1
Introduction

1.1 Motivation of work

One of the biggest challenges that the modern world face is that of minimizing, if not nullifying, the use of fossil fuels from daily and the industrial ways of work [1-5]. The use of fossil fuel for energy generation leads to increase in concentration of CO_2 in the atmosphere and it is estimated that a global temperature increase of 2°C [6] with a probability of 67% [7] the CO_2 concentration has to be limited at 450 ppm by 2050. Now, as the requirement of energy increases every year, it is necessary to hunt for ways of energy generation which are non- replenishing and free from environmental damages. Various renewable sources like Solar (Photovoltaic and Solar Thermal), Wind energy and Tidal energy could be harvested to meet the energy demand

As a source of energy, Sun is nearly inexhaustible and offers a pollutant free alternative to fossil fuels. The rate in which energy from the sun is received on the earth's atmosphere is 5.4 x 10^{24} J/year or 170 trillion kW, which may be estimated as 27,000 times the amount of energy produced by all possible man-made means across the world as of today. Improving the utilization and increasing their efficiency of Solar Energy will play a key role in the domain of renewable energy.

The concept of solar concentration was known to the ancient Greeks as used a *burning mirror* to enlighten the Olympic flame. Later on, in the 15th century, Leonardo da Vinci proposed a technique to weld copper using concentrated solar radiation and much later, in the 18th century first prototypes of parabolic dish concentrators was introduced to generate steam. In the 19^{th} century, oil and natural gas were extensively used as fuels. In the early 1970s, at the time of the first oil crisis, solar concentration research started in several industrialized countries. And the first high temperature commercial solar power tower systems started to operate around ~ 30 years ago in California, USA.

This work was encouraged by the usage of Concentrated Solar Thermal Energy generation which may be used for further generation of electricity.

1.2 Photovoltaic and Solar Thermal

The harvesting of Solar Energy, broadly speaking may be classified into Photovoltaic (PV) and the Solar Thermal (ST) [1]. In PV absorption of photons and its conversion directly into electricity, while in ST deals with trapping of heat of solar radiation and converts that heat into electricity. ST uses the concept of concentration of solar radiation to generate heat to run steam turbine which is further used in large scale power plants for generation of electricity for powering the city–level necessities. Geographical positions with high solar irradiation for major duration of the year are proposed for ST. A major difference between these two forms of energy is that in case of ST the entire solar spectrum is considered for work while in case of PV systems uses the approach of a wavelength dependent bands of its operation.

1.3 Solar thermal and other renewable sources of energy

Solar Power (ST and PV combined) stand as the third biggest renewable power source in the world. Global ST capacity, by the end of 2018 reached 5.5 GW and increasing. In the international scenario, Spain has maximum share of the CSP power generations with more than 75% of the global CSP capacity [2].

One of the interesting work in this field would be hybrid manner to unitize the land where the field area on ground filled with heliostat mirrors, along with PV may be installed.

1.4 Concentrated Solar Power (CSP)

The concept of CSP is known for many centuries as per available literature [1-5]. Parabolic Trough (mentioned in section 3.2.1.1) based CSP technology was initially developed by Egypt in the second decade of twentieth century. In modern times, the concept of CSP was known and used over the last six decades. Along with Parabolic Trough (PT), Linear Fresnel Reflector, Heliostat Field with central receiver systems and Schiffler Dish were used as primary concentrators in CSP [5]. As on December 2019, there were 68 CSP plants installed worldwide, totaling 6.210 GW. A large number of CSP based power plants are installed in countries like Spain and U. S. A.

However, as an independent technological development, CSP was developed in the first decade of twenty first century. Spain took an initiative in this regard where in 2004, Planta Solar 10 (detail given in table below) near Sevelli was constructed and was commissioned in 2007 [8] and in 2017 it recorded turbine capacity of 11 MW [3]. Countries like Morocco, United States, Spain, China , South Africa etc., took a lead role in this regard.

