Chapter One: Introduction to Renewable Energy

1. Introduction

From the standpoint of energy conservation, energy resources may be classified into two broad categories:

1. **Non-renewable** (discontinuous) resources, which have definite, although sometimes unknown, it is limitations.

Non-renewable resources of energy include:

Coal, Natural gas, Crude oil, ... etc.

2. **Renewable** (continuous) resources that can be freely used without depletion or have the potential to renew for a reasonable period.

Renewable resources of energy include:

Solar energy (Thermal Solar Energy & Electricity Solar Energy), Wind energy, Hydropower, Biomass, Geothermal (Earth heat), Tidal power, Ocean thermal.

Renewable energy is the energy, which can be obtained from natural sources such as sunlight, the wind, water, and earth heat. Renewable energy replaces conventional fuels in two distinct areas: electricity generation, air and water heating/cooling.

Many power stations across the world burn fossil fuels (including coal, oil and gas) to generate energy. Coal is the remains of ancient plants and trees that grew over 200 millions of years ago. Oil and gas are made up of the remains of microscopic plankton. Over millions of years, these remains become the carbon-rich coal, oil and gas we can use as fuel.

When fossil fuels burn, it produces Greenhouse Gases (Carbon dioxide CO_2, Methane CH4, Nitrous oxide N_2O, and Fluorinated gases). Greenhouse gases are a group of compounds that are able to trap heat (longwave radiation) in the atmosphere, keeping the Earth's surface warmer than it would be if they were not present. These gases are the fundamental cause of the greenhouse effect. Increases the number of greenhouse gases in the atmosphere enhance the greenhouse effect, which is creating Global Warming and consequently climate change.

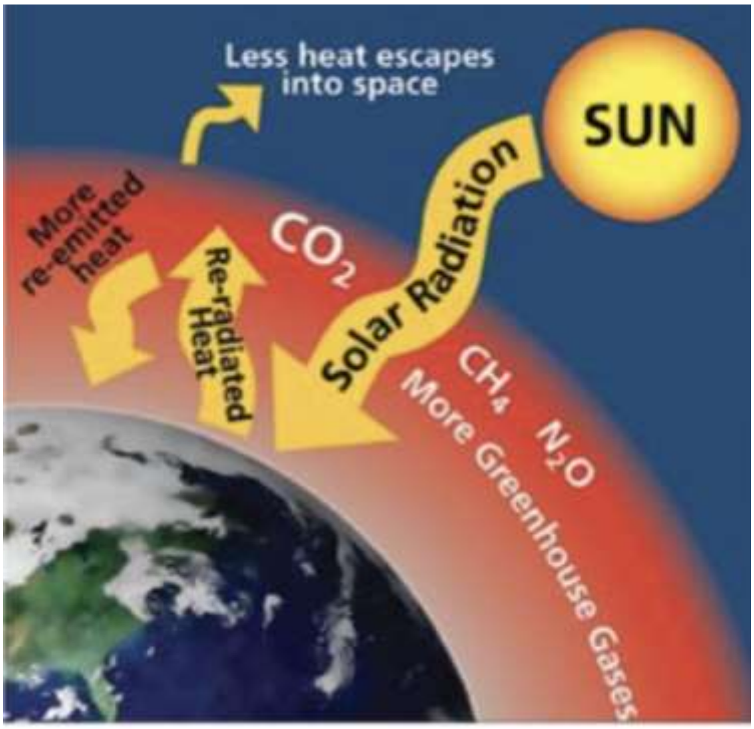


Figure 1: Green house gasses effect

2. Advantages of non-conventional energy sources:

1. **No fuel cost**: Renewable energy resources provide energy continuously at negligible fuel cost and hence these are a cheap source of energy, which makes them favourable over other sources of energy.

Figure 1: world solar energy production

2. **Pollution free and Eco-Friendly**: These Non-Conventional Energy Resources are pollution free and hence are Eco-friendly. This is one of the best things to be considered in this age of global warming.
3. **Lower maintenance cost**: Being simple in design the maintenance cost of these plants is very less and these plants can thus produce electricity at much lower cost than other plants.
4. **Available at plants**: These plants can be installed remotely and at locations completely off grid. Hence better choice for single plant use.

3. **Disadvantages of non-conventional energy sources:**
   1. **High initial cost**: Although running cost and maintenance cost of these plants is very low but installation cost for these plants is very high which is a major disadvantage to these plants.
   2. **Low energy density**: Low energy density is another problem these plants have. Energy per unit area is small in some plants that make them huge in size and hence the large area is required installing them.
   3. **Large land (area) requirement:** such as wind energy field, solar energy and PV cells require large land to create renewable energy plants.
   4. **Seasonal**: These sources are seasonal in nature as solar energy is not available in rainy and winter days. Hydro energy is not available on dry days.

Chapter Two: Introduction to Solar Energy

1. Introduction

Solar energy is the energy that is obtained from sunlight.The two primary ways of harvesting solar energy use either solar collectors that convert the incident solar radiation into heat (Flat solar collector or Concentrating solar power CSP) or photovoltaic (PV) cells that convert incident solar radiation (sunlight) into electricity.

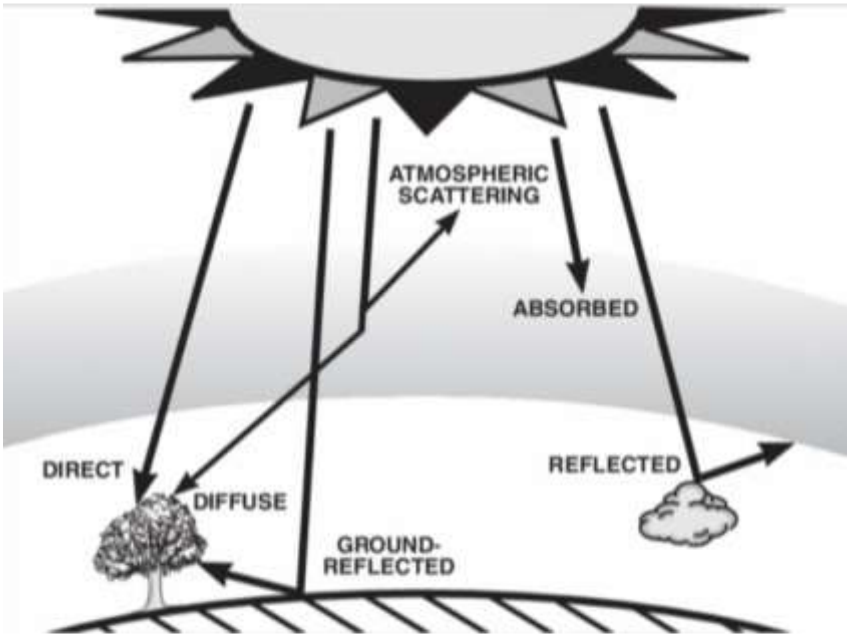


Figure 3: total global, direct, scattered, reflective radiation

<u>The main losses of the solar radiation</u> are largely due to the permanent gases and to water vapour. There is also some diffusion of the direct sunlight caused when direct (and indirect) radiation facing cloud. Not all the solar energy removed from direct radiation by the processes of scattering and absorption reaches the surface of the earth. Some are scattered back to space, and the absorbed energy that is re-radiated at a longer wavelength (mostly from water vapour) is also partly lost to outer space.

Some direct energy is additionally lost by reflection from the upper surfaces of clouds. However, a good deal of the energy which direct radiation loses do eventually reach the surface of the earth in a scattered form.

Notes:

- The solar radiation (the solar constant) is variable during the year because of the eccentricity of the earth's orbit around the sun. Thus, the solar constant varies by ± 3.3% over the year. Its maximum value is at the winter solstice (21-22 Dec.) and its minimum value is at the summer solstice (21-22 June).
- The shortest sun – earth distance $=1.471\times10^{11}$m
- The longest sun – earth distance = 1.521×10^{11}m

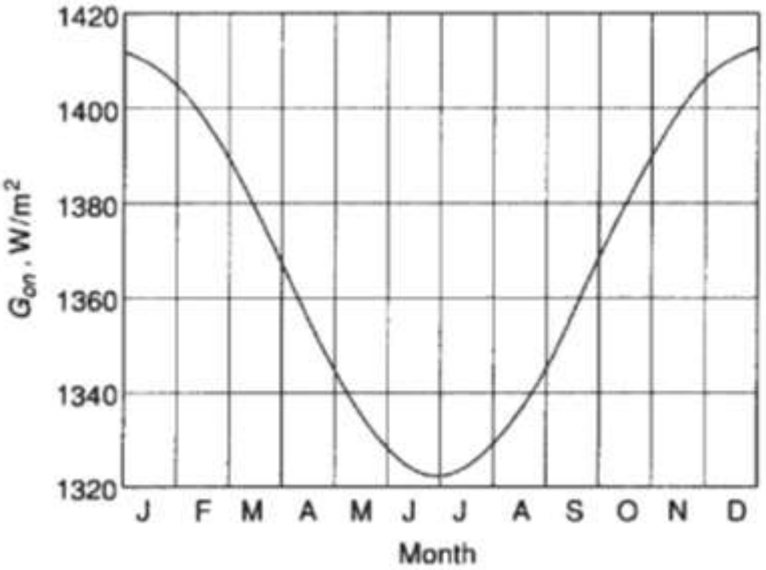


Figure 4: variation of solar radiation during a year

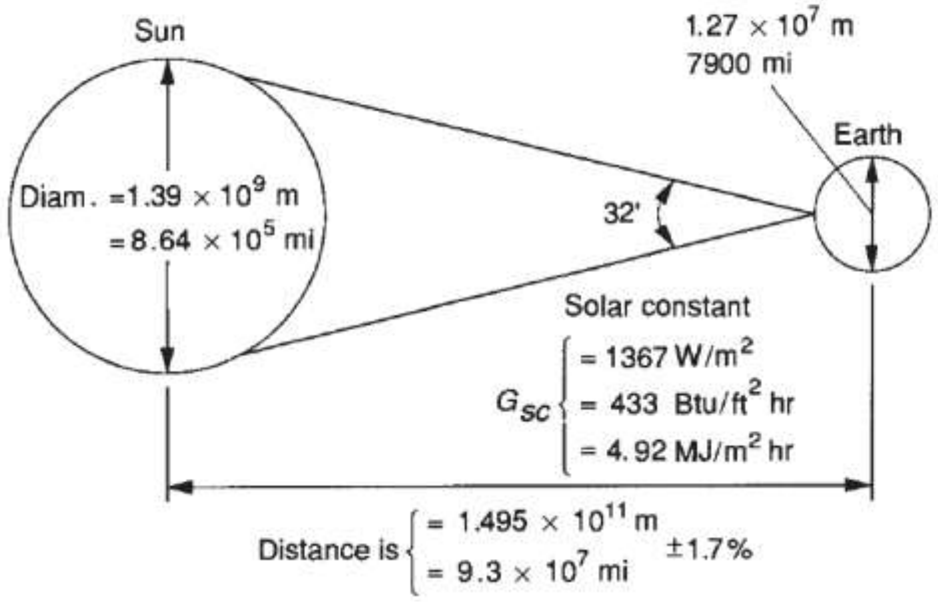


Figure 5: The relationship between Sun & Earth

2. Principal Definitions

There are basic terms in common use to describe the characteristics of solar radiation:

1. Solar time: it is the time in hours (1-24) hr, before and after solar noon. Noon being defined as the time when the sun is highest in the sky at 12:00.

$$\boldsymbol{Solar\ time = standard\ time + E + 4\ (SL - LL)} \qquad (\boldsymbol{hr})$$

where

$\boldsymbol{E}$: the equation of time in minutes, from **Table (1)**

$\boldsymbol{SL}=\boldsymbol{L_{st}}$ the standard longitude meridian for the local time zone in degrees.

$\boldsymbol{LL}=\boldsymbol{L_{loc}}=\boldsymbol{Log}$: the local longitude of the location in question in degree west.

$SL=L_{st}= 44.14^o$ and $LL=L_{loc}= 45^oW$ for Baghdad city.

2. Solar hour angle (h_s): this is the angular displacement of the sun from noon. It is positive before solar noon and negative after solar noon, as shown in Figure 6

$$\boldsymbol{h_s = (12 - solar\ time) \times 15}, \qquad (\ {}^{\boldsymbol{o}})$$

Ex.: Find the solar hour angle when the solar time is 11:15, 12:00, 14:30

Solution:

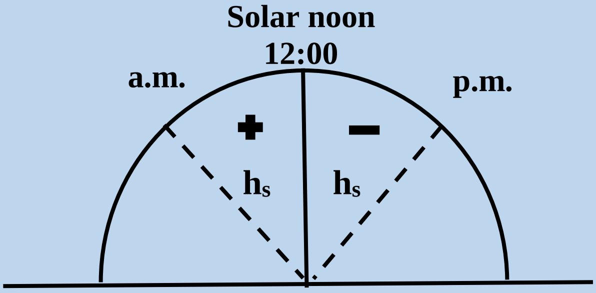


Figure *6*: Solar hour angle (h_s)

3. Solar altitude angle (ALT): is measured from the local horizontal plane upward to the direct solar radiation, as shown in Figure 7.

$$\boldsymbol{ALT = \sin^{-1}[\cos(DEC)\cos(LAT)\cos(h_s) + \sin(DEC)\sin(LAT)]}$$

4. Solar declination (DEC): the declination of the sun is the angle between the sun ray and the directly overhead (the zenith direction) at noon the earth's equator; -23.45° ≤ DEC ≤ 23.45°, as shown in Figure 8.

$$\boldsymbol{DEC = -23.45\cos[0.986(n + 10.5)]}$$

n: the number of the day counted from January from **Table 2.**

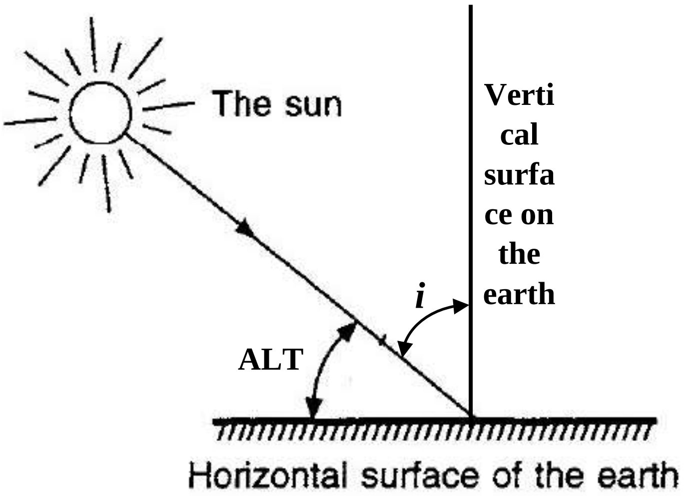


Figure 7: Solar altitude angle (ALT) and Incidence angle (i)

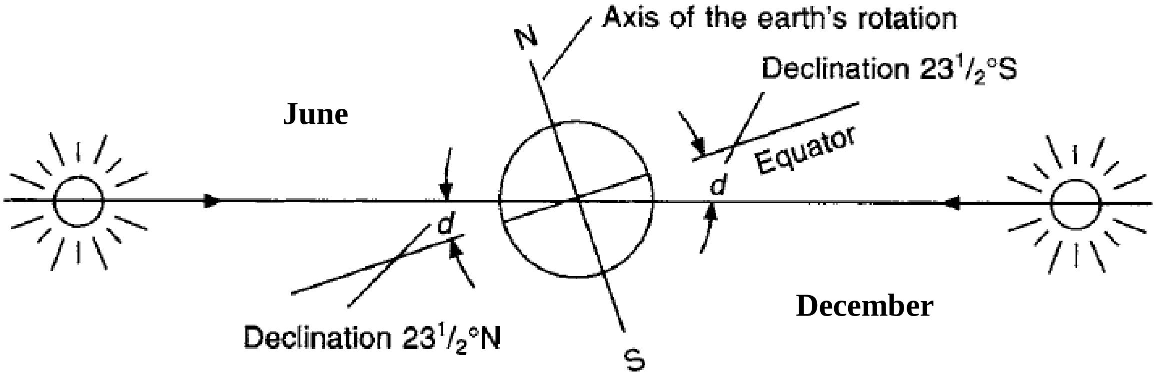


Figure 8: Solar declination (DEC) in June & December

5. Latitude (Lat): The angular location north or south of the equator, measured from the centre of the earth. It is positive for the north position; -90° ≤ Lat ≤ 90°.

LAT for Ramadi city Baghdad city is 33.3°, London city is 15°

6. Longitude (Log): This is the angle, which the semi-plane through the poles, and a particular place on the surface, makes with a similar semi-plane through Greenwich. The semi-plane through Greenwich is an arbitrary zero. Longitude is measured east or west of Greenwich and so its value lies between 0° and 180° Latitude and longitude together are co-ordinated, which locate any point on the surface of the earth.
7. Incidence angle (i): is the angle between the solar radiation and the normal on the surface.

South Facing Horizontal & Vertical Surface Fixed

For vertical surface facing to south that is $a_w=0^o$ & $\beta=90^o$

$$\cos(i) = -\sin(DEC)\cos(LAT) + \cos(DEC)\cos(h_s)\sin(LAT)$$

For Horizontal surface $\beta=0^o$

$$\cos(i) = \sin(DEC)\sin(LAT) + \cos(DEC)\cos(h_s)\cos(LAT) = \sin(ALT)$$

South Facing Titled Surface

For titled surface facing to south $\beta = 0^o\text{-}90^o$

$$\cos(i) = \sin(DEC)\sin(LAT-\beta) + \cos(DEC)\cos(h_s)\cos(LAT-\beta)$$

8. Sunrise time & Sunset time: the sun is a rise or set when the altitude angle (ALT) = 0.

$$\sin(ALT) = [\cos(DEC)\cos(LAT)\cos(h_{ss}) + \sin(DEC)\sin(LAT)]$$

$$0 = [\cos(DEC)\cos(LAT)\cos(h_{ss}) + \sin(DEC)\sin(LAT)]$$

$$\cos(h_{ss}) = -\tan(LAT)\tan(DEC)$$

$$\boldsymbol{Sunset\ time = \frac{h_{ss}}{15}}$$

$$\boldsymbol{h_{sr} = 180 - h_{ss}}$$

$$\boldsymbol{Sunrise\ time = \frac{h_{sr}}{15}} \qquad \text{a.m.}$$

While the day length is calculated from: ***Day length = 2 × Sunset time***

h_{ss}: Sunset angle

h_{sr}: Sunrise angle

Table 1: Different variable data for 21st for each month.

Month	**Jan.**	**Feb.**	**March**	**April**	**May**	**Jun.**
E	-11.2	-13.4	-7.5	1.1	3.3	-1.4
A	2.150	2.050	1.925	1.750	1.600	0.512
I_o	1395	1390	1361.5	1336	1319	1309
B	0.142	0.153	0.177	0.152	0.158	0.184
C	0.058	0.06	0.071	0.097	0.121	0.134
Month	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
E	- 6.2	- 2.4	7.5	15.4	13.8	1.6
A	1.462	1.487	1.580	1.736	1.975	2.050
I_o	1311	1324	1355.5	1368	1387.5	1397
B	0.204	0.180	0.155	0.155	0.181	0.204
C	0.136	0.122	0.092	0.073	0.063	0.057

I_o: Extraterrestrial (outside of earth) solar radiation intensity (W/m^2)

A: Correction factor

B: Shielding coefficient

C: Diffusion factor

Ex. : Find the altitude angle (ALT), solar declination (DEC), solar hour angle (h_s), sunset time, sunrise time and day length if the standard time at Baghdad is 9:15 a.m. for: 21/March, 30/Nov, 15/Feb. and 1/Jan.

Solution:

3. Total Beam, Diffuse and Reflected Solar Radiation on a Surface

Daily, weekly and hourly totals of beam radiation on a surface are important quantities in the prediction of solar system performance.

1. Solar constant ($I_{sun\text{-}earth}$ or I_o): is the average amount of the solar radiation in near the earth space, and its unit is W/m^2.
2. Direct solar radiation (I_{direct}): or beam solar radiation is the solar radiation received from the sun without change of discretion, and its unit is W/m^2.
3. Diffuses solar radiation ($I_{diffuse}$): is the solar radiation received from the sun after its direction has been changed by reflection and scattering due to the atmosphere, and its unit is W/m^2.

The average solar radiation on a surface (W/m^2):

$$\boldsymbol{I_{DN} = I_{ave} = \frac{I_o}{e^{\left[\frac{\mathbf{A.B}}{\sin(ALT)}\right]}}}$$

The direct radiation on a surface (W/m^2):

$$\boldsymbol{I_{direct} = I_{ave}\cos(i)}$$

The diffuse solar radiation on a surface (W/m^2):

$$\boldsymbol{I_{diffuse} = C.F_{ss}.I_{ave}}$$

where **F_{ss}**: angle factor between the surface and sky $\boldsymbol{F_{ss} = \frac{1}{2}(1 + \cos\beta)}$

The total solar radiation on a Surface (W/m^2):

$$\boldsymbol{I_{total} = I_{direct} + I_{diffuse}}$$

The reflected solar radiation on a surface (W/m^2):

$$\boldsymbol{I_R = R[C + \sin(ALT)].(1 - F_{ss}).I_{ave}}$$

R: reflectance factor varies from 0.1-0.7, for white snow and the average value is 0.2. In addition, **I_o, A**, **B** and **C** are taken from **Table 1**.

Ex. : Determine the average solar radiation (I_{DN}), the direct, diffuse, reflected and total solar radiation for Baghdad at solar noon on 15/Dec.

Solution:

Chapter Three: Designing of Solar Thermal Collectors

1. Introduction

Solar energy can be converted to (1) thermal (2) electrical (3) chemical processes. Photovoltaic cells convert solar energy into electricity. Thermal collectors convert the solar energy to thermal energy that is used for space heating and cooling, domestic water heating, power generation and distillation.

In this chapter, we will deal with the thermal solar energy.

