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Studying the factors affecting solar power generation systems performance (SPGSP)

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Abstract
Solar energy is a huge, clean and renewable source of energy. It is also available everywhere on the earth. However, there are many technical and economic difficulties need to be solved so that solar energy becomes a strong competition against the traditional energy sources. Energy from the sun can be used successfully in electric power generation systems. Depending on the climate conditions and the use of a properly designed, installing and maintained system can meet a large demand in this request. Work plane for this research will include many steps, the first step will include an introduction to solar energy. The second step will be a short review of the solar energy availability, geometry, fields of applications and the largest commercial application of solar energy is the solar thermal power generation. In addition, the most common types of solar thermal power plants, the solar field, heat transfer fluid and the power conversion system types will be explained in detail. The third step, a simple analysis for the solar thermal power plant will be explained in order to predict the optimum conditions leading to maximum performance. Discussions of results will be the fourth step. The last step a conclusion and recommendation for future work will also be included.

I. Introduction to Solar Energy

The sun is the origin of all energy sources on the Earth. Solar energy is most abundant form of these energies. Solar energy is characterized as:

1. Clean energy (does not cause any environmental pollution).
2. Renewable energy.
3. Available everywhere on the Earth i.e. does not need to be transported from place to place.
4. Promising energy source, because of the lack and environmental restrictions on fossil fuel.
5. Needs medium technology.

The sun is the center of our solar system; it is a tremendous star with a diameter of 1.39 Million km. The sun is composed of many elements. The most important of them are Hydrogen, Helium and other known elements. The source of solar energy is the fusion reaction of four Hydrogen atoms to form one Helium atom:

$H+H+H+H \Rightarrow He + \text{Solar energy}$

The huge energy released from this fusion reaction is transmitted in all directions as electromagnetic waves (Solar radiation) away from the sun with the speed of light (300×10^3 Km/s). Solar radiation reaches the earth in 8.5 minutes.

Rate of produced energy	$8x l0^{27}$ KW
Rate of energy reaching the earth	$1.7 X 10^{17}$ KW

This energy is about 5000 times all energy sources on the Earth.

From above, the importance of solar energy is obvious.

Fields of Applications

- Water and space heating.
- Power Generation.
- Refrigeration and air conditioning.
- Seawater desalination.
- Power generation.
- Irrigation.
- Many industrial and agriculture processes.

However, there are many technical and economical difficulties need to be solved so that solar energy becomes a strong competition against the traditional energy sources.

In general, it might be said that, solar energy has achieved significant success in some areas such as water heating, drying, refrigeration and air conditioning, water distillation, irrigation and electric power generation.

This work presents a comprehensive explanation about solar radiation and how to be dealt with quantitatively and qualitatively, then some detailed analysis for one of the most worldwide used application that is solar power generation.

Solar Radiation

At the outer space, extraterrestrial solar radiation is only rays that form the direct (beam) light coming nearly parallel to the imaginary line connecting the sun and earth's centers. .

When this solar radiation enters the atmosphere, a large part of it is exposed to scattering and absorption due to the following reasons:

a. Reflection on the air and water vapor molecules existed in the atmosphere. Some of the sunrays bounce back to the outer space. The other part is scattered in various directions in the atmosphere and the remaining part reaches the surface of the earth as a diffuse radiation.
b. The rest of solar radiation after whatever being reflected or absorbed reaches the surface of the earth in a form of light bundle called beam (direct) solar radiation.

On such basis, the total solar radiation reaching the surface of the earth is in two forms:

Direct (beam) solar radiation.

Direct (beam) solar radiation which is composed of rays coming parallel to the imaginary line sun-earth centers. For any surface, the intensity of such radiation depends the on the incidence angle of the solar radiation on such surface.

The intensity of solar radiation is maximum when the incidence angle (i) is zero, i.e. when the solar radiation is normal to the surface as shown in Fig. 1-1. It is clear from the figure that the intensity of solar radiation decreases as the incidence angle increases.

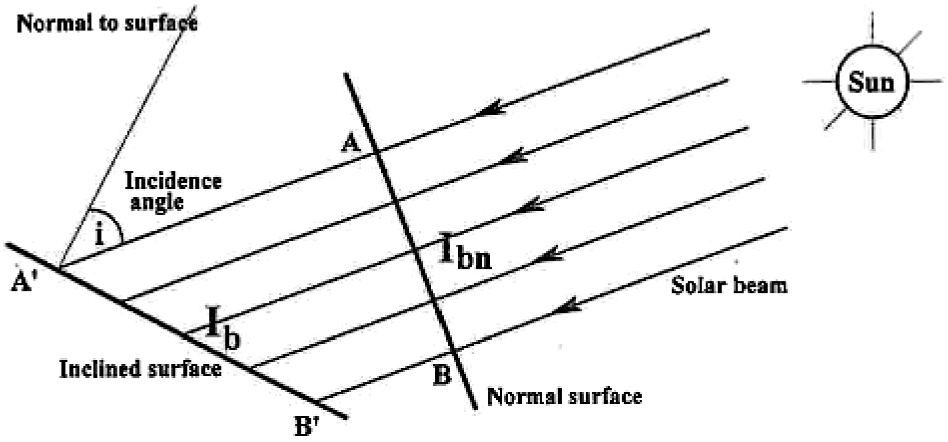


Fig. 1-1. Solar beam radiation intensity is maximum when it is normal to a surface.

If the normal solar radiation intensity at the earth's surface is I_{bn}, then the beam solar radiation intensity on the tilted surface, I_b is given by the following equation

$I_b = I_{bn} \cos i$

Diffuse (sky) solar radiation.

The diffuse (sky) solar radiation is the part of direct radiation that exposed to scattering, reflection and absorption by air and water vapor molecules during its passing through the atmosphere and is re- reflected once again to reach the surface of the earth from all directions. This form of solar radiation is scattered in nature and its intensity is not much affected by change in direction. It has a maximum value for a horizontal surface, I_{dh} and decreases with the tilt angle, β as:

$$I_d = I_{dh} \cos\left(\frac{\beta}{2}\right)$$

Where, I_{dh} is the diffuse solar radiation intensity on the tilted surface.

The total solar radiation falling on a surface is the sum of direct (beam) solar radiation, I_{bn} cos i and diffuse (sky) solar radiation falling on such surface:

$$I = I_b \cos i + I_{dh}\left(\frac{\beta}{2}\right)$$

Solar constant

Solar constant is defined as the amount of solar radiation falling on one square meter normal to solar radiation

(solar irradiance) at the outer limit of atmosphere. The value of solar constant changes all over the year according to distance between the sun and the earth (inverse square rule). The average value of solar constant as measured by NASA is $I_{sc} = 1.353$ KW/m^2
The daily value of solar constant I_o is given by

$$I_o = I_{sc}\left[1 + 0.034\cos\frac{2\pi N}{365}\right]$$

Where, N is the number of the day starting from 1anuary first
This equation is graphically represented in Fig. 1-2.

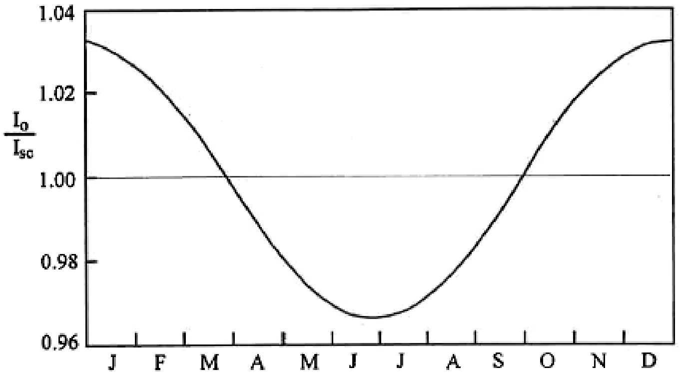


Fig. 1-2. Ratio of actual value of solar constant to its average value

Spectral Distribution of Solar Radiation
Solar radiation is electromagnetic waves with different wave lengths. The extraterrestrial spectral irradiance of solar radiation is shown in Fig. 1-3

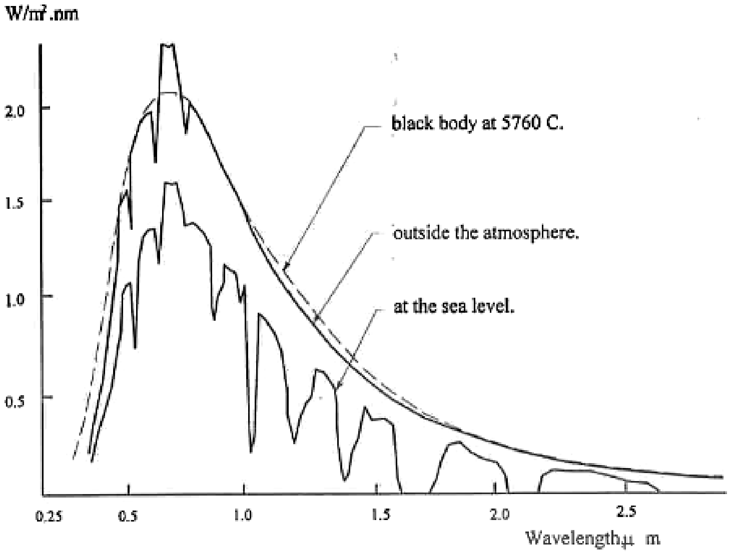


Fig. 1-3. The extraterrestrial and terrestrial spectral irradiance.

The terrestrial spectral irradiance of solar radiation is also shown in the figure. The depletion of solar radiation through the atmosphere is obvious in the terrestrial spectral irradiance. It is clear from the figure that the sun is equivalent to a black body at 5760 C (dotted line).
The difference between the intensity of solar radiation in the outer space and the total solar radiation reaching the surface of the earth depends mainly on the distance passed by the radiation through the atmosphere, and the suspended haze. The diffuse radiation is minimum (about 10%) in clear sky conditions.
However, with the increase of hazy or in cloudy conditions, direct solar radiation is depleted, and diffuse radiation increases up to 100% in fully hazy or cloudy sky conditions. In such case, direct (beam) solar radiation may reach 0%.

II. Geometry of solar radiation

At a certain place on the earth, the following angles must be defined: Latitude angle, L
L = the latitude of the place in degrees

L = 0°	at the Equator
L=900N	at the North Pole
L = 90° S	at the South Pole

Generally, the latitude of the place can be defined as shown in Fig. 2-1.

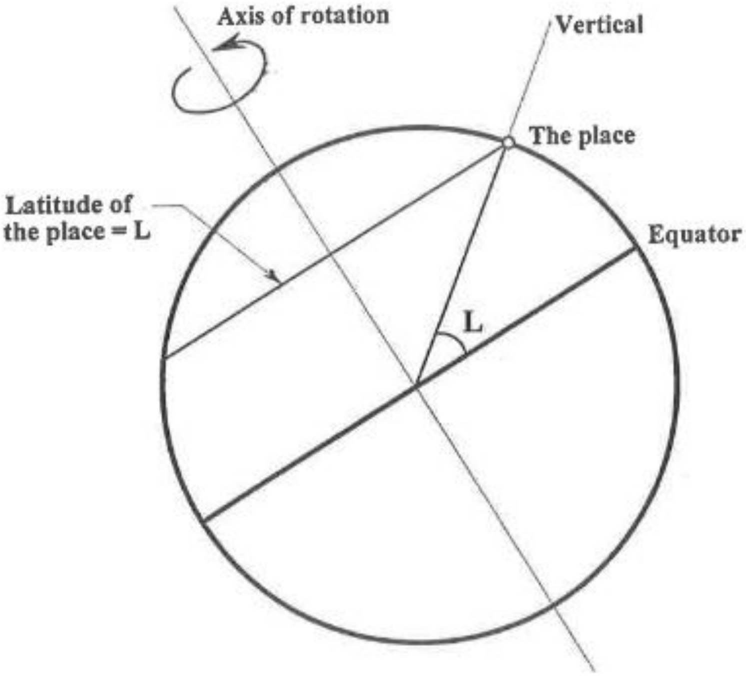


Fig. 2-1 Definition of the Latitude angle

Solar altitude angle, as and Zenith angle, Z
Solar azimuth angle, as
Solar azimuth angle, as measures the deviation from the south direction. It is the angle between the projection of sun rayon the horizontal plane and the south direction as shown in Fig. 5;

$a_s = 0$	At noon time, (the sun is due south)	
a_s	is (+)	Before noon
a_s	is (-)	After noon

The definitions of sun altitude angle, a and zenith angle, z are also given in Fig. 2-2.

