. Problems caused by unusual utility voltages should be the responsibility of the utility because they are commonly associated to more complicated problems. It is important to understand that customer compliance to any standard should be independent to utility compliance to the same issue; the utility should not assume that the customer has total responsibility. The disadvantage of operating using current control is that it cannot operate as an isolated power source. Some inverters are able to handle both control functions to operate as grid connected and also provide conversion for storage batteries working as a backup.

- According to a survey from the IEA for inverters under 50kW, 19 % of inverters in the market use voltage control and while 81% use current control. High switching frequencies (3– 20 kHz) are used in some designs; therefore lower current harmonic content is possible without the need of using large filtering networks. The only problem is that higher switching frequencies result in higher losses reducing the efficiency of the inverter. Designers must find a balance between efficiency, power quality and size.

Energy Storage

In a PV system the energy produced by PV modules does not always coincide with energy demanded. A PV array that it is not grid-connected needs to store the energy excess produced by solar cells. Electrical storage batteries are often employed in Stand Alone PV systems. The primary functions of a storage battery in a PV system are :

1. Energy Storage and Autonomy: Store electrical energy produced by PV modules and supply energy as needed for the load.

2. Voltage and Current stabilization: To supply power to electrical loads at stable voltages and currents.

3. Supply Surge Currents: Supply high peak operating currents to electrical loads or appliances.

In PV systems, lead-acid batteries are most common due to their wide availability in many sizes, low cost and well known characteristics. Electrical storage batteries can be divided into Primary and Secondary Batteries. Table 5.12 shows secondary batteries charge characteristics.

Nickel-Cadmium Charge/discharge characteristics and high cost make them impractical for most PV systems. Flywheels, hydrogen, and other gas storage also have limited applicability in residences.

Charge Controllers

The charge controller is a DC to DC converter whose main function is to control the current flow from the photovoltaic modules array with the purpose of charging batteries. Most of these devices can maintain the maximum charge of the battery without overcharging or reaching the minimum design charge. The main functions of a Charge Controller are:

- Overcharge Protection: The purpose is to prevent the damage in the batteries when they are charged and the PV array still supplies energy. This protection interrupts or restricts the current flow from the modules to the batteries and regulates the batteries voltage.

- Over discharge Protection: During periods of excessive use of energy or little solar irradiation the charge of the batteries could be affected approaching to the point of minimum discharge. The charge controller disconnects the batteries or stop the current flow from the batteries to the load (Load Management) to prevent batteries damage.

There are two basic methods for controlling the charging of a battery from a PV module array:

Shunt Controller: Since PV cells are current-limited the basic operation of shunt controller is short-circuiting the PV modules and arrays. For this reason most shunt controller require a heat sink to dissipate power. The regulation element of these controllers typically is a power transistor or MOSFET.

Shunt Interrupting: The shunt interrupting controllers completely disconnect the array current when the batteries reach the voltage set point. When the batteries voltage decreases, the controller reconnects the array to resume charging the batteries.

Shunt Linear: When the batteries become nearly fully charged, the controller maintains the battery near a set point voltage by gradually shunting the array through a semiconductor regulation element.

Series Interrupting: This is the simpler of series controller (on-off type). The charge controller constantly monitors the batteries voltage and disconnects the arrays once the batteries reach the set point. When the batteries voltage drops this controller reconnect the array to charge the batteries.

Series interrupting, 2 step, Constant Current: The 2 step, constant current controller is similar to the series interrupting but when the voltage reaches the set point, instead of totally interrupt the array current, a limited constant current remains flowing to the batteries. This continues either for a pre-set period of time, or until the voltage drops to the cycle repeats.

Series interrupting, 2 step, Dual Set Point: This type of series charge controller has two distinct voltage regulation set-points. During the first charge cycle of the day, the controller uses a higher regulation voltage to maximization of the charge and in the other cycle uses a voltage lower voltage set-point. The purpose is minimizing the battery gassing and the water loss for flooded lead-acid type.

Series Linear, Constant Voltage: The linear constant voltage controller maintains the battery voltage at the voltage regulation set-point. The regulation element acts like a variable resistor controlled by the battery voltage sensing circuit of the controller, and dissipates the excess of charge.

Series Interrupting, Pulse Width Modulated: The PWM uses algorithm with a semiconductor switching element between the array and the batteries. The algorithm switches on-off the charge of the batteries with a variable frequency and variable duty cycle to maintain the voltage of the batteries very close to the set-point voltage.

Table 5.14 Controllers Design for Particular Battery types.

Controller Design	Type of Batteries
Shunt Interrupting	All battery types, but recommended by gel and AGM lead-acid battery manufactures.
Shunt Linear	Sealed VRLA batteries.
Series Interrupting	Flooded batteries rather than the sealed VRLA types.
Series Interrupting, 2 step, Constant Current	
Series Interrupting, 2 step, Dual Set Point	Flooded lead-acid types.
Series Linear, Constant Voltage	All battery types.
Series Interrupting, Pulse Width Modulated	Preferred use with sealed VRLA.

