Chapter 1

Introduction and Background

1.1 Introduction

Energy is one of the mainspring for growth and social development. However, such growth and development can be detrimental to the environment and thereby reducing the quality of life on Planet. In this way, it's normal to have a basic conflict between growth and development. There are two types of energy resources: Renewable and Non-renewable. 80% of the world's energy requirement is fulfilled by consuming Non-renewable energy resources (IEA, 2016) which causes environmental problem at local, regional and global scale [1]. Therefore, output of energy consumption should fulfill the criteria of economic growth and sustainable development to overcome the conflict of interest. Sustainable development is generally designated as the marriage of economy and ecology to serve the economic development without compromising the ecological balance [2]. When It was thought about the sustainable development, it really means the development under three main pillars: economy, environment and society (UN Department of Economic and Social Affairs, 2014). Consumption of energy resources without having environmental concerns will just like a slow poison for all living beings at present and in future. Therefore, one should be aware of the importance of utilizing renewable energy resources more efficiently.

In the present scenario of huge energy demand, dependency on conventional energy resources certainly creates crisis in future especially for developing country [3]. Since the rapid consumption of fossil fuel over billions of people across the world are still unable to assess electricity. Furthermore, if the consumption of fossil fuel will be continued then our future generation will certainly have to face the shortage of it. Excessive use of conventional energy resources creates environmental issues like global warming potential (GWP) and ozone layer depletion (ODP) [4]. Ultimately, one and all have to depend upon renewable energy resources to fulfill our current energy requirements together with economic growth and sustainable development.

1.2 Renewable Energy Resources

Renewable energies are the energy resources that are refreshed by nature continuously. It is derived directly and indirectly from the sun or from other natural movements and mechanisms of the environment. Solar thermal, photo-chemical, and photo-electric) are energies that are directly derived from the sun whereas wind, hydro power, and photosynthetic energy stored in biomass are the energies obtained from sun indirectly. Geothermal and tidal energy are also included under category of renewable energy resources since these are formed due to natural environmental movements. Fossil fuels and waste products will not come under the category of renewable energy [5].

1.2.1 Classification of Renewable Energy Resources

There are various forms of renewable energy resources like solar, wind, hydroelectric, biomass, hydrogen and fuel cells, geothermal, tidal and ocean energy etc. Most of these kinds of renewable energies, somewhere, depend on the sunlight in one way or another. Solar energy is the direct conversion of sunlight either using collectors, flat plat collector (FPC) and concentrating collector (CC) or using photo voltaic (PV) cells. Wind and hydroelectric power are somewhere the direct consequences of the gradient heating of the Earth's surface which leads to air movement (wind) and air lifted (precipitation forming). Even biomass energy is the sunlight stored in the plants. Geothermal and tidal energy resources do not depend on sunlight. Geothermal energy results from the combined effect of radioactive decay in the crust and the original heat in the core of the Earth. Tidal energy is basically a conversion of gravitational energy to wave energy [6]. Fig. 1.1 shows the classification of renewable energy resources.

The market of renewable energy resources for electricity generation, heating and transportation have been growing abruptly since the last five years. The spreading of

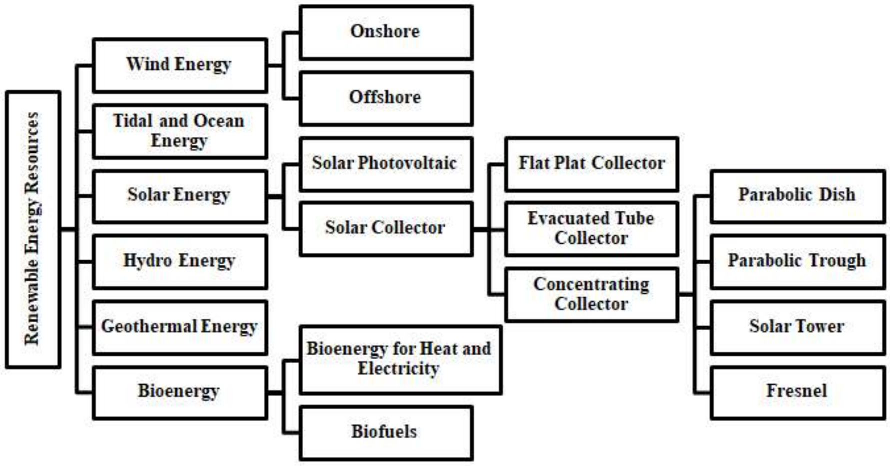

Figure 1.1: Classification of renewable energy resources [6]

well-known technologies, such as hydro power and reintroduced technologies like wind and solar thermal/photo voltaic have increased on a broad scale. These technologies have increased confidence by providing us a new opportunities to exploit energy at reduced costs [7]. Table 1.1 indicates that the global electricity generation from different types of renewable energy resources [8]. It is expected to grow 2.7 times more in the year 2035 in comparison to the year 2010. Consumption of biofuels is projected to be three times more over the same period. The requirement of renewable energy to produce heat will almost double, from 337 Mtoe (mega ton of oil equivalent) in 2010 to 604 Mtoe in 2035.

1.2.2 History of Renewable Energy Resources

In the mid 19th century when the coal was not developed, almost all energy used was non conventional or renewable. The oldest known use of renewable energy is biomass dates from 7.9×10^5 years ago [9]. Most probably the second oldest use of renewable energy is the wind. In ancient time (7000 years ago), wind was used to drive ships over seas or river. This practice was traced back in the Persian Gulf and on the Nile. Moving into the time of recorded history, the primary sources of traditional renewable energy were human labor, animal power, water power, wind, and firewood, a traditional biomass [10]. In the 1860s and 70s, it had already been realized that one day or the other day the civilization would have to face a reduction of fossil fuels and the need was felt for a better source [11].

Table 1.1: Prediction of world renewable energy use by type [8]

Renewable energy type	World renewable energy use		
	2010	2020	2035
Electricity generation (TWh)	4206	6999	11,342
Bioenergy	331	696	1,487
Hydro	3431	4513	5,677
Wind	342	1272	2,681
Geothermal	68	131	315
Solar PV	32	332	846
Concentrating solar power	2	50	278
Marine	1	5	57
Share of total generation	20%	25%	31%
Heat demand (Mtoe)	337	447	604
Industry	207	263	324
Buildings and agriculture	131	184	280
Share of total production	10%	12%	14%
Biofuels (mboe/d)	1.3	2.4	4.5
Road transport	1.3	2.4	4.4
Aviation	–	–	0.1
Share of total transport	2%	4%	6%

In 1873 Professor Augustin Mouchot predicted [12] that: The time will arrive when the industry of Europe will cease to find those natural resources, so necessary for it. Petroleum springs and coal mines are not inexhaustible but are rapidly diminishing in many places. Will man, then, return to the power of water and wind? Or will he emigrate where the most powerful source of heat sends its rays to all? History will show what will come [13].

Werner von Siemens had commented on the discovery of photo voltaic effect in the solid state in 1885 wrote: In conclusion, It would say that however great the scientific importance of this discovery may be, its practical value will be no less obvious when one reflects the supply of solar energy is both without limit and without cost, and that it will continue to pour down upon us for countless ages after all the coal deposits of the earth have been exhausted and forgotten [14].

Max Weber mentioned in the concluding paragraphs of his Die protestantische Ethik und der Geist des Kapitalismus, published in 1905 about the end of fossil fuel. Development of solar engines continued until the outbreak of World War I but its importance was understood in 1911 AD. It was said that in the foreseeable future, no place of natural

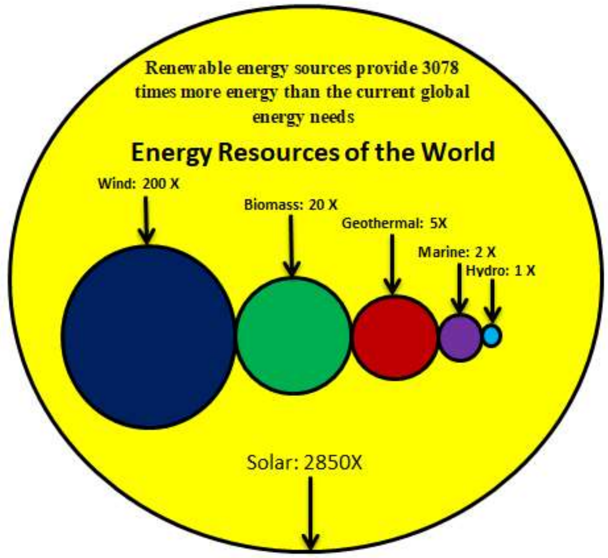

Figure 1.2: Renewable energy potential worldwide [19]

gas will be left. solar power will remain as the only means of survival of mankind [15].

In the present scenario, if attentions are focused toward the exploitation of renewable energy resources then we'll find that the consignment of renewable energy has increased. There is awareness among the people and everybody is thinking that renewable energy is our future. The international energy agency (IEA) 2014 projected a growth of renewable energy supply from 1,700 gigawatts in 2014 to 4,550 gigawatts in 2040 [16].

Based on the report REN21's 2017, renewable energy resources contributes 19.3% and 24.5% to global energy consumption 2015 and 2016, respectively. Out of which 8.9% of global energy consumption was come from the traditional biomass, 4.2% in the form of heat energy (modern biomass, geothermal and solar heat), 3.9% hydro electricity and 2.2% electricity consumed from wind, solar, geothermal, and biomass. Investment in renewable technologies across the world was more than 286 billion US dollars in 2015. Countries like the United States and China make huge investments in solar, wind, water and biofuel [17]. Globally, 7.7 million jobs related to renewable energy industries have been estimated and solar photovoltaics are the biggest renewable employer [18]. Fig. 1.2 demonstrates the ability of renewable energy resources to provide 3000 times more energy than the present global energy needs [19].

1.3 Solar Energy

Sun is a sphere which contains extremely hot gaseous matter with an average diameter of 1.39×10^9m and the average distance of 1.5×10^{11}m from the Earth surface. The sun takes 4 weeks for one complete rotate about its own axis. However, it is not a rigid body rotation . It takes about 27 days for equator and approximately 30 days for polar regions for each rotation. The sun is considered as a dark body whose surface temperature is around 5777 K. The temperature at the core of sun varies between at 80×10^6 to 40×10^6K and the density is estimated to be about $10^5 kg/m^3$ [20].