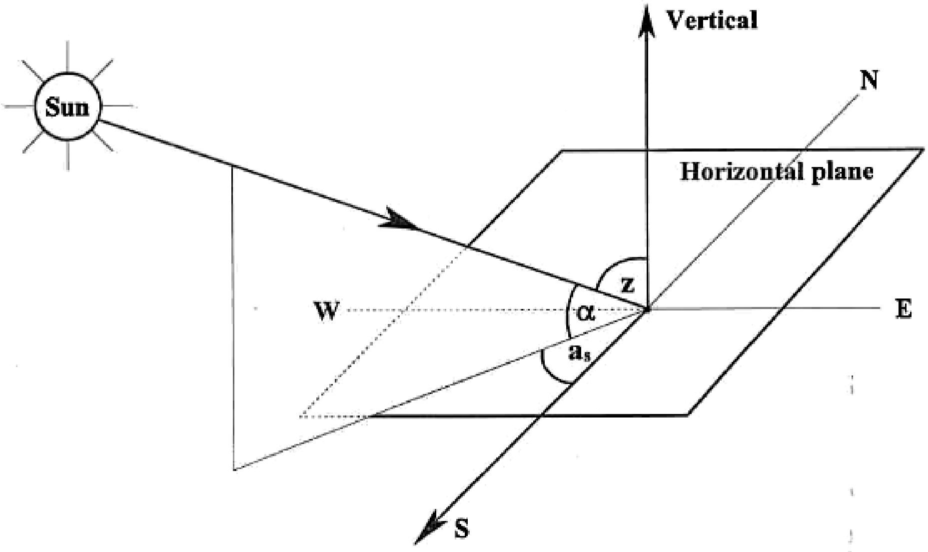


Fig. 2-2. Definition of altitude, zenith, and solar azimuth, angles.

Relative Motion of the Sun-Earth
Any point on the Earth's surface rotates on a circle which is the latitude of the place. The most important latitudes are:

Arctic Circle 66.5° N,
Tropic of Cancer 23.5° N,
Equator 0°,

The Day and Night
Earth rotates about its axis in front of the sun once each 24 hours creating the day and night.
And rotates around the sun (in elliptical orbit) once each 365.25 days (Year), creating the seasons.
The axis of the Earth’s rotation is fixed in direction and makes 23.5° with the orbital plane allover the year as shown in Fig. 2-3.

Therefore, The day length depends on the latitude of the place. In the north hemisphere

Winter solstice, December 21	Day time < Night time (Arctic circle is dark 24 hrs)
Summer solstice, June 21	Day time > Night time (Arctic circle: sun 24 hrs)
Spring equinox, March 21	Day time = Night time
Autumn equinox, Sept. 21	Day time = Night time

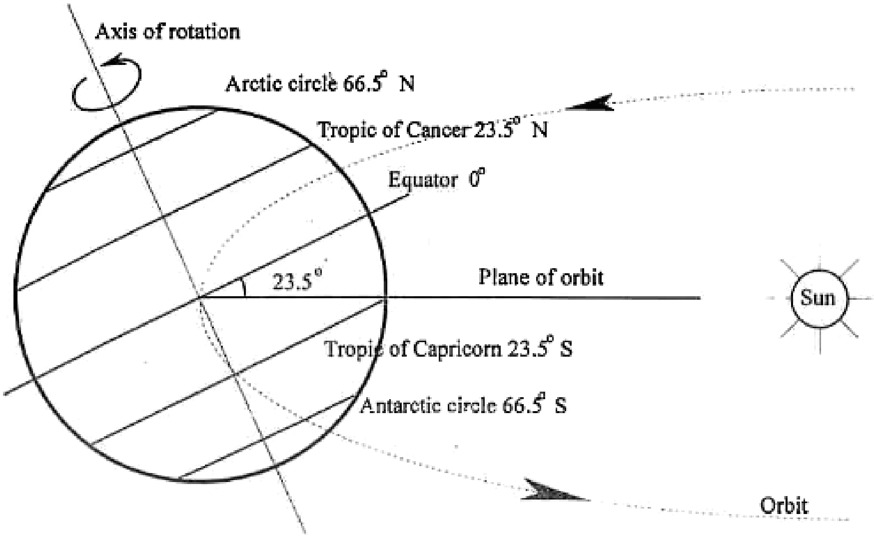


Fig. 2-3. Rotation of the earth about a fixed direction axis in front of the sun.

Figure 2-4. shows that the day length in the North hemi-sphere decreases in the north direction in the winter solstice 21 December, while night increases. The Antarctic Circle 66.5° S to the North Pole are dark during the 24 hours at the same day. Figure 2-5 shows the reverse at the summer solstice, 21 June.

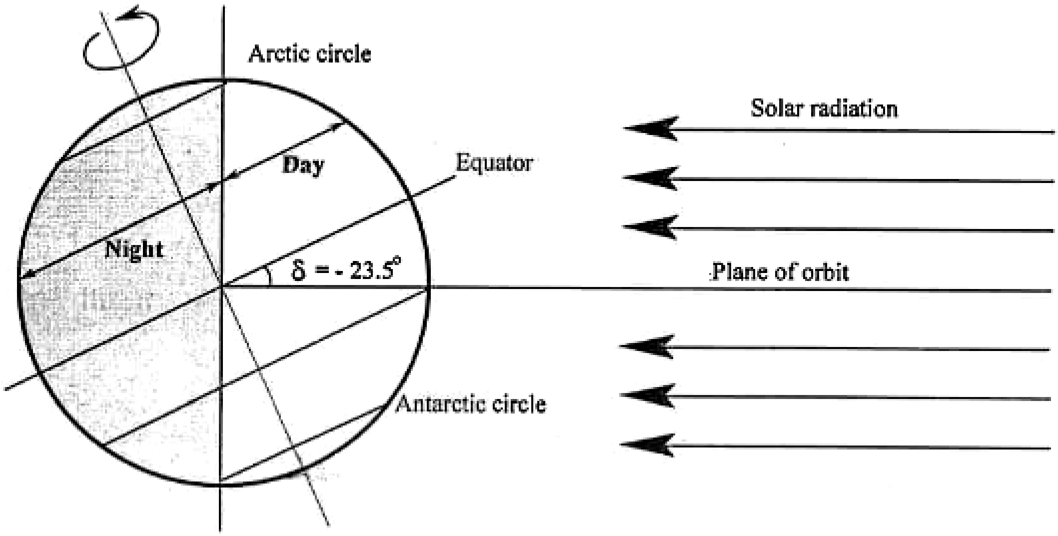


Fig. 2-4. Creation of the day and night due to the rotation of earth. Winter solstice in the northern half of the earth.

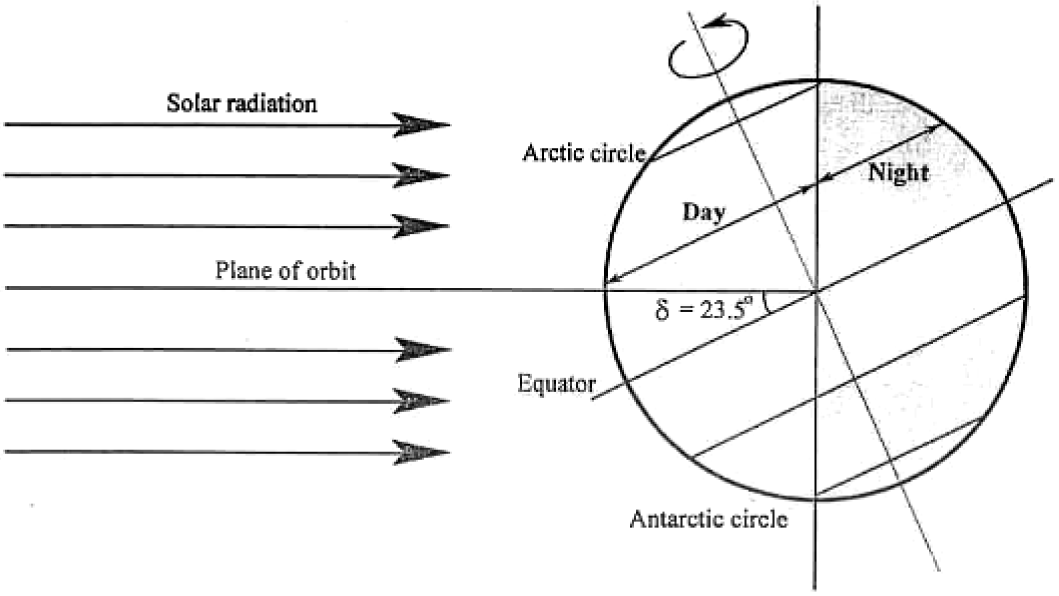


Fig. 2-5. Creation of the day and night due to the rotation of earth.
Summer solstice in the northern half of the earth.

Solar declination angle, δ

Solar declination angle, δ is the angle between the line of sun-earth's centers and Equatorial plane. δ has the same value of Latitude when the sun is overhead at Noon and changes from -23.5° to 23.5° as:

δ = -23.5°	21 December
δ = 0°	21 March
δ = 23.5°	21 June
δ = 0°	21 September

The sun can be only overhead between the tropic of Cancer (23.5° N) & tropic of Capricorn (23.5° S). At tropic of Cancer (23.5° N), the sun is overhead at noon time, June 21, Where 0 = 23.5° (Summer Solstice).
At tropic of Capricorn (23.5° S), the sun is overhead at noon time, Dec. 21, where δ = -23.5° (Winter Solstice).
At the Equator (0°), the sun is overhead at noon at March 21 and Sept. 21, where 0= 0° (Equinoxes).
The value of declination angle, δ can be expressed as

$$\delta = 23.5\ \mathrm{Sin}\left[\frac{360}{365}\ (284 + N)\right]$$

The declination angle, δ can be represented graphically allover the year as shown in Fig. 2-6.
Figure 2-7. explains the relative motion between the earth and the sun allover the year.

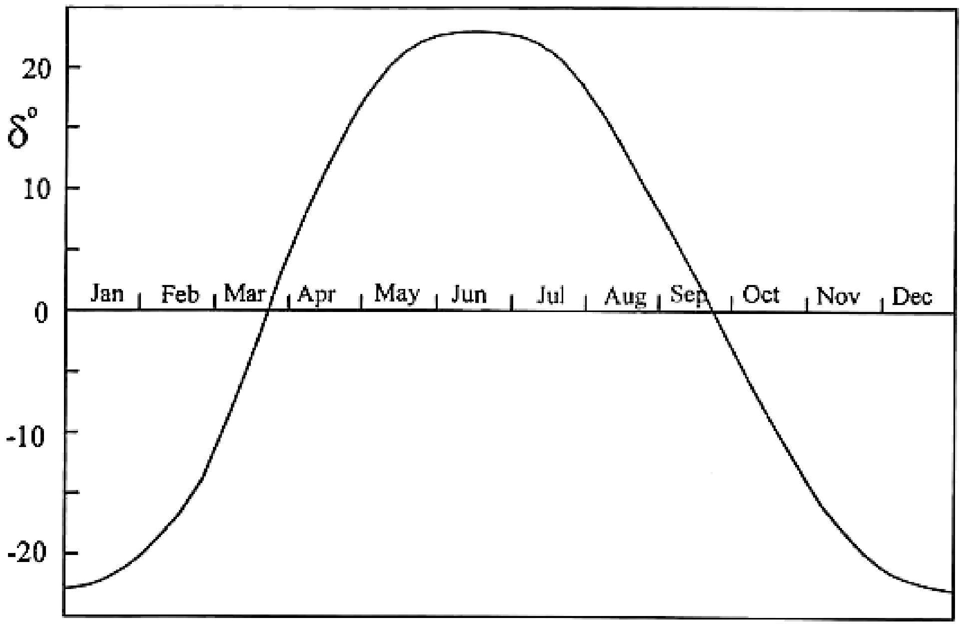


Fig. 2-7. Solar declination angle.

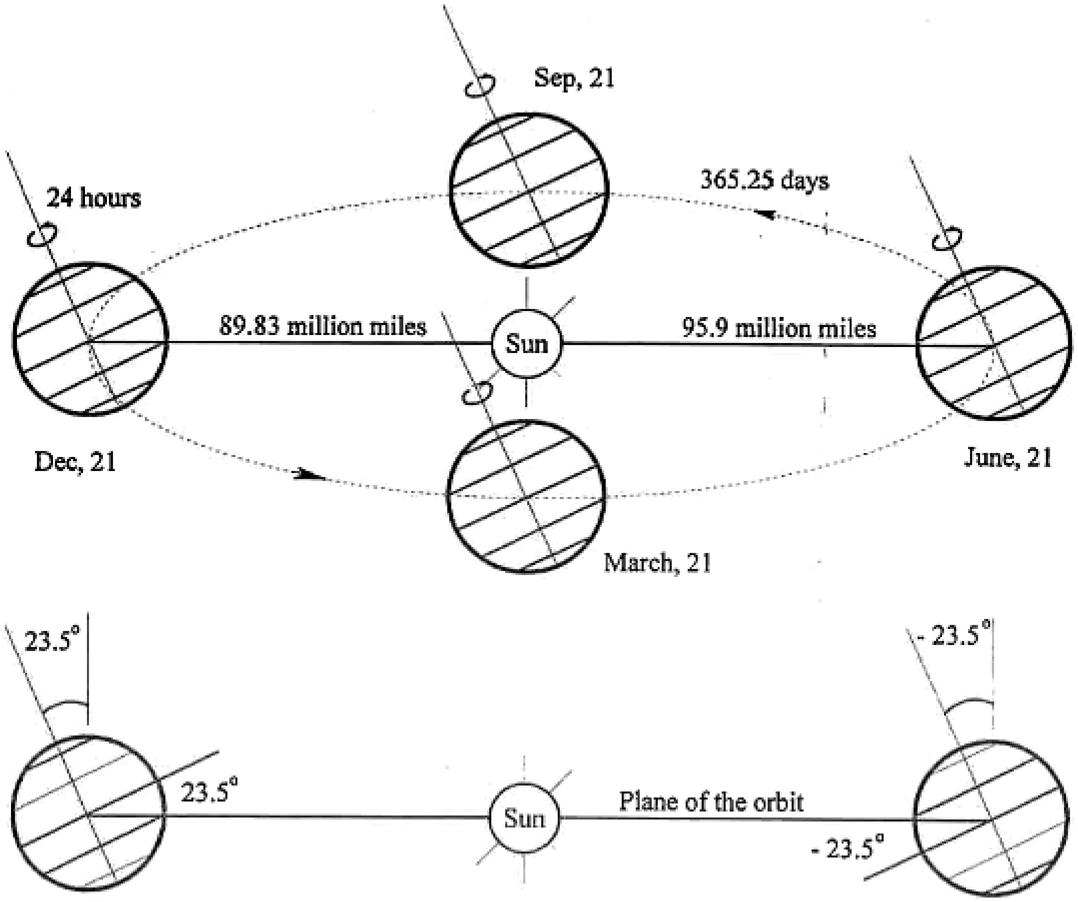


Fig. 2-7. Relative motion of the earth with respect to the sun.

