**SOLAR GEOMETRY AND APPLICATIONS**

1. **INRODUCTION**

The sun is an outstanding source of heat energy and is the world’s most large source of energy. Sun having an approximate mass of 2 × 1030 kg which is made of 74% hydrogen, 25% helium and remaining 1% traces of heavier elements. Actually, the sun is a *nuclear reactor,* where a continuous fusion reaction of hydrogen atoms takes place to form helium and the heat energy is generated. The core region of the sun has a very huge temperature. This heat energy is continuously dissipated by the radiation and thus outer surface of the sun is considered at temperature of 5800 K approximately.

The construction of the sun is a nearly spherical body of a diameter of 1.39 × 106 km. It is located at a mean distance of 1.496 × 108 km from the earth. The earth has its mean diameter of 1.27 × 104 km and its surface gets only small fraction of sun’s energy because the sun subtends the only an angle of 32 minutes at the earth’s surface.

Sun emits the energy at the rate of 3.8 × 1020 MW, that is equal to 63 MW/m2 of the sun’s surface and the amount of the solar energy falls on the earth is 5000 times greater than the sum of all other inputs: terrestrial, nuclear, geothermal and gravitational energies and lunar gravitational energy. Even though, the total amount of sun energy received by earth in an hour is more than the total energy demand by word during a year. The Earth intercepts only a small amount of sun energy approximately 1.7 × 1014 kW. Approximately its 30 percent energy is reflected back to space, 47 percent is converted to low-temperature heat and reradiated to space and 23 percent powers the evaporation/precipitation cycle of the biosphere. The sun emits electromagnetic radiation with an average intensity of 1353 W/m2 on the earth’s surface.

The solar radiation incident on the Earth’s surface is ranging in the wavelengths from the ultraviolet to the infrared (0.1 μm to 3 μm). The visible region of the solar radiation lies within wavelength of 0.4 μm to 0.76 μm is called photosphere. The spectrum of solar radiation is shown in Fig.1.1.



Fig.1.1 Spectrum of Solar Radiation

Sun is the main source of all types of energy on the earth and sunlight can be harnessed via a variety of natural and synthetic processes. Oil, coal, natural gas and wood were originally produced by photosynthetic processes followed by complex chemical reactions in which decaying vegetation was subjected to very high temperatures and pressures over a long period of time. Generally, photosynthesis is the synthesis of glucose from sunlight, carbon dioxide and water with oxygen as a waste product. The wind and tide energy are also originated from the sun since they are caused by differences in temperature in various regions of the earth.

A partial list of solar applications includes space heating and cooling through solar architecture, potable water via distillation and disinfection, day lighting, solar hot water, solar cooking, solar drying, solar pasteurisation and high-temperature process heat for industrial purposes.

1. **Solar Energy Advantages**

**Saves money:**

1. The payback period for the solar gadgets are very short and after recovery of an initial investment, the solar energy is practically FREE.
2. State and central Governments offer financial incentives in terms of subsidy that reduces the cost of solar appliances and make them attractive.
3. If the installed system produces more energy than use, then utility company can buy it back, building up a credit on a consumer account.
4. Solar energy does not require any fuel.
5. It's not affected by the supply and demand of fuel and is therefore not subjected to the ever-increasing price of gasoline.
6. The savings are immediate and for many years to come.
7. The use of solar energy indirectly reduces health costs.
8. Solar Energy can be utilized to offset utility-supplied energy consumption. It does not only reduce your electricity bill but will also continue to supply your home/ business with electricity in the event of a power outage.
9. The use of Solar Energy reduces our dependence on foreign and/or centralized sources of energy, influenced by natural disasters or international events and so contributes to a sustainable future.
10. Solar Energy supports local job and wealth creation, fuelling local economies.
11. Solar Energy systems are virtually maintenance free and will last for decades.
12. Once installed, there are no recurring costs.