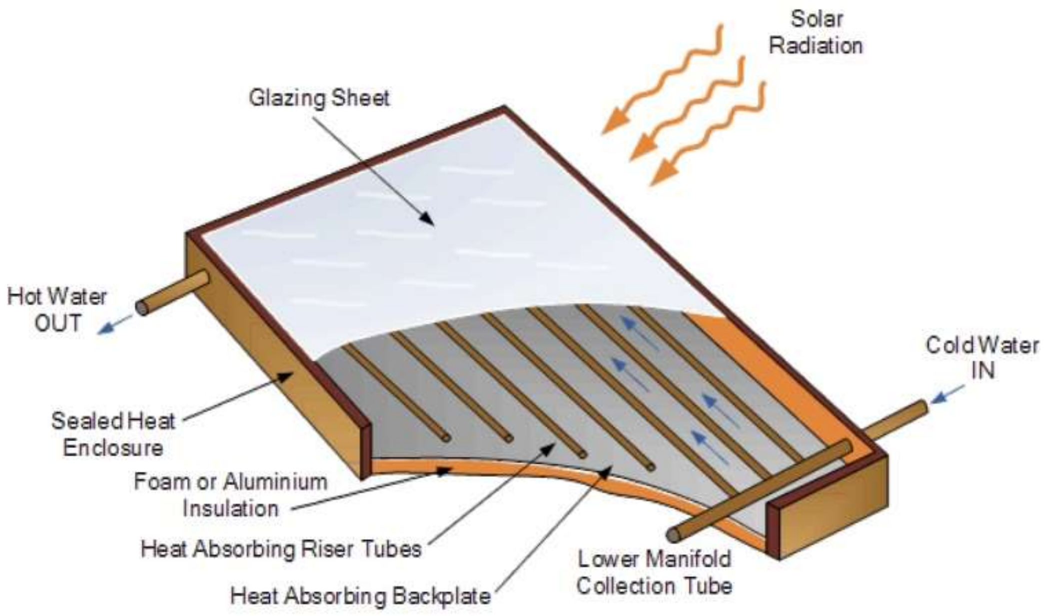
2. Solar Thermal Collectors

Thermal solar collectors are classified into two types: Thermal Solar Flat Collectors and Thermal Solar Concentrating Collectors.

2.1 Solar Thermal Flat Collectors

This type of collector, which is as air and water solar collector, consist of, as shown in:

1. **Glass**: one or more sheets of glass or radiation-transmitting material to pass solar radiation through it, meanwhile losing as little heat as possible to the atmosphere.
2. **Passages, fins, tubes**: fluid passes through the collector to remove heat from the inlet to the outlet of the collector.
3. **Black absorber plate**: flat, corrugated, grooved plates, finned plates. The fluid passes over them to absorb heat and convert it to thermal energy.
4. **Insulation**: to minimise the thermal losses from the back and sides of the collector.
5. **Container or casing**: to surround the collector and protect it from dust, moisture and bad weather conditions.



The principle of physical work of solar collector

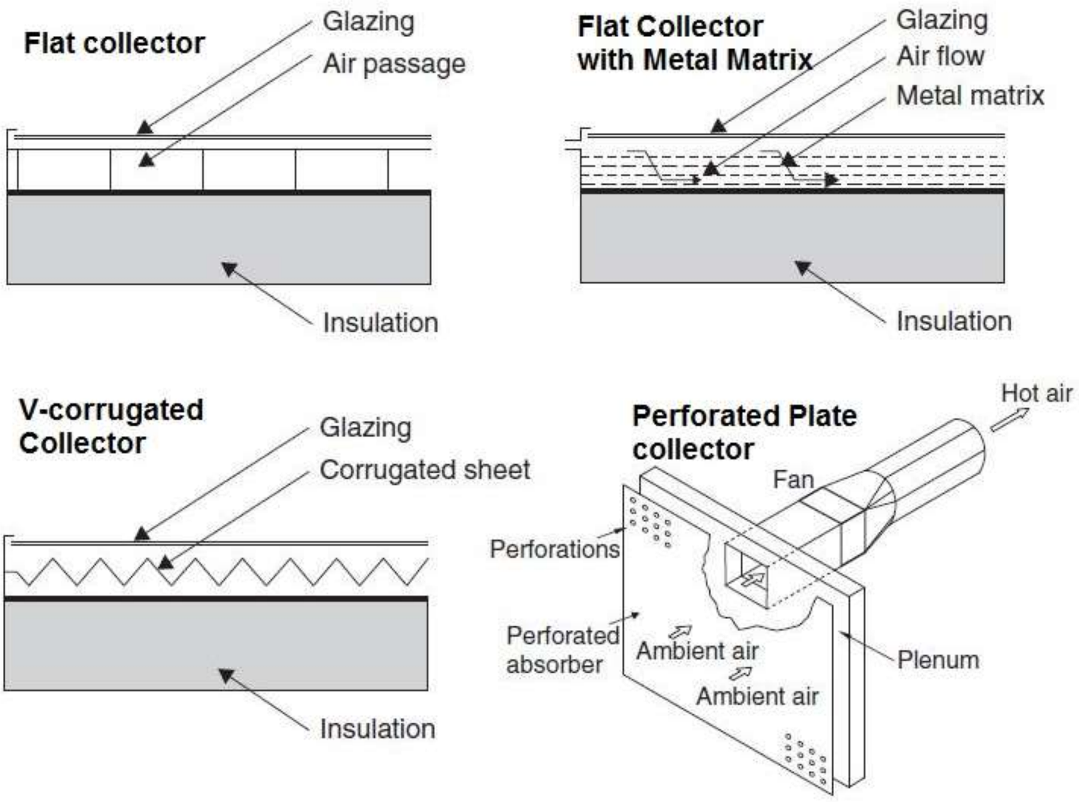
Solar energy collectors are special kinds of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The major component of any solar system is the solar collector. This is a device that absorbs the incoming solar radiation, converts it into heat, and transfers the heat to a fluid (usually air, water, or oil) flowing through the collector.

The basic parameter to consider is the collector thermal efficiency. This is defined as the ratio of the useful energy delivered to the energy incident on the collector aperture. The incident solar flux consists of direct and diffuse radiation. While flat-plate collectors can collect both, concentrating collectors can utilise direct radiation only.

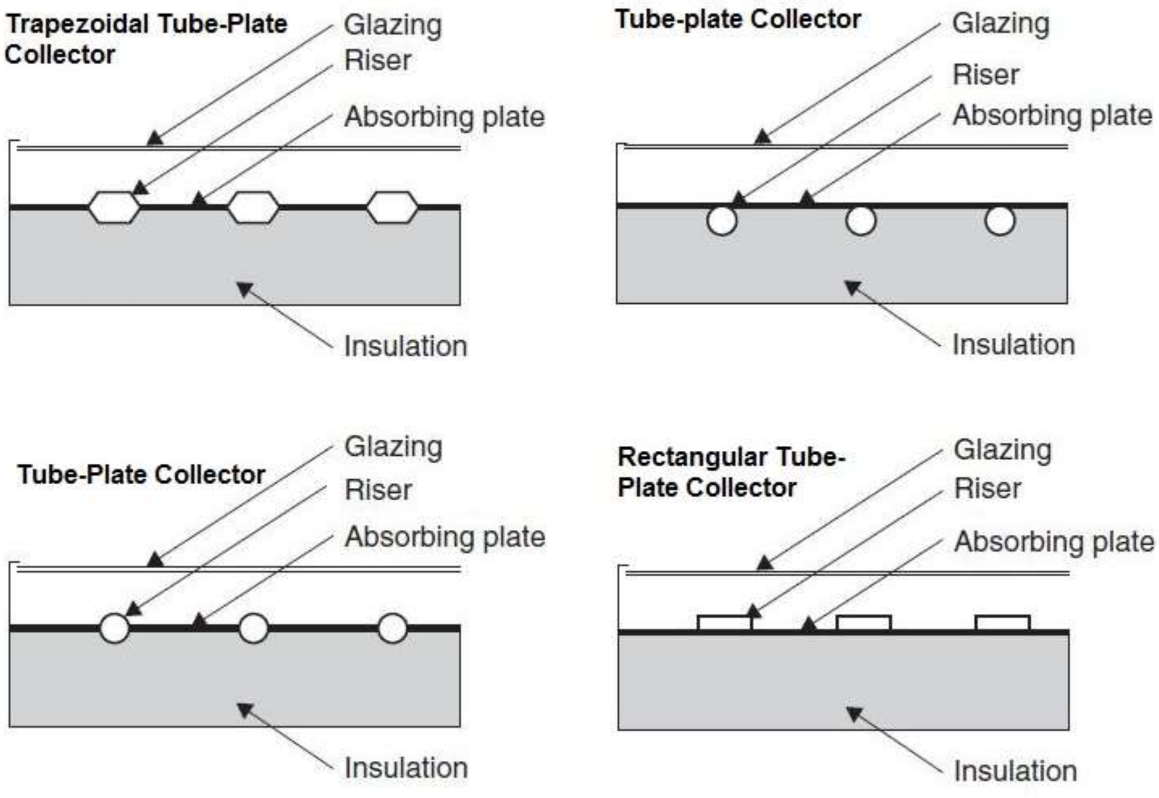
The performance of the solar thermal collector depends on the following criteria:

1. Area of the solar collector
2. Total amount of solar radiation incident on the collector
3. The positioning of the collector's tilt and the collector's orientation.
4. Heat gain.
5. The conversion factor.
6. Heat loss through conduction and convection.

Low-temperature solar collector models operate at high efficiency levels when the temperature difference is between 5 and 30°C and medium-temperature models operate when the temperature difference is between 15 and 200°C.



Types of air solar collectors



Types of water solar collectors

2.2 Solar Thermal Concentrating Collectors

Solar concentrating increase the amount of incident energy on the absorber surface as compared to that on the concentrator aperture. The increase is achieved by the use of reflecting surfaces, which concentrate the incident radiation onto a suitable absorber/receiver.

Ideally, the concentrator system should follow the sun so that sun rays are always focused on the absorber.

Solar concentrator consists of:

1. A focusing device
2. An absorber/receiver
3. Tracking device for continuously following the sun.

Concentrating Collectors systems can be divided to two categories which are line focus technologies and point focusing technologies. The below shows some of the systems belonging to each category.

Concentrated Solar Power

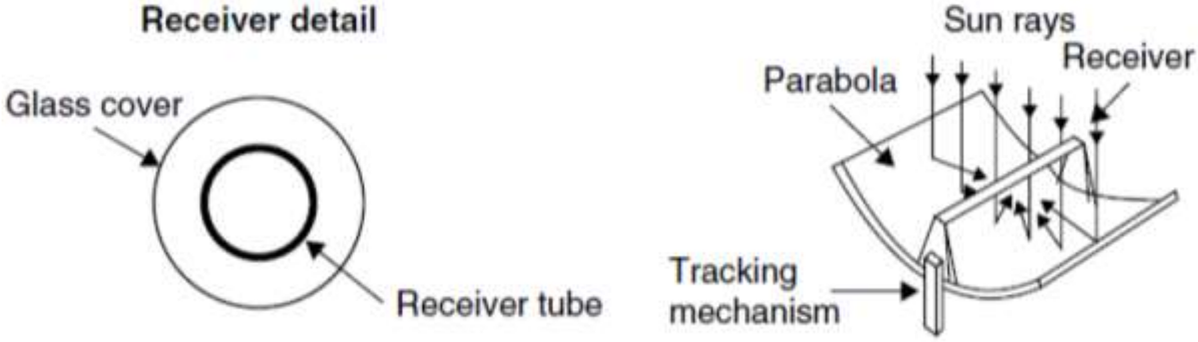
- Line Focus
    - ✓ Parabolic Trough Solar Collectors
    - ✓ Linear Fresnel Reflector
- Point Focus
    - ✓ Dish Solar Collector
    - ✓ Solar Power Tower

I. Parabolic Solar collector (PSC)

To deliver high temperatures with useful efficiency, a high-performance solar collector is required such as concentrating collector. PTCs can effectively produce heat at temperatures between 50 and 400°C.

Parabolic trough collectors are made by bending a sheet of reflective material into a parabolic shape. A black metal tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver. The space between the glass envelope and the tube is evacuated for reducing heat losses as well.

Parabolic trough collectors are the most mature solar technology to generate heat at temperatures up to 400°C for solar thermal electricity generation. PTSCs can be integrated with solar thermal power plants by, heating up a heat transfer fluid (HTF) in the solar field, and then use it in a heat exchanger to generate steam that drives the steam turbine.



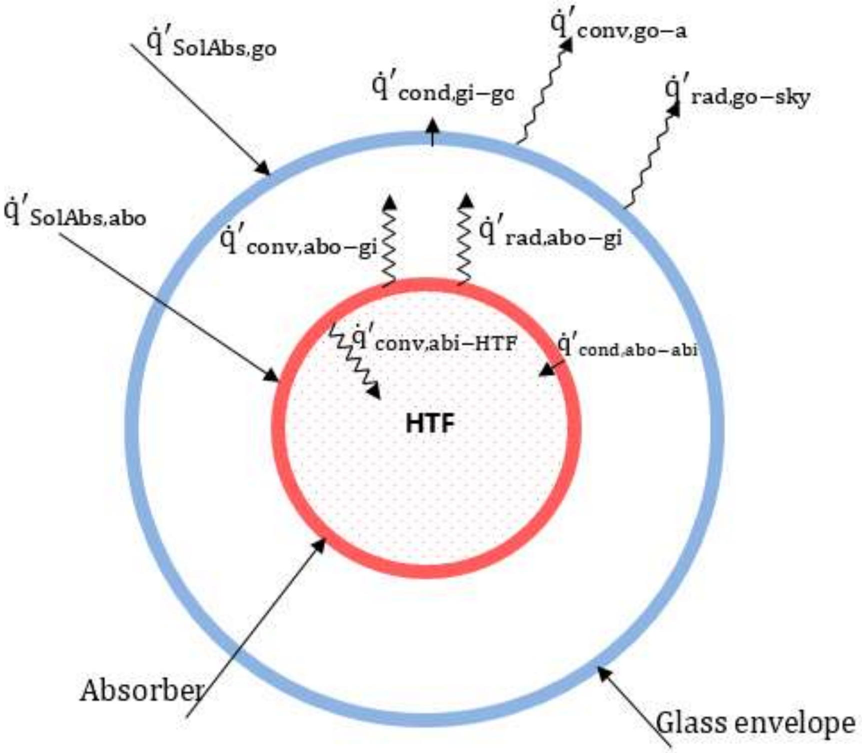
Thermal model

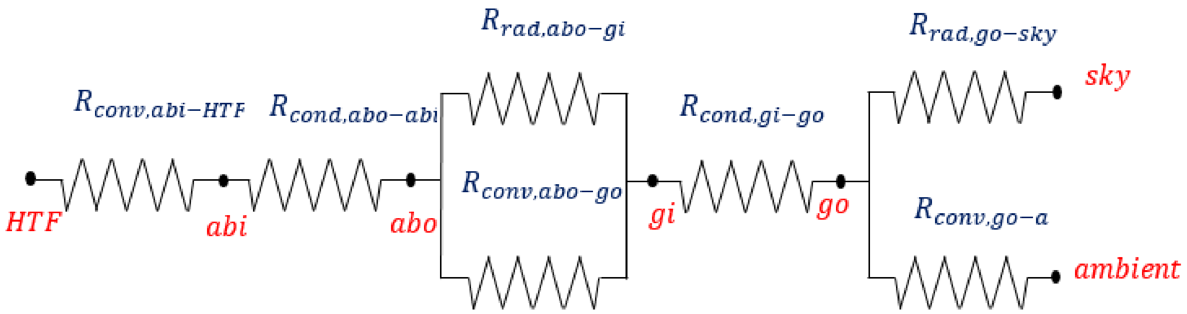
The goal of the thermal model is to determine the energy that is absorbed by the heat transfer fluid (HTF) and describe all the heat losses from the receiver to the atmosphere due to heat transfer mechanisms: conduction, convection, and radiation. Then, the thermal efficiency which is the ratio of the delivered energy to the energy arrived to the reflector can be estimated.

This performance model is based on the energy balance between the heat transfer fluid and the atmosphere. It covers all the correlations and equations needed to describe the energy balance terms.

1. The solar radiation reflected by the reflector is absorbed by the glass envelope ($q_{SolAbs,go}$) and the absorber tube($q_{SolAbs,abo}$).
2. The majority of the energy absorbed by the absorber coating is transferred through the absorber by conduction ($q_{cond,abo-abi}$) and then to the heat transfer fluid (HTF) by convection ($q_{conv,abi-HTF}$).
3. The rest of the energy is transferred back to the glass tube by radiation ($q_{rad,abo-gi}$) and convection ($q_{conv,abo-gi}$).
4. The energy transferred back by convection and radiation is conducted through the glass envelope ($q_{cond,gi-go}$).

5. Then, this energy is lost to the ambient by convection ($q_{conv,go-a}$) and radiation ($q_{rad,go-sky}$).



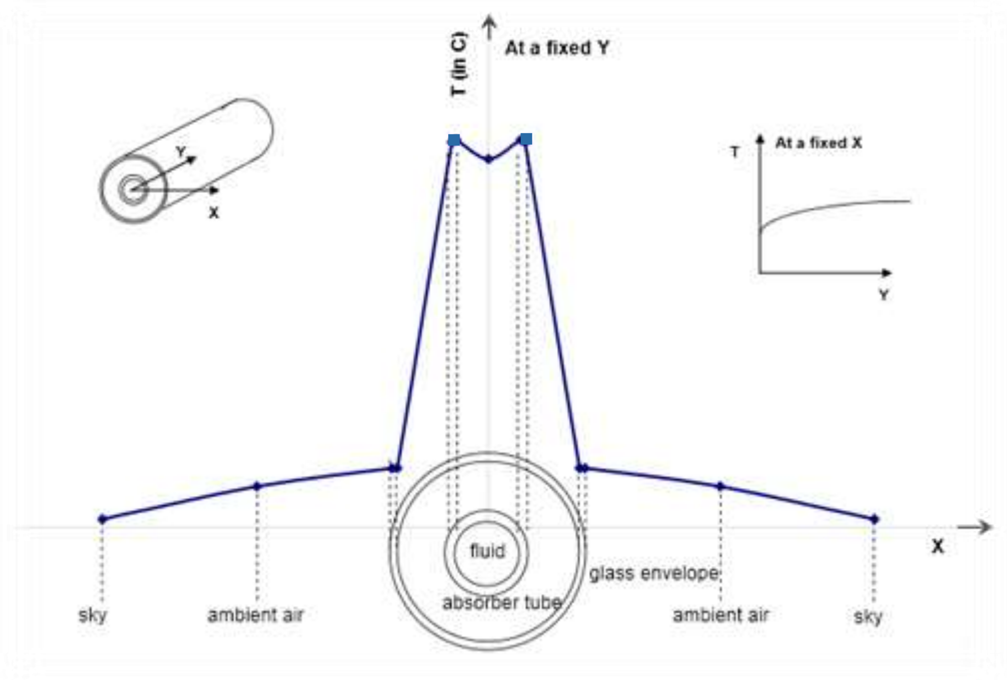


Temperature distribution in parabolic trough collector

There are two directions of temperature distributions, x and y. For x direction, at any a fixed y. The temperature distribution order from the highest to the lowest is presented in the following:

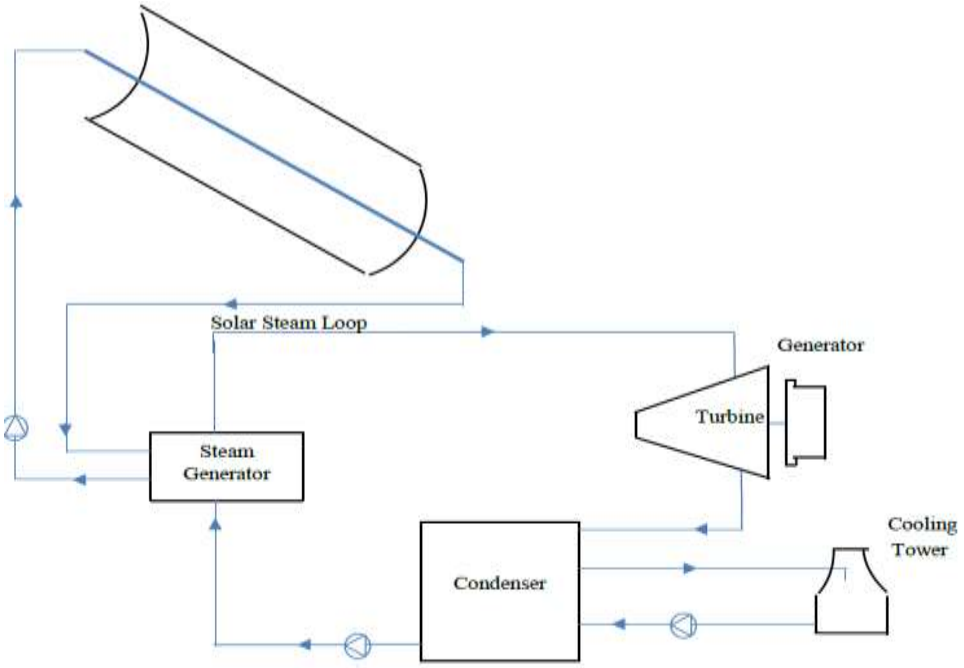
- Outer absorber surface temperature
- Inner absorber surface temperature
- Heat transfer fluid (HTF) temperature
- Inner glass envelope temperature
- Outer glass envelope temperature
- Ambient temperature
- Sky temperature

For y direction, at a fixed x, temperature distribution is seen in the figure below. The heat transfer fluid temperature (HTF) increases gradually as it passes through the absorber.



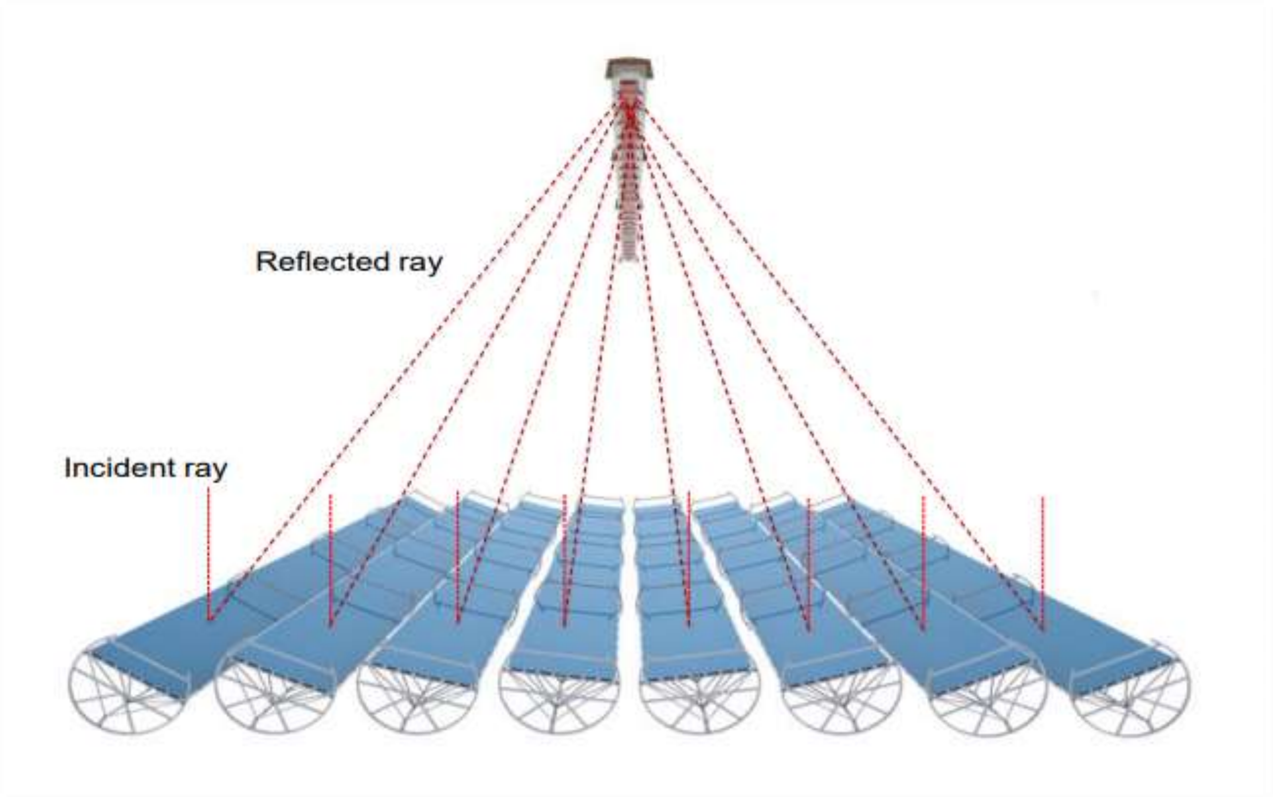
Solar thermal power plant

On the solar field side, a heat transfer fluid (HTF) is heated by PTSCs and then pumped to a steam generator (heat exchanger) where steam is generated and piped back to the PTSCs. On the power generation side, the steam transferred to the turbine producing mechanical power that drives an electric generator. The steam leaving the turbine is cooled by a condenser and pumped again to the heat exchanger



II. Linear Fresnel Reflector

The linear Fresnel reflector technology receives its name from the Fresnel lens, which was developed by the French physicist Augustin-Jean Fresnel for lighthouses in the 18th century. The principle of this lens is the breaking of the continuous surface of a standard lens into a set of surfaces with discontinuities between them. This allows a substantial reduction in thickness (and thus weight and volume) of the lens, at the expense of reducing the imaging quality of the lens. Where the purpose is to focus a source of light this impact on the image quality is not of major importance.