Meridian plane and solar noontime
Meridian plane is that contains the earth’s axis of rotation and cuts the earth’s surface at the longitude of the place. It contains the sun-earth’s center line at the solar noon time as shown in Fig. 2-8.
Therefore, at solar noon time, the altitude angle, α is maximum and the solar azimuth angle as is 0.

The solar hour angle

The earth rotates about its axis 3600 each 24 hours, with a constant angular velocity, ω.

Then,

$$\omega = \frac{360}{24} = 15^\circ \text{/hour}$$

The angle of rotation is calculated from noon time.
Solar hour angle, h is the number of degrees from noon

$$h = (12 - t_S,) \times 15^\circ$$

Where, t_S is the solar local time.

t_S = 0 or 24 at midnight and 12 at noon.

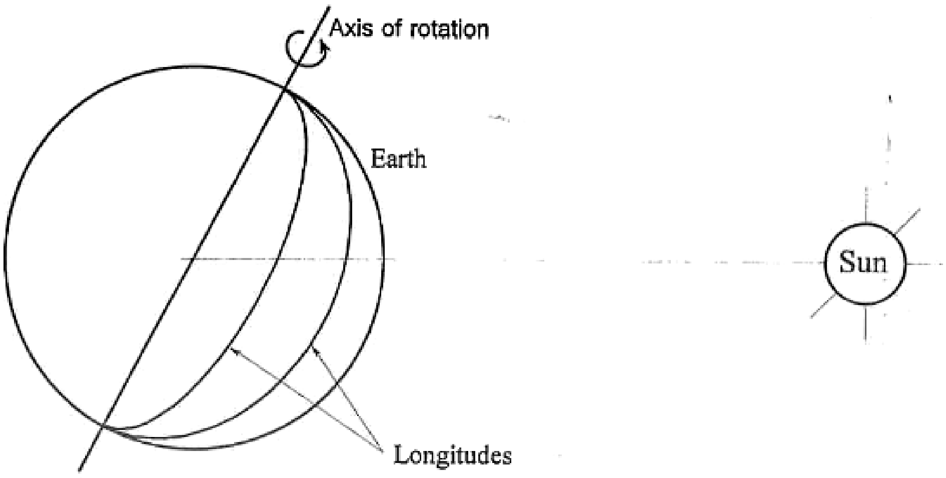


Fig. 2-8. Meridian plane.

Incidence Angle on a Tilted Plane

Figure 2-9. shows the angle of incidence on a fixed plane, tilted β on the horizontal. Other solar angles are shown on the figure.

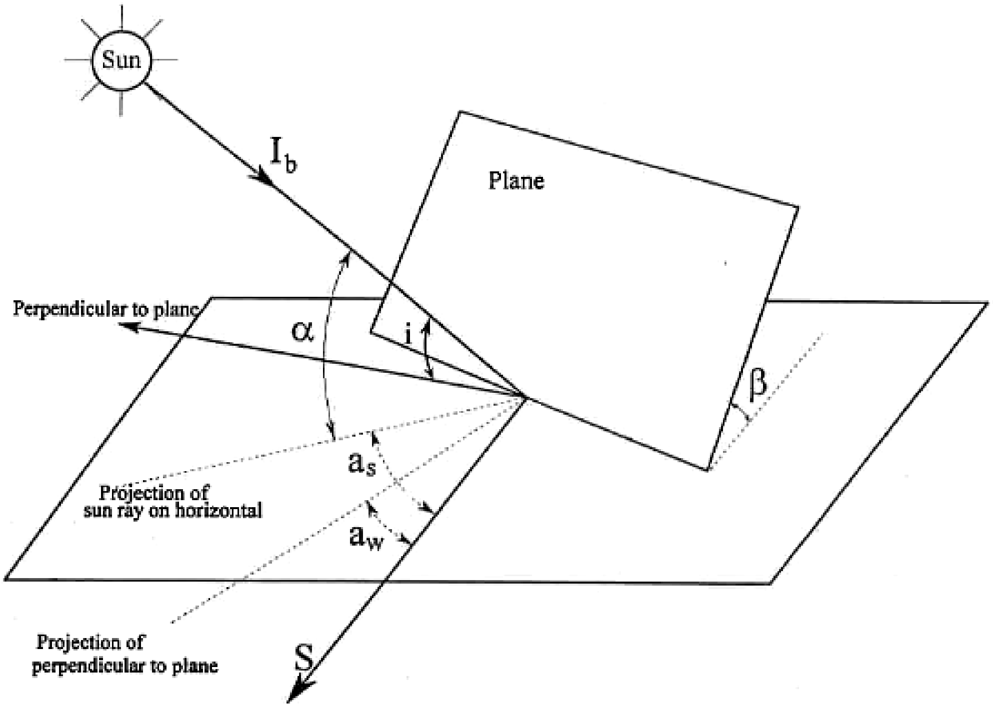


Fig. 2-9. Incidence angle, i on a tilted plane.

From the geometry of the system, the angle of incidence on the plane, i is given from the equation,

$$\begin{aligned}\cos i = {} & \sin L \sin \delta \cos \beta - \cos L \sin \delta \sin \beta \cos a_w \\ & + \cos L \cos \delta \cos h \cos \beta + \sin L \cos \delta \cos h \sin \beta \cos a_w \\ & + \cos \delta \sin h \sin \beta \sin a_w\end{aligned}$$

Where, a_w is the plane azimuth angle (its deviation from south direction). The above equation is very important to calculate the angle of incidence on a fixed plane, tilted β on the horizontal and deviated a, from south, at any place L in the earth, at any time of the day h, at any day of the year δ.

Intensity of Solar Radiation

Extraterrestrial Solar Radiation intensity

Outside the atmosphere, all solar radiation is only of the beam type. The extraterrestrial intensity of normal solar radiation (Solar constant, I_o) is only a function of the distance between the sun and the earth.

Since the distance between the earth-sun centers change with the day number, N, the extraterrestrial intensity of normal solar radiation (Solar constant, I_o) can be calculated from

$$I_o + I_{sc}\left[1 + 0.034 \cos\left(\frac{2\pi N}{365}\right)\right]$$

Where, $\varepsilon = 1 + 0.034 \cos\left(\frac{2\pi N}{365}\right)$ is the eccentricity factor, which is equal to the ratio between the actual distance between centers and the average distance (I50 x 10^6) Km. The eccentricity factor is in fact created because the sun is not exactly located at the centre of the orbit.

The above equation can be graphically represented by Figure 2-10.

It can be noticed that the sun is closer to the earth in winter, but solar radiation intensity is lower. This is due the lower solar altitude angle. The shorter day length in winter decreases the solar warming period.

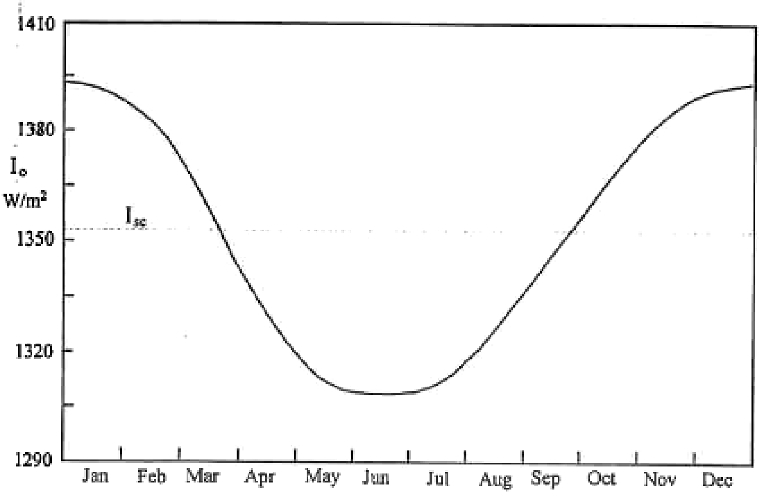


Fig. 2-10. Variation in Solar constant.

Terrestrial Solar Radiation Intensity

The solar radiation is subjected to depletion through the atmosphere. The sun rays undergoes a longer pass (PB) as the altitude angle a increases as shown in Fig. 2-11. The minimum pass (PA) takes place when the sun is exactly overhead.

The air mass ratio, m is defined as the relative length of the sun rays
through the atmosphere (dimensionless path length of the sun ray in the atmosphere),

$$m = \left(\frac{PB}{PA}\right) \approx \csc\alpha$$

m = 1 when the sun is overhead ($\alpha = 90°$) & m = 2 When ($\alpha = 30°$)

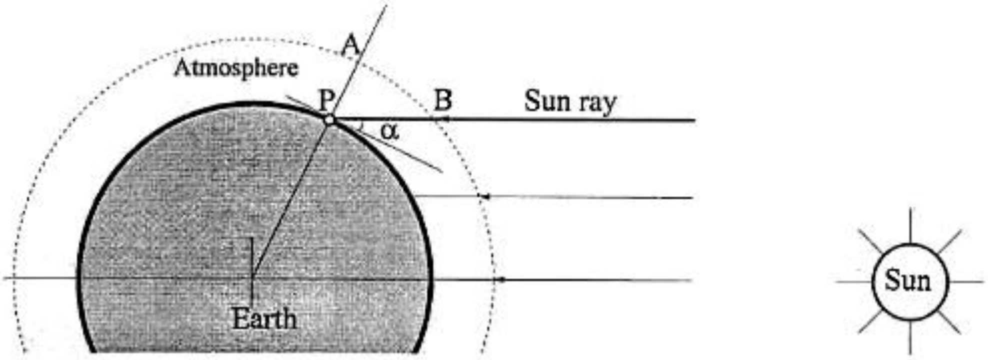


Fig. 2-11. Air mass ratio, m = BP/AP = esc α.

Considering AB curvature

$$m = \sqrt{1229 + (614\sin\alpha)^2} - 614\sin\alpha$$

Air mass is also a function of altitude m (z,a)

$$m\,(z,\alpha) = \frac{p(z)}{p(0)}\,m\,(0,\alpha)$$

Where,
m (0,a) is the air mass ratio at sea level,

P(0) is the atmospheric pressure at sea level - P(z) atmospheric pressure at altitude (z).
As a result, the intensity of beam solar radiation can be given according Bouger's law as

$$I_b = I_o\,e^{-km} = I_o\,\tau_a$$

Where, k is the absorption constant of atmosphere,
τ_a is the atmospheric transmittance.

The diffuse solar radiation intensity Id can be estimated as before on the earth's surface. Figure 2-12. shows the total solar radiation intensity on a horizontal surface outside the atmosphere at different days of the year.

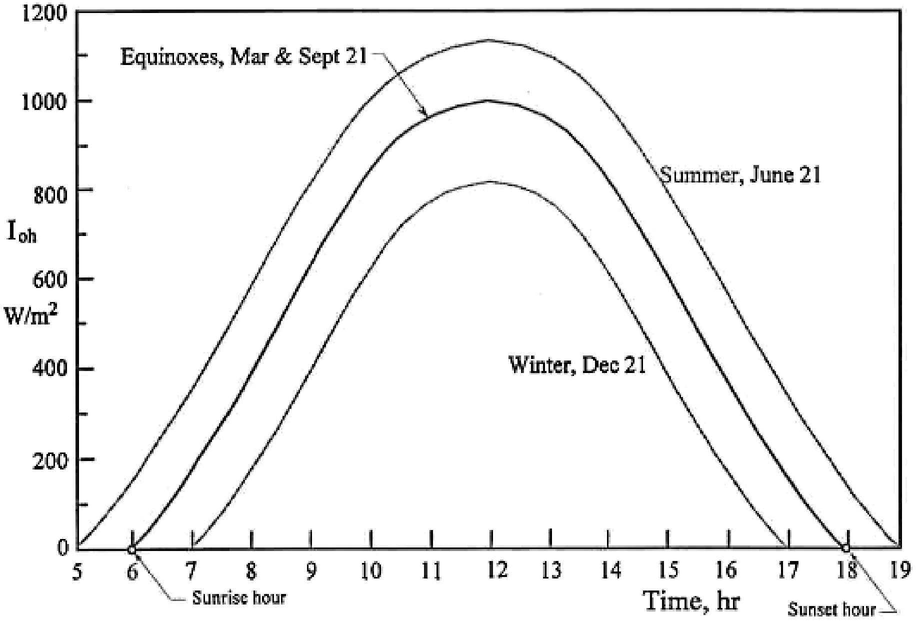


Fig.2-12. Solar radiation intensity on a horizontal surface outside the Earth's atmosphere.