In the extraterestrial region, the Earth takes174 petawatts (PW) of incoming solar radiation (insolation). Major portion of the solar radiation is absorbed by land masses, clouds and oceans meanwhile 30 % of it is reflected back to extraterestrial region. The spectrum of solar radiation that falls on the Earth's surface is belong to visible, infrared and ultraviolet range but mostly comes under visible range with a small part near-infrared ranges and very small part in the near-ultraviolet [21].

1.3.1 Solar Energy Utilization

Solar energy can be utilized basically in two different ways: direct and indirect as shown in figure 1.3 [22]. Indirect utilization of solar energy considered the use of renewable energies, the secondary effects of solar energy [23, 24]. Wind energy, hydro energy, ocean energy, biomass and biofuels belong to indirect use of solar energy. Solar energy that is used directly incluids two fundamental methods of energy conversion: photothermal and photoelectric conversion of solar radiation. Technologically, Solar energy can be utilized by three different technological processes: heliochemical, heliothermal and helioelectrical. Hellochemical belongs to a process of photosynthesis in which solar energy is converted into chemical energy through which the plants make food and hence the cause of servival for all of us. Biomass and biofuels are the examples of heliochemical process. In helioelectrical, photovoltaic effect is considered. In this process, sun light is directly converted into electrical energy using p-n junction of a semi conductor. This principle is used in developing a solar cell, solar moduel and finally solar PV pannel. In heliothermal,

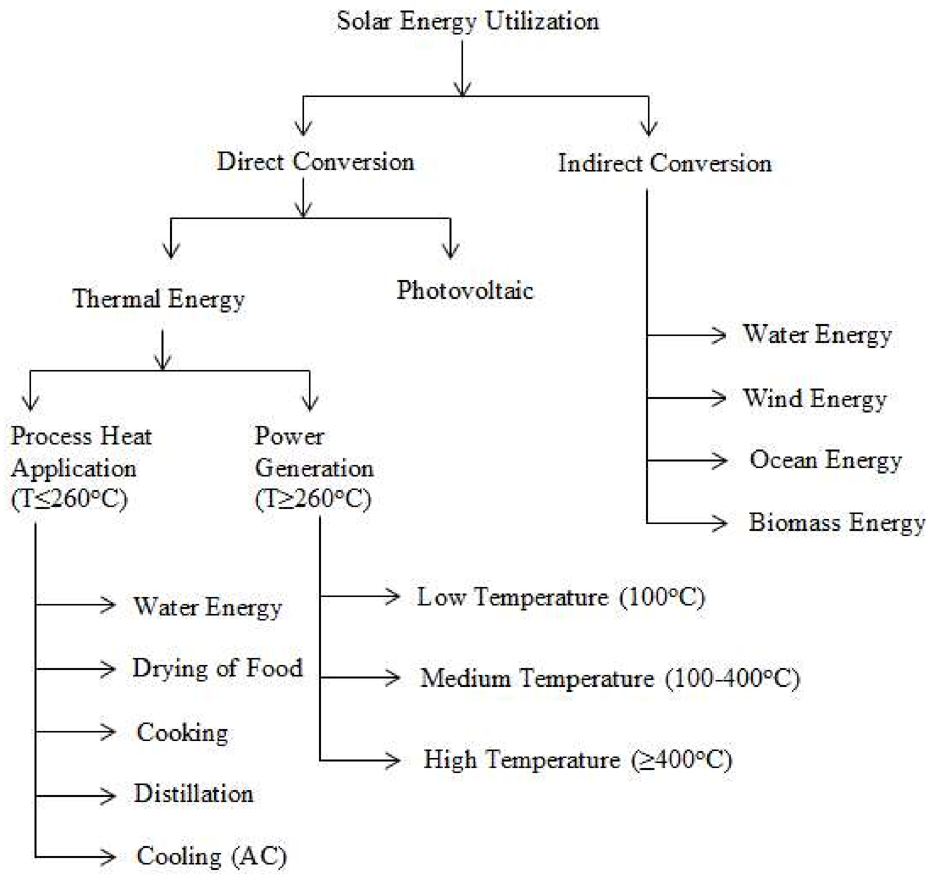

Figure 1.3: Methods of solar energy utilization [22]

thermal effect of solar energy is considered to convert sun energy to thermal energy using the devices like, flat plate collectors or focussing collectors [25].

1.3.2 Available Solar Radiation

It is convenient to consider radiation in two wavelength categories: short-wave irradiation radiates from the sun in the walength ranges from 0.3 to 3 μm. This short-wave radiation passes through the outer space and terrestrial area, eventually absorbed by the environment, by solar divices, or by another body at normal temperature. Long-wave radiation is radiation which originates from sources at ordinary ambient temperatures greater than 3 μm. About 48% of the solar radiation falls in the range of visible region whereas about 45.6% belong to infrared region and the rest is in ultraviolet spectrum as depicted in figure using π-chart. Expectral distribution of extraterestrial radiation has been shown in figure

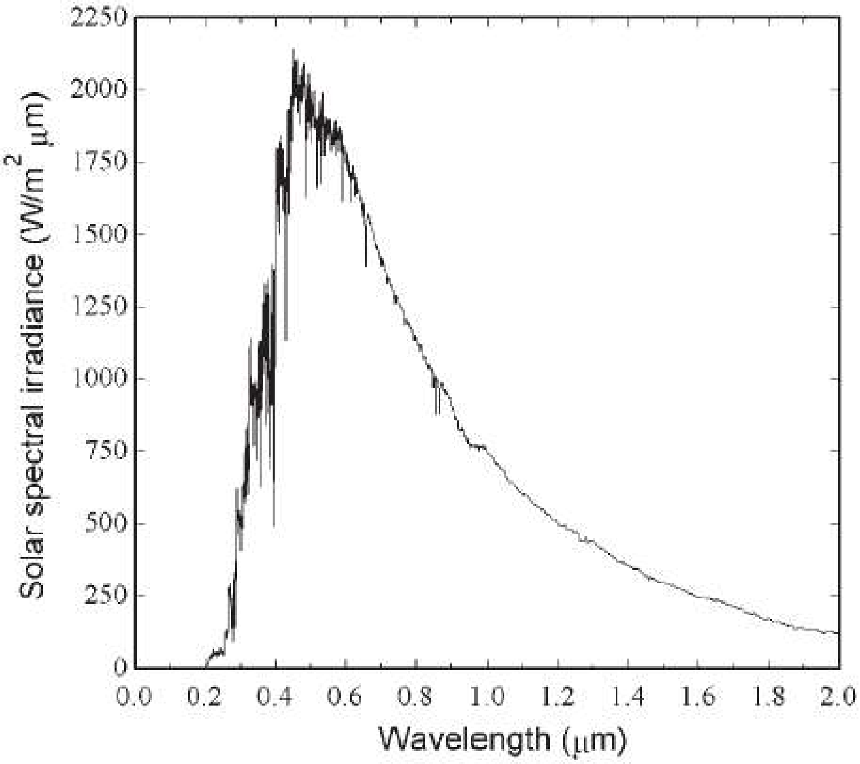

Figure 1.4: Spectral distribution of extra terestrial radiation at mean sun-earth distance [26]

1.4 [26].The solar radiation that reaches on the earth's surface can be further divided into two types, extraterrestrial and terrestrial.

1.3.3 Extraterrestrial Solar Radiation

Outside the Earth's atmosphere, solar radiation is called extraterestrial radiation (ETR). The extra terestrial radiation depends upon many factors like orientation and the average distance between sun and the earth$(1.496 \times 10^{11}\, m)$ and orientation. The solar radiation thar falls on the mean sun earth distance, D_m is termed as the solar constant, The term solar constant was first introduced by the French scientist Pouillet in 1837 [27] and its current value was considered by NASA equivalent to 1353 W/m^2. As the earth revolves around the sun in an eliptical orbit, the sun-earth distance has varied by 1.7$\%$ .As shown in the following equation, I_{ext} varies with the inverse square law [28].

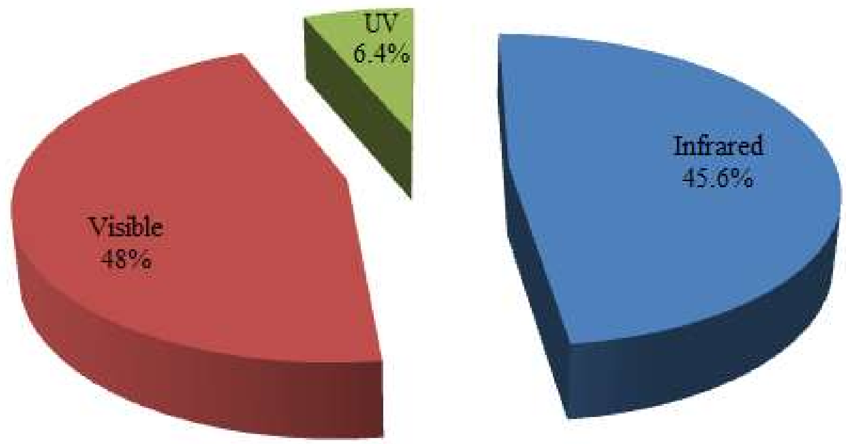

Figure 1.5: Extraterrestrial solar spectrum

$$I_{ext} = I_{sc} \left[\frac{D_m}{D_{e-s}} \right]^2 \tag{1.1}$$

Where, D_{e-s} is the mean sun earth distance between earth and the sun. The value ofI_{ext} for a given day is approximated by the following empirical relation [29].

$$I_{ext} = I_{sc} \left[1 + 0.033 \cos \frac{360n}{365} \right] \tag{1.2}$$

1.3.4 Terrestrial Solar Radiation

In fact, the amount of solar radiation reaching the surface of the Earth passes through the gaseous molecules present in the atmosphere, due to which various reduction processes occure like scattering, reflection and absorption. The total radiation incident on a horizontal surface is comprised of two forms: beam radiation, I_b(no reduction in intensity) and diffuse radiation, (significantly affected by the atmosphere) [28]. Global radiation, or terrestrial solar radiation is assumed to be equal to the summation of the beam and diffuse radiation [30]. Hottel suggested a simple clear day model [31] for dircet solar radiation normally incident to horizontal surface,I_b, is given by Shah [32]:

$$I_b = I_{ext} \left[a_o + a_1 e^{-k(airmass)} \right] \tag{1.3}$$

The air mass which can be defined as the ratio of minimum optical path length to the optical path length under consideration. It is determined by the reciprocal cosine of zenith angle $Airmass = 1/cosz$. Duffie and Beckman suggested the parameters k , a_o, and a_1 are the empirical constants [26].

$$a_o = 0.94 \times [0.42370 - 00821(6 - AL)^2] \tag{1.4}$$

$$a_1 = 0.98 \times \left[0.5055 - 0.00595(6.5 - AL)^2\right] \tag{1.5}$$

$$k = 1.02 \times [0.2711 - 0.01858(2.5 - AL)^2] \tag{1.6}$$

where, AL, is abbreviated as the altitude of the place above sea level (km).