The mirrors focus the sun onto a receiver which contains the heat transfer medium which could be water, oil or even molten salt in some designs. The heat transfer medium used will depend on the operating temperature of the system. The main difference between the two systems lies in the way that the sun's rays are tracked, and this is what gives rise to the cheaper cost of Fresnel.

In the Fresnel system the individual mirrors rotate to track the sun. There is no mechanical connection between the mirrors and the collector.

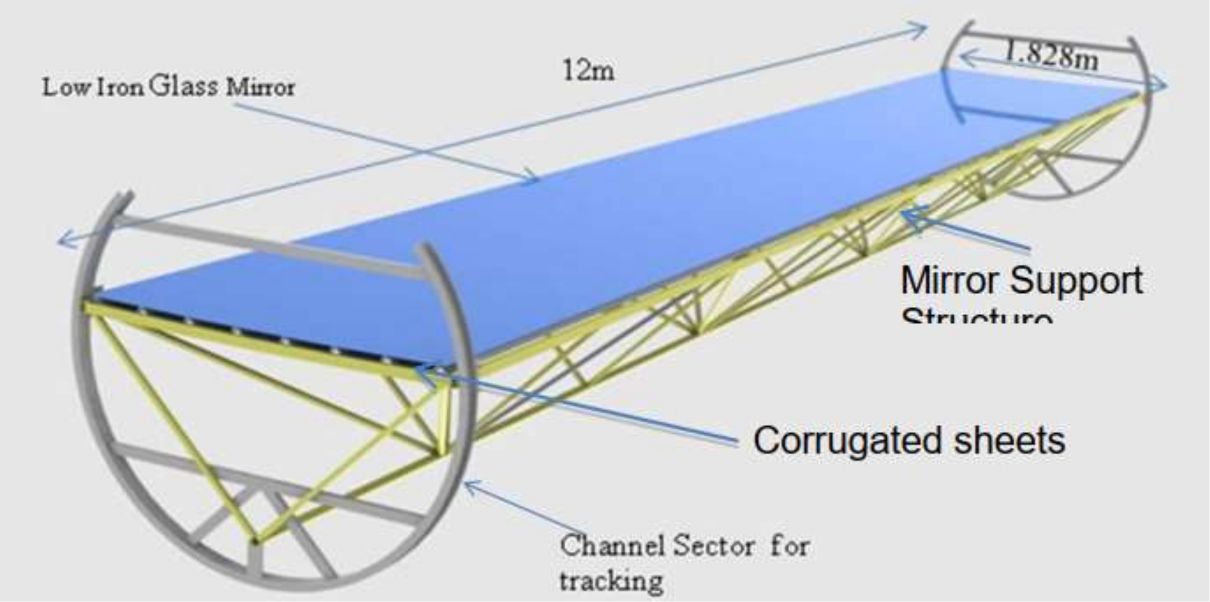
Linear Fresnel Reflector system comprises of the following components:

- Reflectors
- Receiver
- Tracking System

Reflector

Main components of reflector are:

1. **Mirror:** High reflective mirror is used as the reflector. It reflects sun rays to the receiver.
2. **Corrugated Sheet:** It is a wavy structure made up of GI or any other equivalent metal. Mirror is pasted on this sheet. It gives a good support to the mirror and also protects reflective paint of mirror from corrosion.
3. **Support Structure:** Reflector (mirror) tracks sun with the help of mirror support structure.
4. **Elastically Curved Low Iron Glass Mirrors:** They are adhered to the corrugated sheets. The mirrors along with the corrugated sheet are supported by the **Mirror Support Structure (MSS)**

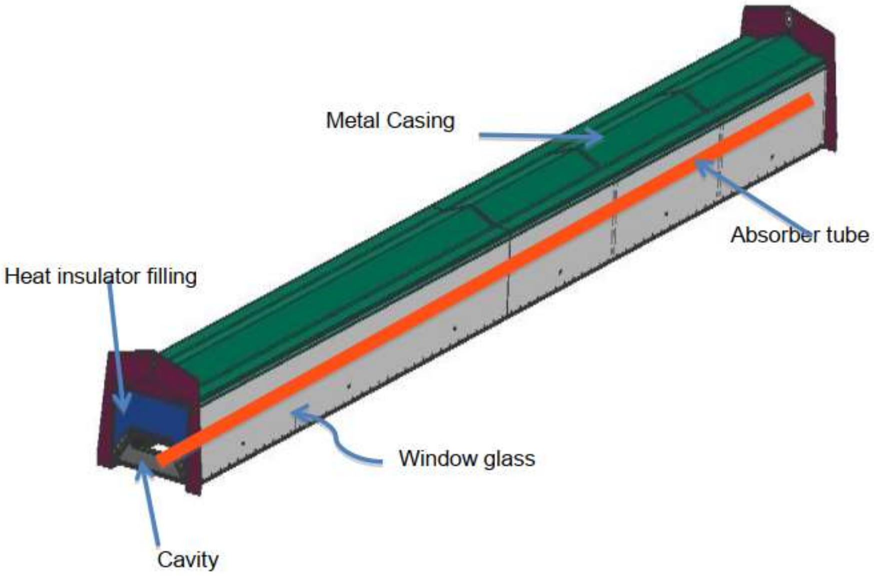


Receiver

Main components of the receiver are as follows:

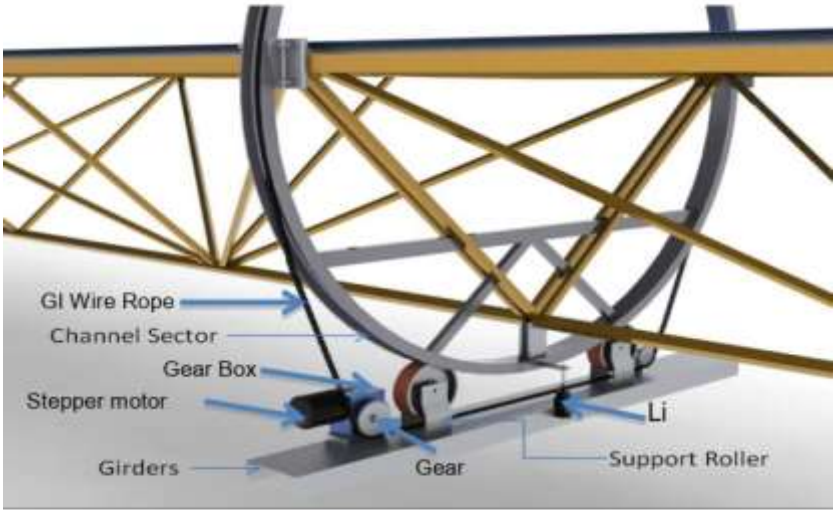
- **Absorber Tube:** It is made up of stainless steel with solar selective absorber coating (high absorbance and low transmittance). Number of absorber tubes depends upon the concentration ratio5. Inner diameter and wall thickness of the tube depends on the operating pressure and flow velocity.

- **Insulated Casing:** This is low iron casing filled with heat insulator and its inner side has anti-reflective coating. Absorber tube is mounted in the cavity of the casing and this cavity is further sealed with a glass sheet (window glass) cover and silicon beading.
- **Support Structure:** The receiver is supported by steel **A-Frame** structure that in turn is grouted to concrete foundation. Wind arrestor (metal wire) reduces the wind load and provides support to A-frame structure



Tracking System

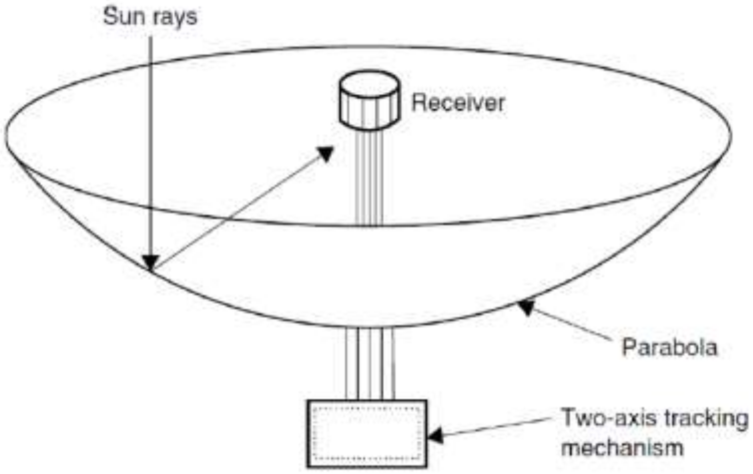
Since the sun moves from east to west therefore reflector should also move along with the sun to receive maximum energy. Reflector needs a tracking system to track the sun. GPS is used to synchronize the reflector with the sun. The mechanical component of the tracking system comprises of Sprocket & Chain Drive Transmission Mechanism driven by a stepper motor.

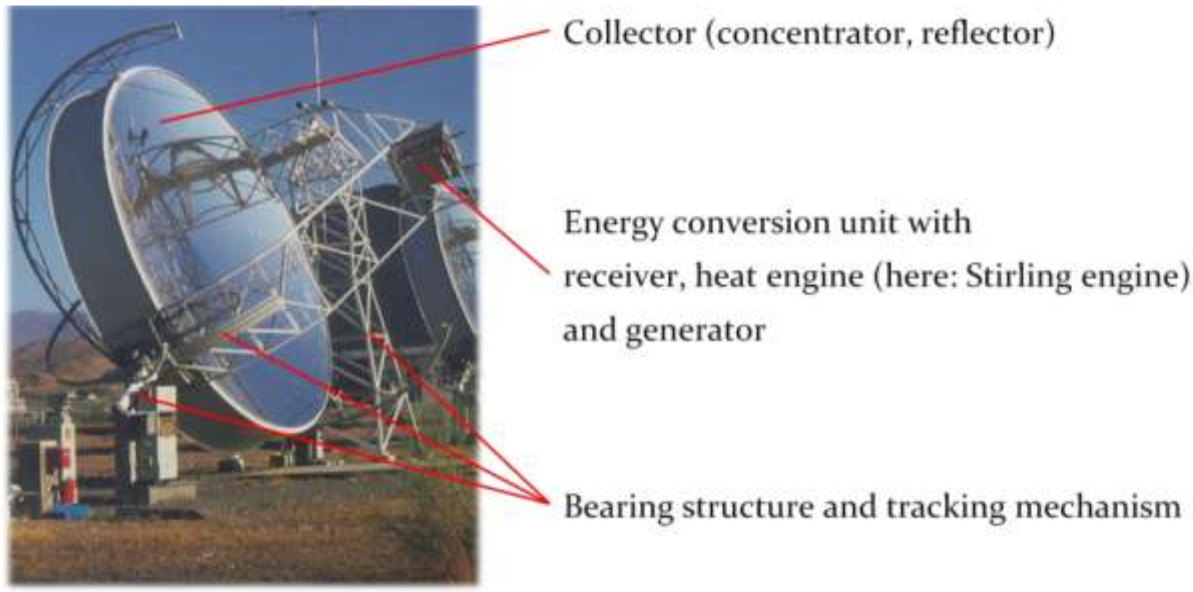


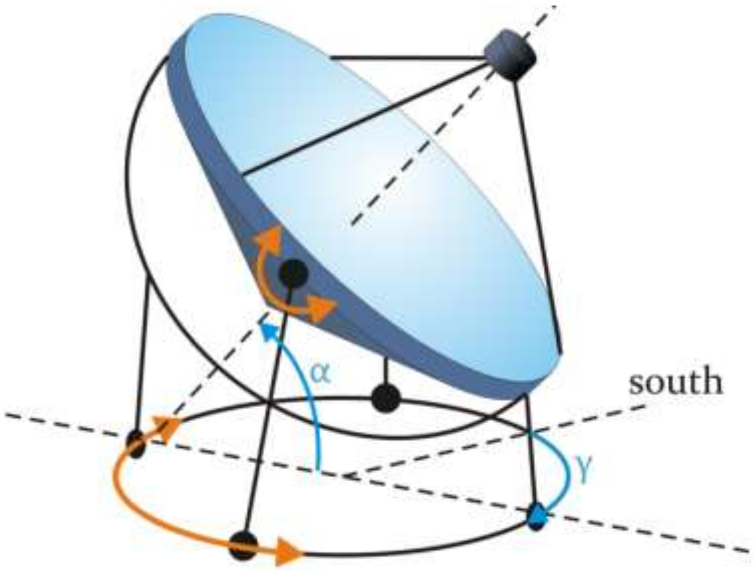
III. Dish Solar Collectors (DSCs)

A parabolic dish reflector (PDR), is a point-focus collector that tracks the sun in two axes, concentrating solar energy onto a receiver located at the focal point of the dish. The dish structure must fully track the sun to reflect the beam into the thermal receiver. For this purpose, tracking mechanisms employed in double, so the collector is tracked in two axes.

The receiver absorbs the radiant solar energy, converting it into thermal energy in a circulating fluid. The thermal energy can then be either converted into electricity using an engine-generator coupled directly to the receiver or transported through pipes to a central power conversion system.







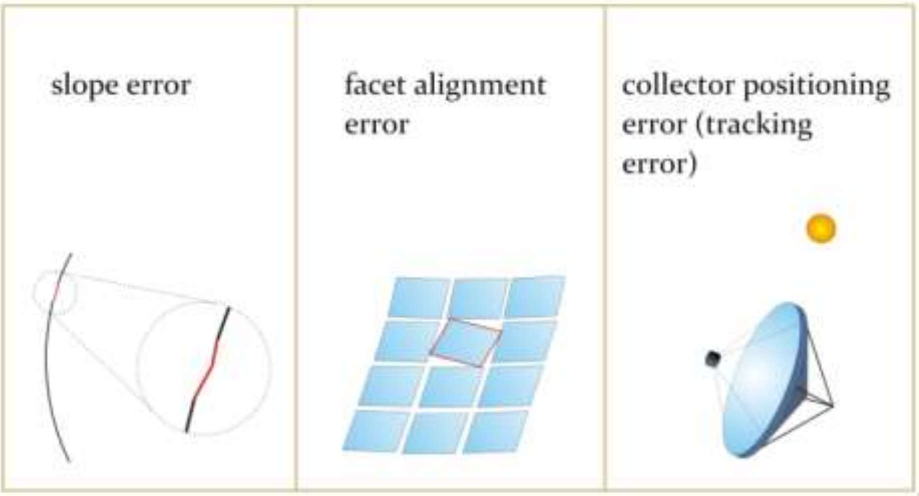
Components of Dish Solar Collector

Collector

Geometrically, the collector, the solar dish, is a rotationally symmetric section of a rotational paraboloid or some kind of approximation to that. A paraboloid mirror has a focal point in which the direct radiation is concentrated that reaches the mirror parallel to its optical axis.

There are geometrical collector errors resulted from geometrical errors and from the limited reflectivity of the reflecting material.

- Slope error: The surface of an ideal dish would have the shape of a circular paraboloid. Angular aberrations of the mirror surface in relation to the ideal shape are called slope errors.
- Facet alignment error: In the case of multi facet reflectors, which are assembled with a number of facets that are mounted to a supporting frame, geometrical errors can be caused by inexact assembling, so that the light reflected on even perfectly shaped facets may partially or totally miss the receiver.
- Positioning errors of the whole reflector: As the parabolic dish needs a two axis tracking in order to maintain its optical axis in line with the Sun, it is prone to positioning and tracking errors. Positioning errors imply that the optical system axis is not in line with the Sun.



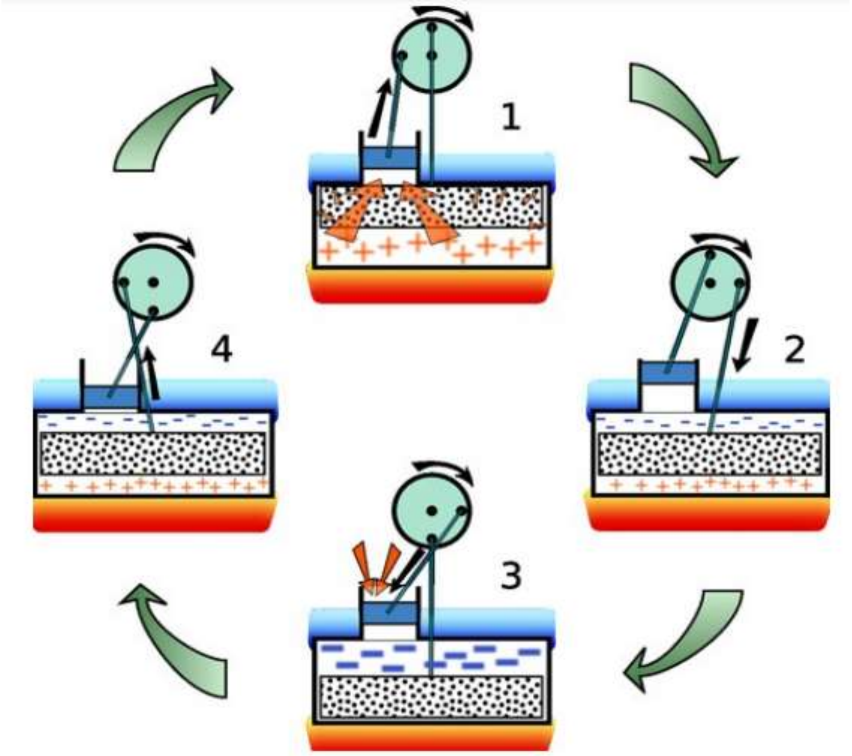
Receiver

The receiver of a solar dish system is the interface between the concentrator and the heat engine. It has two functions:

- First, it absorbs a large part or the radiation reflected by the collector and converts it
  into heat.
- Second, it transfers the heat to the working gas of the heat engine.

Stirling Engine

A Stirling engine is a heat engine that is operated by the cyclic compression and expansion of air or other gas (the *working fluid*) at different temperatures, resulting in a net conversion of heat energy to mechanical work.



1. The air at the bottom heats up, creating pressure on the small power piston, which moves up and rotates the wheel.
2. The rotating wheel moves the big displacer down.
3. The air cools down at the top, reducing the pressure and allowing the power piston to move down.
4. This motion of the power piston moves the displacer upwards and the air at the bottom is heated again.

IV. Solar Power Tower

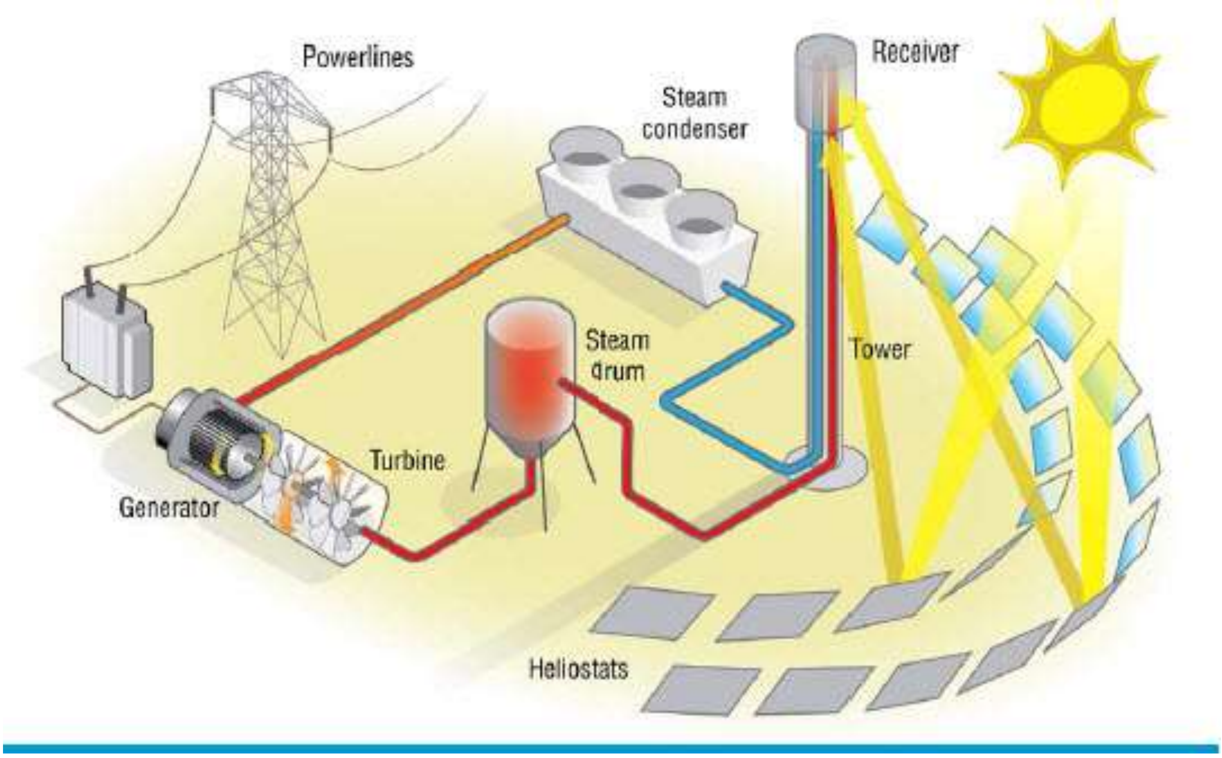
Solar tower technologies use a ground-based field of mirrors to focus direct solar irradiation onto a receiver mounted high on a central tower where the light is captured and converted into heat. The heat drives a thermo-dynamic cycle, in most cases a water-steam cycle, to generate electric power.