The total solar radiation intensity on the earth's surface has the same trend, but lower value and depletion effects of the atmosphere as shown in Fig. 2-13.

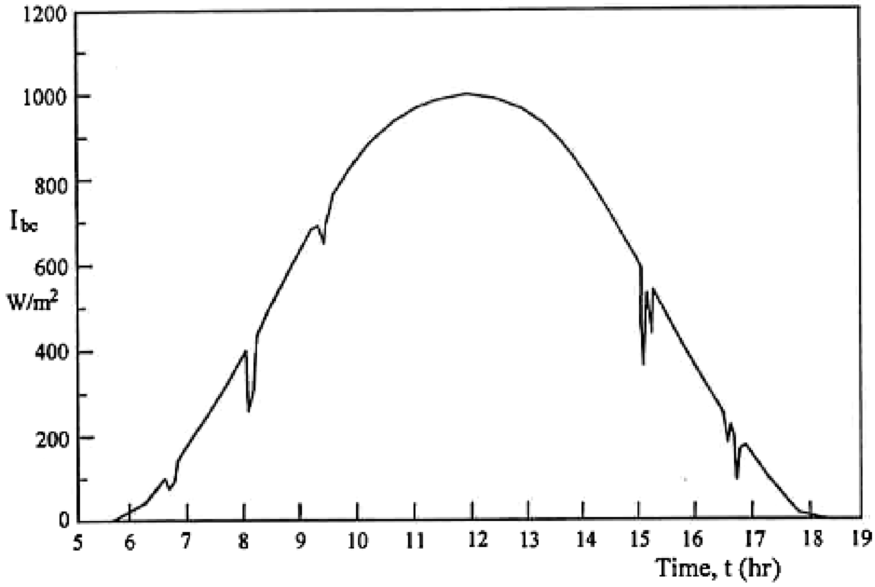


Fig. 2-13. Total solar radiation intensity on the earth's surface

Measurement of Solar Radiation

Intensity of total solar radiation in terms of daily, monthly, seasonal and annual averages would be measured for both

- Beam (direct) radiation.
- Diffuse radiation.

These measurements are essential for the design any solar energy system. The solar energy data can be obtained from any observatory. The data from observatory usually is measured for a horizontal surface. These data can be recalculated for any tilted surface of a solar collecting surface.

To measure the total solar energy data on a tilted collector surface, a pyranometer can be fixed on its surface. The pyranometer is a device that measure the total solar radiation intensity on a surface by means of a thermopile.

Another device called prheliometer measures the direct (beam) solar radiation intensity. The prheliometer has a long tube that directed to the sun and sees only the sun disk.

III. Solar Energy Collection

Solar energy can be converted to other useful forms of energy:

1. Naturally without man interference, through which solar energy is converted to other forms of energy such as wind energy, sea energy, ocean energy, biological conversion, etc.
2. Solar energy can also be converted into other useful forms by various technological methods:

Thermal Energy Conversion

When the solar radiation falls on a black surface, the temperature of such surface raises due to absorption of solar radiation. The black surface (absorber) converts solar radiation to thermal energy. The amount of absorbed solar energy can be removed by a fluid such as water or air. The absorbed heat can be used in water heating, space heating, refrigeration, air conditioning or any other industrial process. The absorber is covered with a glass cover to enhance the efficiency of the solar collector as shown in Fig. 3-1. There many designs of the flat plate solar collector. .

The increase of the temperature of the absorber, the more thermal loss it suffers towards atmosphere through thermal convection and thermal radiation. That is why a glass cover is placed to reduce the thermal loss. Also the absorber should be insulated from all other sides and the bottom surface. This design is called flat plate solar collector, which is widely used in domestic purposes for water heating, swimming pools, space heating, solar refrigeration and air conditioning systems. Such systems work in low temperature and their thermal efficiency is less than 70%. The flat plate solar collector is widely used because of its technical simplicity, cheapness and easy using and maintenance.

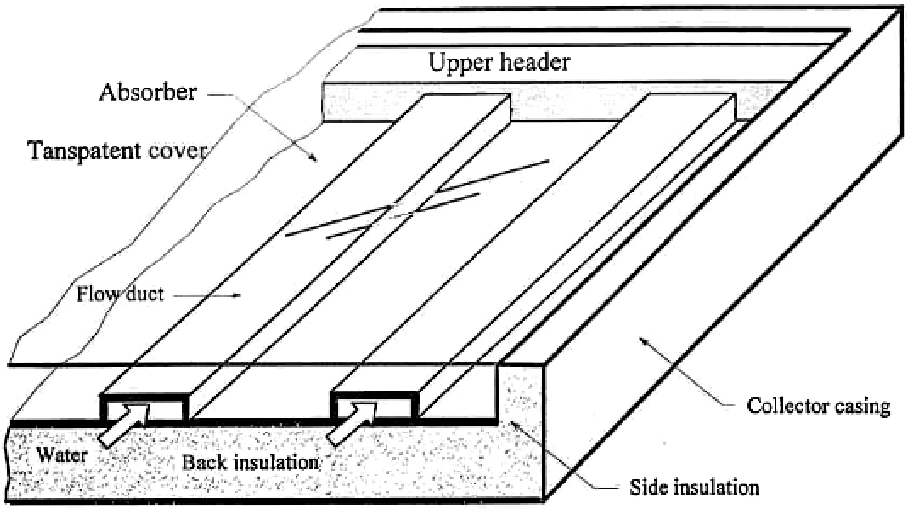


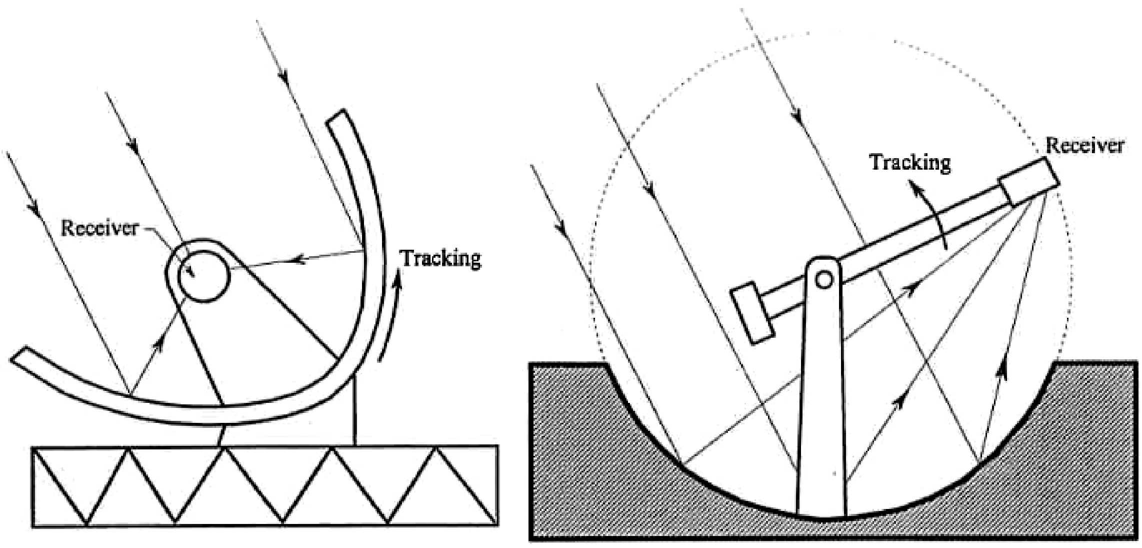
Fig.3-1.Flat-plate solar collector.

The performance of the flat plate solar collector can be simply defined by the equation,

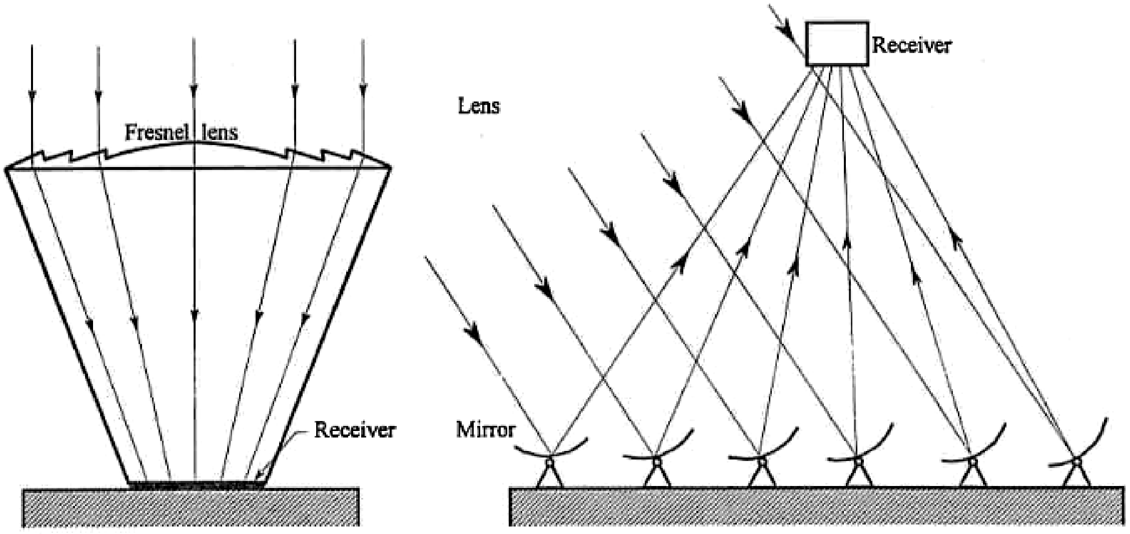
$$\eta_c = F_R\left[(\alpha\ \tau) - \frac{U_L}{I_c}(T_{wl} - T_a)\right]$$

Where, η_c is the collector thermal efficiency,
F_R is the collector heat removal factor
$(\alpha\ \tau)$ is the transmitivity-absorptivity product of the collector,
U_L is the overall heat loss coefficient,
T_{wl} is the inlet fluid temperature,
T_{wl} is the outlet fluid temperature.

There are other systems for solar radiation collection that work at higher temperatures, where mirrors and concentrators (Figure 3-2) are used for focusing direct solar radiation to a small size absorber. These systems can obtain temperatures may reach 4000°C. Such systems can be used in solar furnace for metal melting and vapor generation with high pressure needed to operate solar power stem plants.



a- Parabolic trough (Tracking). b- Circular trough (Tracking absorber).



c- Fresnel lens. d- Fresnel mirror.

Fig. 3-2. Some types of solar concentrators.

Direct Conversion

The solar radiation can also be converted directly to electricity by the photovoltaic cells:

Photovoltaic cells

For dozens of years, photovoltaic cells are used for direct conversion of solar energy into electrical energy especially in space stations and space ships. In photovoltaic cells, energetic photons make the electrons at the interface between two semiconductor material to flow in due to solar radiation and produce direct current (DC) in an external circuit. Theoretically, the conversion efficiency is not more than 24%, practically, it is within 15%.

Although, the easiness of power conversion by the use of photovoltaic calls, the price of the generated kilowatt may reach 100 times the price of the energy produced by traditional fuel sources. This explains of not being used largely on commercial uses.

For example, silicon cells proved great success in the field of space applications but there is a difficulty to be produced on the commercial level in spite of efforts and researches carried out to reduce the cost, of production. Markets now, sell photovoltaic cells manufacture by the use of polycrystalline materials, however their efficiency may reduce reach 6% or 7%.

It is worthy to mention that photovoltaic cells work only in the presence of beam solar radiation. The photovoltaic cells could not convert the diffuse solar radiation to electricity.

IV. Solar Power Generation

There are three solar thermal electric technologies are being developed in the field of solar power generation:

1. Parabolic Trough Concentrators
2. Central Receivers
3. Parabolic Dishes

All the three technologies concentrate sunlight onto a central object and can operate independently or in a hybrid system, with other renewable or fossil fuels power systems. All these technologies use tracking mirrors to reflect and concentrate sunlight onto a receiver, where the conversion to high temperature energy takes place.

Parabolic Trough Concentrators

Parabolic troughs consist of long rows of concentrators that are curved in only one dimension, forming troughs. The troughs are mounted on a single-axis tracking system that tracks the sun from north to south. They are lined with a reflective surface that focuses the beam solar onto a pipe located along the trough's focal line as shown in Fig. 4-1.

A heat transfer fluid is circulated through the pipes and then pumped to a central storage area, where it passes through a heat exchanger. The heat is then transferred to a working fluid, usually water, which is flashed into steam to drive a conventional steam turbine. In utility scale applications, the steam produced from the parabolic trough plant typically is supplemented with a natural gas fired superheater. The biggest advantage that parabolic troughs have relative to the other solar thermal electric technologies is their relatively advanced stage of commercialization.