**Solar is Environmentally Friendly**

1. Solar Energy is clean, renewable and sustainable and environmentally friendly.
2. It does not pollute air by releasing any harmful gas like carbon dioxide, nitrogen oxide, sulphur dioxide or mercury into the atmosphere like many traditional forms of electrical generation does. Therefore Solar Energy does not contribute to global warming, acid rain or smog etc...
3. It actively contributes to the decrease of harmful greenhouse gas emissions.
4. Solar Energy does not contribute to the cost and problems of the recovery and transportation of fuel or the storage of radioactive waste.
5. A Solar Energy system can operate entirely independently, not requiring a connection to power or gas grid at all. Systems can, therefore, be installed in remote locations, making it more practical and cost-effective than the supply of utility electricity to a new site.
6. The solar energy systems operate silently, have no moving parts, do not release offensive smells and do not require you to add any fuel.
7. **Sun-Earth Geometric**

The earth makes one rotation about its axis every 24 hours and completes one rotation about the sun in approximately 365 days and 6 hours. The earth takes a path around the sun, which is located slightly off center, thus making the earth closest to the sun at the winter solstice, at a distance of 1.471×1011 m, and furthest from the sun at the summer solstice, at a distance of 1.521×1011 m, when located in the northern hemisphere.



Fig.1.2 Motion of the earth about the sun

**3.1 Solar Declination Angle**

The earth’s equator is considered to be in the equatorial plane. By drawing a line between the center of the earth and the sun as shown in Figure 1.2, the angle of declination δ, is derived. The declination varies between −23.45° on December 21 to +23.45° on June 21. The declination has the same numerical value as the latitude at which the sun is directly overhead at solar noon on a given day where the extremes are the tropics of Cancer (23.45° N) and Capricorn (23.45° S). The angle of declination δ, is estimated by use of the following equation. It can also be obtained from graph in Fig. 1.3:

 ... (1.1)

Where *n* is the day number during the year with the first of January set as *n* = 1. The strength of solar radiation (solar insolation) dependent upon the angle at which it strikes the earth’s surface and as this angle changes during the year, the solar insolation changes.



Fig.1.3. Variation of Declination angle as a function of the date

In order to simplify calculations, it will be assumed that the earth is fixed and the sun’s apparent motion is described in a coordinate system fixed to the earth with the origin being at the site of interest. The position of the sun can be described at any time by the altitude and azimuth angles.

***Azimuth angle*** αs, is the angle that shadow of object makes with true South direction.

***Altitude angle*** , is the angle between a line collinear with the sun’s rays and the horizontal plane.

For the azimuth angle, the sign convention used is positive if west of south and negative if east of south. The angle between the site to sun line and vertical at site is the zenith angle, *z*, which is found by subtracting the altitude angle from ninety degrees:

*z* = 90° −  …(1.2)

**3.2 Hour Angle**

The altitude and azimuth angles are not fundamental angles and must be related to the fundamental angular quantities of **hour angle** (*h*s), **latitude angle** (**), and **declination** (δ). The hour angle is based on the nominal time requirement of 24 hours for the sun to move 360° around the earth, or 15° per hour, basing solar noon (12:00) as the time that the sun is exactly due south. The hour angle, *h*s, is defined as:

*hs* = 15° × (hour from solar noon) =  … (1.3)

The latitude angle **, is defined as the angle between the line from the centre of the earth to the site of interest and the equatorial plane; and it can easily be found by use of the Global Positioning System (GPS).

**3.3 Solar Time and Angles**

The solar time is also called the sun time. Sun time is approximated as time elapsed between two successive noons. When the sun crosses meridian, sun reaches the highest point, it is noon. Solar time is sometimes more or less than 24 hours of clock time. For example near about September 1, the daytime is only 23 hours 59 minutes and 41 seconds and on 25th December, the daytime is 24 hours 31 seconds long. The solar time can be defined with the help of local standard time (LST), *l*st is the standard time meridian, and *l*local is the local longitude.

Solar Time = *LST* + *ET* + ( *lst* −*l*local ) × 4min/ degree … (1.4)

*ET* is equation of time that is a correction factor, accounts for

1. The irregularity of the speed of the earth’s motion around the sun.
2. The earth’s orbit around the sun is an ellipse.

Solar time is used in predicting the direction of the sun’s rays relative to a particular position on the earth. Solar time is location (longitude) dependent, and is nominally different from that of the local standard time for the area of interest.



Fig. 1.4. Equation of time (in minutes) as a function of the time of year

The equation of time (*ET*) is calculated by use of the following empirical equation:

*ET* = 9.87sin (2*ϕ*) − 7.53cos (*ϕ*) −1.5sin (*ϕ*) (minutes) …(1.5)

Where *ϕ*, in degrees, is defined as:

*ϕ* = 360°× …(1.6)

The equation of time can also be estimated from Fig. 1.4, in which Eqn. (1.5) is plotted to the time of year.