The diffused solar radiation on a horizontal surface may be calculated by using the following equation [33]:

$$I_d = I_o \cos\theta_z \left[0.2710 - 0.2939(a_o + a_1 e^{-k(airmass)})\right] \tag{1.7}$$

The diffused solar radiation has no effect on the design of the concentrating collector because it is difficult to concentrate diffuse solar radiation at the focus of concentrator.The fraction of direct solar radiation is particularly important to the performance of focusing collector.

1.4 Elements of Solar Geometry

With view to track the sun every day of the year, there is a geometric connection to the position of the collector in relation to the time which is required to be known to derive the various parameters of solar collector.

Followings are the important sun-earth angles necessary to investigate the performance of solar collector:

- **Angle of incidence** (θ): It is defined as the angular displacement of the beam

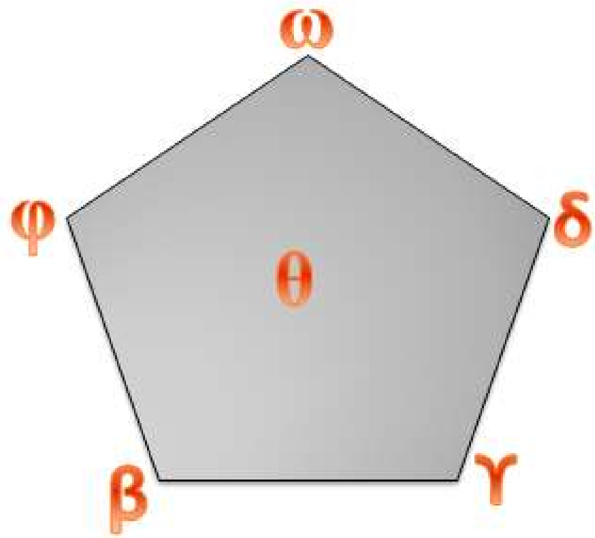

Figure 1.6: Solar angle of incidence is a function of different solar angles

solar radiation on the surface with respect to the normal to that surface. It is a function of different solat angles which can be shown using the diagram 1.6. Solar angle of incidence can be calculated using the equation mentioned below

$$cos\theta = (cos\varphi cos\beta + sin\varphi sin\beta cos\gamma)cos\delta cos\omega + (sin\varphi cos\beta + cos\varphi sin\beta coscos\gamma) \times sin\delta + cos\delta sin\omega sin\beta sin\gamma \quad (1.8)$$

where,

$\theta = Solar\, angle\, of\, incidence$

$\gamma = Surface\, azimuth\, angle$

$\delta = declination\, angle$

$\varphi = Latitude$

$\omega = Hour\, angle$

$\beta = surface\, inclination\, angle$

- **Latitude** (ϕ) : It is defined as the angular position of observer with the equatorial plan. The range of variation of latitude is ; $-90^o \leq \phi \leq 90^o$.
- **Declination** (δ): It is defined as the angular position of the line joining between

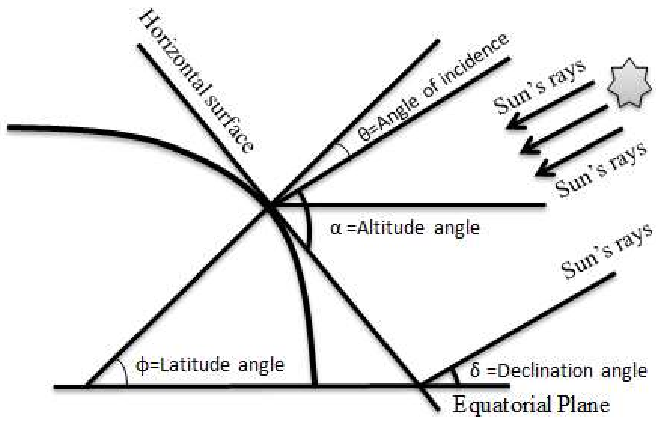

Figure 1.7: Different sun earth angles

centres of earth and the sun with respect to the equatorial plane. Its value is positive for nothern hemisphere and negative for southern hemisphere. The range of variation of solar declination angle is; $-23.45^o \leq \delta \leq 23.45^o$. Latitude and declination angle can be easily by the figure

- **Slope** (β): It is defined as the the angle between the plane of the surface in question and the horizontal; $0^o \leq \beta \leq 180^o$. Slope of surface in question and angle of incidence have been shown in figure 1.8

- **Surface azimuth angle** (γ): It is defined as the angular position of the projection of the normal to the surface from the local meridian. Its value is zero when the surface is faced due south. Surface azimuth angle can be ranges from; $-180^o \leq \gamma \leq 180^o$

- **Hour angle** (ω): It is defined as the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15^oper hour. In morning, its value is taken as negative while in afternoon, it will become positive. At the time of sun rise and sun set, the value of hour angle becomes maximum and at solar noon it is zero. Hour angle and its function has been shown in figure 1.9

- **Zenith angle** (θ_z):It is defined as the the angle between the vertical and the sun's rays. Zenith angle can be called as solar angle of incidence for horizontal surface.

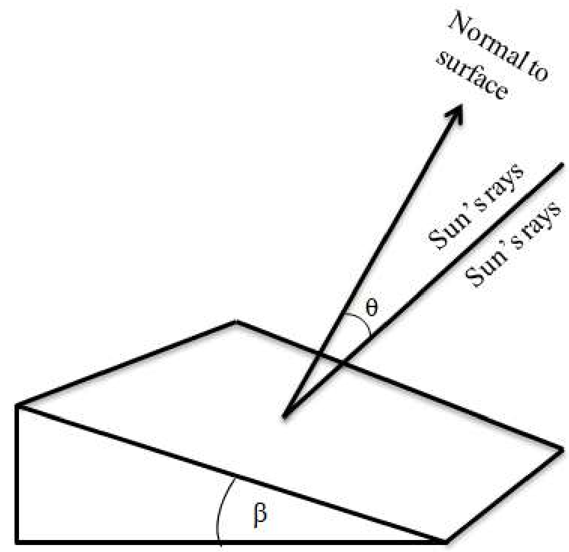

Figure 1.8: Solar angle of incidence and slope of surface

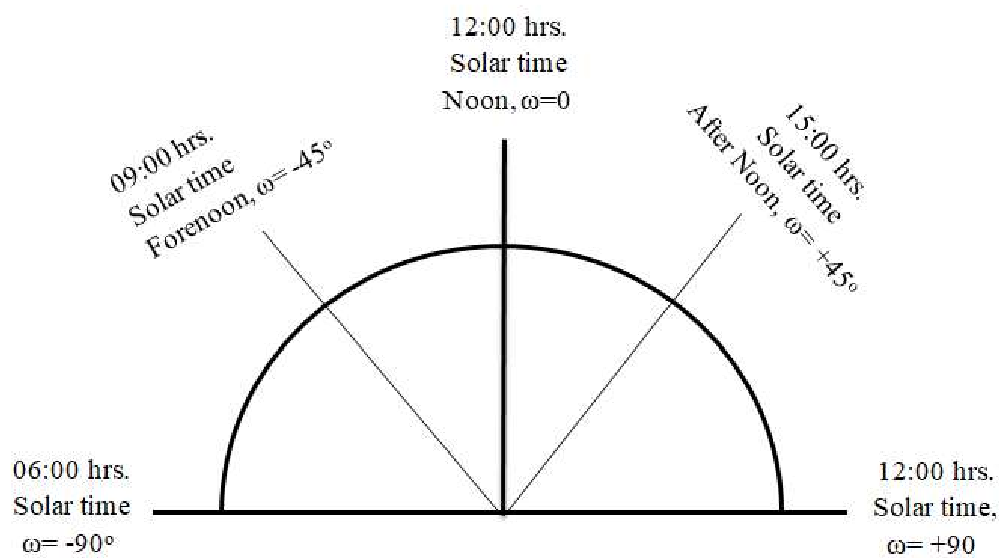

Figure 1.9: Hour angles varies with time of the day

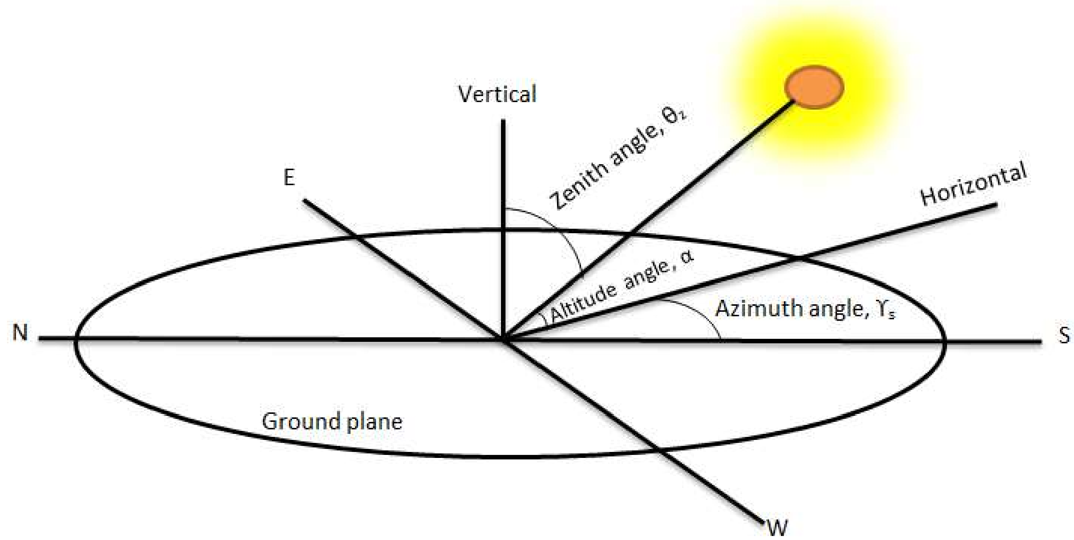

Figure 1.10: Position of sun in the sky

- **Solar altitude angle** (α): It is defined as the angle between the horizontal surface with the sun's rays. It is complementry to zenith angle.