Apollo Solar	GeoSolar	Morningstar Corporation	Trace Engineering
Blue Sky Energy	Heliotrope	Pulse Energy Systems Inc	Uhlmann Solarelectronic GmbH
BZ Products	ICP Solar	Ses Flexcharge USA	Vario
DIREC	Lyncom	Specialty Concepts Inc.	
Enermaxer	Outback Power	Sunwize Steca	
ETA Engineering	Pico Electronics Inc.	Sun Selector	
Flexcharge	Plasmatronics	SunAmp Power	

BAND GAP THEORY OF SEMICONDUCTORS

In semiconductors and insulators, electrons are confined to a number of bands of energy, and forbidden from other regions. The term "band gap" refers to the energy difference between the top of the valence band and the bottom of the conduction band. ... In contrast, a material with a large band gap is an insulator

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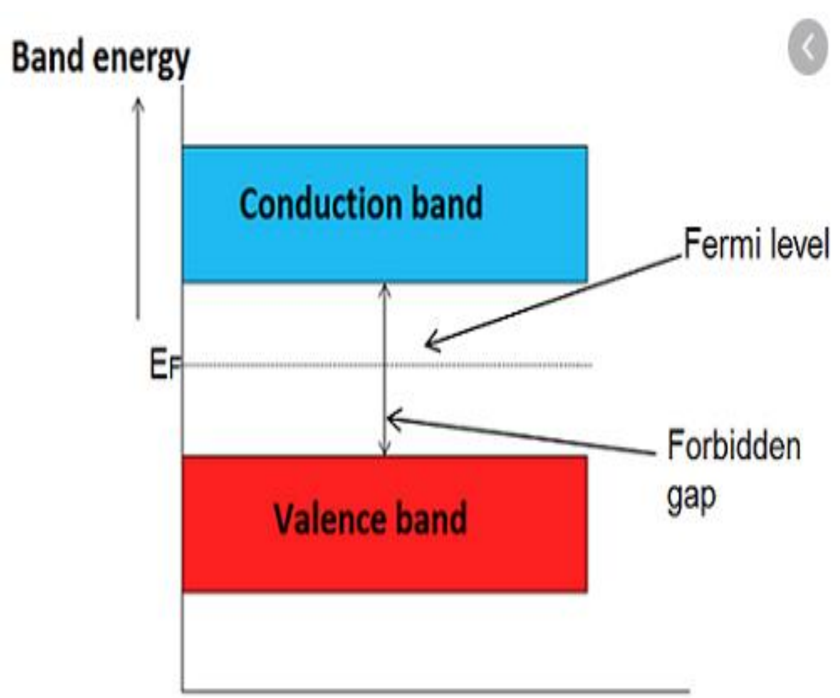
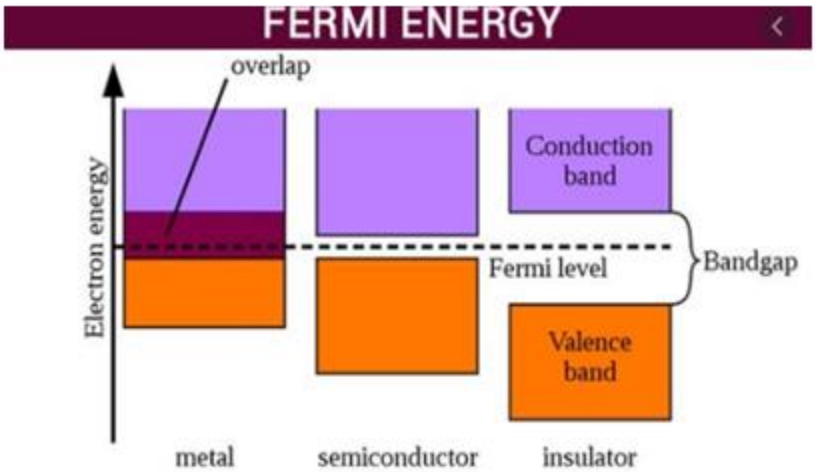
So, one good semiconductor material for the future is C (diamond). It has the largest thermal conductivity and band gap of any of the materials from Table 10.2. Diamond also has the largest electron mobility of any material from Table 10.2 with a band gap larger than Si.