The solar field consists of a large number of computer-controlled mirrors, called heliostats, that track the sun individually in two axes. These mirrors reflect the sunlight onto the central receiver where a fluid is heated up.

Solar towers can achieve higher temperatures than parabolic trough and linear Fresnel systems, because more sunlight can be concentrated on a single receiver and the heat losses at that point can be minimised.

The upper working temperatures can range from 250°C to perhaps as high 1000°C for future plants. Solar towers can use synthetic oils or molten salt as the heat transfer fluid and the storage medium for the thermal energy storage.

Synthetic oils limit the operating temperature to around 390°C, limiting the efficiency of the steam cycle. Molten salt raises the potential operating temperature to between 550 and 650°C, enough to allow higher efficiency supercritical steam cycles although the higher investment costs for these steam turbines may be a constraint.

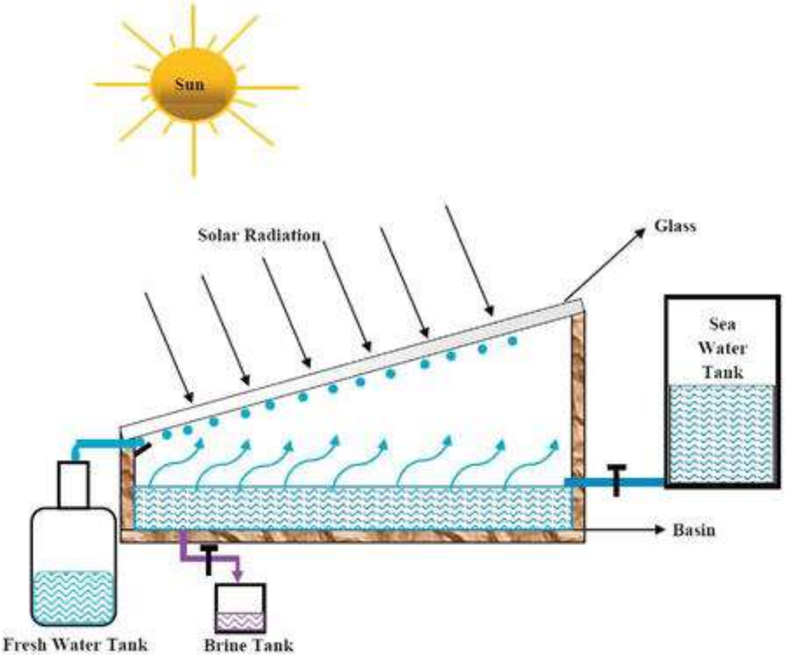


Other Applications of Solar Thermal Energy

Solar desalination

Water desalination requires large amounts of energy. 230 million tons of oil per day has been estimated to be used to desalinate 25 million m^3/day of salty water.

The solar still is one of the oldest and by far the simplest water desalination method. A solar still consists of a structural element called a basin covered with a transparent material to allow the incident solar radiation to pass through to the basin saline water for thermal absorption and evaporation.



Typically, the basin is colored in dark or black to enhance solar flux absorption. The water is heated by the solar rays absorbed by the basin, which increases the water vapor pressure until some portion of the saline water evaporates. The water vapor moves upward and typically condenses on the cool glass cover and run downs through a guiding channel to the collection reservoir.

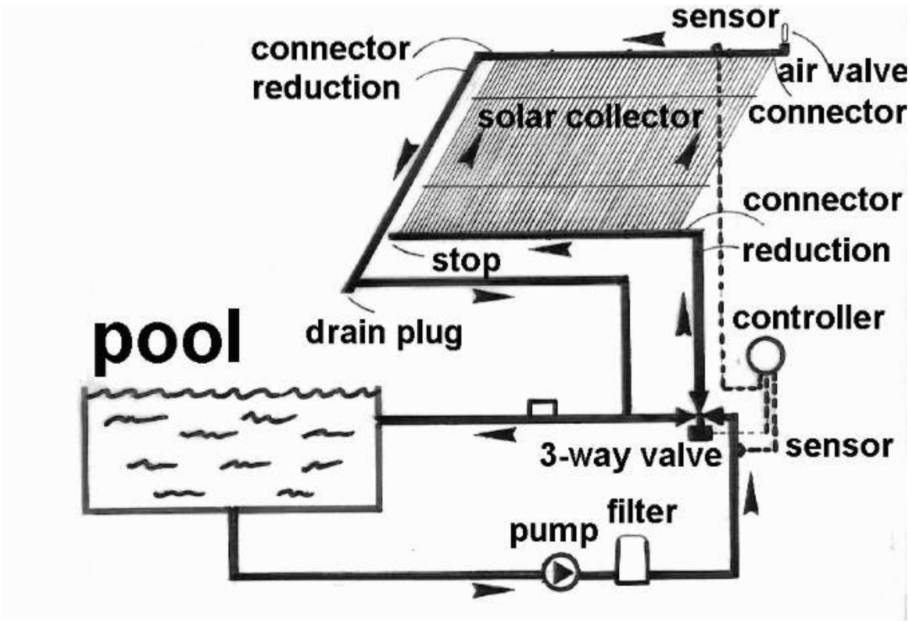
Solar Cooking

A solar cooker uses the energy of direct sunlight to heat, cook, bake or pasteurize food or drink. It only works when the sun shines, so solar cooking can never be a stand-alone technology.

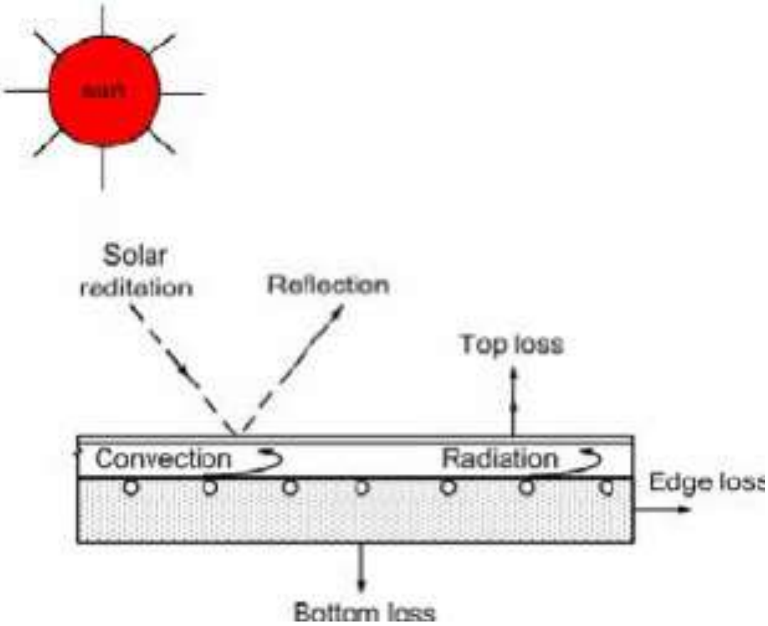
One of the best solar cookers types is parabolic solar collectors. Parabolic cookers can be made from aluminium sheets, iron, or even concrete coated with aluminium foil. Through their parabolic shape, they focus radiation from the sun onto the bottom of the pot. They generally have a higher energy output than box cookers and can reach temperatures of up to 250 °C. These high temperatures enable users to do cooking, stir-frying and baking. Aluminium parabolic cookers are lightweight and can easily be transported.

Solar Swimming Pool Heating

Heating a swimming pool can consume a lot of energy and add up to high heating bills. You can improve your swimming pool's heating and energy efficiency by installing an energy efficient pool heater and by taking steps to reduce pool heating costs. Here’s how it works: First, the water pumps through the filter. Then the water enters the solar collector, where it is heated and pumped back into the pool.


sensor
connector
reduction
air valve
solar collector
connector
connector
reduction
stop
controller
pool
drain plug
3-way valve
sensor
filter
pump

Thermal Energy Losses from Solar Collector (U_T)



The thermal energy losses can be calculated by the following steps:

1. The thermal losses from the backside of the system (U_b), (W/K):

$$\mathbf{U}_b = \mathbf{k}_{ins}\, \mathbf{A}_b/\mathbf{t}$$

where $k_{ins.}$: thermal conductivity of insulation (W/m.K),

A_b: backside surface area (m^2)

t: thickness of insulation (m)

2. The thermal losses of the other wall sides (edges) of the system (U_{side}), (W/K):

$$\mathbf{U}_s = \mathbf{k}_{ins}\, \mathbf{A}_{side}/\mathbf{t}$$

where A_{side}: wall sides (edges) surface area (m^2)

3. The thermal losses of the frontal side of the system for single cover glass (U_f) is calculated by: (**A**) Heat Transfer Coefficient (**B**) Empirical Equation

A. By Heat Transfer Coefficient, (W/K):

Heat transfer coefficient for the temperature of 10°C (h_{10}):

$$\boldsymbol{h_{10} = 1.14\frac{(\Delta T)^{0.31}}{L^{0.07}}}$$

ΔT: $T_p - T_c$

L: spacing between the plate & the cover of collector

T_p: mean plate temperature

T_c: cover or glass temperature ≈ $(T_p + T_{air})/2$

Convection heat transfer coefficient between the plate & the cover of collector:

$$\boldsymbol{h_{p-c} = h_{10}[1 - 0.0018(T_{ave} - 10)]}$$

$T_{ave} = \bar{T} \approx (T_p + T_c)/2$: temperature average of absorber palate & the cover (glass) plate in ^oC.

Radiation heat transfer coefficient between absorber plate and glass plate (W/m^2 K)

$$\boldsymbol{h_{r(p-c)} = \frac{\delta(T_p + T_c)({T_p}^2 + {T_c}^2)}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_c} - 1}}$$

δ: Stefan-Boltzman constant = 5.678×10^{-8} W/m^2.K^4

ε_p: plate emissivity ≈ 0.95 or it is given in the question.

ε_g: cover (glass) emissivity ≈ 0.95 or it is given in the question.

Wind heat transfer coefficient (h_w):

$$\boldsymbol{h_w = 5.7 + 3.8V}$$

V: wind speed (m^2)

Radiation heat transfer coefficient between absorber plate and sky ($h_{r(c\text{-}sky)}$):

$$\boldsymbol{h_{r(c-sky)} = \epsilon_g \delta(T_c^2 + T_{sky}^2)(T_c + T_{sky})}$$

Then, the thermal losses of the frontal side of the system (U_f) as tilt angle 45°:

$$\boldsymbol{U_{f(45^o)} = A_c \left[\frac{1}{h_{p-c} + h_{r(p-c)}} + \frac{1}{h_w + h_{r(c-sky)}}\right]^{-1}}$$

where A_c: frontal surface area of the collector (m^2)

B. <u>Empirical Equation:</u> for multiple glass covers & $40^oC \le T_p \le 130^oC$

$$\boldsymbol{U_{f(45^o)} = A_c \left[\left(\frac{N}{(\frac{344}{T_p})\left(\frac{T_p - T_{air}}{N + f}\right)^{0.31}} + \frac{1}{h_w}\right)^{-1} + \frac{\delta(T_p + T_{air})({T_p}^2 + {T_{air}}^2)}{[\epsilon_p + 0.042N(1 - \epsilon_p)]^{-1} + \left[\frac{2N + f - 1}{\epsilon_c}\right] - N}\right]}$$

N: number of glass covers

$$\boldsymbol{f = [1 - 0.04h_w + 5 \times 10^{-4}(h_w)^2][1 + 0.058N]}$$

The thermal losses of the frontal side of the system (U_f) as tilt angle β:

$$\boldsymbol{U_{f(\beta)} = U_{t(45^o)}\left[1 - (\beta - 45)(0.0026 - 0.0014 \times \epsilon_p)\right]}$$

Then, the total thermal losses of solar collector (U_T):

$$\boldsymbol{U_T = U_f + U_{side} + U_b}$$

A number of overall heat losses from the system (Q_{losses}):

$$\boldsymbol{Q_{losses} = U_T(T_p - T_{air})}$$

3. The amount of heat absorbed by a collector (Q_{abs})

$$\boldsymbol{Q_{abs} = I_{direct} \cdot F_t \cdot A_c}$$

$$\boldsymbol{F_t = F_{sh} \cdot F_d \cdot \alpha_p \cdot \tau_g}$$

F_t: climate losses factor

α_p: absorptivity of the absorber plate = 0.94-0.97

F_{sh}: shadow factor = 0.3 for a cloudy day - 0.97 for a clear day

F_d: dust factor = 0.3 for a cloudy day - 0.97 for a clear day

τ_g: transmittance of glass

4. The amount of useful thermal energy gain from a collector (Qu)

The experimental amount of useful thermal energy gain from a collector ($Q_{u(exp)}$):

$$\mathbf{Q_{u(exp)}} = \boldsymbol{\dot{m}.C_p(T_{out} - T_{in})}$$

where

$\dot{m}$: airflow rate per area unit collector (kg/s)

C_p: air specific heat (J/kg K),

T_{out}: outlet air temperature (K),

T_{in}: inlet air temperature (K).

The theoretical amount of useful thermal energy gain from a collector ($Q_{u(the)}$):

$$\mathbf{Q_{u(the)} = Q_{abs} - Q_{losses}}$$

5. Efficiency of Solar Collector

The experimental & theoretical efficiency of the solar air collector (η_{act}), (η_{the}):

$$\boldsymbol{\eta_{act}} = \frac{\mathbf{Q_{u(exp)}}}{\boldsymbol{Q_{abs}}} \mathbf{100}\%$$

$$\boldsymbol{\eta_{the}} = \frac{\mathbf{Q_{u(the)}}}{\boldsymbol{Q_{abs}}} \mathbf{100}\%$$

Ex. : The glass of a 1×2 m flat-plate solar collector is at a temperature of 80ºC and has an emissivity of 0.90. The environment is at a temperature of 15ºC and wind speed is 3m/s. Calculate the convection and radiation heat losses. Find the overall losses from the front side of glass.

Solution:

Ex. : Plate and glass of 1×2 m flat-plate solar collector is at a temperature of 75°C & 50°C respectively. It is inclined 45°, 30° and 60° about horizontal plane. The temperature of air surrounding is at 10°C & wind speed (2.5m/s). Find the thermal losses from the system by (**A**) heat transfer coefficient (**B**) empirical equation. Find the heat losses from this collector?

Solution: (**A**) heat transfer coefficient

(**B**) Empirical equation

Ex.: Find the energy absorbed by the flat-plate collector of 1×2 m^2 when the solar direct radiation is 650W/m^2 for a clear day. Also, determine the useful thermal energy gain from this collector and the thermal efficiency as the outlet & inlet temperature are 50^{o}C & 10^{o}C respectively, the mass flowrate is 0.02kg/s.

Solution:

Ex.: For the collector operates at a temperature difference of 5°C, calculate the useful energy and the thermal efficiency as the solar direct radiation is $300 W/m^2$ for a cloudy day, absorber plate area ($3m^2$) and mass flowrate (0.01kg/s). Take the overall thermal losses (overall heat coefficient) is $5\ W/K.m^2$, the temperature of plate and surrounding air are 9°C & 5°C.

Solution:

Chapter Four: Designing of Solar Electrical Collectors (PV cells)

1. Introduction

A solar panel is composed of a package of photovoltaic cells (PV). It can be used in a larger photovoltaic system for generating and supplying electric energy to residents and other commercial applications. Solar radiation that falls directly on the solar panel is converted into direct current. The electric energy output of each panel varies from 100 to 320 W. Most of the solar panels are around 11-15% efficient. The efficiency of the panels is measured by the amount of sunlight hitting the panel, which in turn is converted into electricity. Solar panels with the small surface area are highly efficient. The efficiency of the panels is also affected by the orientation of the panel, pitch or tilt of the roof and panel, temperature and shade of the roof.

The main advantage and disadvantage of PV panels

The key benefits of solar panels include the following:

1. Environment-friendly
2. Noise-free with no moving parts
3. Low maintenance cost

4. Easy to install
5. Promotes energy independence

The following are some of the disadvantages involved in the utilisation of solar panel:

1. High initial costs
2. Repairing of damaged solar panel installations is expensive
3. It does not produce power during night or inclement weather conditions
4. The efficiency of solar panels can be affected by pollution.

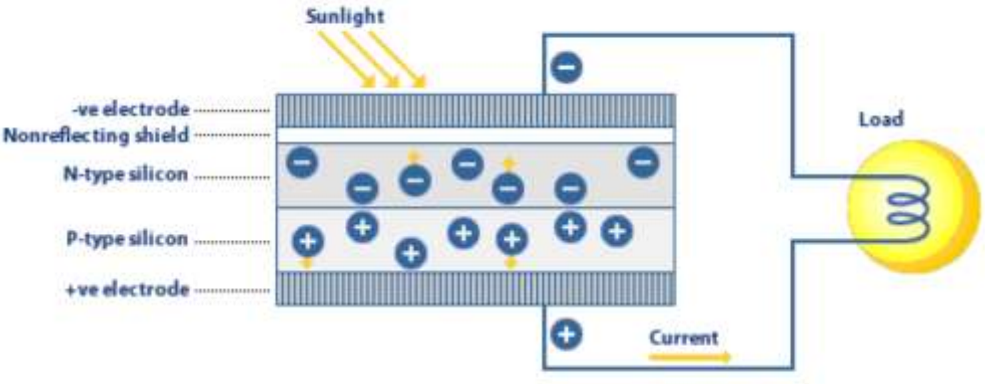
The major application of PV panels

Some of the applications of solar panels include the following:

1. Solar-powered fans and pumping.
2. Solar flashlights.
3. Solar night-lights.
4. Charging batteries.

2. The Principal Working of PV Cell

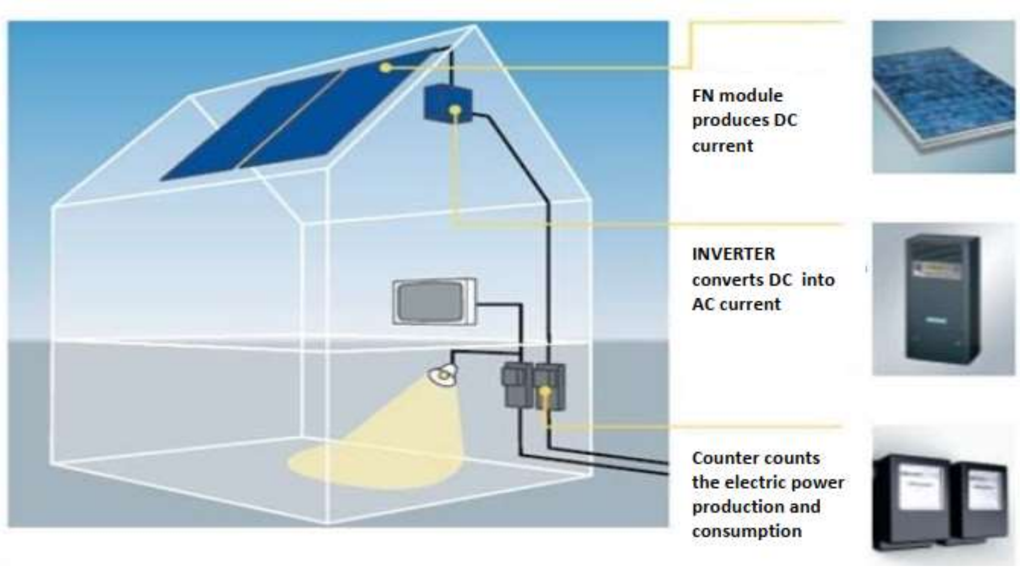
A typical photovoltaic cell consists of semiconductor material (usual silicon) having a PN junction. Sunlight striking the cell raises the energy level of electrons and frees them from their atomic shells. The electric field at the PN junction drives the electrons into the N region while positive charges are driven to the P region. A metal grid on the surface of the cell collects the electrons while a metal back-plate collects the positive Charges.



Note: The kilowatt-hour (symbolized kW·h as per SI) is a composite unit of energy equivalent to one kilowatt (1 kW) of power sustained for one hour.

3. Photovoltaic system types

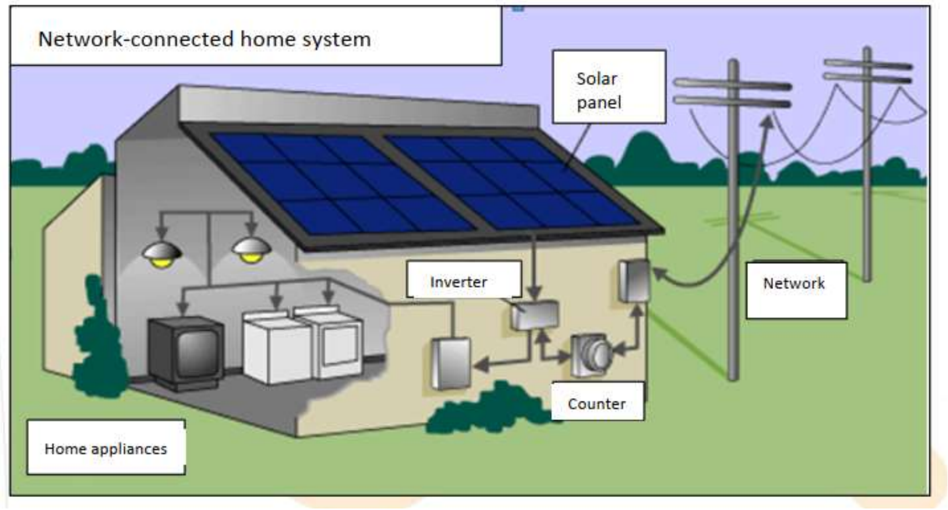
- **Network-connected photovoltaic systems (off-grid)**



The main components of PV systems are photovoltaic modules, photovoltaic inverter, mounting subframe and measuring cabinet with protective equipment and installation. Photovoltaic modules convert solar energy into DC current, while photovoltaic inverter convert the DC current into AC current.

- **Photovoltaic systems connected to public electricity network (on-grid)**

Connection to the local electricity network allows selling to the local distributor of electric energy any excess of electricity generated and not used in the household consumption, because the PV system is connected to the network via a home installation in parallel operation with the distribution system. Also, the home is supplied with electricity from the grid when there is no sunny weather.



- **Network-connected solar power plants (farms)**

These systems, also connected to the network, are generating large amounts of electricity by a photovoltaic installation on a localized area. The power of such photovoltaic power ranges from several hundred kilowatts to tens of megawatts, recently up to several hundred megawatts.