The altitude angle, ** , is calculated by use of the following equation:

sin(**) = sin(**)×sin() + cos(**) ×cos() ×cos(*h s* ) …(1.7)

The azimuth angle, αs, is defined as

sin(**s) = cos()  …(1.8)

The sunrise (*h*sr) and sunset (*h*ss) times can be estimated by obtaining the hour angle for when α = 0 into Eqn (1.7);

*h ss* or *h sr* = ±cos−1[−tan(**) × tan( **)] …(1.9)

The sunrise and sunset times at any location are dependent on the day of the year, with the longest day being the summer solstice. The hour angle corresponds to the time from solar noon with the hour angle changing at a rate of 15 degrees per hour. Thus the length of the days can be estimated by use of Eqn (1.10), yielding Fig. 1.5.

Day Length =  …(1.10)



Fig. 1.5. Length of day, in hours, as a function of the date

However, it may appear that the calculated times are off by several minutes as to when the sun actually rises and sets. This is due to the observers’ line of sight and their interpretation of sunrise and sunset.

1. **Solar Radiation**

**4.1 Extraterrestrial Solar Radiation**

When the extraterrestrial solar radiation passes through the atmosphere, part of it is reflected back into space, part is absorbed by air and water vapour and some is scattered as shown in Fig. 1.6.



Fig.1.6 Direct and diffuse solar radiation distribution

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Extraterrestrial solar radiation (*I*) is the solar radiation which falls on a surface normal to the rays of the sun outside the atmosphere of the earth. Due to elliptical orbit of the earth about the sun, the earth-sun distance has a variance of ±1.7 percent. The extraterrestrial solar radiation, *I*, varies by the inverse square law, as

*I* = *I*0 ×  …(1.11)

Where *D0*, is mean earth-sun distance and *D* is the distance between the sun and the earth. The  factor is approximated by:

 = 1.00011 + 0.034221 × cos(θ) + 0.00128× sin(θ)

+ 0.000719 × cos(2θ) + 0.000077×sin(2θ) …(1.12)

Where θ =  degree



Fig. 1.7. The variation of extraterrestrial radiation with time of year

Solar constant*,* *I0* is the rate at which the solar radiation flux is received on a surface normal to the sun rays just outside the earth’s atmosphere, when the earth is its mean distance from the sun . The radiation coming from the sun is equivalent to blackbody radiation. Using the Stefan Boltzmann law, the solar constant can be calculated as:

*I0* =  = 1353 W/m2 …(1.13)

Where *D*0= 1.496×1011 m and *r*sun = radius of sun = 6.9598 × 108 m.

 = Stefan Boltzmann Constant = 5.67× 108 W/m2.K4,

*T*sun = Effective temperature of sun = 5862 K

Due to very small eccentricity in the earth, the distance between the earth and sun varies throughout the year. Therefore, solar constant also varies from its maximum value of 1399 W/m2 on December 21 to a minimum of 1310 W/m2 on June 21 and on any day of year, it can be approximated by:

 … (1.14)

Where *n* is the day of year. A plot of estimating the amount of the extraterrestrial solar radiation as function of time of year is shown in Fig. 1.7.

The extraterrestrial solar irradiation *G*0 incident normal to outer surface of the earth’s atmosphere is calculated as

*G*0 = *I*0cos θ (W/m2) …(1.15)

**4.2 Terrestrial Solar Radiation**

The solar radiation incident on the Earth’s surface is comprised of two types of radiation – beam and diffuse. The solar radiation that reaches the surface of the earth is known as beam (direct) radiation, and the scattered radiation that reaches the surface from the sky is known as sky diffuse radiation.

As the direct beam radiation forms, a larger proportion of the total radiation received. It depends on varying factors such as the weather, cloud cover and the time of day. It is interesting to note that whilst both direct and diffuse radiation is useful the diffuse radiation cannot be concentrated. Fig. 1.8 shows the distribution of solar energy on the earth’s surface. Actually 45% of sun’s energy reaches the earth’s surface. The lower left-hand figure shows how this sun energy is, in turn, returned to atmosphere and space.

The sun radiation incidents on the earth surface is a sum of direct and scattered (diffused) components. The part of solar radiation that reaches the earth’s surface without being scattered or absorbed is called the direct solar radiation *IT*. The scattered part (diffuse solar radiation *Id*) reaches the earth surface uniformly from all directions and it varies from about 10% of total on a clear day to almost 100% on a totally cloudy day.