- **Solar azimuth angle** (γ_s): It is defined as the angular displacement projection of beam solar radiation from south. Displacements east of south are negative and west of south are positive. Zenith angle, solar altitude angle and solar azimuth angle represent the position of sun in the sky as shown in figure 1.10.

1.5 Basics of Solar Collector Technology

Solar thermal collector is a device that collects heat by absorbing solar radiation. The term "solar concentrating collector" usually consign to solar hot water system but it might be refered to the installation of devices such as solar PTC, parabolic dish, and solar towers for power generation. It also includes the basic solar devices like solar air heaters etc. Concentrated solar energy (CSP) technology typically uses more complex collectors to generate steam and eventually electricity [34]. Solar collectors are typically used in quarters and commercial constructions to heat the space. The first solar thermal collector was designed and patented by William H. Goettlfor for building roofs and called it by the name "Solar heat collector and radiator for building roof [35].

The main function of solar collection is to absorb solar radiation incident on it. Thus, increasing the surface temperature of tube through which the heat transfer fluid flows. The higher temperature of heat transfer fluid is used to heat water, air and also to generate steam in the case of concentrated solar power, CSP. As the surface temperature of the collector increases then the rate of losses of heat from the hot surface to the surroundings increases. The condition will be called by name, steady state condition when the net solar heat energy received by the heat transfer fluid is balanced by the heat loss to the ambient [26]. Solar collector may be divided into two categories: flat plate collector and concentrating collector. The basic difference between flat plate collector and concentrating collector is that in the case of concentrating collector more amount of solar radiation is intercepted by the receiver as compared to flat plat collector for the same aperture. Solar concentrations are mainly consists of three basic components: a focusing device, a receiver (with or without transparent cover) and a tracking device to track the sun [36].

1.5.1 Solar Concentrating Technology

Any general setup that converts solar energy into useful energy incluides a receiver: a device capable of converting sunlight into a thermal energy. It can be an absorber for harnessing thermal energy or photovoltaic cell to convert light energy to the electrical energy. For harvesting thermal energy, there are two options: flat plat collector and concentrating collecter. In the latter case, the solar radiation provide heat to a heat transfer fluid that is used to drive a one complete thermodynamic cycle. In this thermodynamic cycle, the heat transfer fluid gets heated by solar radiation and finally transfer it to other fluid to be heated. unlike photovoltaic cells or flat plate collectors, the diffuse part of the solar irradiation cannot be concentrated and of no use for concentrated solar power (CSP) plants. The most commonly used concentrators are reflectors (mirrors) and refractors (lenses), which redirects the incident beam radiation. Some of the examples of different types of con-

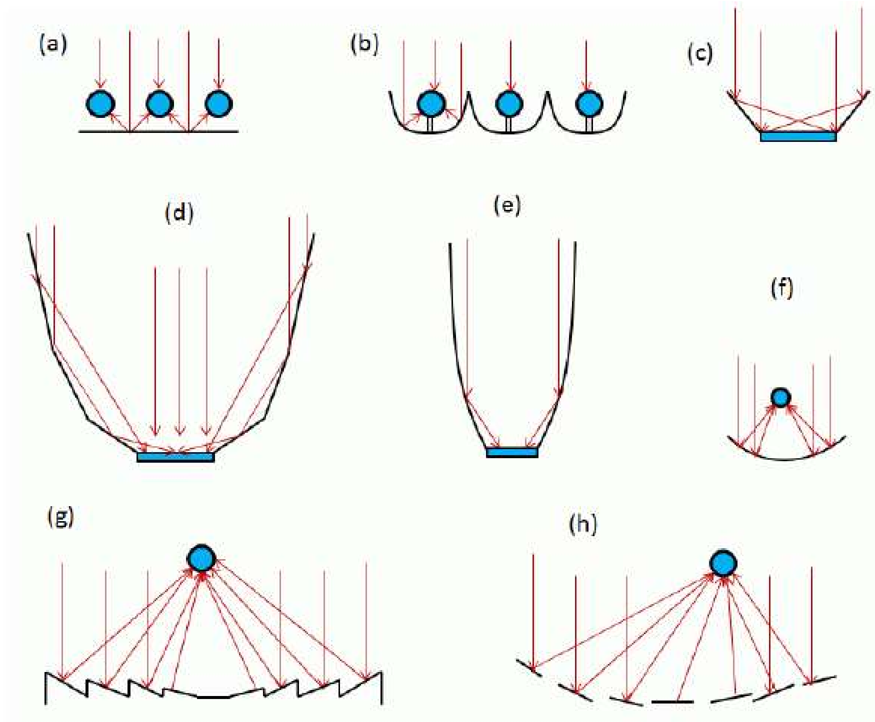

Figure 1.11: Various types of solar concentrator : (a) tubular diffuse collector, (b) tubular specular collector, (c) plane reflectors (V-trough), (d) multisectional flat collector, (e) compound parabolic collector (f) parabolic trough, (g) fresnel (h) central receiver. [37, 38]

centrating collectors on the basis of shaped mirrors and applied for the solar-to-thermal energy conversion are shown in Figure 1.11 [37, 38]. In all those cases, solar radiation is concentrated unto the receiver that can be obtained by shaping the aperture of reflector (mirror) near the receiver(signified by the blue ring).

The concentrator can be classified into two groups on the basis of image formation at the focal point: imaging and non-imaging. Imaging concentrators produce an optical image of the sun on the absorber tube while the non-imaging concentrators do not produce such an image. Non imaging concentrator can utilize diffuse solar radiation. The value of the concentration ratio for non-imaging collector (<10) is relatively less than the imaging concentration.

Out of the various types of concentration described below, basically, four types were adopted based on their applications:

- Parabolic dish

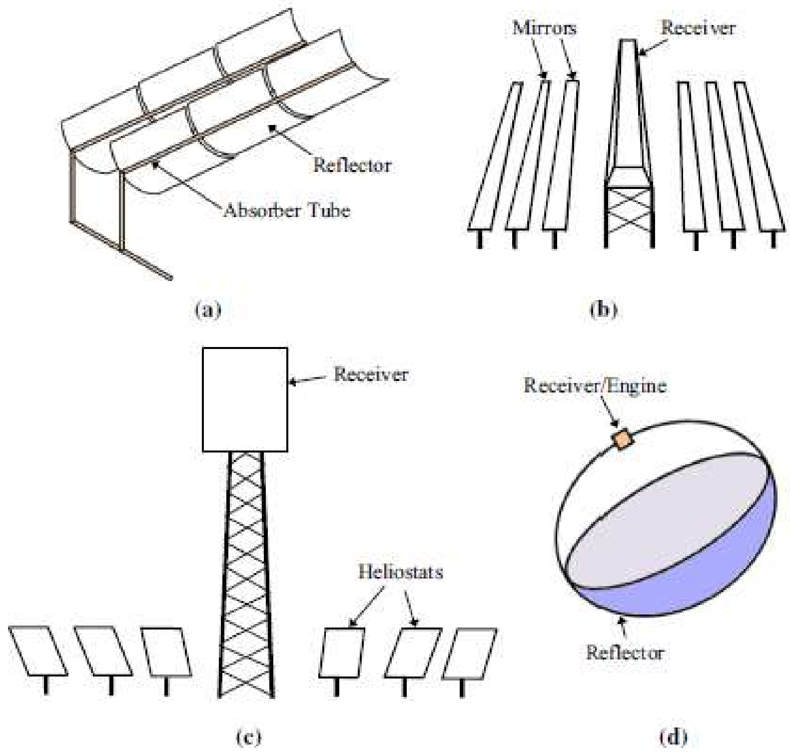

Figure 1.12: Solar concentrating technology[39]

- Parabolic trough
- Solar tower
- Linear Fresnel reflector

Fig. 1.12 shows the schematics of various types of concentrating collectors [39]: (a) paraboloid dish (b) parabolic trough collector (c) solar power tower (d) linear Fresnel reflector

Above mentioned concentrators belong to imaging concentrators that allow relatively high temperatures at the focal point: The temperature achieved for the collectors like parabolic trough, sterling dishes and solar towers are about 400°C, 650°C and above 1000°C respectively. Non-imaging concentrators can produce temperature up to a maximum of 200°C [37]. Moreover, different solar concentrating technologies developed and demonstrated today can be divided in two groups according to the method of concentration [40]: line concentrating and point concentrating.

1.5.1.1 Line Concentrating

Line concentrating unit use a trough shaped concave mirror which concentrates the incident solar radiation onto the the receiver tube by single axis tracking system. In the case of small parabolic trough system, double axis tracking can be used to increase the performance of concentrator. Parabolic trough collectors (PTC) and linear fresnel reflector systems (LFR) are the examples of the most important line concentrating technologies as shown in figs. 1.12(a,b).

PTC and LF are able to concentrate the incoming solar radiation intensity 30 to 80 times more than the terestrial solar radiation in order to heat a heat transfer fluid upto 400^{o}C. The absorber tube (made up of copper or steel) is kept at the focus of line concentrating unit and is coated with a heat resistant black paint. Line concentrating unit especially Parabolic trough collector is considered as a fully mature technology where the financial and technological risks are almost negligible.