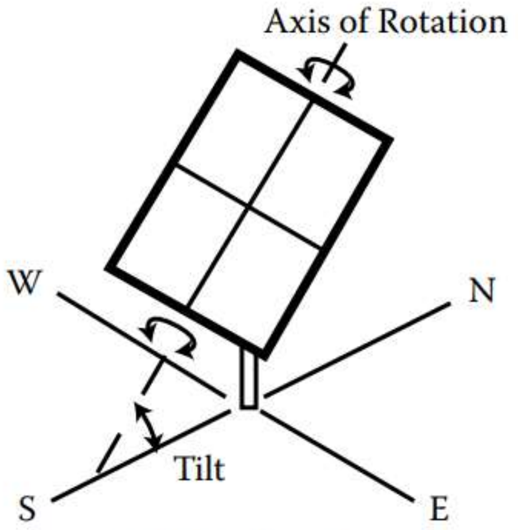
To have a feeling of size, talking about solar farms, it is worth to mention an example of a large-scale solar farm in the former military airport in Germany. 40 MW power, surface area 110 hectares, which is equivalent to an area of 200 football stadiums. The expected annual production of 40 million kWh of electricity, saving 25.000 tonnes of CO_2, and cost about 150 million $.

4. Tracking system

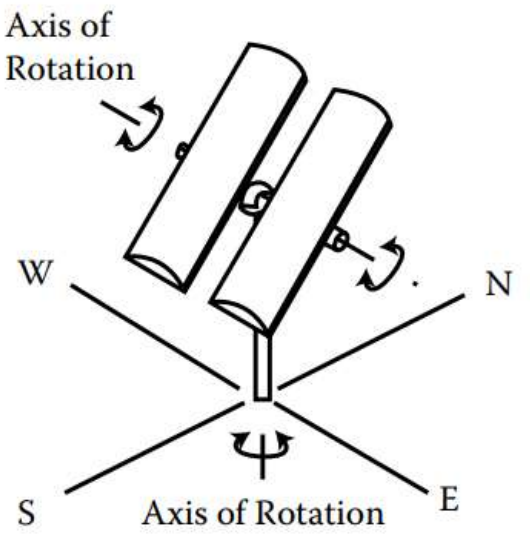
There are one- and two-axis tracking systems. Common PV systems have a flat plate and fixed angle (tilt), so one way to improve the performance of flat-plate collectors is by tracking the sun. Methods for improving performance by tracking are as follows:

One-axis tracking: The axis of rotation can be either the north–south or east–west line.

Two-axis tracking: One possibility is to have passive east–west tracking and change the tilt angle by month manually. Otherwise, it requires an active tracking mechanism, with inherent problems of power and moving mechanical parts. One method of control is to track the sun, and a newer method of control is to use a geographic position system.

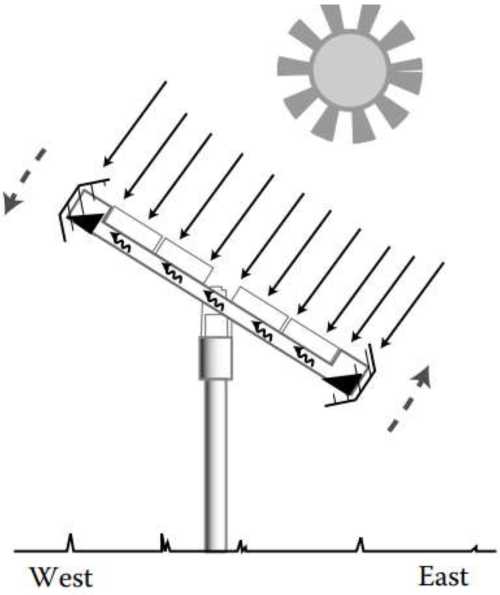


One-axis tracking flat-plate collector with axis oriented north-south



Two-axis tracking concentrator

Passive trackers use two canisters where the solar direct radiation increases the vapor pressure, driving liquid from one side to another to keep panels oriented toward the sun. Passive tracking systems do not require extra energy or motors and gears (which require more maintenance). However, in windy areas, passive trackers may not work well as the wind force is larger than the passive tracking force



5. Calculation the power of the domestic house devices

The power of the domestic house devices (W/day) = No. × Power (W)× working hours

The power of the domestic house devices (W/month) = Power (kW/day)× 30 (day)

The cost of the power of the domestic house devices = power (kW/month)× cost ($/kW/month)

Air conditioning:

The power of AC = 1 × 1200W × 8 hours = 9600W = 9.6 kW/day

The power of AC (kW/month) = 9.6 kW × 30 (day) = 288 kW/month

The cost of power AC = 288 kW/month × 0.1 $ = 28.8 $/month = 2880 cents

Lighting fixtures:

The power of lighting = 10 × 40W × 10 hours = 4000W = 4 kW/day

The power of lighting (kW/month) = 4 kW × 30 (day) = 120 kW/month

The cost of power lighting = 120 kW/month × 0.1 $ = 12 $/month = 1200 cents

Fans:

The power of fans = 3 × 100W × 10 hours = 3000W = 3 kW/day

The power of fans (kW/month) = 3 kW × 30 (day) = 90 kW/month

The cost of power fans = 90 kW/month × 0.1 $ = 9 $/month

TV & receiver:

The power of TV and receiver = 1 × 100W × 10 hours = 1000W = 1 kW/day

The power of TV and receiver (kW/month) = 1 kW × 30 (day) = 30 kW/month

The cost of power TV and receiver = 30 kW/month × 0.1 $ = 3 $/month

Laptop:

The power of laptop = 1 × 80W × 8 hours = 640W = 0.64 kW/day

The power of laptop (kW/month) = 0.64 kW × 30 (day) = 19.2 kW/month

The cost of power laptop = 19.2 kW/month × 0.1 $ = 1.92 $/month

Iron:

The power of iron = 1 × 1000W × 0.15 hours = 150W = 0.15 kW/day

The power of iron (kW/month) = 0.15 kW × 30 (day) = 4.5 kW/month

The cost of power iron = 4.5 kW/month × 0.1 $ = 0.45 $/month

Refrigerator:

The power of refrigerator = 1 × 200W × 24 hours = 4800W = 4.8 kW/day

The power of refrigerator (kW/month) = 4.8 kW × 30 (day) = 144 kW/month

The cost of power refrigerator = 144 kW/month × 0.1 $ = 14.4 $/month

Vacuum Cleaner:

The power of vacuum cleaner = 1 × 1600W × 0.25 hours = 400W = 0.4 kW/day

The power of vacuum cleaner (kW/month) = 0.4 kW × 30 (day) = 12 kW/month

The cost of power vacuum cleaner = 12 kW/month × 0.1 $ = 1.2 $/month

Washing Machine:

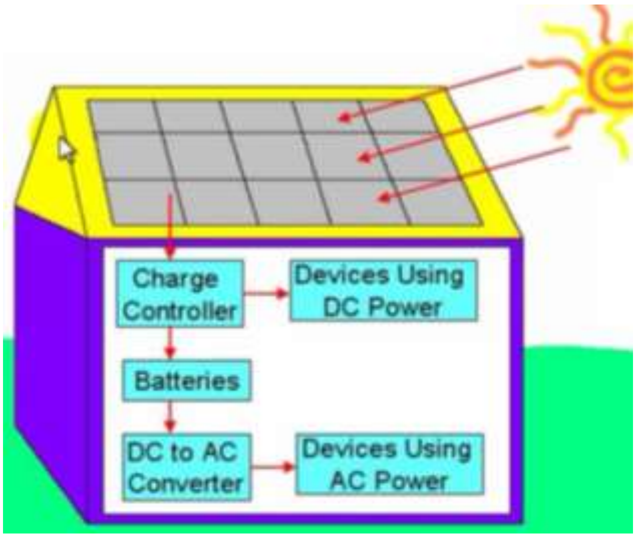
The power of washing machine = 1 × 1200W × (3/4) hours = 900W = 0.9 kW/day

The power of WM (kW/month) = 0.9 kW × 30 (day) = 27 kW/month

The cost of power WM = 27 kW/month × 0.1 $ = 2.7 $/month

The total power of all domestic house devices (kW/day) = 9.6 + 4 + 3 + 1 + 0.64 + 0.15 + 4.8 + 0.4 + 0.9 = 24.5 kW/day

The total cost of all these devices ($) = 28.8 + 12 + 9 + 3 +1.92 + 0.45 + 14.4 + 1.2 + 2.7 = 73.5 $/month

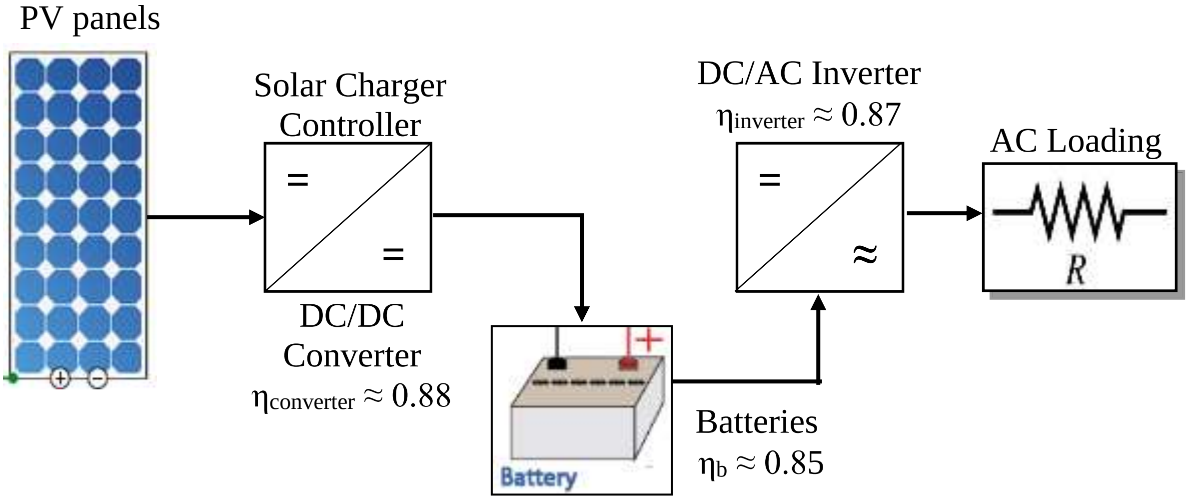


Notes: This is assumed that all domestic house devices are working simultaneously.

DC: direct current

AC: Alternating current

6. Calculation the losses power of Inverter & Converter



Block diagram of PV system

The max number of hour of solar radiation ≈ 5.5 hour

The total power of all domestic house devices (kW/day) = 0.9 + 4 + 3 + 1 + 0.64 + 0.15 + 4.8 + 0.4 + 0.9 = 24.5 kW/day

The efficiency of inverter ($\boldsymbol{\eta_{inverter}}$) ≈ 0.87

$$\boldsymbol{\eta_{inverter}} = \frac{\boldsymbol{The\ total\ power\ of\ all\ domestic\ house\ devices}}{\boldsymbol{Input\ power\ of\ inverter}}$$

$$0.87 = \frac{24.5\ \mathrm{kW/day}}{\mathrm{Input\ power\ of\ inverter}}$$

Input power of inverter (DC/AC) = 28 kW/day

The efficiency of convertor ($\eta_{\mathbf{converter}}$) ≈ 0.88

$$\eta_{\mathbf{converter}} = \frac{\boldsymbol{Input\ power\ of\ the\ inverter}}{\boldsymbol{Input\ power\ of\ converter}}$$

$$0.88 = \frac{28\ \mathrm{kW/day}}{\mathrm{Input\ power\ of\ converter}}$$

The input power of converter (DC/AC) = 31.8 kW/day

This is the Input power of converter (DC/DC) that should be provided from PV panels for 5.5 hours per a day ≈ 32 kW/day.

7. The number, cost and area of PV panels

$$\boldsymbol{The\ power\ of\ PV} = \frac{\boldsymbol{Input\ power\ of\ the\ converter}}{\mathbf{The\ max\ No.\ hour\ of\ solar\ radiation} \approx \mathbf{5.5\ hour}}$$

$$\mathrm{The\ power\ of\ PV} = \frac{32\ \mathrm{kW/day}}{5.5}$$

The power of PV = 5.8 kW

If the 1 m^2 of PV panel = 100W

$$\boldsymbol{The\ number\ of\ PV\ panels} = \frac{\boldsymbol{The\ power\ of\ PV\ (kW)}}{\boldsymbol{The\ power\ of\ PV\ for\ 1m^2}}$$

$$\mathrm{The\ number\ of\ PV\ panels} = \frac{5.8\ kW}{0.1\ kW}$$

The number of PV panels = 58 PV panels ≈ 60 PV panels

Let the cost of PV panels ≈ 300 $ for each 1 m^2 (Market)

The total cost of PV panels = the number of PV panels × the cost of PV panels **for each 1 m^2**

The total cost of PV panels = 58 × 300 $ = 17400 $

Or = 60 × 300 \$ = 18000 \$

The area of PV panels = the number of PV panels × the area of PV each panel

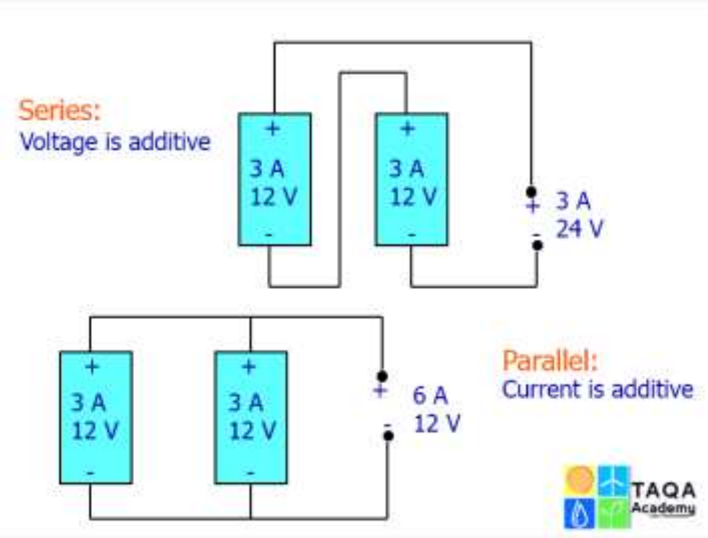
The area of PV panels = 58 × $1m^2$ = $58m^2 \approx 60m^2$

8. The number & cost of Batteries

It should be considered the connection of batteries:

1. Series Connections:
   $V_T = V_1+V_2+ \ldots + V_n$
   $I_T = I_1 = I_2 = \ldots = I_n$

2. Parallel Connections:
   $V_T = V_1=V_2= \ldots = V_n$
   $I_T = I_1 + I_2 + \ldots I_n$



12V/100Amp., 24/100Amp., … etc based on the design requirement & market.

Batteries energy per a day = the power of inverter = 28 kW/day

$$\eta_{\text{batteries}} = \frac{\textbf{Batteries energy per a day}}{\boldsymbol{DoD \times Voltage_B \times \ Current\ _B}}$$

DoD: the depth of discharge of batteries = 75%

Voltage $_B$: the total voltage of batteries (V)

Current $_B$: the total current capacity of batteries (Amp.)

$$0.85 = \frac{28\frac{\text{kW}}{\text{day}} \times 1000}{0.75 \times 24 \times \ Current\ _B}$$

the total current capacity of batteries = Current $_B$ = 1830 Amp. hr

$$\textbf{The total discharge current capacity of batteries} = \textbf{Current}_B \times \textbf{time of discharge}$$

the total discharge current $_B$ = 1830 × 1.5 (day) = 2745 Amp.hr

$$\textbf{The number of batteries} = \frac{\boldsymbol{The\ Total\ Discharge\ Current_B}}{\boldsymbol{The\ Current\ of\ each\ Battery}}$$

$$\text{The number of batteries} = \frac{2745}{100} = 27.45\ batteries \approx 28\ batteries$$

The cost of batteries = the number of batteries × the cost of a single battery ($)

The cost of batteries = 28 × 200 $ = 5600$

5. The cost of others equipment and accessories of PV System

Inverter, converter (Solar Charger Controller), wires,… etc. based on the requirement design & market.

6. The total cost of PV System for a single house

The total cost of PV system = PV_{cost} + $Batteries_{cost}$ + $Inverter_{cost}$ + $Converter_{cost}$ + $Wires_{cost}$ + $others\ accessories_{cost}$

The total cost of PV system = 18000 + 5600 + 2000 = 25600$

Chapter Five: Wind Energy

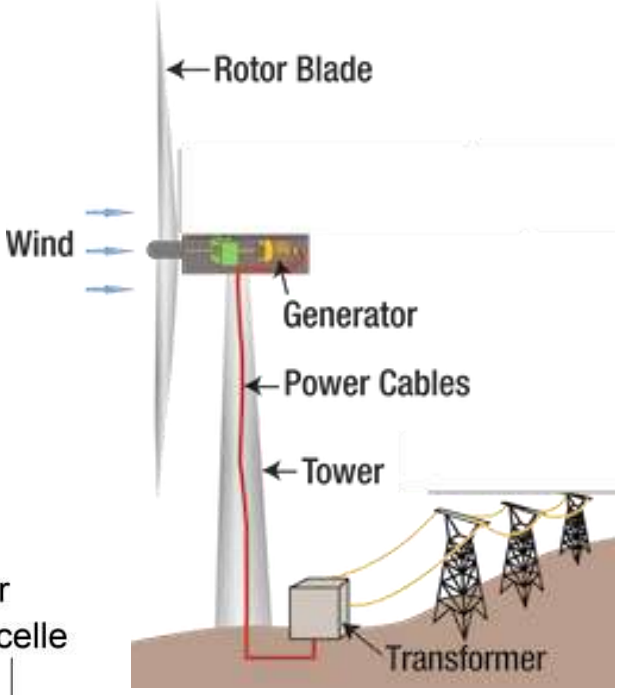
1. Introduction

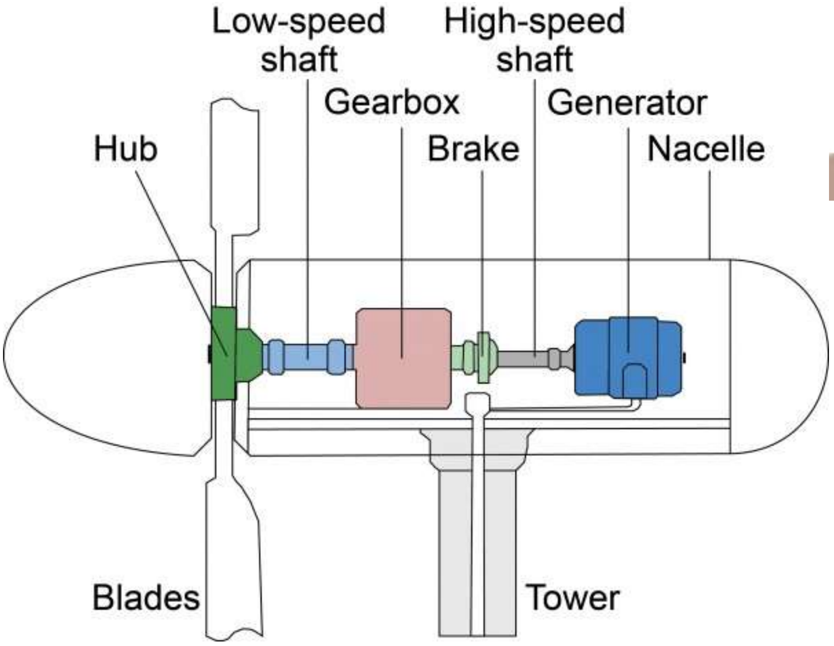
The electrical energy can be generated by wind energy. The wind energy, which is an indirect source of energy, can be used to run a wind mill, which in turn drive a generator to produce electricity.

2. Wind Power Plant

Figures below show the various parts of a wind-electric generating power plant. These are:

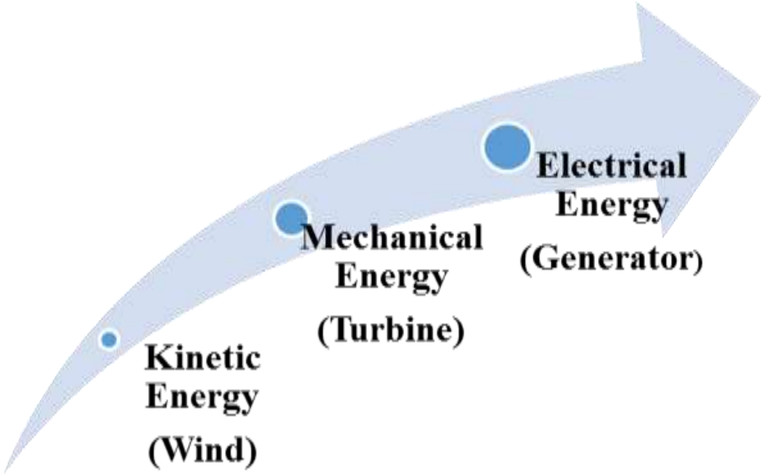
1. Tower
2. Rotor (blades)
3. High speed and low speed shafts
4. Gear box
5. Generator
6. Housing





3. The Principal Working of Wind Energy

1. The Wind (moving air that contains kinetic energy) blows toward the turbine's rotor blades.
2. The rotors spin around slowly, capturing some of the kinetic energy from the wind, and turning the central drive shaft that supports them.
3. Inside the housing, the gearbox converts the low-speed rotation of the drive shaft (about 16 revolutions per minute, rpm) into high-speed (1600 rpm) rotation fast enough to drive the generator efficiently.
4. The generator, immediately behind the gearbox, takes kinetic energy from the spinning drive shaft and turns it into electrical energy.
5. The electric current produced by the generator flows through a cable running down through the inside of the turbine tower.
6. A substation transforms the voltage of the electricity so it can be transmitted efficiently to nearby communities.



processing of electricity generation by wind energy

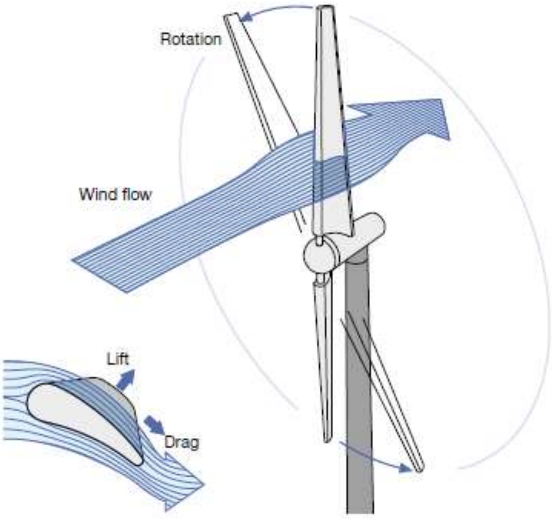
4. Siting of the wind turbine

The placement or "siting" of wind systems is extremely important. In order for a wind turbine system to be effective, a relatively consistent wind-flow is required. Obstructions such as trees or hills can interfere with the rotors. Because of this, the rotors are usually placed on towers to take advantage of the stronger winds available higher up.