Fig.1.8. Approximate distribution of sun’s energy to the earth’s surface

**4.3 Atmospheric Extinction of Solar Radiation**

As the extraterrestrial solar radiation is attenuated upon entering the earth’s atmosphere, the beam solar radiation at the earth’s surface is shown in Fig. 1.9.



Fig. 1.9. Solar radiation reaching the earth’s atmosphere

The solar radiation travels in the atmosphere about 30 km outside the earth’s surface. As solar radiation passes through this atmosphere, it is absorbed and scattered by the atmospheric material. The absorption occurs mainly due to a presence of ozone, water vapours, CO2, NO2, CO, O2 and CH4 etc. The *ozone* absorbs complete ultraviolet radiation at wavelength below 0.3 μm. Thus the *ozone layer* in the upper regions of atmosphere guards biological systems on the earth from the harmful ultraviolet radiation.

**4.4 Radiative Properties**

For most of the surfaces, when the radiation incidents on a body, a part of it is absorbed, a part is reflected and remaining part is transmitted as shown in Fig. 1.10.

The fraction of incident radiation reflected is defined as the reflectance, ρreflectance, the fraction absorbed as the absorptance, αabsorptance, and the fraction transmitted as the transmittance, τtransmittance.



Fig. 1.10. Reflection, Absorption and transmission of incident radiation .

When it comes to solar radiation, there are two types of radiation reflection: specular and diffuse. Specular reflection is when the angle of incidence is equal to the angle of reflection and the diffuse reflection is the reflected radiation is uniformly distributed in all directions. The specular and diffused reflections are shown in Fig. 1.11.



(*a*) Specular reflection (*b*) Diffused reflection

Fig. 1.11. Types of reflections .

1. **Absorptive Surfaces**

Selective surfaces are a combination of high absorptance for solar radiation with a low emittance for the temperature range in which the surface emits radiation. Such surfaces are commonly used in solar absorber surfaces (receiver) and for satellite temperature control. The typical designs use thin oxide coatings, sprayed or baked on finishes and vacuum deposited films. Table 1.1 shows some typical selective coatings.

**Reflective Surfaces**

Reflecting surface has high absorptivity and emission in infrared range but reflects most of the low wavelength solar irradiation. The solar concentrator is surfaced with high specular reflectance in the solar spectrum. Reflecting surfaces are usually obtained by enamels painting, ceramic coatings or metal coatings on substrates, some of which are shown in Table 1.2 with the materials reflectivity value.

Under laboratory conditions, polished silver has the highest reflection for the solar energy spectrum; however a silvered surface is expensive. Chromium plating is used in the automotive industry seem tempting but it has shown such a low reflectance in laboratory use that it is usually no longer a consideration for solar reflectance [17]. A better choice, which makes a compromise between price and reflectivity, is the use of a reflective plastic film such as anodised aluminium. Anodized aluminized is available with a high reflectance, almost as high as 90% in some cases and is the choice for design in many solar collector projects due to the low cost, high reflectivity and its light-weight and ease of workability. However, after long exposure to the ultraviolet rays, Anodized aluminized tends to degrade, but new stabilizers can be added to aid in slowing the degradation of the film.

Table 1.1. Solar absorbance of some selective materials

|  |  |
| --- | --- |
| **Material** | **Absorptivity (**α**)** |
| Black Cr on Ni plate | 0.95 |
| CuO on Cu (Ebanol C) | 0.90 |
| Nickel black on steel | 0.81 |
| Sputtered cermet on steel | 0.96 |

Table 1.2.Specular reflectance values for different reflector material

|  |  |
| --- | --- |
| **Material** | **Reflectivity (ρ)** |
| Copper | 0.75 |
| Aluminized type-C Mylar (from Mylar side) | 0.76±0.03 |
| Gold | 0.76 |
| Various aluminum surfaces-range | 0.82-0.92 |
| Anodized aluminum | 0.82±0.05 |
| Aluminized acrylic, second surface | 0.86 |
| Black-silvered water-white plate glass | 0.88 |
| Silver (unstable as a front surface mirror) | 0.94±0.02 |
| Snow | 0.82 |
| White paint : Acrylic  Zinc Oxide | 0.92  0.93 |

1. **Solar Thermal Conversion**

The basic principle of solar thermal conversion is that when sun radiation incident on a surface, a part is reflected, a part is transmitted and remaining part is absorbed, that increases the temperature of the surface, a part. As the temperature of the body increases, the surface loses heat at an increasing rate to the surroundings. Steady-state is reached when the rate of the solar heat gain is balanced by the rate of heat loss to the ambient surroundings. Two types of systems can be used to utilize this solar thermal conversion: passive systems and active systems.