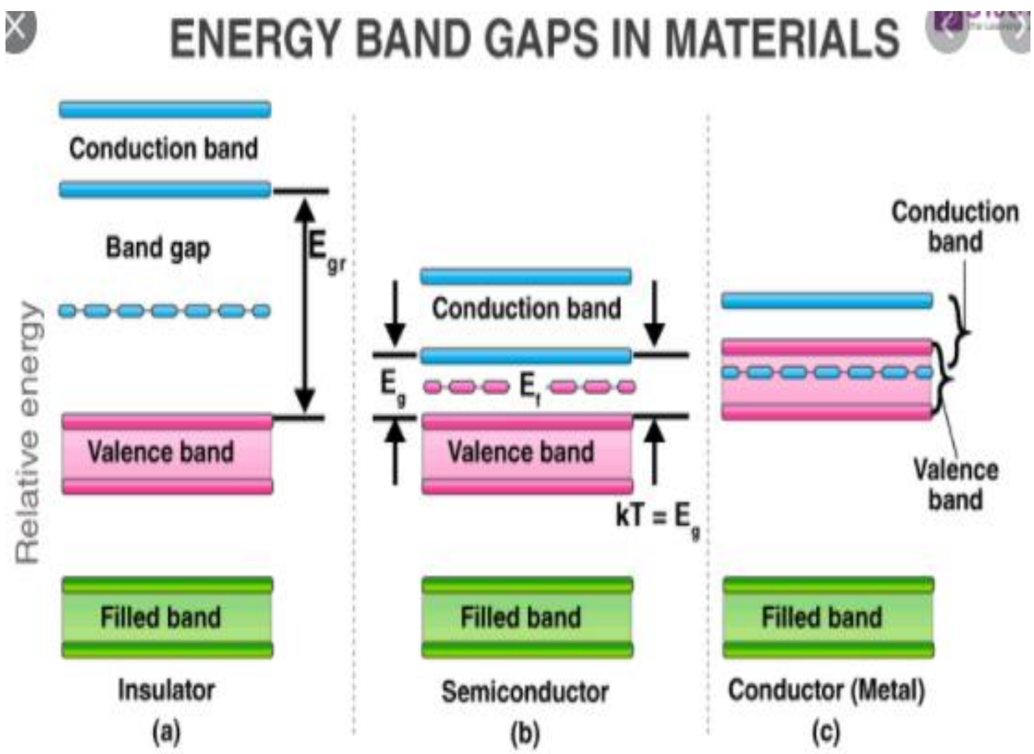
What is p type and n type?

In a p-type semiconductor, the III group element of the periodic table is added as a doping element, whereas in n-type the V group element is the doping element. In the n-type semiconductor, electrons are majority carriers, and holes are minority carriers.

The Fermi Level is the energy level which is occupied by the electron orbital at temperature equals 0 K. ... There is a gap between the valence and conduction band called the energy gap; the larger the energy gap, the more energy it is required to transfer the electron from the valence band to the conduction band




FERMI ENERGY
overlap
Electron energy
Conduction band
Fermi level
Bandgap
Valence band
metal
semiconductor
insulator


ENERGY BAND GAPS IN MATERIALS
Conduction band
Band gap
E_gr
Relative energy
Valence band
Filled band
Insulator
(a)
Conduction band
E_g
E_f
Valence band
kT = E_g
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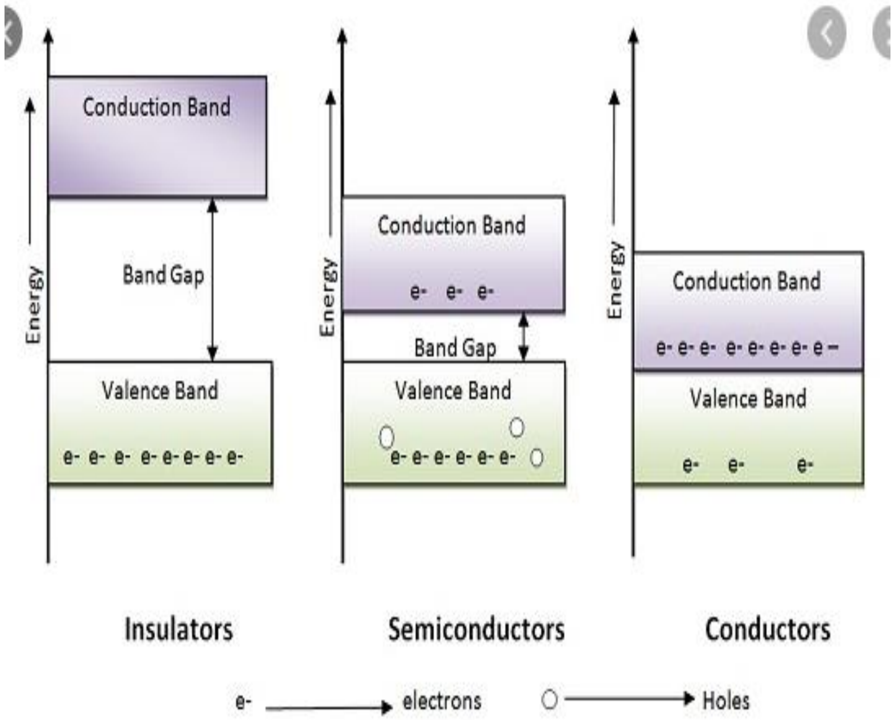

Thermo photo voltaic cells

TPV systems are systems that convert thermal energy into electrical energy. These systems are an alternative to current electrical energy production. Photovoltaic cells convert photon energy from the emitter into electricity energy

Principle of solar cells

1. Emitter converts heat into radiation
2. This is selectively filtered by optical filter. part of it is transmitted to PV diode and the rest is reflected back to emitter
3. the PV diode converts the transmitted photons with energies in excess of the diode energy band gap into charge carriers