The greatest disadvantages associated with solar parabolic trough systems include a low conversion efficiency (compared with other solar thermal technologies), the need for a supplemental fuel source (primarily to prevent the heat transfer fluid from freezing) and considerable volumes of coolant water. Although dry cooling is possible, it results in performance degradation and an increase in initial capital costs.

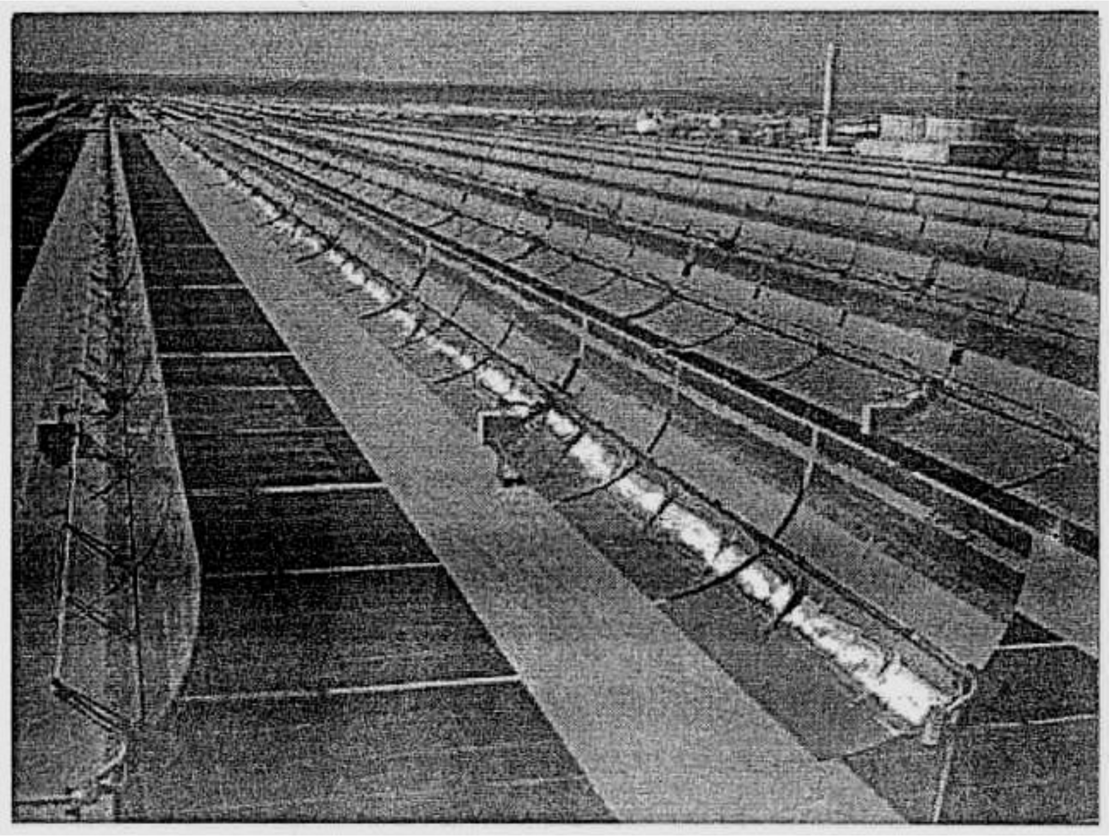


Figure 4.1 Power plant using parabolic trough concentrators.

Central Receivers

Central Receivers or 'Power Towers' consist of a fixed receiver mounted on a tower surrounded by a large array of mirrors known as heliostats as shown in Fig. 4-2. The heliostats track the sun and reflect its rays onto the receiver, which absorbs heat. Within the receiver, a fluid absorbs the receiver's heat energy and then is transported from the receiver to a turbine generator or a storage tank.

Advantages of central receiver technology include:

- The ability to store energy and offer dispatchable power - important to energy providers
- High conversion rates
- Potentially lower capital and operating costs because there is not a need for the extensive piping and plumbing found in parabolic trough concentrators.

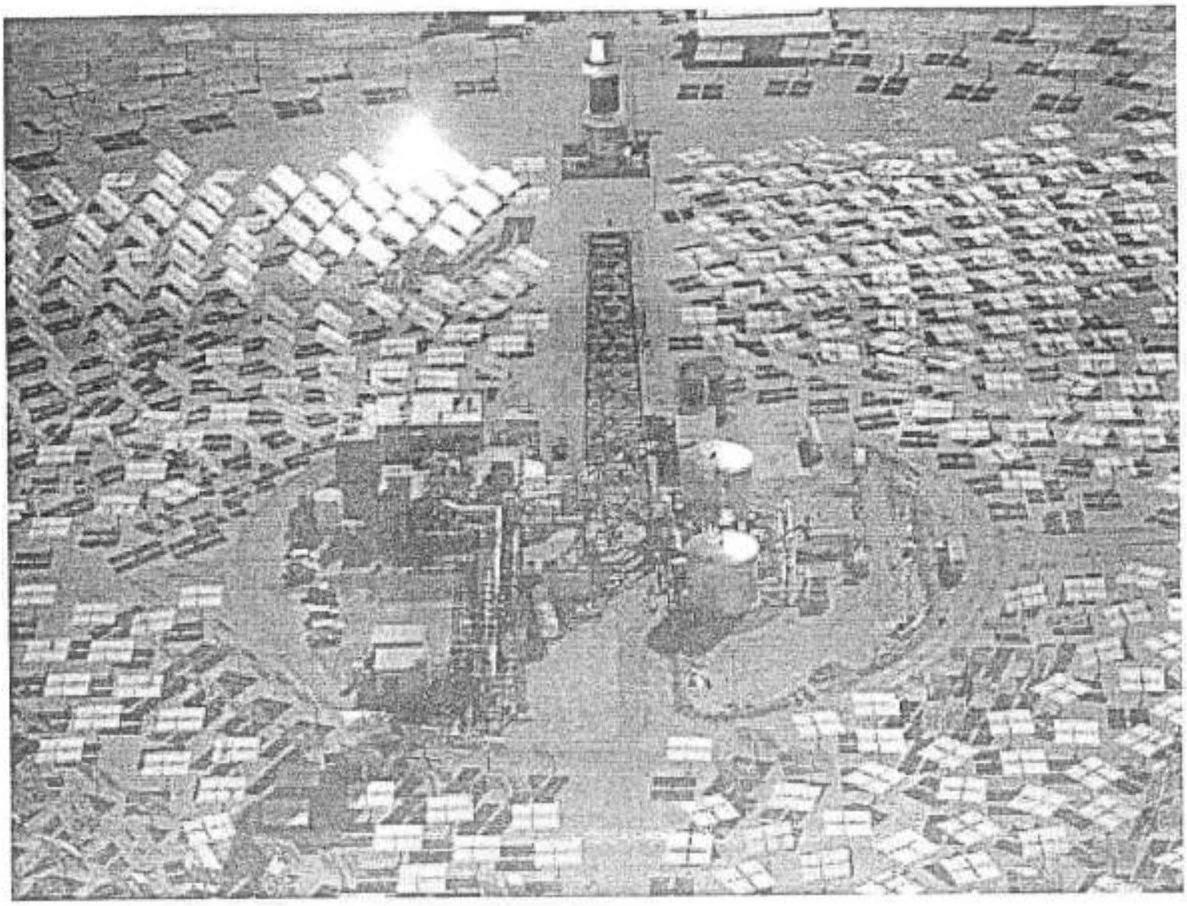


Figure 4-2 Solar thermal power plant using central receiver.

Parabolic Dishes

Parabolic dish generating systems consist of parabolic-shaped point-focus concentrators that reflect solar energy onto a receiver mounted at the focal point. Parabolic dishes typically use dozens of curved reflective panels made of glass or laminated films as shown in Fig. 4-3.

These concentrators are mounted on a structure that uses a two-axis tracking system to track the sun. The concentrated sunlight is focused on a receiver, where it may be utilized directly by a cycle heat engine mounted on the receiver, or the sunlight can be used to heat a fluid that is transmitted to a central engine. Point-focus concentrator systems, such as parabolic dishes and central receivers, typically achieve higher conversion efficiencies than line focus concentrators, such as parabolic troughs, because they operated at higher temperatures.

Parabolic dishes are considered a promising solar thermal technology because of their:

- Modularity.
- Short installation times.
- Siting flexibility.
- Minimal water requirements.
- High conversion efficiencies.

Disadvantages that hinder the commercialization of parabolic dish technologies include:

- Lack of commercial experience.
- Concerns that deployment of the technology in the distributed engine mode may suffer from excessive operation and maintenance costs.
- The lack of storage capacity.

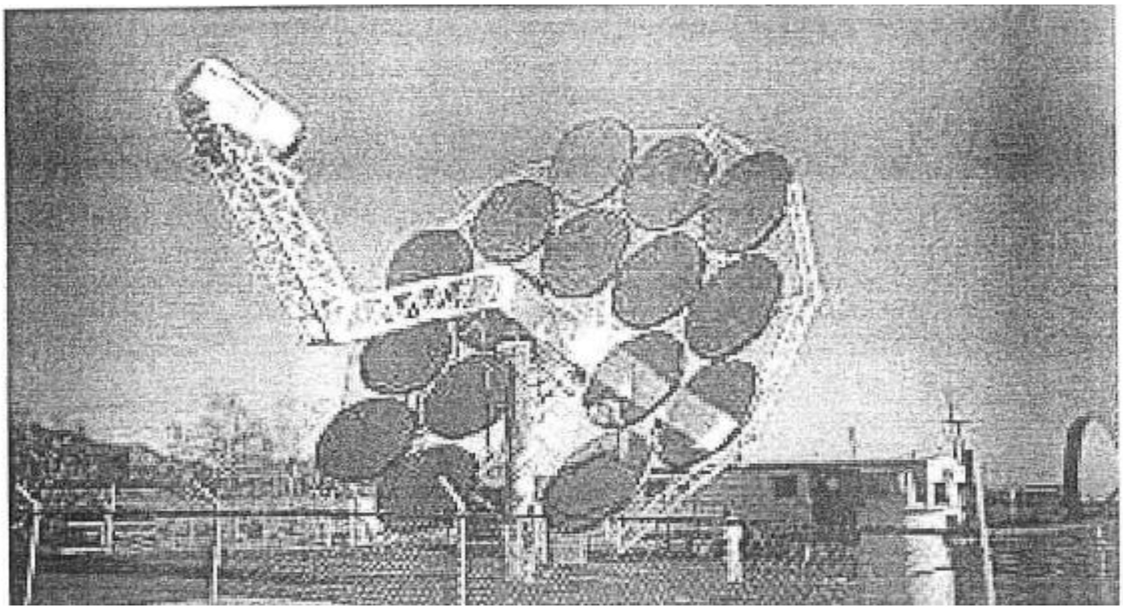


Figure 4-3 Solar thermal power plant using parabolic dishes.

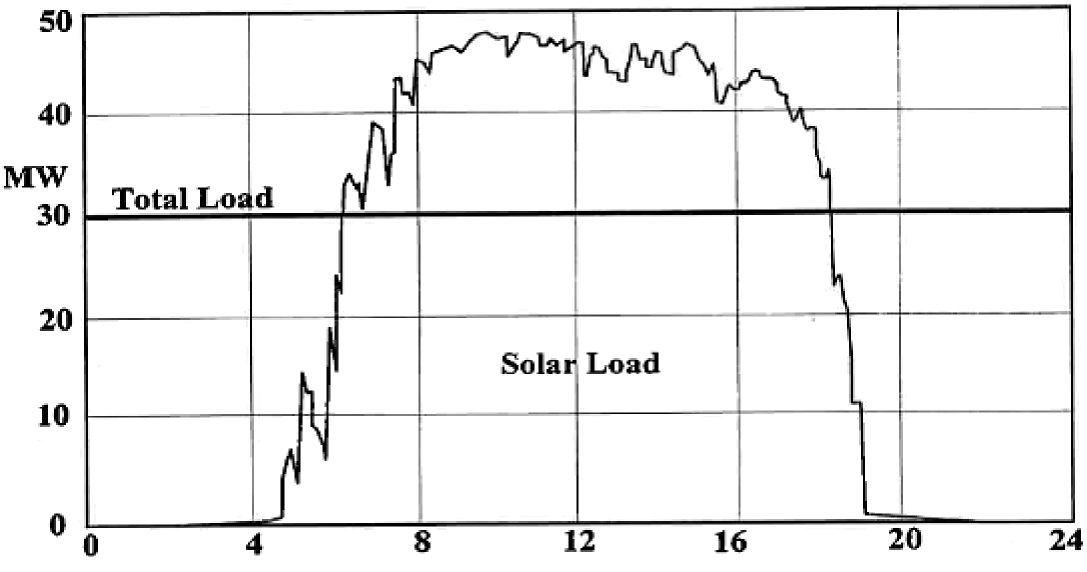
Each of the above solar concentrators has working conditions as shown in table 4.1. Table shows a comparison between them regarding the temperature, power generation, efficiency, hybrid potential, grid status and the cost.