Active solar techniques include the use of photovoltaic panels and solar thermal collectors to harness the energy. The photovoltaic technique converts solar radiation directly into electricity. In the solar thermal technique, the solar radiation is used to provide heat to a thermodynamic system, thus creating mechanical energy that can be converted to electricity. In commercially available photovoltaic systems, efficiency is of the order of 10 to 15 percent, where in a solar thermal system, efficiency is as high as 30 percent are achievable.

Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties and designing spaces that naturally circulate air. Use of solar energy protects the environment.

**6.1 Solar Collectors**

Concentrated solar power (CSP) has hardly contributed to the overall installed solar power capacity in the country. CSP technologies are Parabolic Trough Collector (PTC), Linear Fresnel Reflector (LFR), Paraboloid Dish and Solar Power Tower. The experimentation of CSP in solar parabolic dish concentrator is to understand thermal aspect like thermal efficiency, optical efficiency, useful heat gain, heat losses, solar irradiation, etc. for various applications and current and future development. The current scenario of global CSP is to meet the future challenges and need of the society.

* + 1. **Parabolic trough collectors**

In order to deliver high temperatures with good efﬁciency a high performance solar collector is required. Systems with light structures and low cost technology for process heat applications up to 4000C could be obtained with the help of parabolic through collectors (PTCs). PTCs can effectively produce heat at temperatures between 50 and 4000C for solar thermal electricity generation or industrial process heat applications. PTCs are made by bending a sheet of reﬂective material into a parabolic shape. A metal black tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver as shown in Fig. 1.12. When the parabola is pointed towards the sun, parallel rays incident on the reﬂector are reﬂected onto the receiver tube. It is sufﬁcient to use a single axis tracking of the sun and thus long collector modules are produced. The collector can be orientated in an east–west direction, tracking the sun from north to south, or orientated in a north–south direction and tracking the sun from east to west. The advantages of the former tracking mode is that very little collector adjustment is required during the day and the full aperture always faces the sun at noon time but the collector performance during the early and late hours of the day is greatly reduced due to large incidence angles (cosine loss).

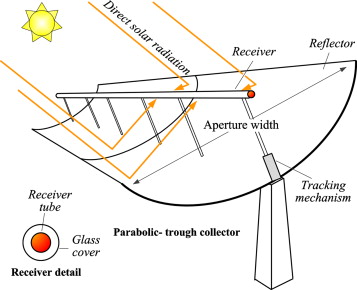


Fig.1.12 Schematic of a parabolic trough collector

* + 1. **Linear Fresnel Reflector (LFR)**

LFR technology relies on an array of linear mirror strips which concentrate light on to a ﬁxed receiver mounted on a linear tower. The LFR ﬁeld can be imagined as a broken-up parabolic trough reﬂector, but unlike parabolic troughs, it does not have to be of parabolic shape, large absorbers can be constructed and the absorber does not have to move. A representation of an element of an LFR collector ﬁeld is shown in Fig.1.13. The greatest advantage of this type of system is that it uses ﬂat or elastically curved reﬂectors which are cheaper compared to parabolic glass reﬂectors and these are mounted close to the ground, thus minimizing structural requirements.

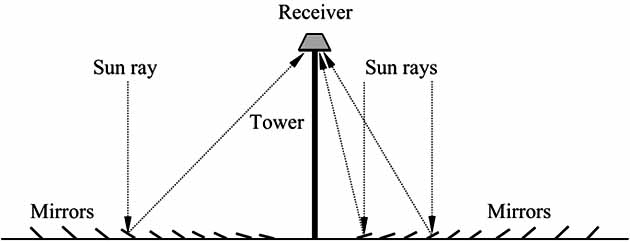


Fig. 1.13 Downward facing receiver illuminated from an LFR ﬁeld

**6.1.3 Solar Power Tower**

For extremely high inputs of radiant energy, a multiplicity of ﬂat mirrors or heliostats, using altazimuth mounts can be used to reﬂect their incident direct solar radiation onto a common target as shown in Fig.1.14. By using slightly concave mirror segments on the heliostats, large amounts of thermal energy can be directed into the cavity of a steam generator to produce steam at high temperature and pressure.