The absorber tube at the focus of concentrator is typically covered by a glass (borosilicate or alluminosilicate) tube with vacuum in the annular space. Vacuum in the annulus is created so as to reduce the losses due to convection and conduction from the receiver tube. A selective coating may be used for better performance. Selective coating should have high solar absorptivity and low thermal emissivity sothat the solar energy can be utilized more and more. Various categories of thermal oil is used to circulate through the absorber tube for the conversion of sun energy to thermal energy and carries heat to the boiler for driving a Organic Rankine stream turbine for solar thermal power plant application.

Linear Fresnel collectors is different from the parabolic trough collectors. The basic difference between PTCs and LFCs is in the design of aperture. In LFCs, several parallel mirrors facets are used instead of parabolic bent mirrors to concentrate the sunlight onto the receiver. Receiver is kept at several meters above the primary mirror field [41]. LFCs are cost effective due to simple structure but produces much lower energy per unit area of solar collector field in comparison to the PTC system thereby need to improve the optical efficiency of LFCs field [42, 43].

1.5.1.2 Point Concentrating

The concentrating devices which concentrate the sun light onto a point and forms a point image of sun at the focal point. Parabolic dish (PD) and solar power tower or central receiver systems (CRS) are the most common examples of point concentrating technology as shown in figs. 1.12(c,d).

PD are the three dimensional concentrator that can achieve high concentration ratios between 1000 to 4000: needed two-axis tracking system to track the sun for maintaining high intensity of solar radiation at the focal point. Parabolic dish type concentrator systems are relatively small units containing a motor-generator unit (stirling engine or a small gas turbine) at the focus of concentrator [44, 40].

1.6 Parabolic Trough Technology

Parabolic trough concentrated solar power technology is one of the most established, cost effective and large-scale solar power technology to utilize sun energy to thermal energy. Parabolic trough power plants basically consist of the following components: parabolic trough collectors (large field), a heat transfer fluid/steam generation system (receiver), a Rankine steam turbine/generator cycle, and optional thermal storage and/or fossil-fired backup systems.This technology is capable of generating temperatures greater than 260^{o}C and initially were developed for industrial process heat (IPH) applications [45]. Fig. 1.13 [45] shows how the solar radiation incident on the aperture of parabolic trough collector reflected back to the receiver located at the focal line of the parabolic mirrors.

Most of the parabolic trough plants, under operation have capacities lies between 14 and 80 MW. The efficiencies (the ratio of solar irradiation to net electric output) are found to be around 14-16 % whereas the maximum operating temperatures is 390^{o}C [46].

The application of PTC system can be categorize in to two main groups depending on the temperature range: electricity generation (300 to 400^{o}C)and heating purposes (100 to 250^{o}C). Industrial process heat (IPH), low-temperature heat demand, space heating and swimming pool and heat-driven refrigeration and cooling are the applications of

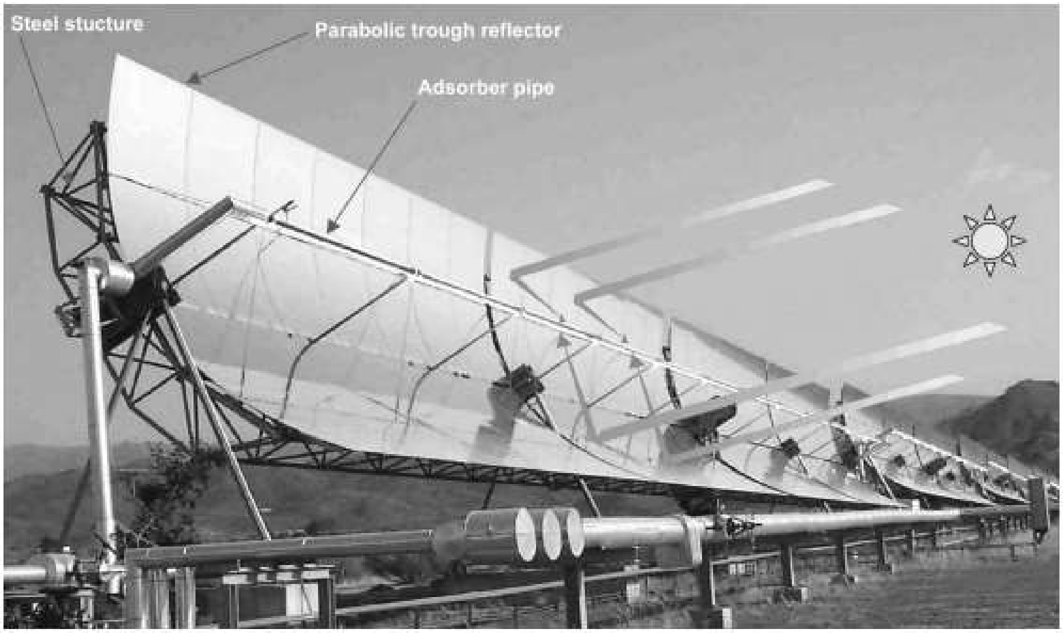

Figure 1.13: Solar parabolic trough concentrator[45]

parabolic trough technology under the temperature range of (100 to 250^oC). The present thesis is concerned with both kinds of applications.

1.6.1 Solar Receiver Tube

The receiver tube, sometimes also called heat collecting element (HCE) is assumed to be the heart of the PTCs. It consists of pipe with circular cross section, made up of steel or copper material. To maximize absorption of incident solar radiation and minimize losses from receiver tube, it is coated with a selective coating and surrounded by an anti-reflective evacuated glass tube. Selective coating (multi layer cermet coating) used over receiver tube should have high solar absorptivity and low thermal emissivity. The HCE imbodies conventional glass-to-metal seals or glass to glass seal depending upon the number of glass cover over the receiver tube. It also incorporates the metal bellows to ensure the presence of vacuum in the annulus and compensate for the differences in thermal expansion difference between the steel and glass tubes. The vacuum created in the annulus is typically maintained at about 0.013 Pa to reduce convection losses [47]. Fig. 1.14 [47]shows the diagram of heat collecting element of parabolic trough concen-

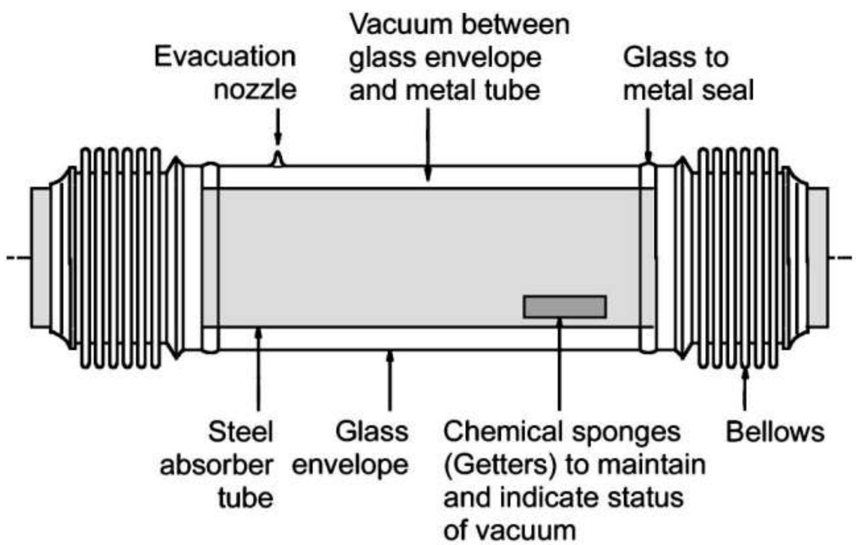

Figure 1.14: Heat collecting element of PTCs[47]

trator. Heat transfer from receiver to ambient without vacuum at the annular space is due to conduction, convection and radiation but when the vacuum is created the the conduction loss vanishes and convection loss are categories into two groups: natural convection $(\geq 1) toor$ and free molecular diffusion $(\leq 1 torr)$.

1.6.2 Heat Transfer Fluid

Heat transfer fluid (HTF) is the working fluid that carry heat from sun and transfer it to the fluid to be heated. It may be solid, liquid or gaseous depending upon the states of matter under normal operating conditions. Becker (1980) [48] studied and explain different potential HTFs for CSP plants on the basis of their thermal and transport properties. Following are the important thermophysical properties of heat transfer fluid for better performance of receiver system [49]:

- Evaporation temperature or thermal stability limit should be high at low pressures
- Solidification temperature should be low
- Less viscous→ so that pumping power requirements can be low

- High value of thermal conductivity →receiver temperature should be closer to the temperature of heat transfer fluid
- No environmental hazard
- It can be probably used as working fluid
- Low toxicity
- Low cost and high availability
- Low flammability
- Low corrosivity →should be chemically stable when it is in contact with materials
- Lowc explosivity and
- High density and heat capacity → so that it can be able to use as storage medium

The selection of the heat transfer fluid depends upon the temperature that would be achieved at the focal line and the storage system used in the PTCs to store heat energy from the sun. In the present thesis, liquid heat transfer fluid ,thermal oil is used. Thermal oils are used in PTC plants whenever the temperature is greater than 200^oC. Water is generally not used as working fluid because it would produce high pressures inside the receiver tube and piping. Use of water creates the phenomenon of corrosion thereby damaging the receiver tube. At present, Biphenyl-diphenyl-oxide, known by trade names Therminol VP-1 [50] and Dowtherm A [51] are widely used as a heat transfer fluid to convert sun energy into thermal energy. It shows excellent stability comparison to other HTFs. Although it is flammable but requirement related to safety and environmental protection can be satisfied with reasonable effort.

1.6.3 Structure, Mirrors and Glass Cover

PTCs mainly consist of reflector and receiver tube surrounded by glass cover. Solar radiation incident on aperture reflected specularly to the glass cover and finally absorbed by receiver. There are two types of reflection: specular and diffuse. Specular reflection is possible on smooth and policed surface like mirror. In rough or unpolished surfaces, the angle of incidence is not equal to the angle of reflection. For better utilization of solar energy, the concentrating collector should have high specular reflectance. Specular reflectance greater than 88% is assumed to be better reflector to reflect as much solar radiation as possible. The mirrors used in the reflector are commonly silvered on the back side and set permanently on the frame. It is covered with various selective coatings so that their durability and solar reflectance can be better than that of the polished aluminium and metallized acrylic available in the market. Solar reflectance of silvered glass mirrors (0.93) is greater than that of the polished aluminium (0.87) [40]. The support structure of the parabolic reflector is made up of steel with pylons foundation. Ceramic pads are used to mount the mirrors to the structure of collector and attached with an adhesive. The net performance of parabolic trough plant also depends on the mountings and installation of the support structure. The support structure should have the following basic structural requirements [52]:

- **Stiffness:** The structure should be robust. It contains a rigid frame and capable to maintain exact geometry (optical precision) at all times: The PTCs should be strong enough to withstand deformations caused by collector weight, wind pressure and the temperature differences between ambient and the receiver.