Collector	**PTC**	**Central Receiver**	**Parabolic Dish**
Temperature	400 C	560 C	750 C
Power	150 MW	200 MW	10 MW
Efficiency	60 %	46 %	Higher
Hybrid Pot.	Proven	Possible	Low Hybrid efficiency
Grid Status	Connected	Connected	Stand alone
New Tech.	Promising	Multi-Tower	Stiriling Cycle
Cost	Not	Yet	Proven

Table 4.1 Comparison between PTC, central receiver and parabolic dish.

In the hybrid system, solar energy carries the total load only when the solar load is equal or larger than the total load as shown in Fig. 4-4.

Excess solar energy in this period can be stored and used later to share other fossil fuel energy in the rest of the day.



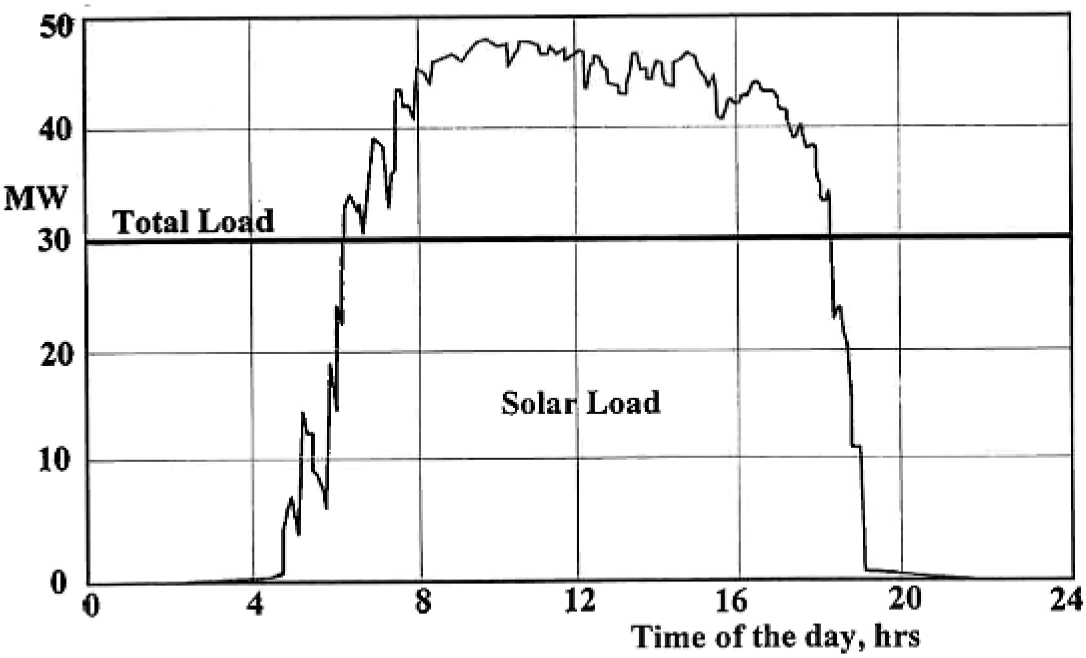


Figure 4-4 Solar load vs. total load in a hybrid solar thermal power plant.

V. Solar Thermal Power Plant

The Solar Thermal Power Plant (STPP) consists mainly of; the solar collector field, the heat transfer fluid (RTF) and the power conversion system. The main objective of each is as follows:

1. Solar collector field
   Converts the solar radiation to heat.
2. Heat transfer fluid (RTF)
   Transfers the produced heat to the power system.
3. Power conversion system
   Converts the heat to electricity.

The solar and power systems can be combined in different technologies and schemes to produce electricity.

Power Conversion System

1. **Steam Power Plant (SPP)**
   The SPP operates on Rankine cycle with reheat and feed water heaters.
2. **Gas Turbine (GT)**
   The gas turbine unit operates on the Brayton cycle
3. **Combined Cycle Power Plant (CCPP)**
   The combined power plant (CCPP) consists of a Gas turbine unit and a Steam power plant. It can be used with solar energy in power generation because of the following:
   - Good performance and low emissions
   - Fits the solar concentrator collectors.

The Combined Cycle Power Plant

The combined cycle power plant is the most suitable technique that can be used in the field of solar power generation. The cycle consists of a gas turbine unit and a steam cycle as shown in Fig. 5-1. The steam cycle uses the hot exhaust gases from the gas turbine through a heat recovery boiler.

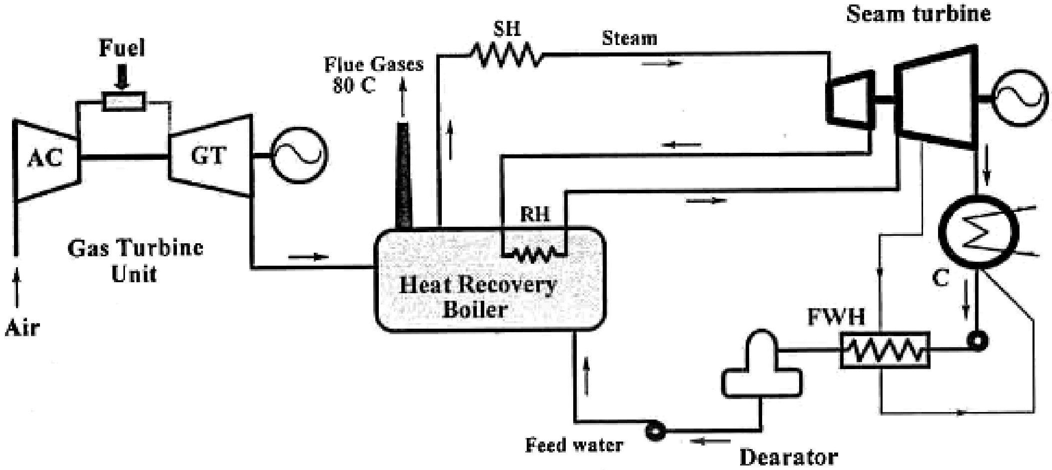


Figure 5-1 The combined cycle power plant.

Solar Collector Field

The solar collector field can use either of the following concentrator techniques:

1- Parabolic Trough Concentrator (PTC)

- Concentrates solar radiation on receiver tubes
- Heats a HTF inside up to ~ 400 C

2- Central Receiver (Power Tower)

- Heliostats array concentrates solar radiation onto a central receiver (Mounted on a Tower).
- HTF is heated up to ~ 560 C

3- Parabolic Dish (Dish Engine)

- Concentrates sun light on a receiver at a focal point
- HTF is heated up to ~ 750 C

Heat Transfer Fluid

The heat transfer HTF Plays an important role in STPP performance

- ❖ Transfers Heat from Absorber
- ❖ Thermal Storage

HTF properties should be carefully chosen to satisfy the following conditions:

- ➢ Thermal stability (Decomposition Temp.)
- ➢ Chemical stability
- ➢ Large thermal capacity
- ➢ Good heat transfer properties
- ➢ Suitable Boiling & Freezing points
- ➢ Low viscosity (Low pumping power) & Volatility
- ➢ Low thermal expansion coefficient
- ➢ Safety (Not exclusive, not filmable, intoxicate, .. etc)
- ➢ Good corrosion & erosion properties

Used HTF

Water-Steam	USA, Spain, Japan & Russia
Oil	USA & Spain
Molten Salt	USA, France & Spain
Sodium	Spain

Under Study HTF

Ionic Liquids
Inorganic Molten Salts

Researchers are concentrated on reducing the cost, increasing the availability and improving the operating conditions of the above heat transfer fluids.

Central Receiver Solar Collector

The central receiver has a high CR up to 3000. The receiver is subjected to high energy flux (from 1 to 2 MW/m^2) at a reasonable high temperature (up to 1000 K). Therefore, the reflector mirrors must have precise optical properties. The heliostats follow the sun with a hydraulic computerized tracking system. The thermal loss from the receiver is less than that of PTC. The central receiver is promising for large scale power plants. One of the earlier central receiver systems is built in the USA in 1982. The following are the characteristics of this system (Solar 1).

Solar 1

1800 heliostats(10 MW)
California 1982-1988

- Water was converted to steam in the receiver and used directly to power a steam turbine
- Storage system tank filled with rocks using oil as a heat-transfer fluid.

Another system (Solar 2) has been built (1996-1988). The molten-salt storage technology was used in this system.

The simple steam Rankine cycle can be powered using a central receiver as shown in Fig. 5-2. Besides the receiver, there is a boiler operated by fossil fuel to supply steam in the low solar radiation periods.

The central receiver can also be used in a hybrid solar steam power plant with a gas turbine - steam turbine combined cycle as shown in Fig. 5-3. A heat recovery boiler is used to make use of the heat in the hot exhaust gases from the gas turbine unit.

The fossil fuel can be supplied to the heat recovery boiler or to a separate boiler as shown in the figure.

The superheater (SH) can also is supplied with fossil fuel or solar energy or both as shown Fig. 5-3.

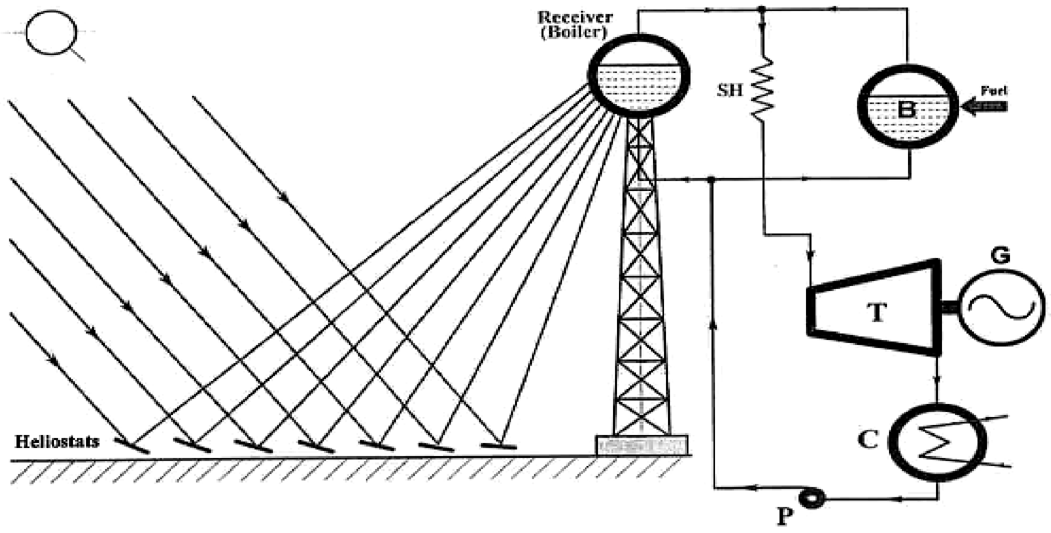


Figure 5-2 Solar steam power plant using central receiver.

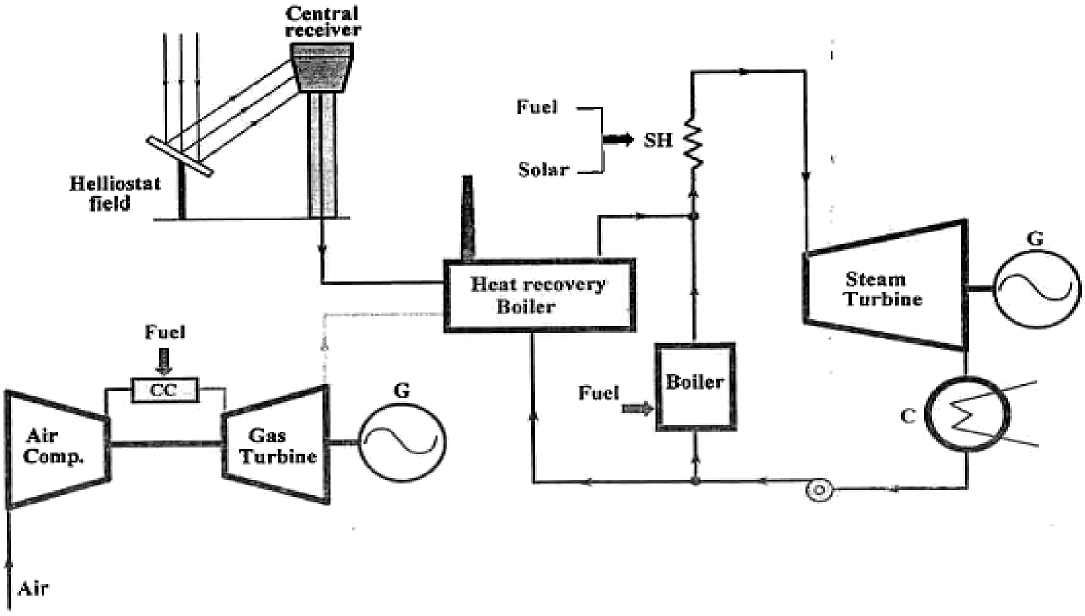


Figure 5-3 Hybrid solar steam power plant with a heat recovery boiler.