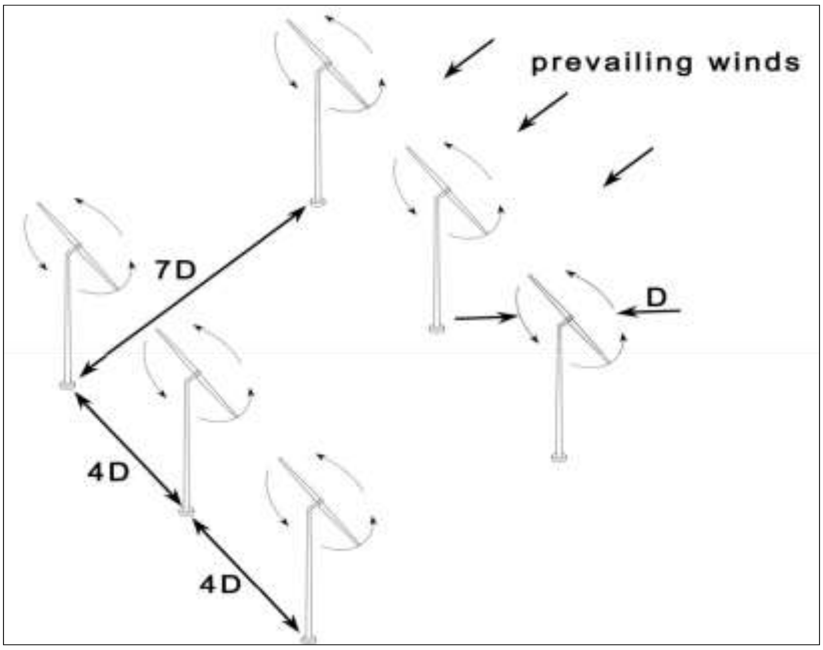
The amount of Wind Energy available at any location depends on two sets of factors:

- Climatic factors including: Time of day, Season, Geographic location, Topography, and Local weather.
- Mechanical factors including: Diameter of rotor, and Type of Turbine

Wind farm, off shore, or on shore.



Lift and drag forces



Wind farm optimal placement

5. Wind Energy and the Environment

Positive environmental benefits of Wind energy

There are significant environmental benefits obtained from using a renewable energy device attributed to preventing the release of Green house gases associated with fossil fuels. The general equation for estimating the reduction in emitted gas is:

Gas-emission reduction (in tonnes) = A x 0.8 x h x kG Where

A = the rated capacity of the development in kW

h = the number of operational hours per year, = 8000 h

kG = the specific emitted gas constant.

Hence the following equations are used to predict environmental benefits from based on 1 kWe system:

CO2 emission reduction (in tonnes)= 1x0.8x8000x862/106

= 5.5

SO_2 emission reduction (in tonnes)= $1x0.8x8000x9.9/10^6$

= 0.063

NO_2 emission reduction (in tonnes)= $1x0.8x8000x862/10^6$

= 0.018

Negative Impacts of Wind energy

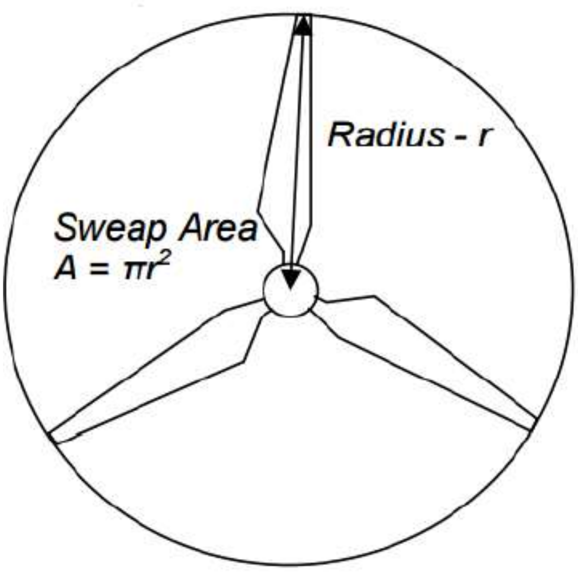
1. Occupation of large area & land requirements.
2. Audible noise
3. Various impacts on natural habitat and wild life.
4. Bird-kill

6. Calculation Performance of wind power

The kinetic energy (J) of any movement partial is:

$$\boldsymbol{K.E.=\frac{1}{2}mV^2}$$

Consider a wind rotor of cross sectional area **A** (m^2) exposed to this wind stream as shown in below Figure. The amount of air passing through an area with a velocity of air (**V**) is:



$$\boldsymbol{\dot{m}=\rho AV}$$

Then, the performance of wind turbine or extracted power (W) is determined by the following:

$$\boldsymbol{P_{wind}=\frac{1}{2}\dot{m}V^2=\frac{1}{2}\rho AV^3}$$

where P_{wind}: the available wind power (W)

ρ: density of air (kg/m^3)

A: swept area of wind blades (m^2)

V: wind speed (m/sec)

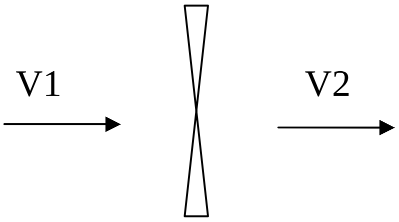
R: length of wind blade (m)

m: the amount of air (kg)

$\dot{m}$: mass flow rate (kg/sec)

Effect of the wind velocity is more prominent owing to its cubic relationship with the power.

7. Theory of Wind Turbines



The Power produced ($P_{K.E.}$) by the wind turbine is the net kinetic energy change across the wind turbine (from initial air velocity of V1 to a turbine exit air velocity of V2) is given as:

$$\boldsymbol{P_{K.E.} = \frac{1}{2}\dot{m}(V_1^2 - V_2^2)}$$

$$\boldsymbol{P_{K.E.} = \frac{1}{2}\rho A V_a(V_1^2 - V_2^2)}$$

Since the rotor speed is the average speed (V) between inlet and outlet:

$$\boldsymbol{V_a = \frac{1}{2}(V_1 + V_2)}$$

Hence, the power is

$$\boldsymbol{P_{K.E.} = \frac{1}{4}\rho\, A\, V_1^3\left[1 - \left(\frac{V_2}{V_1}\right)^3 - \left(\frac{V_2}{V_1}\right)^2 + \left(\frac{V_2}{V_1}\right)\right]}$$

To find the maximum power extracted by the rotor, differentiate the above equation with respect to V2 and equate it to zero

$$\boldsymbol{\frac{dP_{K.E.}}{dV_2} = 0}$$

The equation would became

$$\boldsymbol{(3V_2 - V_1)(V_2 + V_1) = 0}$$

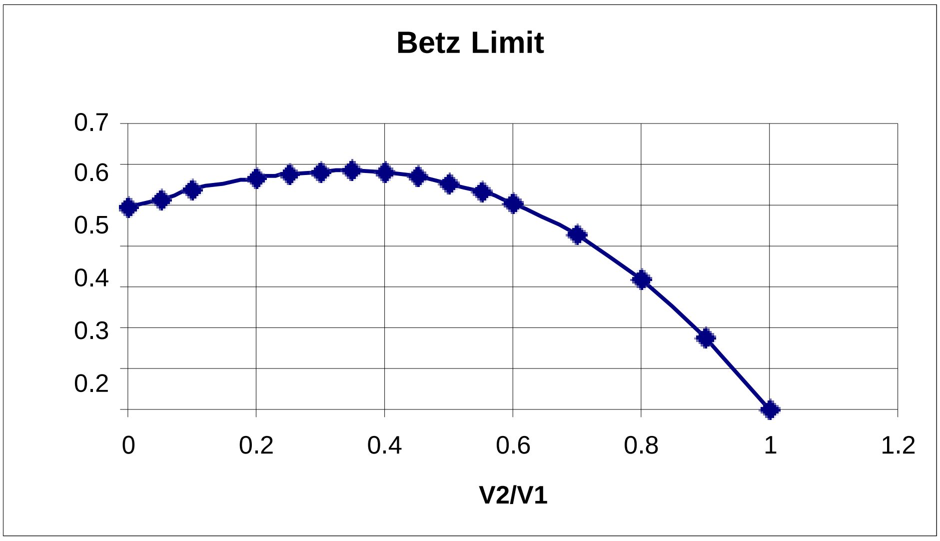
$$\boldsymbol{V_2 = \frac{1}{3}V_1}$$

So,

$$P_{K.E.} = 0.5925 \times \frac{1}{2}\left[\rho\, A\, V_1^3\right]$$

The theoretical maximum fraction of the power in the wind which could be extracted by an ideal windmill is, therefore the fraction 0.5925 is called the Betz Coefficient.

Because of aerodynamic imperfections in any practical machine and of mechanical loses, the power extracted is less than that calculated above.



The world's largest wind turbine generator has a rotor blade diameter of 126 metres and is located on offshore, at sea-level and so we know the air density is 1.2 kg/m3. The turbine is rated at 5MW in 30mph (14m/s) winds,

Rotor Swept area A= $(\pi.\ 126^2)/4 = 12469\ m^2$

Wind Power $= 0.5\ A\ \rho\ V^3$

$= 0.5 x 12469 x\ 1.2\ x\ (14)^3 = 20.5$ MW

Why is the power of the wind (20MW) so much larger than the rated power of the turbine generator (5MW)?

The answer lies in the fact that the Betz limit and inefficiencies in the system seriously absorbs over 60% of the apparent power.

There are two further factors to be considered when estimating the power output from a turbine,

- mechanical transmission
- the generator's efficiency

both of which are less than unity, hence the real power is proportionately less than the ideal value.

Ex. 16: Find the wind power and power produced by the turbine if the wind velocity, air density, and blade length are 10, 1.217kg/m^3 and 30m respectively. The generator efficiency is 96%. Assume maximum power extraction by the rotor.

Solution:

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

$$P_{wind} = \frac{1}{2} \times 1.217 \times \pi \times 30^2 \times 10^3 = 1714 \text{ kW}$$

$$V_2 = \frac{1}{3} V_1$$

$$V_2 = \frac{1}{3} \times 10 = 3.33\ m/s$$

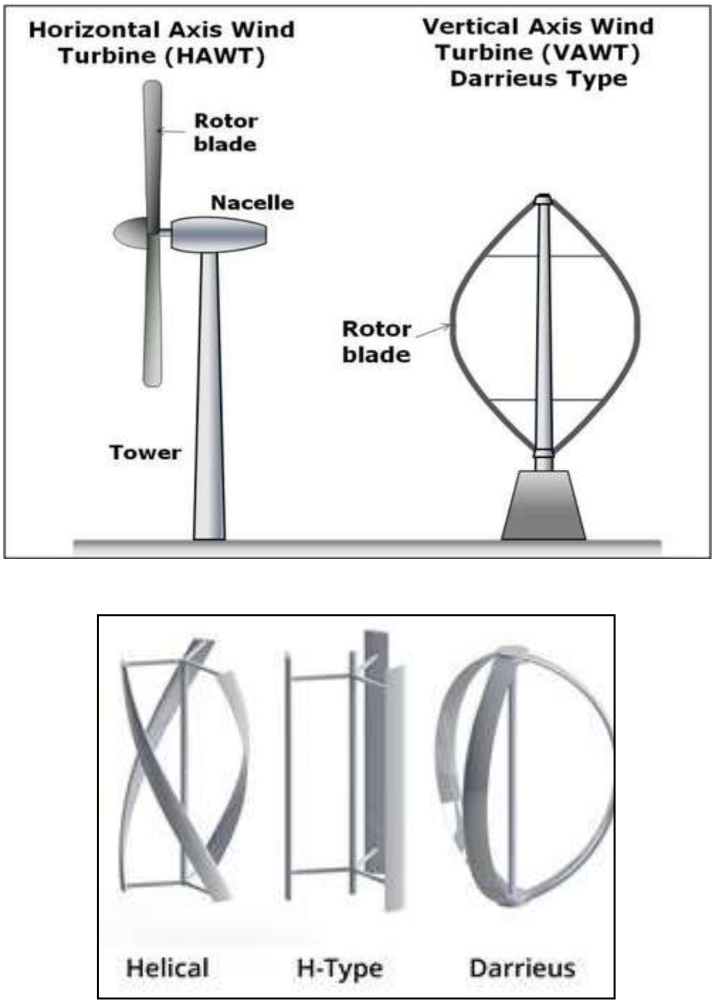
$$P_{K.E.} = 0.5925 \times \frac{1}{2}\left[\rho\ A\ V_1^3\right] \eta_g$$

$$P_{K.E.} = 0.5925 \times \frac{1}{2}\left[1.217 \times \pi \times 30^2 \times 10^3\right] \times 0.96 = 978.12\ kW$$

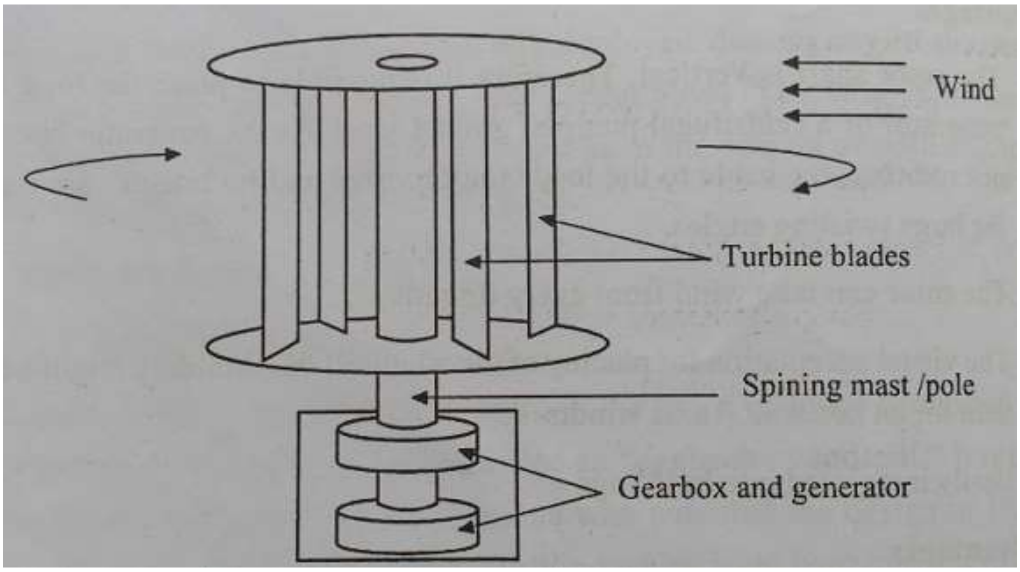
8. Wind Turbine Classification

A wind turbine can be grouped into two types based on the axis in which turbine rotates:

1. The turbine that rotates around the Horizontal axis is more common.
2. Vertical axis turbines are less frequently used.



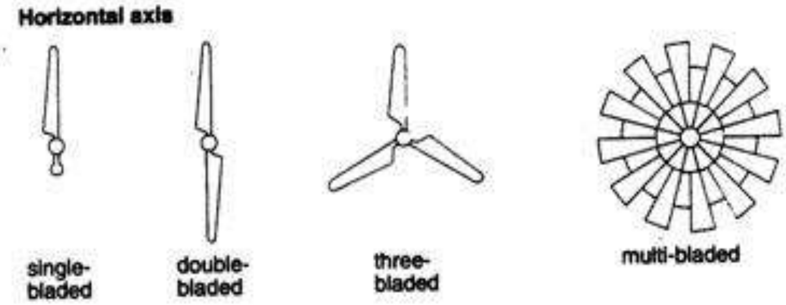
Horizontal & Vertical axis wind turbine



Working principle of vertical axis wind turbine

9. How many Blades should be used?

Different types of a wind turbine have varying numbers of blades, with older **windmills** having many blades on the rotor. These older machines used **drag forces** rather than **lift forces** to turn the rotor so the more blades that the drag force affected the better.



The number of blades

More common in Scotland are **three blade turbines** that use lift forces to turn the rotor. The three blades system is preferred due to stability. Obviously, it could be still used **numerous blades** but this raises the cost of the machines as you have more blades to manufacture and the structure requires reinforcing to overcome the additional weight.

The manufacture of **two bladed machines** can save money but require a higher wind speed than three bladed machines to produce the same power output. This problem also adds to the problem of noise produced from a turbine. **Single blade** machines are not widely used due to the enhancement of the problems associated with the two bladed machines. Stability becoming an increasing problem and require the position of a counterweight on the opposite side of the hub.

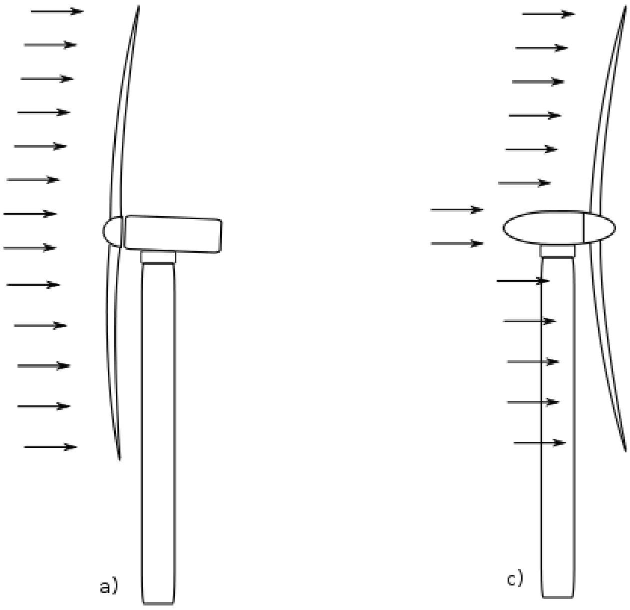
Single Blade	Two Blades	Three Blades
1. Lower blade weight & less cost. **2.** More vibration & unconventional look. **3.** Require a higher wind speed. **4.** Almost not using.	**1.** Similar to a single blade. **2.** Have stability problem. **3.** Require a higher wind speed relatively. **4.** Less using based on the requirements.	**1.** The balance of gyroscopic forces. **2.** Increases cost. **3.** Require a lower wind speed. **4.** More commonly used.

10.Upwind or Downwind Wind Turbine Machines

Another deciding factor is whether to put the blades upwind or downwind of the rotor. Most machines in use today are **upwind machines**. An upwind machine has the blades in front of the nacelle with respect to the wind flow. Upwind machines have the advantage of avoiding any wind shade created by the tower but do have to have the yawing mechanism in place to keep the blades perpendicular to the wind flow.

Downwind machines have the blades placed after the nacelle with respect to the wind flow. The advantage of this design is that the machine does not need a yawing mechanism present, as the machine will automatically yaw into the wind.

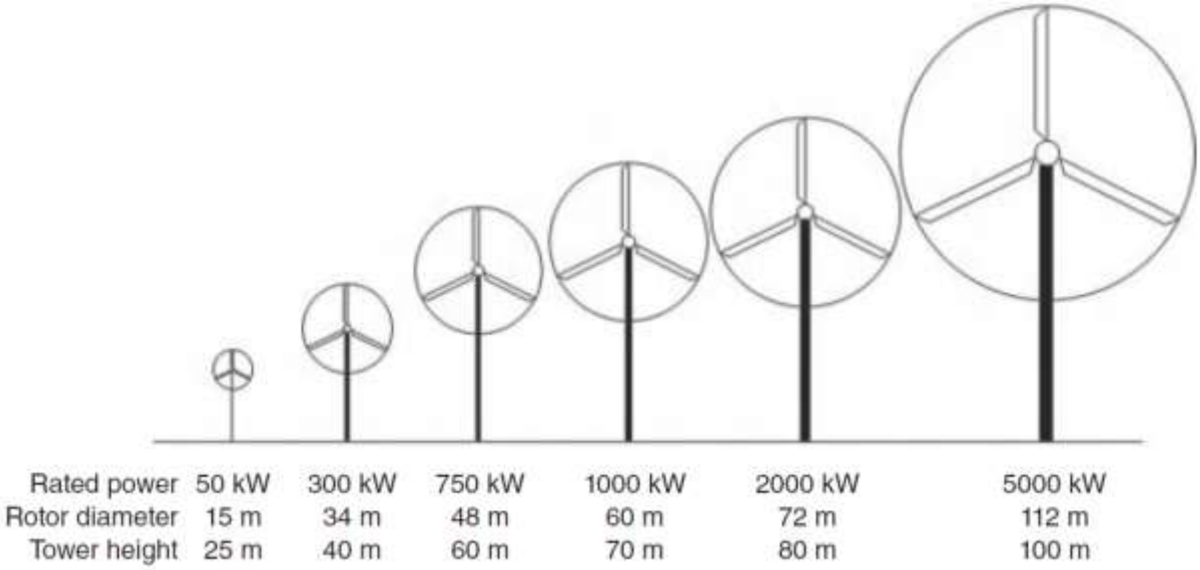
The downside of a downwind machine is that the power output may fluctuate due to the wind shade created by the tower.



Upwind & Downwind machines

11.The Size of Wind Turbine & its Applications

The small design: **less than 10kW** **L≤10 & D≤5**	**The intermediate design: 10-250kW** **L (10-30) & D (5-25)**	**The large design:** **250 kW-5 MW** **L≥30 & D≥25**
Houses Farms Remote applications (batteries charching, water pumping, telecom sites)	Village power Hybrid systems	Central station wind farm Community wind Offshore wind



The relationship between the height tower & diameter of swept area

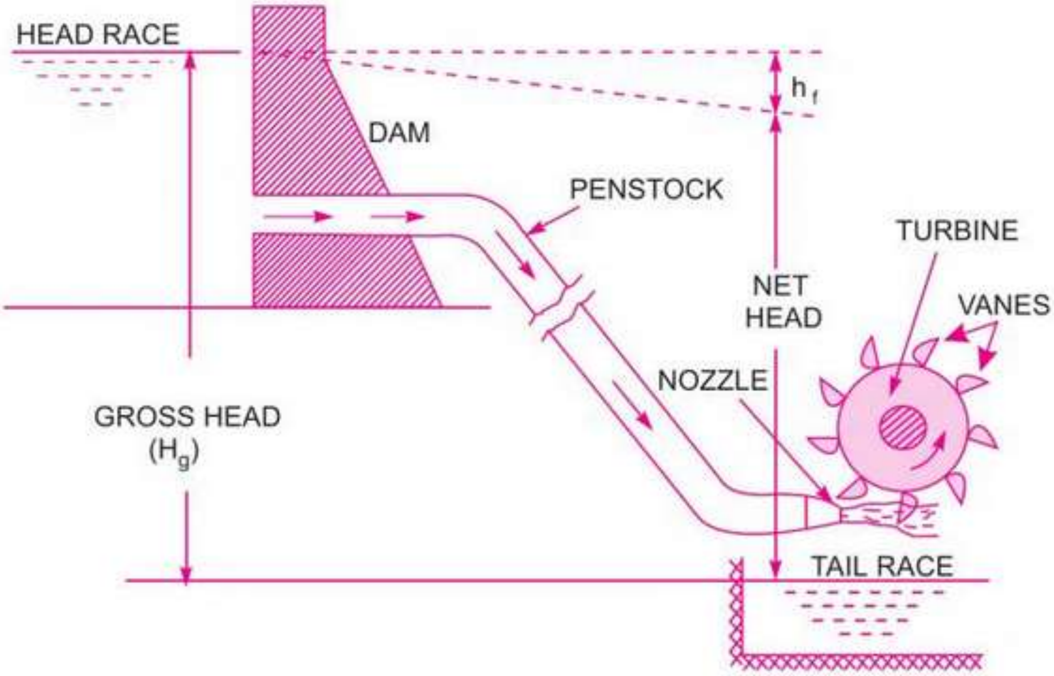
Chapter Six: Hydropower Energy

Hydropower is the power of water (kinetic energy) which can be converted into mechanical energy. The mechanical energy is used in running an electric generator that is directly coupled to the turbine shaft.