- **Weight:** Low weight reduces material and transportation cost.

- **Motion**: PTCs should have a high angular tolerance to enable one-axis tracking requirements. The tracking mechanism of the collector must be accurate, robust and sufficiently strong sothat it has the capability to operate even under extreme weather conditions.

The glass cover over receiver tube certainly adds more to the performance of collectors. It allows sunlight of smaller wavelength to pass through to the absorber but insulate the radiation of higher wavelength radiated by the absorber tube [53]. As per PTCs requirement, a high transmittance glazing material is needed in order to reduce heat loss. Cover material permeates to pass only the visible light not the infrared or UV part of the light

[54]. At present mainly used cover materials are:

- Toughened glass
- Acrylic methyl esters
- Glass steels
- Low iron rate glass

Among above all, low iron rate glass is widely used due to its high transmittance (greater than 90%). But in our experimental setup Borosilicate glass was used that belongs to the low iron rate glass. It can withstand a temperature of about $550^{O}C$.

1.7 Analysis of Parabolic Trough Collector

1.7.1 Basic Terminology and Derivation

- **Aperture area**(A_a)**:** It is the area in which solar radiations enters collector. It may be defined by the physical extremities of the concentrator [55].

- **Absorber area**(A_r)**:** It is the total surface area of the absorber in which the thermic fluid flows. It may be of cylindrical or helical coil shape. It is the heart of collector system through which the solar energy is converted into thermal energy [55].

- **Concentration ratio** (CR)**:** It measures how many times the intensity of solar radiation was incident on receiver after reflection from the collector's aperture. It can be defined in two ways: first is geometric concentration ratio or area concentration ratio which is equal to the ratio of aperture area to the receiver area i.e. $CR_g = \frac{A_a}{A_r}$. Second one is optical concentration ratio which denotes the ratio of intensity of solar radiation at the receiver to the intensity of solar radiation on the aperture i.e. $CR_o = \frac{1/A_r \int I_r dA_r}{A_a}$ [56, 57]. For simple FPC, $CR = 1$, but for concentator $CR \geq 1$.Concentration ratio depends on the tracking system that has been incorporated with the system. The concentrator without tracking have minimum concentration ratio while for single or double axix tracking unit the value of concentration

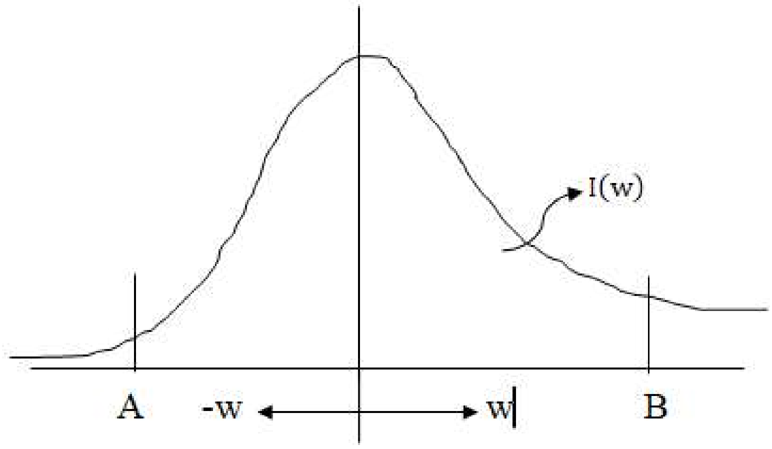

Figure 1.15: Flux distribution in the plane of linear focusing concentrator extended from A to B [59]

ratio is significantly larger. For single axis and double axis tracking system, the maximum possible values of concentration ratio will be [58]:

$$CR_{single\,axis} = \frac{1}{\sin(\frac{\alpha_D}{2})}$$

$$CR_{double\,axis} = \frac{1}{\sin^2(\frac{\alpha_D}{2})}$$

where, $\alpha_D$is the sun beam angle whose value is equal to 0.53^oor $32'$.

- Intercept factor(γ): It is defined as the ratio of the energy intercepted by the receiver to the energy reflected by the focusing device (concentrator). Its value depends on the size of the receiver, the surface angle errors of the parabolic mirror, and solar beam spread. Values of γ greater than 0.9 are common. Intercept factor can be explain by the figure 1.15 [59].

$$\gamma = \frac{\int_A^B I(w)dw}{\int_{-\infty}^{+\infty} I(w)dw}$$

Before going to derive the expression for collection efficiency or thermal efficiency and optical efficiency, the concept of different types of losses are important to know. There are two kinds of losses occurring in concentrator named as optical losses and thermal losses [60].

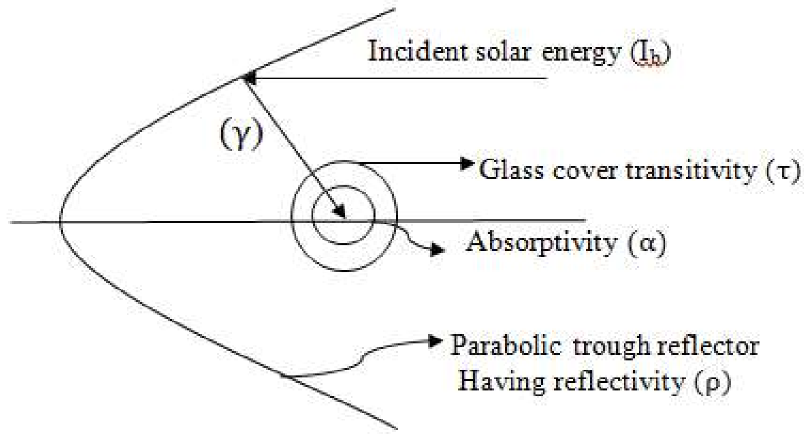

Figure 1.16: Optical parameters of parabolic trough concentrator

- **Optical losses:** The losses which occurs in the path of the incident solar radiation before it is absorbed by the receiver tube are called as the optical losses.

- **Thermal losses:** These losses occurs in the form of conduction, convection & radiation. In conduction loss, it occurs at the supporting structure while conduction and convection losses occur at the receiver tube as shown in figure 1.16.

- **Conductive losses:** It is due to heat transfer which takes place through adjacent surface by conduction

- **Convective losses:** It is due to heat loss which is carried away by some medium like air, can be minimized by closing all air gaps.

- **Radiative losses:** Radiative losses occur at all temperatures can be prevented by the use of spectrally selective absorber coatings.

Rate of useful energy per unit aperture area can be calculated using the equation 1.9 [61, 55].

$$q_u = q_{absorbed} + q_{loss} \tag{1.9}$$

where $q_{absorbed} = S$ and $q_{loss} = U_l\,(T_r - T_a)$

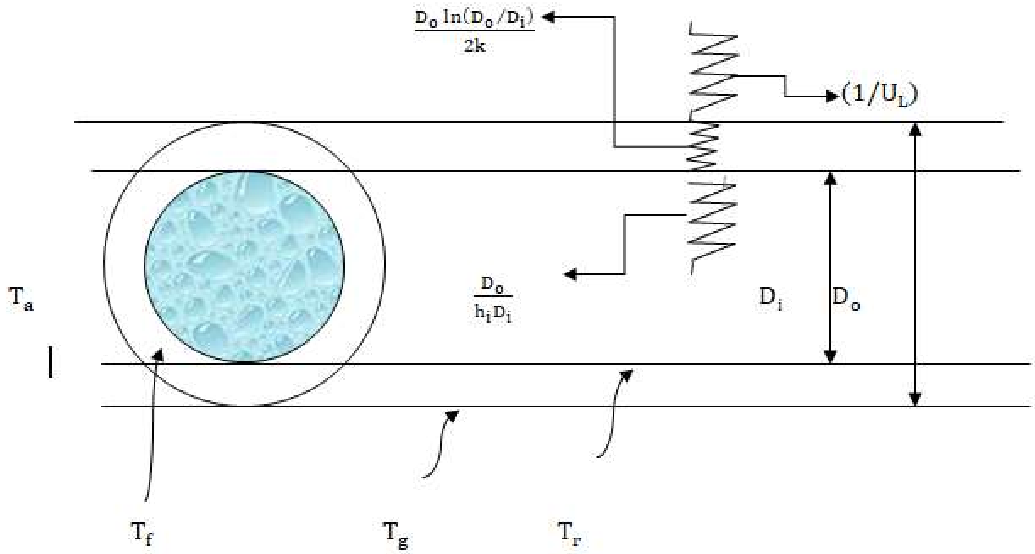

Figure 1.17: Practical understanding of various heat transfer coefficient

so

$$q_u = S + U_L (T_r - T_a) \tag{1.10}$$

and it can be writen as the total useful energy

$$Q_u = A_a S - A_r U_L (T_r - T_a) \tag{1.11}$$

Overall heat transfer coefficient can be calculated as [57]

$$\frac{1}{U_o} = \left[\frac{1}{U_L} + \frac{D_o}{h_l D_l} + \frac{D_o \ln(D_o/D_l)}{2k} \right] \tag{1.12}$$