Parabolic Trough STPP

The parabolic trough solar thermal power plant has the following main components:

Solar field Heat Transfer Fluid		Gas and / or Steam Plant
Solar Steam Generator	+	Components
Rankine Cycle		Combined cycle
Thermal Storage.		No storage
HTF		Field scheme

The PTC normally rotates about the North-South absorber tube to track the sun as shown in Fig. 5-4.

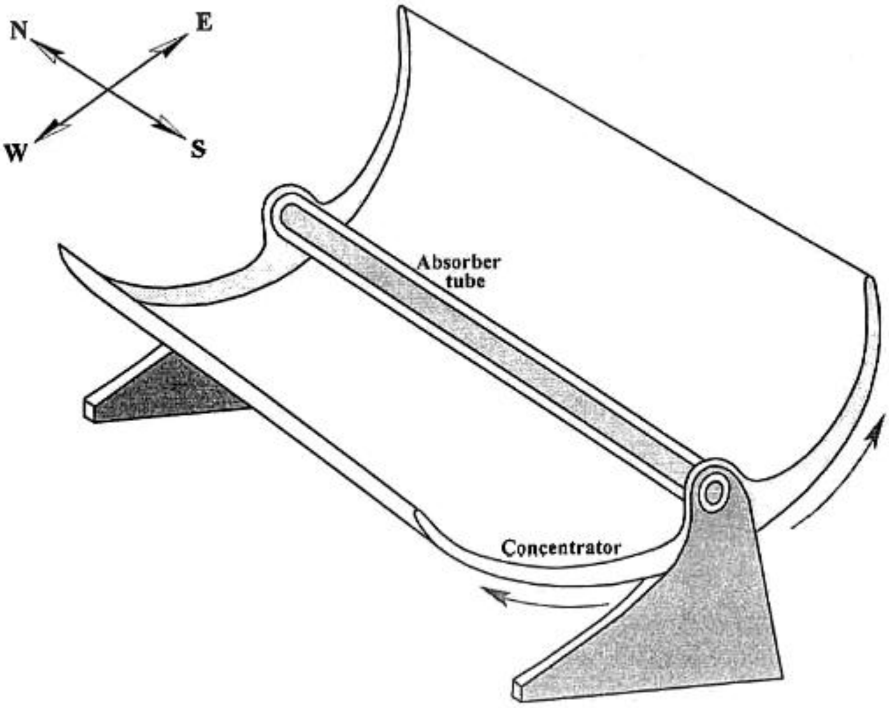


Figure 5-4 Parabolic trough concentrator PTC.

A sophisticated control system does the following tasks:

Drives tracking mechanism during sunny periods
Night sleeping mode
Cloudy periods and storm behavior
Awake tracking system in the morning & ……

Figure 5-5 shows the difference in efficiency between the N-S and E-W oriented PTC. It is clear that the N-S orientation provides almost a uniform efficiency allover the day time ~ 60%.

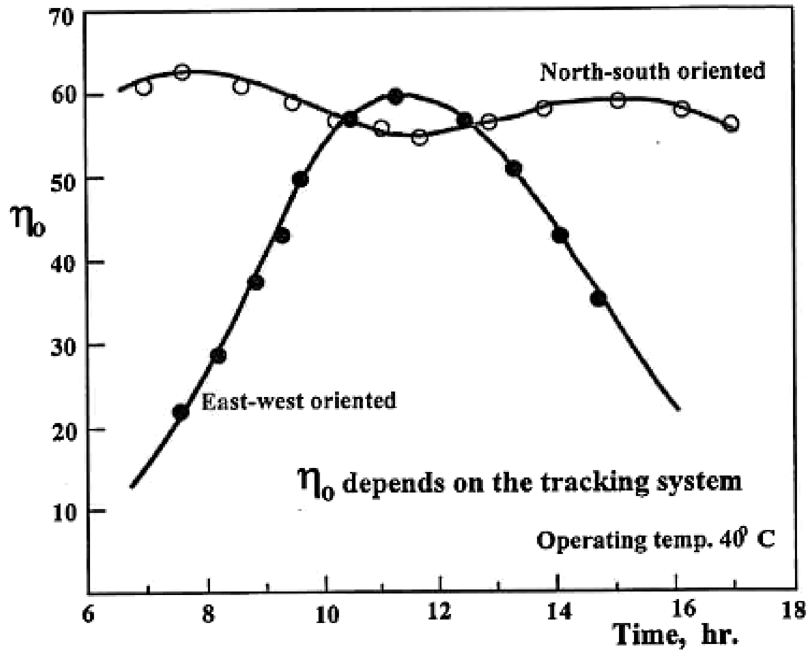


Figure 5-5 Optical efficiency versus solar time.

The tracking accuracy of the PTC should be high. A small error in the tracking will produce large losses as shown in Fig. 5-6.

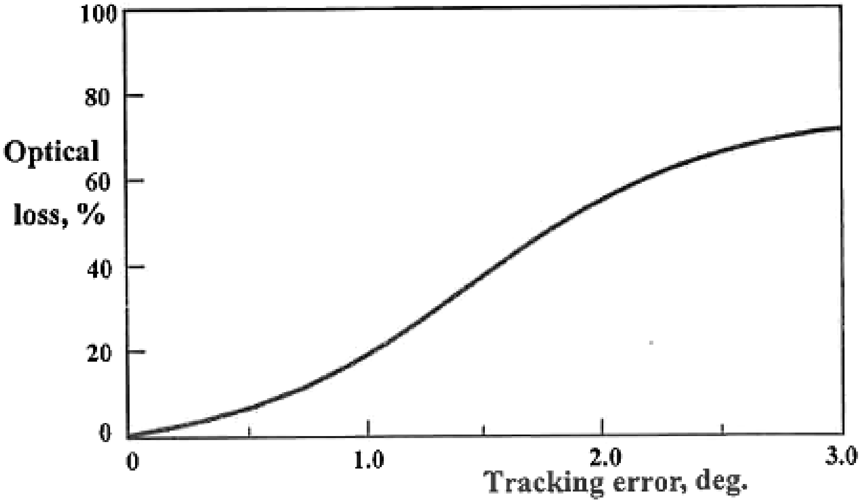


Figure 5-6 Tracking accuracy of the PTC.

Figure 5-7 shows the schematic diagram of solar steam power plant using the PTC. The HTF transfers heat from the receiver to a boiler. The piping system of the solar field is shown in Fig. 5.8. A storage tank is used to collect the HTF from which the heat is transferred to the boiler.

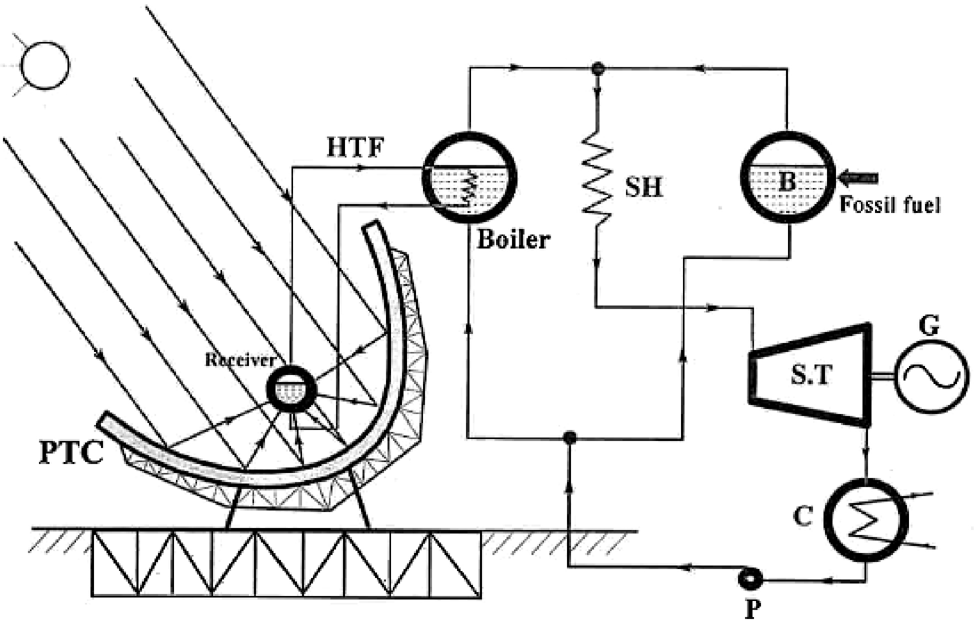


Figure 5-7 The schematic diagram of SSPP using the PTC.

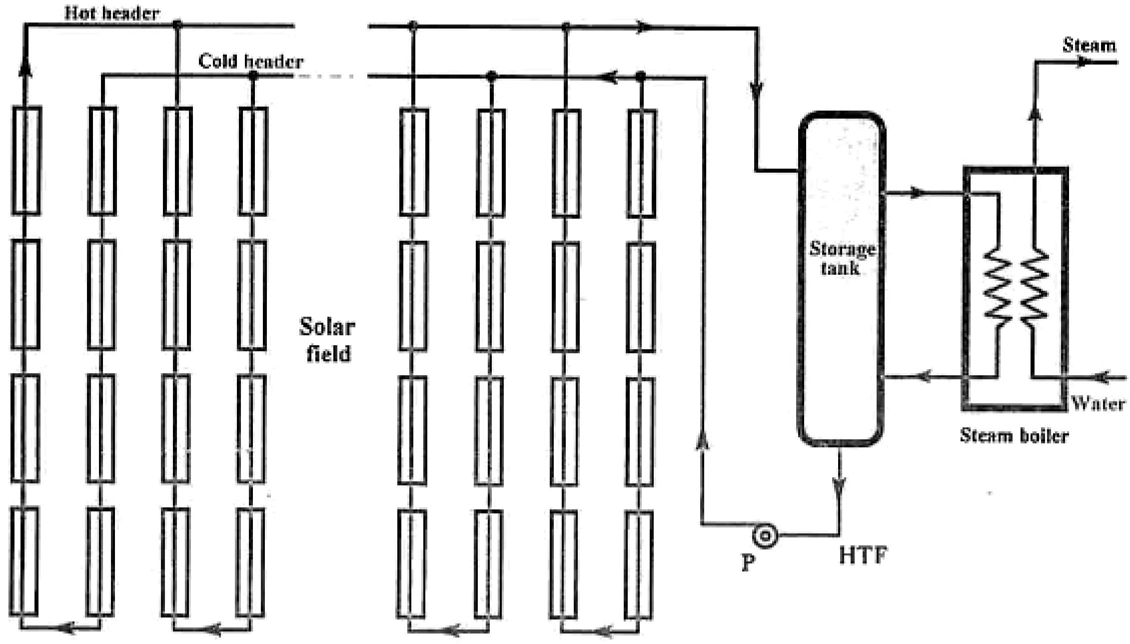


Figure 5-8 Optical efficiency versus solar time.

The Integrated Solar Combined Cycle System has shown a successful in the commercial scale resent years. In this system, the steam is produced in two solar fields; low and high pressures as shown in Fig. 5-9. The low pressure steam supplies the solar steam generator and the low pressure turbine, while the high pressure steam is connected to the heat recovery boiler to supply the high pressure turbine as shown in the figure.

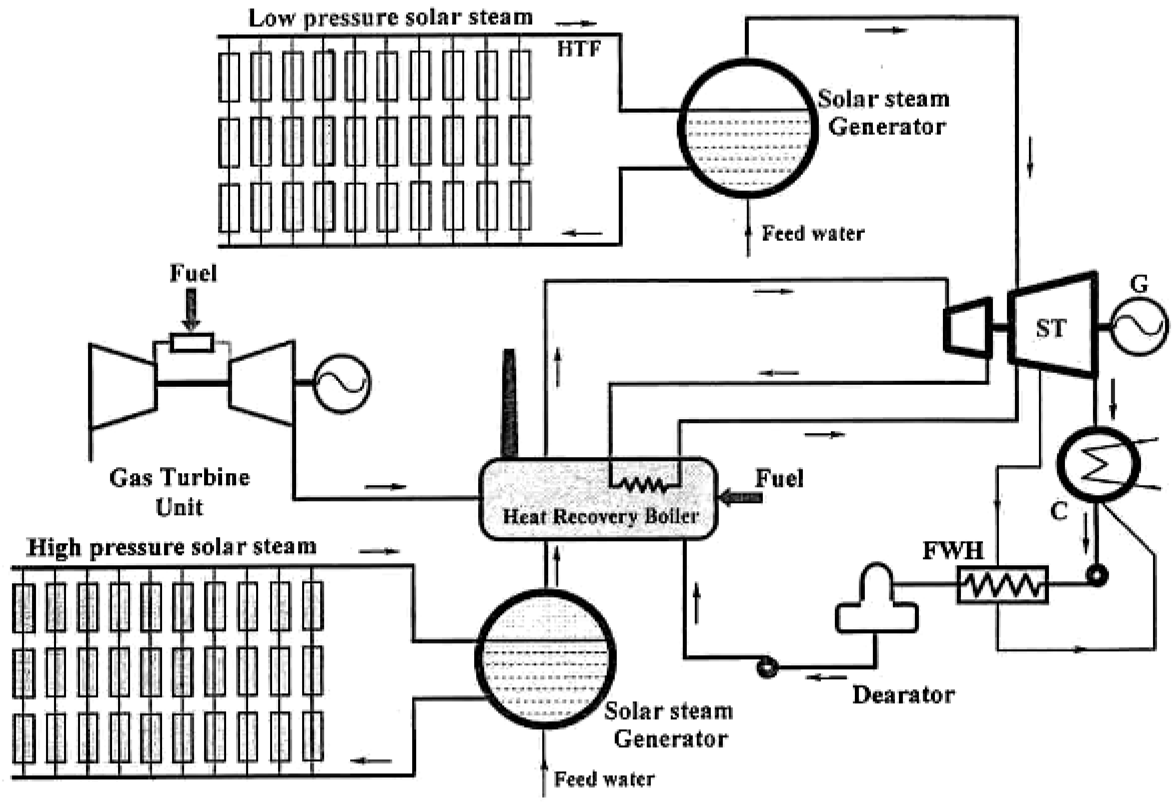


Figure 5-9 Layout of an integrated solar combined cycle system.