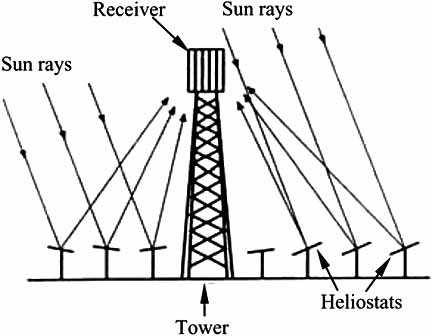


Fig. 1.14 Schematic of central receiver system

**6.1.4 Parabolide Dish**

Solar concentrators are mainly used to concentrate solar energy for high and medium temperature for thermal applications or power generation. Based on the type of focus, solar concentrators can be classified as line-focus concentrators like parabolic trough or point-focus concentrators like solar dish. Generally a solar dish includes a paraboloid reflecting surface, a receiver, a sun tracking system, thermal energy utilization system and the working fluid like water or steam, organic and molten-salt which transfer the heat. All radiation incidents on the reflecting surface are reflected towards the focus shown in Fig.1.15. The reflecting surface may be mirrors or any specially treated metal surfaces. The reflected radiation is concentrated in a focal zone on a smaller area, thus increasing the energy flux in the receiving target. The working fluid in the receiver placed at the focus of the reflecting surface receives concentrated solar energy. The tracking system is designed to track the sun such that the aperture of the reflecting surface is orthogonal to the incident radiation. The concentration ratio (ratio of the aperture area to the receiver area) of solar dish determines the intensity of solar radiation received by the receiver. The increased heat flux makes solar energy suitable for utilization in medium and high temperature applications as well as thermal power generation.

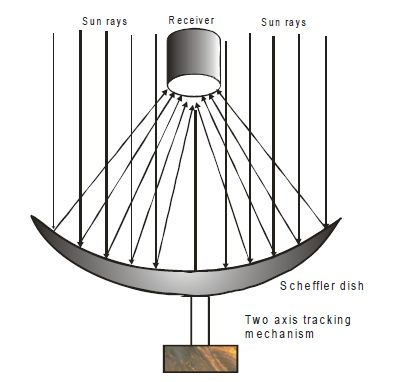


Fig. 1.15Principle of point focus concentration

1. **Solar Thermal Applications**

Solar water heaters utilizing FPC and ETC are well-established technologies. Use of solar box cookers is known since decades. Other emerging solar thermal technologies are solar drying and solar concentrators for mid and high-temperature applications. International Energy Agency’s (2011) [9] Task 33 on solar heat for industrial process reports solar thermal technologies for industrial applications like cleaning, drying, evaporation, pasturisation, sterilisation, preheating boiler feed, heating production halls and solar cooling as most promising areas. Kalogirou [10] presented detailed review of different thermal technologies including FPC, ETC, CPC, troughs, dishes and towers and provided methods of thermal and economic analysis of these solar technologies. Australian National University (ANU) is one of the leading research centers in solar thermal technologies. Lovegrove and Dennis in 2006 presented the review of different solar thermal technologies for Australia with particular emphasis on solar concentrators and linear Fresnel systems developed at ANU. These high capacity concentrators at ANU are primarily developed for CSP through thermal route and can also play big role in solar thermal applications replacing low pressure boilers and other applications below 3000C. Rajamohan et al. in 2009 recommended solar concentrators for industrial heating applications with viability and payback analysis. OPET-TERI (2009) [11] published a report on Status of Solar Thermal Technologies and Markets in India and Europe with extensive analysis and market feasibility study. Almost all reports and market research indicate huge potential for solar thermal applications in coming years.

Kedare (2006) presented solar thermal scenario in Indian context and also provided technical and financial comparative study of two most popular solar concentrators in India, ARUN and Scheffler, with their niche area of applications. Policies of MNRE regarding adoption of solar heat for industrial process application are also presented.

Under Jawaharlal Nehru Solar Mission, Govt. of India (2010) has announced ambitious targets for all solar technologies. These include FPC, ETC and solar concentrators. As per GOI notification, technologies like dish cookers, Scheffler concentrators of 10 and 16 sqm sizes as standalone systems or steam cooking systems and ARUN concentrators are approved for the purpose of subsidy. Subsidy to the tune of 30% and or soft loan at 5% plus accelerated depreciation of 80% in the first year is permitted.