As it is known,

$$q_u^{'} = \frac{Q_u}{L} = \frac{A_a S - A_r (T_r - T_a)}{L} \tag{1.13}$$

Useful energy gain per unit collector length ($q_u^{'}$) can be expressed as energy transfer to the fluid at local fluid temperature T_t

$$q_u^{'} = \frac{Q_u}{L}$$

$$Q_u = q_u \times A_r \tag{1.14}$$

$$Q_u = \frac{temperature\,difference\;(T_r - T_t)}{resistance} \tag{1.15}$$

$$Resistance\,between\,absorber\,and\,heat\,transfer\,fluid = \left[\frac{D_o}{h_o D_l} + \frac{D_o \ln(D_o/D_l)}{2k}\right]$$

$$Q_u = \frac{\left[T_r - T_f\right]}{\frac{D_o}{h_l D} + \frac{D_o \ln(D_o/D_l)}{2k}} \times A_r \tag{1.16}$$

$$q_u^{'} = \frac{\frac{\left[T_r - T_f\right]}{\frac{D_o}{h_l D} + \frac{D_o \ln(D_o/D_l)}{2k}} \times A_r}{L} \tag{1.17}$$

$$q_u^{'} = \frac{(A_r/L)\left[T_r - T_f\right]}{\frac{D_o}{h_l D} + \frac{D_o \ln(D_o/D_l)}{2k}} \tag{1.18}$$

Collector efficiency factor (F') is defined as the ratio of resistance from receiver to the ambient $(\frac{1}{U_L})$ to the resistance from fluid to the ambient $(\frac{1}{U_o})$.

$$F' = \frac{U_o}{U_L} \tag{1.19}$$

$$F' = \frac{1/U_L}{\left[\frac{1}{U_L} + \frac{D_o}{h_l D_l} + \frac{D_o \ln(D_o/D_l)}{2k}\right]} \tag{1.20}$$

Theoretically, collector efficiency factor is defined by the set of equations mentioned below [62].

$$F' = \frac{Actual\,energy\,gain\,by\,collector}{Energy\,that\,would\,be\,gain\,if\,the\,collector\,was\,at\,local\,fluid\,temperature}$$

$$F' = \frac{Q_u}{A_a S - A_r U_L \left(T_f - T_a\right)} \tag{1.21}$$

$$Q_u = F' \left[A_a S - A_r U_L \left(T_f - T_a\right)\right] \tag{1.22}$$

$$Q_u = F' \times A_a \left[S - \frac{A_r}{A_a} U_L \left(T_f - T_a\right)\right] \tag{1.23}$$

$$Q_u = F' \times A_a \left[S - \frac{1}{CR} U_L \left(T_f - T_a\right)\right] \tag{1.24}$$

So, absorbed solar radiation per unit length of receiver is given by :

$$q'_u = \frac{Q_u}{L} = \frac{F' \times A_a \left[S - \frac{1}{CR} U_L \left(T_f - T_a\right)\right]}{L} \tag{1.25}$$

And rate of useful energy per unit aperture area is given by the eq.

$$q_u = F' \left[S - \frac{1}{CR} U_L \left(T_f - T_a\right)\right] \tag{1.26}$$

Now theoretically, heat removal factor (F_R) is defined as

$$F_R = \frac{Actual\,energy\,gain\,by\,collector}{Energy\,that\,would\,be\,gained\,if\,the\,entire\,collector\,is\,at\,fluid\,inlet\,temperature}$$

$$F_R = \frac{Q_u}{A_a S - A_r U_L \left(T_{fi} - T_a\right)} \tag{1.27}$$

The same equation can be used to find out the useful energy gained in terms of concentration ratio and heat removal factor:

$$Q_u = F_R \times A_a \left[S - \frac{1}{CR} U_L \left(T_{fi} - T_a\right)\right] \tag{1.28}$$

So, absorbed solar radiation per unit length of receiver is given by:

$$q'_u = \frac{F_R \times A_a \left[S - \frac{1}{CR} U_L \left(T_{fi} - T_a\right)\right]}{L} \tag{1.29}$$

And the rate of useful energy per unit aperture area is given by:

$$q_u = F_R \left[S - \frac{1}{CR} U_L \left(T_{fi} - T_a \right) \right] \tag{1.30}$$

Now as it can be found out the collector efficiency(η_{th}):

$$\eta_{th} = \frac{useful\,energy\,gain\,per\,unit\,aperture\,area}{Beam\,solar\,radiation\,intensity}$$

$$\eta_{th} = \frac{F' \left[S - \frac{1}{CR} U_L \left(T_f - T_a \right) \right]}{I_b} \tag{1.31}$$

Hence, the expresssion for thermal efficiency can be rewritten in terms of collector efficiency factor as:

$$\eta_{th} = F' \left[\frac{S}{I_b} - \frac{1}{I_b \times CR} U_L \left(T_f - T_a \right) \right] \tag{1.32}$$

Thermal efficiency in terms of heat removal factor or interms of fluid inlet temperature can be written as:

$$\eta_{th} = F_R \left[\frac{S}{I_b} - \frac{1}{I_b \times CR} U_L \left(T_{fi} - T_a \right) \right] \tag{1.33}$$

Optical efficiency(η_o) is given by:

$$\eta_o = \frac{S}{I_b} \tag{1.34}$$

Hence, the above equation for thermal efficiency(η_{th}) can be wtitten in ierms of optical efficiency(η_o)as:

$$\eta_{th} = F' \left[\eta_o - \frac{1}{I_b \times CR} U_L \left(T_f - T_a \right) \right] \tag{1.35}$$

$$\eta_{th} = F_R \left[\eta_{th} - \frac{1}{I_b \times CR} U_L \left(T_{fi} - T_a \right) \right] \tag{1.36}$$

Here, the relationship between heat removal factor (F_R) and collector efficiency

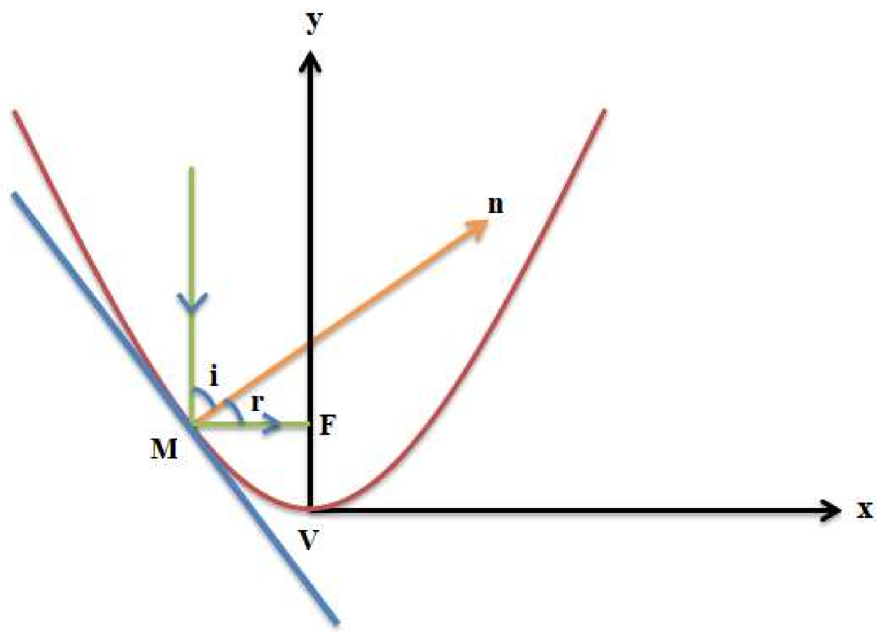

Figure 1.18: Design specification of parabolic mirror reflector

factor (F') is given by [62]

$$F_R = \frac{m \dot{\times} c_p}{A_r \times U_L} \left[1 - exp\left(-\frac{A_r U_L F'}{\dot{m} c_p}\right)\right] \quad (1.37)$$

and

$$F_R = \frac{m \dot{\times} c_p}{A_r \times U_L} \left[1 - exp\left(-\frac{A_r U_o}{\dot{m} c_p}\right)\right] \quad (1.38)$$

1.7.2 Design and Construction Details

A mirror of parabolic dish or trough geometry reflects the incoming solar radiation parallel to the axis of parabola to at its focus (line or point). Concentrator is constructed in parabolic mirror shape on the basis of this property with the receiver placed at its focus. The aperture of a parabolic trough system should be kept in agreement with the state of sun so that it can reflect the incoming beam radiation to the receiver tube. Whenever, there are talking about the concentrator, a significant parameter comes into play so called concentration ratio which can be defined as the ratio of aperture area to the receiver area. Higher concentration ratio accounts for the higher working temperature. Design specification and schematics of parabola has been shown in figure 1.18.

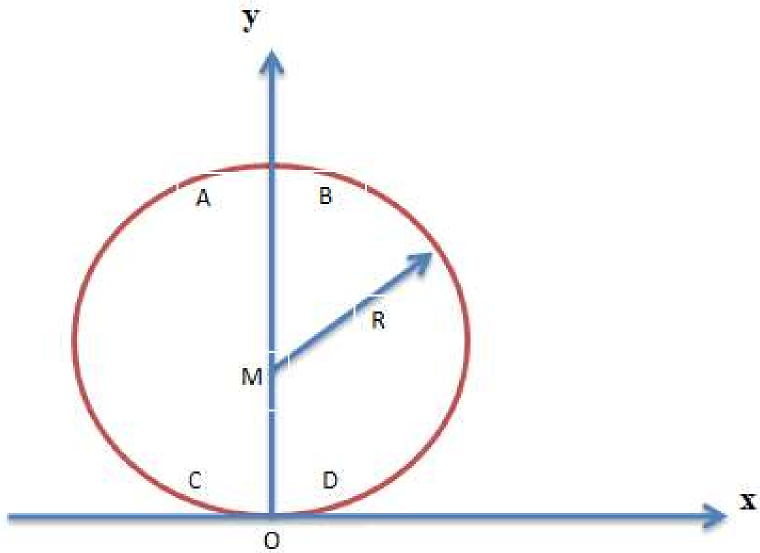

Figure 1.19: Extended arc of parabola

A parabola can be made with a small arc of circle. The arc is assume to be a part of the circle of R. The equation of the arc must be same as the equation of the circle with centre (0, R) as shown in figure 1.19.