Field Problems

- High wind speed (Storm)
- Glass - Metal connection (Receiver tube)
- Metal corrosion
- Reflector surface cleaning

Direct Solar Steam Generation (DSSG)

In the last years, a promising technique has been adapted in European countries. This system is the Direct Solar Steam Generation (DSSG) with the following advantages:

- Lower capital and operating costs (No heat exchanger)
- Less danger (No fire hazards)
- Lower thermodynamic losses (Improved Performance)

Three different DSSG schemes are used as shown in Fig. 5-10:

1- Once-through mode
2- Recirculation mode
3- Injection mode

Differs in Flow stability & Controllability

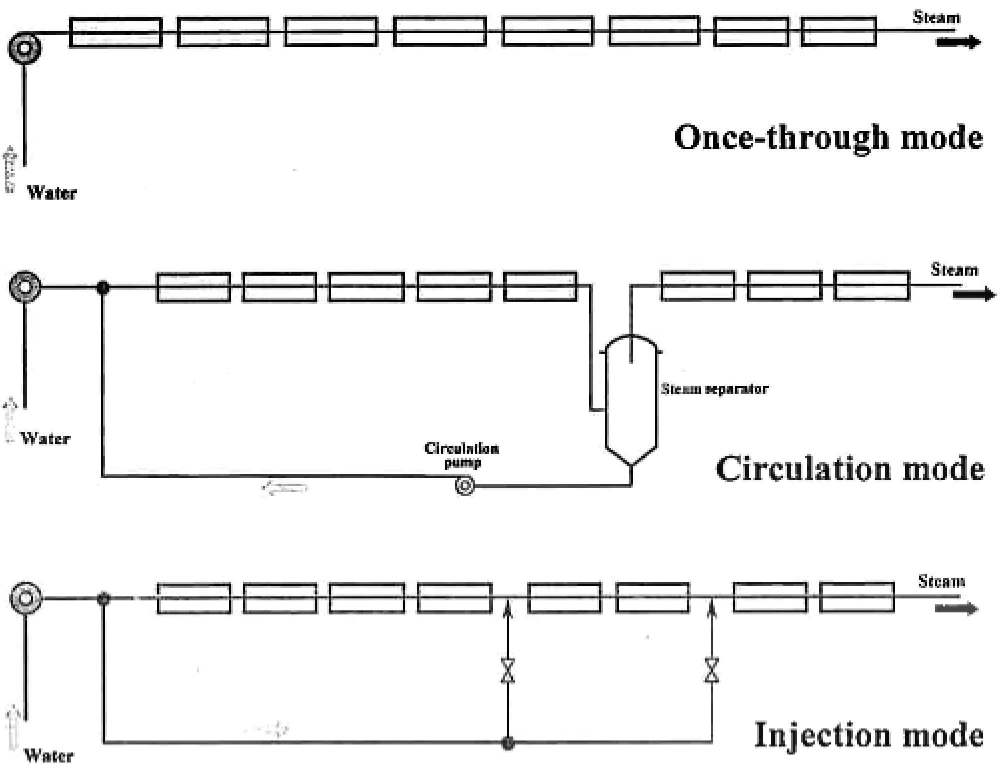


Figure 5-10 The DSSG system.

The System Analysis

For the solar steam power plant with simple Rankine cycle, the maximum possible thermal efficiency is equal to that of Camot 11cwhere,

$$\eta_C = 1 - \frac{T_L}{T_H}$$

For maximum value of η_C, T_L should be minimum and T_H is maximum. The cooling temperature T_L depends on cooling water temperature. The heating temperature T_H increases with increasing the CR.

The overall system efficiency is given by,

Overall efficiency, η_S - η_R η_S

Then Overall max. efficiency, $\eta_{max} = \eta_C \eta_S$

But for high TH the heat losses increases and solar efficiency η_S decreases. Therefore, the value of T_H should be taken as a compromise.

Effect of CR on the system performance

For low CR concentrators:

$$\eta_S = \frac{(\alpha\ \tau)A_r\ I_r - U_r\ A_r\ (T_r - T_a)}{A_a\ I_s}$$

Where,

A_a, A_r Aperture area and receiver area respectively,

I_s, I_r Solar flux and radiation intensity on receiver surface respectively,

T_r, T_a Receiver and ambient temperatures respectively,

U_r Receiver heat loss coefficient.

Put $I_r = I_s\ \rho\ CR$

And considering $\eta_R = \eta_C$

$$\eta_{max} = \left(\frac{T_r - T_a}{T_r}\right)(\alpha\,\tau)\left[\rho - \frac{U_r}{(\alpha\,\tau)CR\,I_s}(T_r - T_a)\right]$$

For the same T_a and I_s. differentiating with respect to T_r and equating to zero, the optimum receiver temperature, T_r,opt can be obtained as,

$$T_{r,opt} = \sqrt{T_a\left(T_a\,\frac{(\alpha\,\tau)\rho}{U_r} + T_a\right)}$$

For high CR concentrators:

$$q_u = A_a\,I_s\,(\alpha\,\tau)\,\rho - \varepsilon_r\,\sigma\,A_r(T_r^4 - T_4^r)$$

$$\eta_S = (\alpha\,\tau)\,\rho - \frac{\varepsilon_r\,\sigma}{I_S\,CR}(T_r^4 - T_a^4)$$

and

$$\eta_{max} = \left(\frac{T_r - T_a}{T_r}\right)\left[(\alpha\,\tau)\rho - \frac{\varepsilon_r\,\sigma}{I_S\,CR}(T_r^4 - T_a^r)\right]$$

Form these equations, it can be seen that 11s increases with CR and decreases with increasing T; Also the infrared emittance, ε_r must be as low as possible and (CR/ε_r) has a strong effect on η_s. This relation is shown in Fig. 5-11

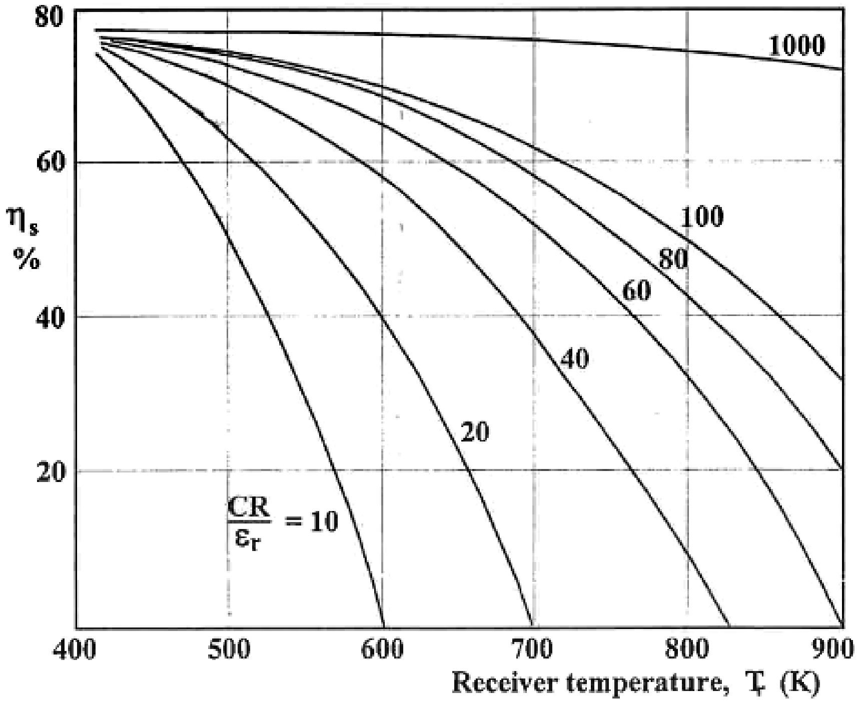


Fig. 5-11 Effect of receiver temperature on the concentrating collector efficiency

Figure 5-11 shows the effect of receiver temperature on the maximum overall plant efficiency η_{max}. The effect of (CR/ε_r)is also shown.

This Analysis can be done for all systems

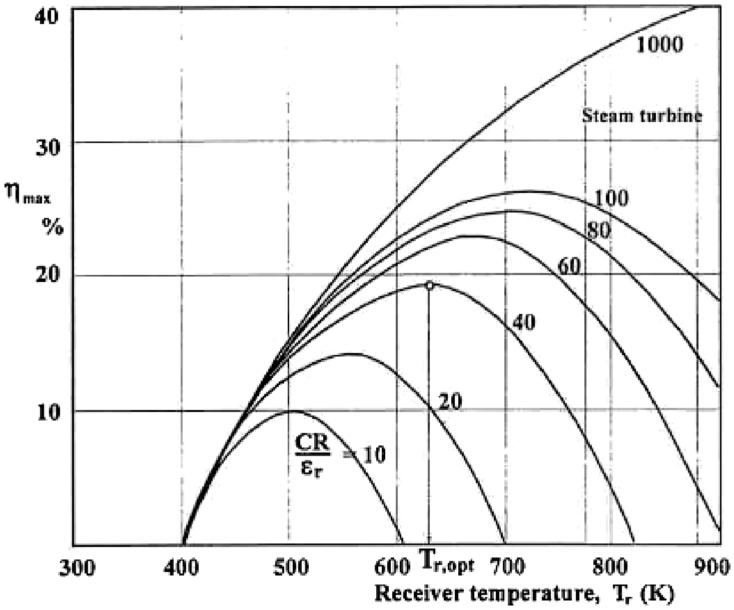


Figure 5-11 Effect of receiver temp. on the max. overall power plant efficiency

The hourly values of the direct normal solar radiation, the thermal solar field efficiency and the gross efficiency of a typical commercial system is shown in Fig. 5-12.

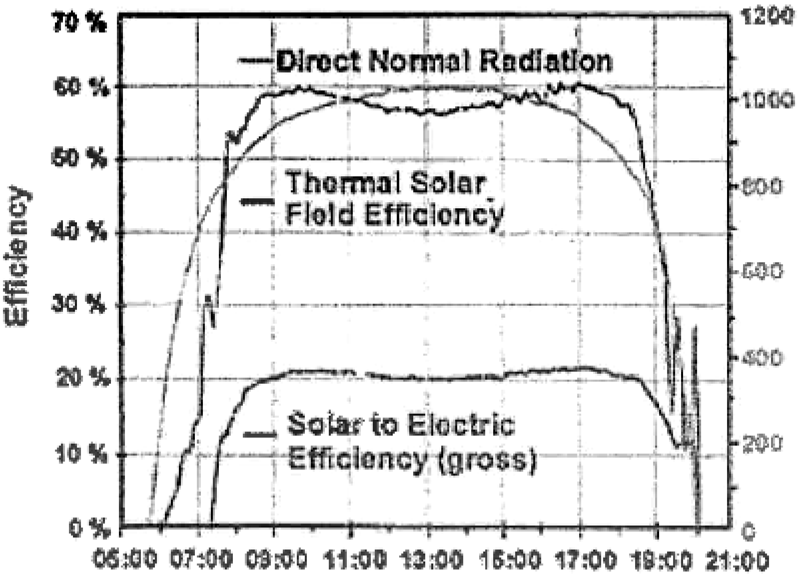


Figure 5-12 Hourly efficiency of a typical solar thermal power plant..

VI. Conclusion

Solar energy is a huge, clean and renewable source of energy. It is also available everywhere on the earth. However, there are many technical and economical difficulties need to be solved so that solar energy becomes a strong competition against the traditional energy sources.

Energy from the sun can be used successfully in electric power generation systems. Depending on the climate conditions and the use of a properly designed, installed, and maintained system can meet a large demand in this respect.

In this work, a short review of the solar energy availability, geometry and fields of applications is reported. The most Largent commercial application of solar energy is the solar thermal power generation.

The techniques of solar thermal power generation are reviewed in detail. A comparison between the most common commercial techniques is also given, namely the PTC, central receiver and the parabolic dish.

The most common types of solar thermal power plants are explained. The solar field, heat transfer fluid and the power conversion system types are also explained with simple schematic diagrams. The different types of the system piping are also demonstrated.

At last, a simple analysis for the solar thermal power plant is explained in order to predict the optimum conditions leading to the maximum system performance. This analysis is very useful and can be performed for any solar thermal power plant.

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