1. General layout of a hydroelectric power plant

The hydroelectric power plant consists of the following:

1. A dam constructed across a river to store water
2. Pipes of large diameters called penstocks, which carry water under pressure from the storage reservoir to the turbine.
3. Turbines having different types of vanes fitted to the wheels.
4. Trail race, which is a channel which carries water away from the turbine after water has worked on the turbines.



2. Definitions

Gross head:

It is the difference between the head race level and trail race level when no water is flowing. It is denoted by ‘H_g’

Net head (H):

It is defined as the head available at the inlet of the turbine. When water is flowing from head race to the turbine, a loss of head due to friction between the water and the penstocks occurs which can be represented as ‘h_f’. So,

$$H = H_g - h_f$$

Where, $$h_f = \frac{4\,f\,L\,V^2}{2\,D\,g}$$

f= friction coefficient

L= length of penstock

V= velocity of flow in penstock

D= diameter of penstock

3. Selection of Site for a Hydro-Electric Power Plant

The following factors should be considered while selecting the site for hydroelectric power plant

- **Availability of water**

The design and capacity of the hydro-plant greatly depends on the amount of water available at the site. The maximum and minimum quantity of water available in a year should be made available to

a) Decide the capacity of the plant
b) Set up the peak load plant such as steam, diesel, or gas turbine plant
c) Provide adequate spillways or gate relief during flood period.

- **Water storage capacity**

The output of a hydropower plant is not uniform due to wide variations of rain fall. To have a uniform power output, a water storage is needed so that excess flow at certain times may be stored to make it available at the times of low flow

- **Head of Water:**

The level of water in the reservoir for a proposed plant should always be within limits throughout the year.

- **Distance from Load Centre:**

Most of the time the electric power generated in a hydro-electric power plant has to be used some considerable distance from the site of plant. For this reason, to be economical on transmission of electric power, the routes and the distances should be carefully considered since the cost of erection of transmission lines and their maintenance will depend upon the selected route.

- **Type of the land of the site**

The land of the site should be cheap and rocky. The foundation rocks of the dam should be strong enough to withstand the stresses in the structure.

4. Efficiencies of hydroelectric power turbine

- **Hydraulic efficiency:**

It is defined as the ratio of power given by water to the runner of the turbine to the power supplied by the water at the inlet of the turbine.

$$\eta_h = \frac{Power\ delivered\ to\ runner}{power\ supplied\ at\ inlet\ (water\ power)}$$

$water\ power = \rho\ g\ Q\ H$ (W)

- **Mechanical efficiency**

The power delivered by the water to the runner of a turbine is transmitted to the shaft of the turbine. Due to mechanical losses, the power available at the shaft of the turbine is less than the power delivered to the runner of a turbine. So,

$$\eta_m = \frac{Power\ at\ the\ shaft\ of\ the\ turbine}{Power\ delivered\ to\ runner}$$

- **Volumetric efficiency**

The volume of the water striking the runner of a turbine is slightly less than the volume of the water supplied to the turbine. Some of the volume of the water is discharged to the trail race without striking the runner of the turbine. So,

$$\eta_v = \frac{Volume\ of\ water\ actually\ striking\ the\ runner}{Volume\ of\ water\ supplied\ to\ the\ turbine}$$

- **Overall efficiency**

It is defined as the ratio of power available at the shaft of the turbine to the power supplied by the water at the inlet of the turbine.

$$\eta_o = \frac{Shaft\ power}{water\ power}$$

5. Environmental concerns

➢ Land use

many large hydropower facilities lead to an altering of the surrounding landscape, especially around reservoirs created by damming rivers. Just as reducing downstream water flow can cause a loss of habitat, creating reservoirs to generate electricity in storage and pumped storage hydropower systems often cause upstream flooding that destroys wildlife habitats, scenic areas, and prime farming land. In some instances, this flooding can even force human populations to relocate.

➢ Greenhouse gas emissions from reservoirs

While generating power by spinning turbines with water doesn't directly use any fossil fuels or emit any greenhouse gases, several recent studies have shown that reservoirs created by damming rivers contribute significantly to atmospheric greenhouse gases. This is because organic material trapped in the reservoirs, such as dead plants, breaks down and releases gases like carbon dioxide and methane into the reservoir water.

➢ Flash floods

rapid flooding due to heavy precipitation and dam failure

6. Classification of hydropower plants

➢ Run of River (RoR)

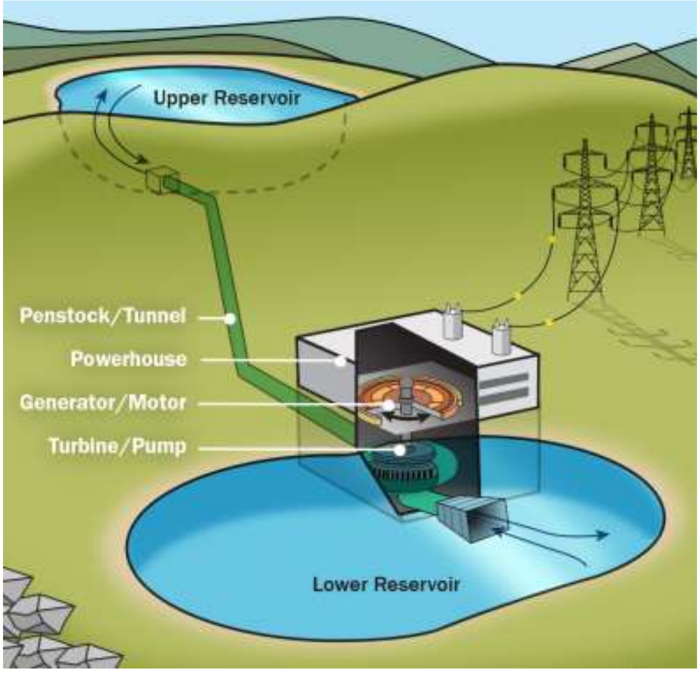
A RoR HPP draws the energy for electricity production mainly from the available flow of the river. Such a hydropower plant generally includes some short-term storage (hourly, daily, or weekly). A portion of river water might be diverted to a channel, pipe line (penstock) to convey the water to hydraulic turbine which is connected to an electricity generator

➢ Storage hydropower

Typically a large system that uses a dam to store water in a reservoir. Electricity is produced by releasing water from the reservoir through a turbine, which activates a generator. Storage hydropower provides base load as well as the ability to be shut down and started up at short notice according the demands of the system (peak load). It can offer enough storage capacity to operate independently of the hydrological inflow for many weeks or even months.

➢ Pumped storage hydropower

Pumped-storage hydropower (PSH) is a type of hydroelectric energy storage. It is a configuration of two water reservoirs at different elevations that can generate power (discharge) as water moves down through a turbine; this draws power as it pumps water (recharge) to the upper reservoir.

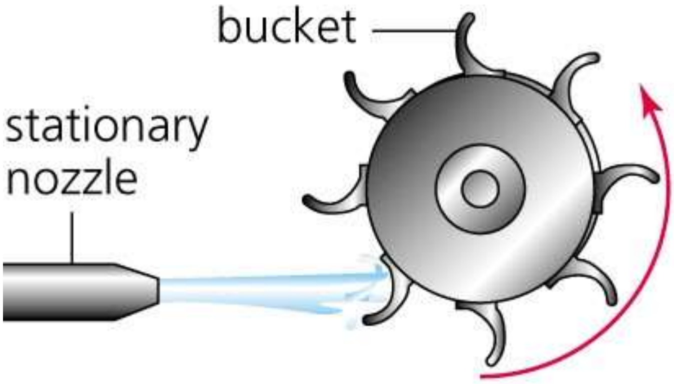


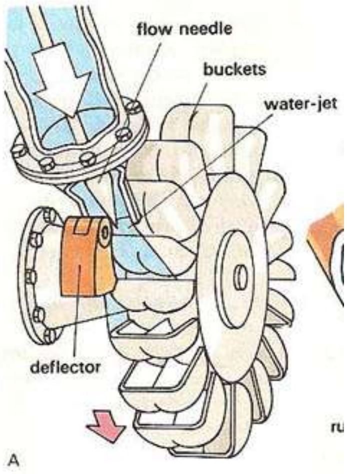
7. Classification of hydraulic turbines

Hydraulic turbines are classified through different ways, but the most important ways are according to the action of water on the turbine blades.

- Impulse turbine- Pelton wheel

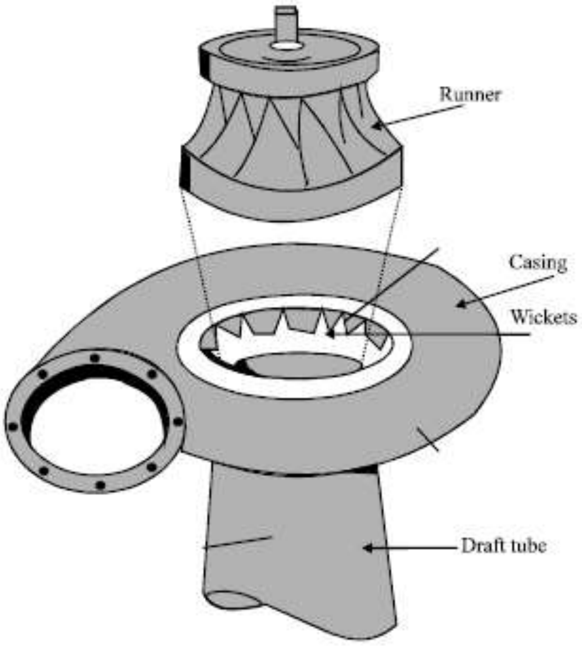
  In an impulse turbine, the pressure energy of water is converted into kinetic energy when passes through the nozzle and forms the high velocity jet of water. The formed water jet is used for driving the turbine.





- Reaction turbine – Francis turbine

  In a reaction turbine, the runner utilises both potential and kinetic energies. As the water flows through the stationary parts of the turbine, there is a change both in pressure and in the direction and velocity of the flowing water. This gives up the energy to the runner and in turn, causes the blades to be rotated.



8. Hydropower costs

➢ The civil works for the hydropower plant construction, including any infrastructure development required to access the site and the project development costs.

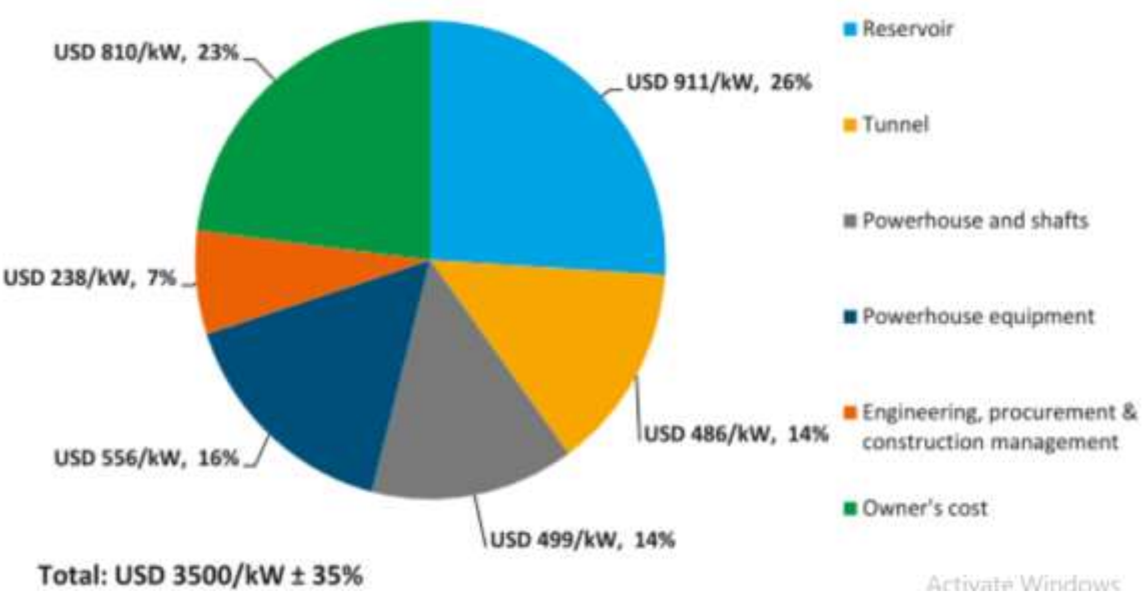
  - Dam and reservoir construction
  - Tunneling and canal construction;
  - Powerhouse construction
  - Site access infrastructure (roads etc)
  - Grid connection

- Developer/owners costs (including planning, feasibility, permitting, etc.)

➢ The cost related to electro-mechanical equipment.

- Turbines, generators, transformers, cabling and control systems

Cost breakdown of an indicative 500 MW power plant in USA



9. Model and prototype

It is necessary to obtain test results, which indicate the performance of the large turbines. This is done by testing smaller model but smaller size.

- The large machine called prototype
- The small machine called model
- The ratio between linear dimensions called scale

For example, one eight scale (1/8) means that the linear dimensions of the model are 1/8 of the linear dimensions of the large machine.

The variables which affect the characteristics of the hydroelectric power plant are:

- Speed, N (rpm)
- Flow rate, Q (m^3/s)
- Head available, H (m)

The dimensionless parameters are:

1. The head coefficient C_H, $\frac{N\,D}{H^{1/2}}$

$$\frac{N_m\,D_m}{H_m^{1/2}} = \frac{N_P\,D_P}{H_P^{1/2}}$$

2. The flow coefficient C_Q, $\frac{Q}{N\,D^3}$

$$\frac{Q_m}{N_m\,D_m^3} = \frac{Q_P}{N_P\,D_P^3}$$

3. The power coefficient C_P, $\frac{P}{N^3\,D^5}$

$$\frac{P_m}{N_m^3\,D_m^5} = \frac{P_P}{N_P^3\,D_P^5}$$

4. The specific speed, $\frac{N\,\sqrt{P}}{H^{5/4}}$

$$\frac{N_m\,\sqrt{P}_m}{H_m^{5/4}} = \frac{N_P\,\sqrt{P}_P}{H_P^{5/4}}$$

Scale ratio 1/5 means $\frac{\boldsymbol{diameter\ of\ the\ model}}{\boldsymbol{diameter\ of\ the\ prototype}} = \frac{\boldsymbol{D_m}}{\boldsymbol{D_P}} = \frac{\mathbf{1}}{\mathbf{5}}$

Ex1. At a location investigation yielded the following data for the instillation of the hydroelectric power plant; head available is 200 m, power available is 40 MW, speed chosen is 500 rpm. A model study was proposed in the laboratory. Head available was 20 m. It was proposed to construct a 1/6 scale model. Determine the speed and the power to test the model. Also, determine the flow rate required in terms of prototype flow rate?

Solution:

Scale 1/6 means $\frac{D_m}{D_P} = \frac{1}{6}$

$\frac{N_m\, D_m}{H_m^{1/2}} = \frac{N_P\, D_P}{H_P^{1/2}}$ $\qquad N_m = N_P \frac{D_P}{D_m}\,(\frac{H_m}{H_P})^{\frac{1}{2}}$

$$N_m = 500 \times 6 \times (\frac{20}{200})^{\frac{1}{2}} \Rightarrow\Rightarrow \boldsymbol{N_m = 948.7\ rpm}$$

$$\frac{P_m}{N_m^3\, D_m^5} = \frac{P_P}{N_P^3\, D_P^5}$$

$$P_m = P_P(\frac{N_m}{N_P})^3(\frac{D_m}{D_P})^5$$

$$P_m = 40000\left(\frac{948.7}{500}\right)^3\left(\frac{1}{6}\right)^5 \Rightarrow\Rightarrow \boldsymbol{P_m = 35.13\ KW}$$

$$\frac{Q_m}{N_m\, D_m^3} = \frac{Q_P}{N_P\, D_P^3}$$

$Q_m = Q_P(\frac{N_m}{N_P})(\frac{D_m}{D_P})^3$

$Q_m = Q_P\,\frac{948.7}{500}\,(\frac{1}{6})$

$\boldsymbol{Q_m = 0.00877 Q_P}$

Ex2. A turbine is to operate under the head of 25 m at speed of 300 rpm. The discharge is 9 m^3/s if the overall efficiency is 90%. Determine the performance of the turbine under head of 20 m

Solution:

Since there is one turbine, scale ratio is unity. So, $D_1=D_2$

N_1= 300 rpm, H_1=25 m, H_2=20 m, Q_1=9 m^3/s, $\eta_o = 90\%$

$$\eta_o = \frac{Power\ at\ the\ shaft}{Water\ power}$$

$$P_1 = \eta_o\ \rho\ \mathrm{Q}_{\,1}\ g\ H_1$$

$$P_1 = 0.9 \times 1000 \times 9 \times 9.81 \times 25 = 1986.52\ KW$$

$$\frac{N_1\ D_1}{H_1^{1/2}} = \frac{N_2\ D_2}{H_2^{1/2}}$$

$$N_2 = N_1\ \sqrt{\frac{H_2}{H_1}}$$

$$N_2 = 300\ \sqrt{\frac{20}{25}} \Rightarrow\Rightarrow \boldsymbol{N_2 = 268.3\ rpm}$$

$$\frac{Q_1}{N_1\ D_1^3} = \frac{Q_2}{N_2\ D_2^3}$$

$$Q_2 = Q_1\ \frac{N_2}{N_1}$$

$$Q_2 = 9\ \frac{268.3}{300} \Rightarrow\Rightarrow \boldsymbol{Q_2 = 8.05\ m^3/s}$$

$$\frac{P_1}{N_1^3\ D_1^5} = \frac{P_2}{N_2^3\ D_2^5}$$

$$P_2 = P_1\ (\frac{N_2}{N_1})^3$$

$$P_2 = 1986.52(\frac{268.3}{300})^3 \Rightarrow\Rightarrow \boldsymbol{P_2 = 1421\ KW}$$

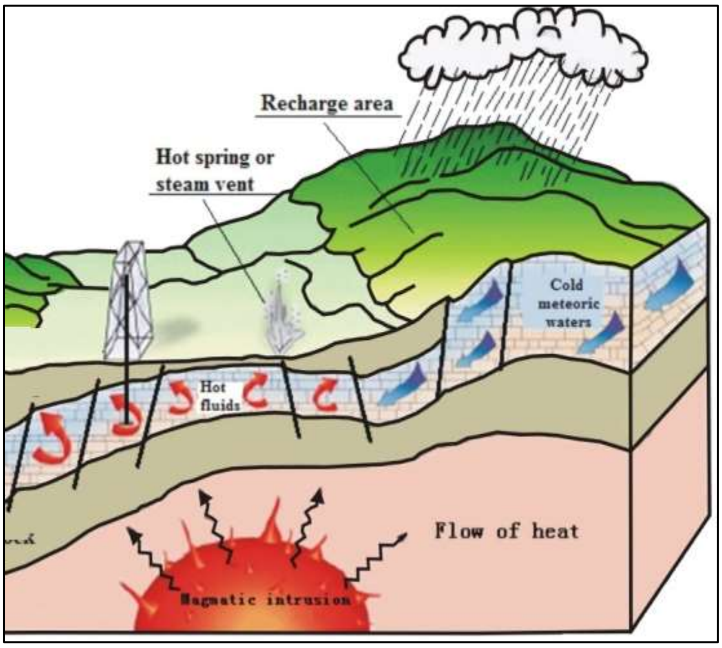
Chapter Seven: Geothermal Energy

1. Introduction

Geothermal energy is heat within the earth. The word geothermal comes from the Greek words *geo* (earth) and *therme* (heat). Geothermal energy is a renewable energy source because heat is continuously produced inside the earth. People use geothermal heat for bathing, to heat buildings, and to generate electricity. Geothermal energy is estimated to be equivalent to 42 million megawatts (MW) of power, and is expected to remain so for billions of years to come, ensuring an inexhaustible supply of energy.

2. How does a conventional geothermal reservoir work?

A geothermal system requires heat, permeability, and water. The heat from the Earth's core continuously flows outward. Sometimes the heat reaches the surface as lava, but it usually remains below the Earth's crust, heating nearby rock and water sometimes to levels as hot as 370°C. When water is heated by the earth's heat, hot water or steam can be trapped in permeable and porous rocks under a layer of impermeable rock and a geothermal reservoir can form. This hot geothermal water can manifest/appear itself on the surface as hot springs or geysers, but most of it stays deep underground, trapped in cracks and porous rock. This natural collection of hot water is called a geothermal reservoir.