Equation of circle with centre (0, R) and radius R can be written as eq.

$$x^2 + (y-R)^2 = R^2 \tag{1.39}$$

$$y = \pm R\left[1 - \frac{x^2}{R^2}\right]^{\frac{1}{2}} + R \tag{1.40}$$

For segments of circle with a very small surface area i.e. $\frac{x^2}{R^2} \leq 1$it can be written the following equation

$$\left[1 - \frac{x^2}{R^2}\right]^{\frac{1}{2}} = 1 - \frac{x^2}{2R^2} \tag{1.41}$$

$$y = \pm R\left[1 - \frac{x^2}{2R^2}\right] + R \tag{1.42}$$

The above eq. 1.42 holds good for both the arc AB and CD. Here, considering the lower arc CD of the circle it get the following equation:

$$y = \frac{x^2}{2R} \tag{1.43}$$

The equation of parabola with vertex (0, 0) and focal length f can be written as:

$$y = \frac{x^2}{4f} \tag{1.44}$$

From eq. 1.43 and eq. 1.44, it is clear that eq. 1.43 represents the parabola with $f = R/2$. Any mirror segment, which satisfies the condition $x^2/R^2 < 1$ can be used as a parabolic concentrator.

1.8 Solar Energy Storage

In the present scenario when the demand is more than resources available, it's our necessity to develop an energy storage device to store energy at the time of availability and supply it whenever demand is more than available. Although Sensible heat storage is the most common method of thermal energy storage, but the recent research on advance material and system shows that density of stored energy is greater for latent heat storage than that of sensible heat storage [63, 64, 65, 66]. Phase change material is generally used in latent heat storage system and this type of system has been widely used for heat pumps, solar engineering, and spacecraft thermal control applications [67]. Sharp increase in the price of fossil fuel and continuous upgrading in the level of greenhouse gas emissions are the main driving forces behind the effective utilization non conventional energy resources. The storage of energy in suitable forms, conveniently converted into the required form, is a present day challenge to the technologists. Solar energy storage unit has the following characteristics: (a) to conserve energy (b) to improve the performance and reliability of energy systems and (c) to reduce the mismatch between supply and demand. Scientists in many parts of the world are in search of new and renewable energy resources and stated that direct solar radiation is a prospective renewable source of energy and the solar energy storage unit is the new source of energy. In other words solar energy storage unit can be called as the sub renewable sources of energy [68, 69]. There are various kinds of phase change materials like paraffin wax, fatty acids, lauric acid etc. but paraffin has been widely used for latent heat thermal energy storage system because of their large latent heat and

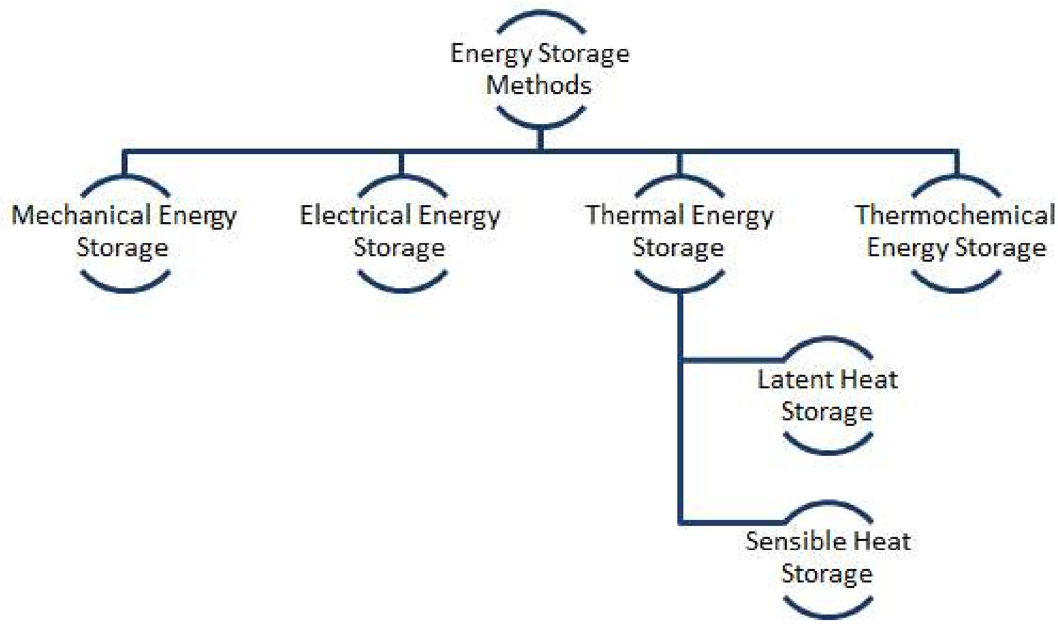

Figure 1.20: Methods to store different types of energy [69]

enhanced thermophysical properties such as no super cooling, low vapor pressure, good thermal and chemical stability and self nucleating behaviour [70, 71, 72, 73].

1.8.1 Energy Storage Methods

There are various forms of energies and their storage methods or mechanisms have been described below. Atul Sharma et al. [67] describes in their review paper on, thermal energy storage with phase change materials and applications, about different type of energy storage methods and their mechanisms as shown in figure 1.20.

1.8.1.1 Mechanical Energy Storage

Mechanical energy storage systems include the storage due to gravitation as for example hydropower storage, storage due to pressure difference, compressed air energy storage and storage due to inertia, flywheels. Hydropower storage and compressed air energy storage can be used for large scale utility of energy while flywheels are more suitable for intermediate storage. Storage is carried out when off-peak power is available and the storage is discharged when power is needed because of insufficient supply from the baseload plant.

1.8.1.2 Electrical Energy Storage

Electrical energy is stored through batteries. When the battery is connected to the direct electric current then ionic reactions happens where the positive and negative ions are separated and hence chemical potentials are formed. At the time when the main supply disappears, this chemical energy is converted into electrical energy. The most common type of storage batteries is the lead acid and *Ni–Cd*. Potential applications of batteries are utilization of offpeak power, load leveling, and storage of electrical energy generated by wind turbine or photovoltaic plants.

1.8.1.3 Thermo Chemical Energy Storage

Sharma et al. [67] said that charging and discharging phenomenon takes place during the breaking and reforming of molecular bonds in a complete reversible chemical reaction. In this case heat stored depends upon the amount of storage material, the endothermic heat of reaction, and the extent of conversion.

Above discussed thermal energy storage technique, latent heat storage technique is one of the best suitable technique because of its high energy storage density and its characteristics to store heat at constant temperature called phase transition temperature of phase change material. Phase change can be in the following form: solid-solid, solid-liquid, solid-gas, and liquid-gas and vice versa.

Solid-Solid transition

- Change in crystalline structure
- Small change in volume
- smaller storage capacity than solid liquid transition
- Less containment required and greater design flexibility

Most preferable materials for solid-solid phase transition are organic solid solution of the followings whose characteristics, melting points and latent heats of fusion are tabulated below.

Solid-gas or liquid gas transition

- Higher latent heat of phase transition
- Larger volume changes on phase transition
- Larger containment required
- Impractical and complex system

Solid-liquid transition

- Intermediate latent heat of phase transition, volume change
- Most practical and economical system

1.8.1.4 Thermal Energy Storage

Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent heat or thermochemical or combination of these. Sensible heat storage is due to temperature change of material while latent heat storage is due to the phase transformation either it is solid-liquid, liquid-gas or solid-solid. Different types of thermal energy storage of solar energy are shown in figure 1.21.

- Sensible heat storage

In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. SHS system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of the medium, the temperature change and the amount of storage material. Water appears to be the best SHS liquid available because it is inexpensive and has a high specific heat. However above 100^oC, oils, molten salts and liquid

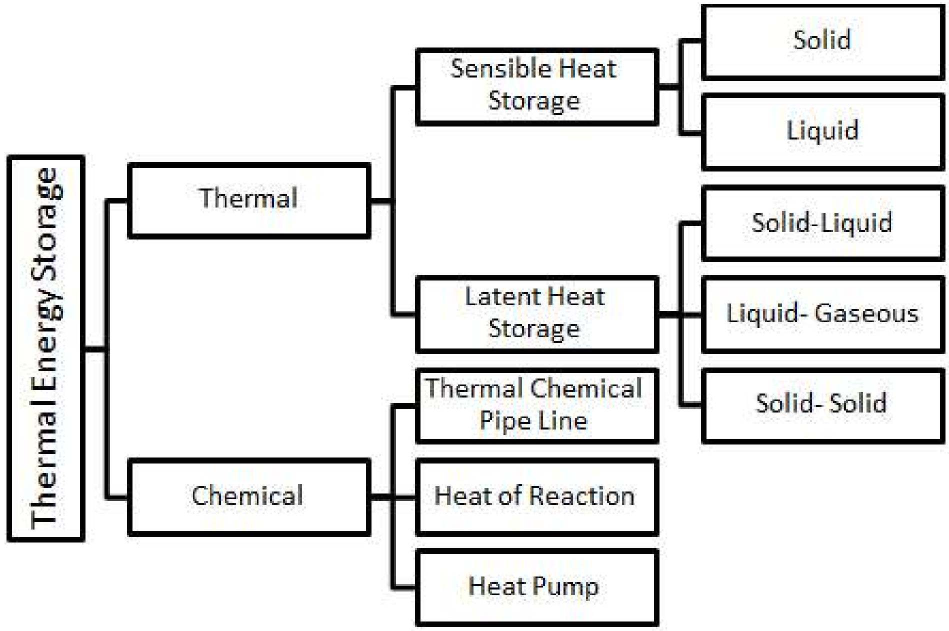

Figure 1.21: Different methods of thermal energy storage [76]

metals, etc. are used. For air heating applications rock bed type storage materials are used [74].

- Latent heat storage

In latent heat storage system charging and discharging phenomenon occur when the storage material undergoes phase change either from solid to liquid, liquid to gaseous or solid to solid. The storage capacity of latent heat storage system with a PCM medium is given by the following equations [74].

1.9 Solar Collector Applications

Following are the applications of solar collector systems [57]:

- Solar water heating systems
- Solar space heating and cooling
- Solar refrigeration & solar air conditioning system
- Industrial process heating application

- Solar desalination for water purification
- Solar thermal power application
- Solar furnaces for highest heating application and
- Solar chemistry applications for power generation
- Solar dryer to get dried grain
- Others

This is all about the introduction that supports the basics of our research work. The problem identification, research objectives, scope and methodology of research have been mentioned in chapter-2.