3. Electricity production

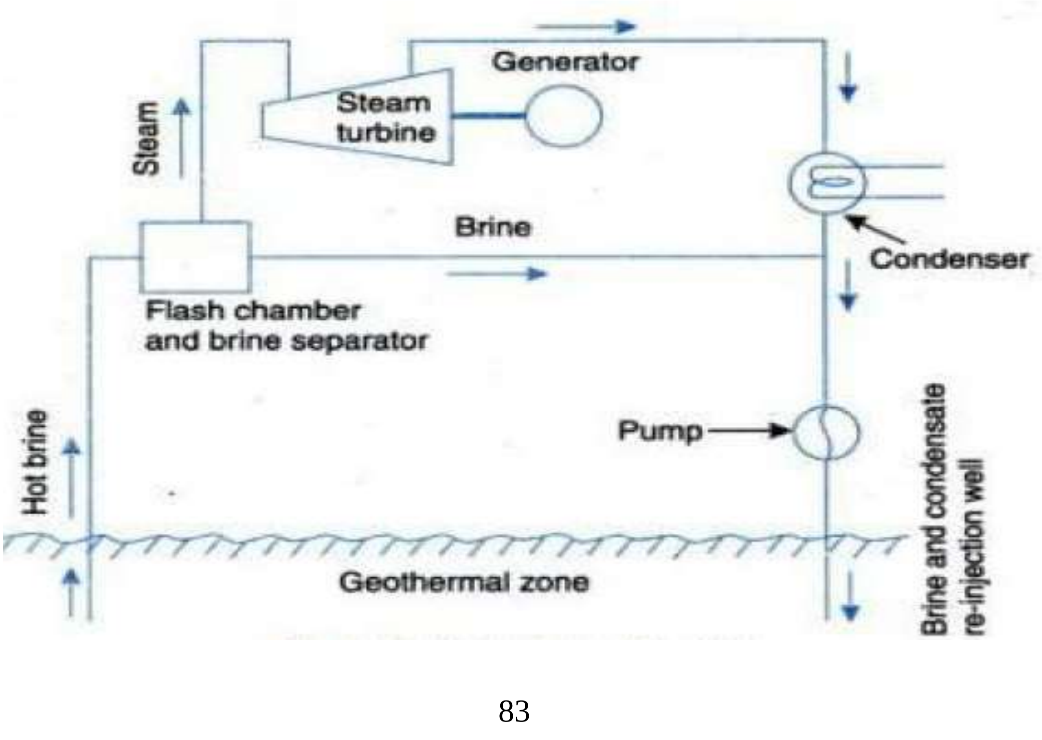
To develop electricity from geothermal resources, wells are drilled into a geothermal reservoir. The wells bring the geothermal water to the surface, where its heat energy is converted into electricity at a geothermal power plant

There are three commercial types of geothermal power plants:

3.1 Flash Power Plant

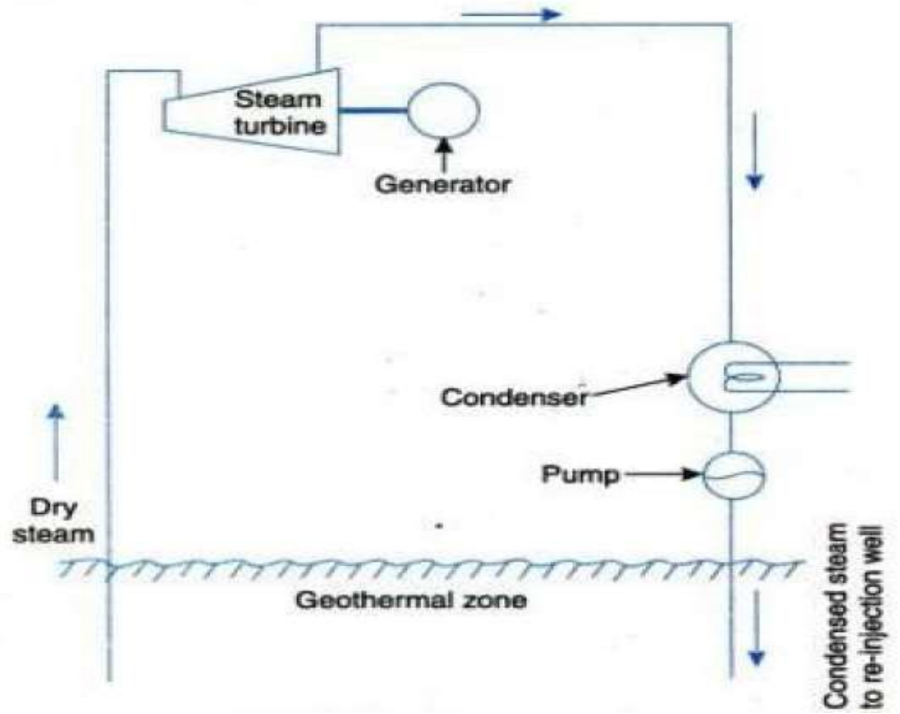
Geothermal flash steam power plants use water at temperatures of at least 182°C (360°F). The term flash steam refers the process where high-pressure hot water is flashed (vaporised) into steam inside a flash tank by lowering the pressure. This steam is then used to drive turbines.

The geothermal fluid enters the well at the source inlet temperature. Due to the well pressure loss, the fluid has started to boil when it enters the separator. The brine from the separator is re-injected in a second well back inside the earth. The steam from the separator enters the turbine. The steam is then expanded through the turbine producing mechanical energy which in turn produces electricity .the expanded steam enters a condenser where it is cooled down and injected back into the earth.



3.2 Dry Steam Power Plant

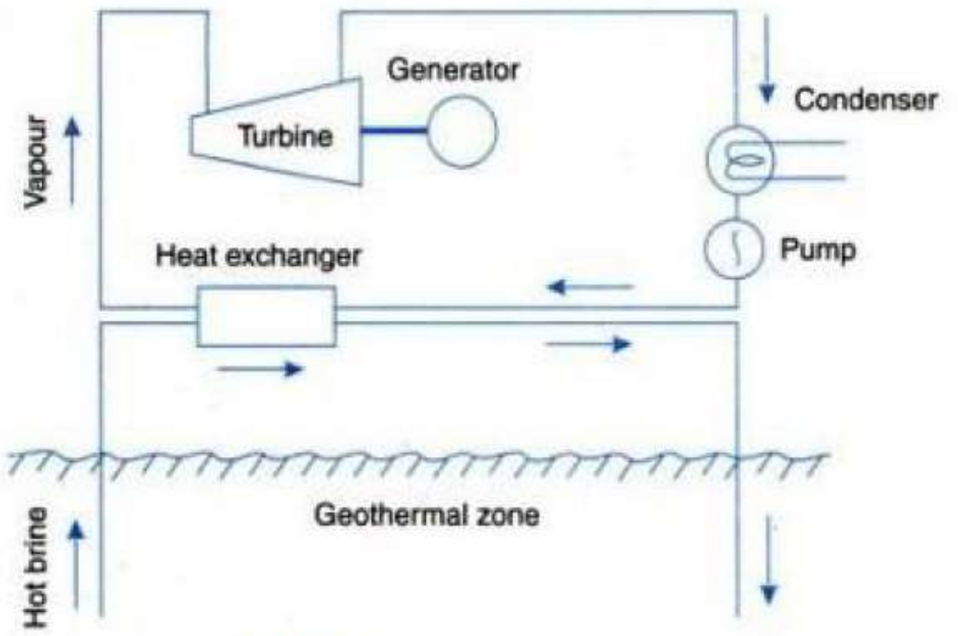
This type of geothermal power plant was named dry steam since water that is extracted from the underground reservoirs has to be in its gaseous form (water-vapor). Geothermal steam of at least 150°C is extracted from the reservoirs through the production wells (as we would do with all geothermal power plant types) but is then sent directly to the turbine. Geothermal reservoirs that can be exploited by geothermal dry steam power plants are rare/unusual.



3.3 Binary steam power plant

This type of plant uses high temperature geothermal water to heat another fluid which has a lower boiling point than water. This fluid vaporises to steam, drives the turbines, and then condenses to liquid to begin the cycle again.

The water, which never comes into direct contact with the working fluid, is then injected back into the ground to be reheated. Since the most resources are with lower temperature, the binary steam power plants are more common.



4. The Ground-Coupled Heat Pump (GCHS)

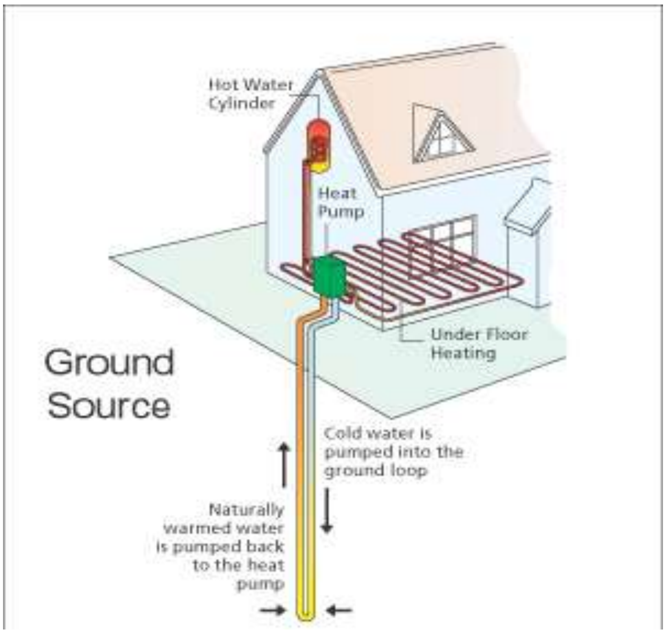
Heat pumps are designed to move thermal energy in the opposite direction of spontaneous heat transfer by absorbing heat from a cold space and releasing it to a warmer one. A heat pump uses a small amount of external power to accomplish the work of transferring energy from the “heat source” to the “heat sink”.

The GCHP is subdivided according to ground heat exchanger design: vertical & horizontal heat exchanger.

The vertical GCHP: generally consist of two small-diameter high-density PE tubes (Pressure Equalizer Tubes). They have been applied in a vertical bore hole which is then filled with a solid medium. Vertical tubes range is from 20-40 mm nominal diameter. Bore depths range is from 15m to 180m depending on the local drilling conditions and available equipment. A minimum base separation distance between tubes of 6m is recommended as loops are placed in a grid pattern.

The advantages of the vertical GCHP:

1. Requires relatively small area of ground.
2. It is in contact with soil that varies very few in temperature and thermal properties.
3. Requires the smallest amount of pipes and pumping energy.
4. It can yield the most efficient GCHP system performance.



The disadvantages of the vertical GCHP:

Higher in cost because of expensive equipment needed to drill the bore hole & limited availability of constructors to perform this work.

The horizontal GCHP: can be divided into at least three subgroups: single pipe, multiple pipes, spiral pipe.

Single pipe horizontal GCHP were initially placed in narrow trenches & it is needed the greatest amount of ground area.

Multiple pipes horizontal GCHP can reduce the amount of required ground area while it is required to increase the total pipe length to overcome thermal interference from adjacent pipes.

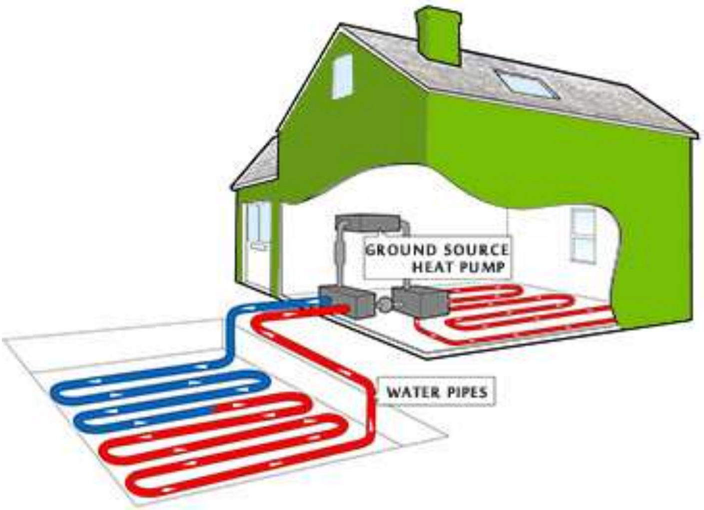
Spiral coil pipes horizontal GCHP can further reduce the amount of required ground area.

The advantages of the horizontal GCHP:

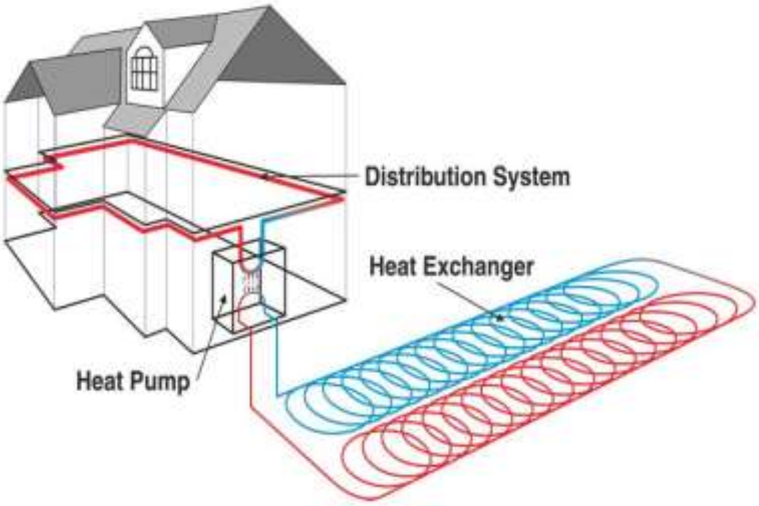
1. They are typically less expensive that vertical GCHP.
2. Trained equipment operators (constructors) are more widely available.

The disadvantages of the horizontal GCHP:

1. Requires relatively large area of ground.
2. Greater variation in performance because of ground temperature & thermal properties fluctuate with the season, rainfall, and burial depth.
3. Slightly higher pumping energy requirement.
4. Lower system efficiency.



Multiple pipes horizontal GCHP



Spiral coil pipes horizontal GCHP

Chapter Eight: Ocean Thermal Energy Conversion (OTEC)

1. Introduction

In tropical seas, temperature differences of about 20°C occur between the warm near-surface water and the cold ‘deep’ water at 500 to 1000 m depth. Heat engines can operate between thermal sources and sinks with such relatively small temperature difference.

Ocean thermal energy conversion (OTEC) is the extraction and conversion of this thermal energy into useful work for electricity generation. Given sufficient scale of efficient equipment, electricity power generation could be sustained day and night at ~200 kWe/km2 in areas of tropical sea. Such power equals about 0.07% of the absorbed solar irradiation input to that area.

2. Working principles

Figure above outlines a system for OTEC; and with a heat engine operating a closed-cycle Rankine process. The working fluid (e.g. ammonia) boils in the ‘evaporator’ at the ~25°C to ~30°C temperature of the surface water, so driving a turbine generator for electricity supply. On the output side of the turbine, the vapor condenses to a liquid at the ~5°C temperature of the pumped deep water.

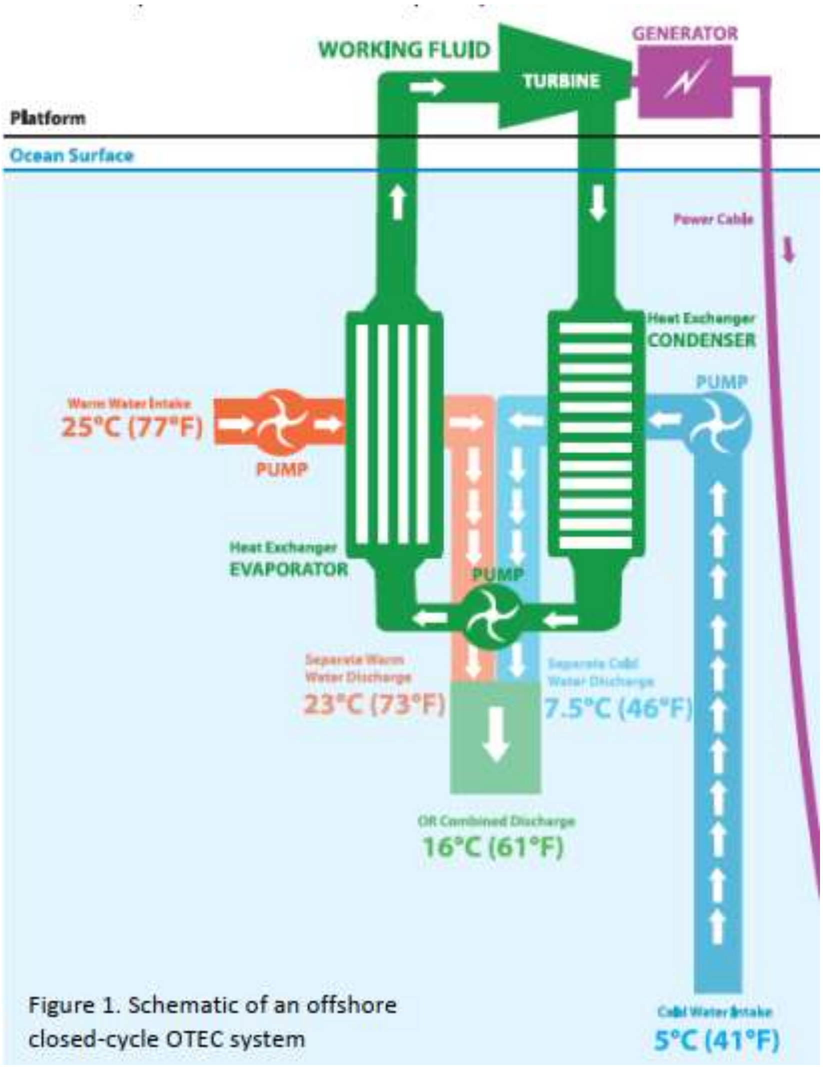
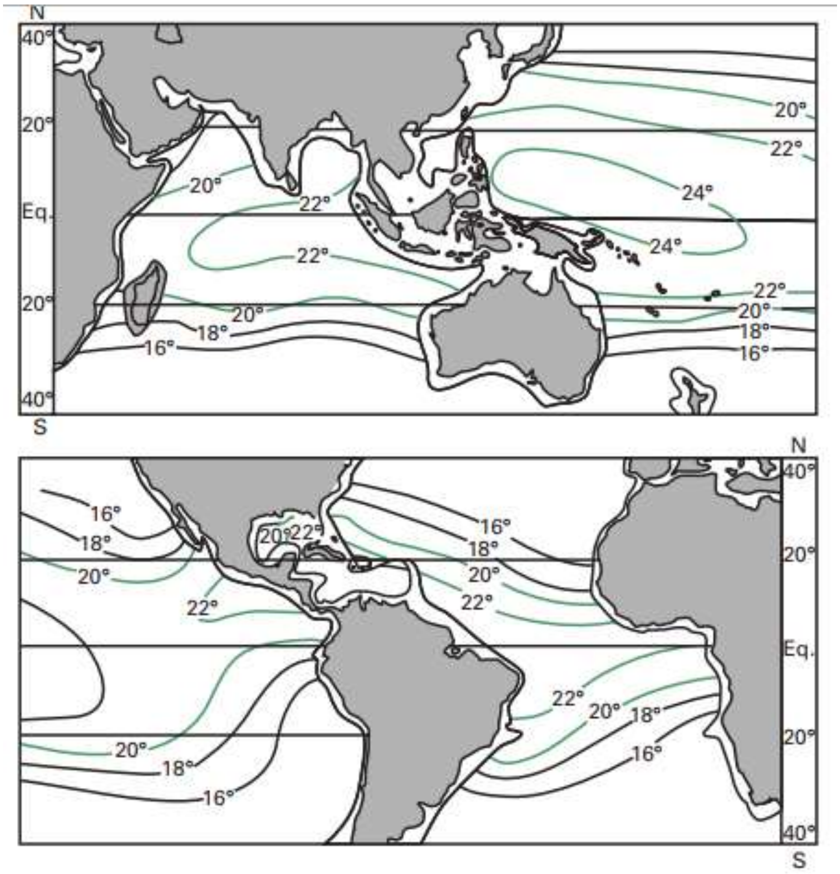
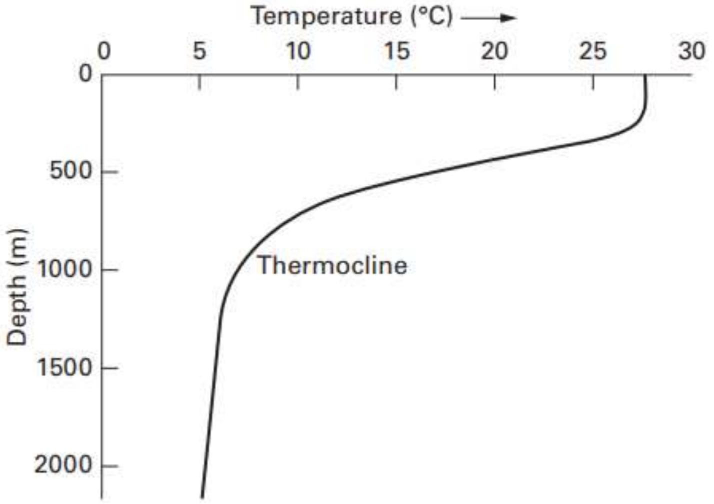


Figure 1. Schematic of an offshore closed-cycle OTEC system

Seasonal average of temperature difference between sea surface and a depth of 1000 m are explained in the following figures. Zones with temperature difference ≥ 20°C are most suitable for OTEC.





3. Advantages of OTEC

OTEC uses clean, abundant, renewable and natural resources to produce electricity. Research indicates that there are little or no adverse environmental effects from discharging the used OTEC water back to the ocean at prescribed depths. As well as producing electricity, OTEC systems can produce cold water for cooling purposes. The use of OTEC also assists in reducing the dependence on fossil fuels to produce electricity.

4. Limitations

- Pumping

Cold saline water has to be pumped up to surface level to become a colder thermal sink for the heat engine, for which considerable pumping power is required. In practice, pumping is at a rate of about 6 m3/s of water per MWe of electricity generated, which may require up to 50% of the generated power. Such systems require large pumps, large-diameter pipes and large heat exchangers, all of which are expensive.

- Small efficiency

In practice, the temperature difference available to operate the heat engine is small (<20°C) and so the efficiency of even a ‘perfect’ engine is small at > ~ 5%.

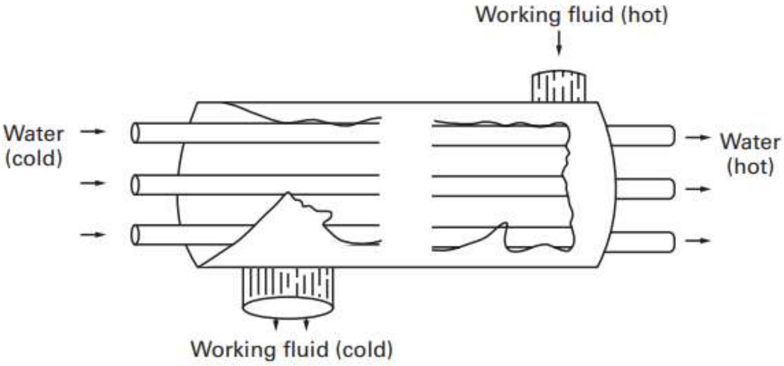
- Remote location

Sites with OTEC potential are either at tropical coastlines or offshore using large floating installations. Such sites are usually far from habitations having the capacity to utilize OTEC output.

5. Practical consideration of OTEC

- Heat exchangers

Figure below is the outline design of a shell and tube heat exchanger suitable for closed-circuit OTEC, but, for 1 MW thermal output at the small temperature differences, this would require several thousand internal tubes with a total surface area >>2000 m^2. Thus OTEC heat exchangers must be relatively large to provide sufficient area for heat transfer at low temperature difference, and are therefore expensive (perhaps 50% of total costs)



- Biofouling and corrosion

The inside especially of the pipes become encrusted by marine organisms, which increase the thermal resistance, so reducing efficiency. Such biofouling is one of the major problems in OTEC design, since increasing the surface area available for heat transfer also increases the opportunity for organisms to attach themselves. In addition, serious corrosion can occur with metal structures, including the inner heat transfer tubing of heat exchangers.

- Construction of the cold water pipe

The suspended cold water pipe is subject to many forces, including those due to drag by currents, vortex shedding, motion of buoys and platforms, and the dead weight of the pipe itself. In addition, there are substantial difficulties involved in assembling and positioning the pipe. Some engineers favour bringing out a prefabricated pipe and slowly sinking it into place; however, transporting an object several meters in diameter and perhaps a kilometre long is difficult