Heliostat field design is non-trivial as it involves two-axis tracking, positioning of heliostats in a given field, selection of the height of the tower and optimization of the heliostat field for a given land area. We briefly discuss some of the challenging investigations carried out in the domain of heliostat filed design. One of initial work towards optimized heliostat field by cell wise were done by Vant-Hull (1975) [9] for large heliostat field with central receiver systems. Collado and Turegano (1989) [10] presented a procedure for evaluating the annual energy produced by a defined heliostat field as a product of annual energy per mirror and annual average mirrors per unit area. They discussed an analytical function for the blocking factor as one of the main parameters in their optimization process using a radial staggered configuration. Pitz-Paal et. al [11] discussed layout of the heliostat field of solar tower systems was optimized for maximum annual solar-to-chemical energy conversion efficiency in high-temperature thermochemical processes for solar fuels production. They have optimized algorithm which is based on the performance function that includes heliostat characteristics, secondary optics, and chemical receiver–reactor characteristics at representative time steps for evaluating the annual fuel production rates. Talebizadeh *et. al.* [12] showed that increase in efficiency of heliostat field can be achieved by incorporating genetic algorithms optimization method. Siala and Elayeb (2001) introduced a graphical method for a no blocking radial staggered layout and introduced a mathematical formulation for the method [13]. They divided the field into certain groups to increase the efficient use of land and also, the procedure was simple as compared cell-wise method. Recently, L. Li et. al. [14] developed an in-house Monte-Carlo ray-tracing model based on a simplified receiver heat transfer model along with compound parabolic collector (CPC) and a cost model based on the System Advisor Model (SAM). An experimental plant in UAE was implemented with 100 kW_{th} using Concentrated Solar Beam-Down Optical Experiment was reported by Marwan Mokhtar [15], wherein the heliostats implemented using canting method. The central tower with reflector having hyperboloid geometry kept at a height of 16 meter was used to reflect the converging rays from the heliostat onto a receiver at ground.

Additional challenges in the design of heliostat field arises from the determination of Solar position and it is it is of utmost importance to generate the most precise and best possible solar angular positions. Tracking of the solar position throughout the day and year is necessary for placing and accordingly generating a two/one dimension tilt on the Solar collectors. The tracking strategy is based on date of year and time of operation and uses computer controlled mechanism to generate solar coordinates and the collector tilt [16]. There are several Sun position calculation algorithms mentioned in the literature [17–18]. These algorithms have applications in solar energy (not only for solar tracing as in CSP, but, also for irradiance measurement instruments and other solar design software. As per literature, the required accuracy for this calculation varies over a range, depending on the application: flat/curved systems tolerate errors of a few degrees with minimal losses while high-concentration systems may require accuracy of the order of 0.01 [19]. Input data inserted was which no. of day of the year is concerned (for declination angle), time of operation and Longitude of the geographic location(for Equation of time and Hour angle), latitude of the geographic location of the place (Altitude/Zenith and Azimuth angle). As the entire work is performed by control systems, the computational complexity of the algorithms is an especially delicate issue. A reduced complexity allows the algorithms to be employed on simple and cheap control systems, even for single elements of the solar field, thus reducing the cost and the chance of error. Although the first work in this regard presented these algorithms as a simple step calculation for incident solar irradiance [20] in 1968, importance of this work in the precision of the irradiance estimation, led the scientific community to deepen on this field and further research was focused on calculating the Sun position. In 1988, an algorithm was adapted from *The Astronomical Almanac* with an accuracy of 0.010 between the years 1950 and 2050 [21]. It calculates solar declination, right ascension, hour angle, azimuth, elevation, equation of time, angle of incidence on a horizontal surface, and atmospheric refraction corrections. The National

Oceanic and Atmospheric Administration (NOAA) is an US agency and its website provides Solar Calculator [22] in a public domain, where the calculations of the Sun position (Zenith, Azimuth etc.) is based on the equations of the Astronomical Algorithms [23].

In addition to the design of heliostat field design and choice of the receiver plays a critical role depending upon the amount of concentration achieved in a given solar field. Further, the efficiency of the receiver plays an important role the overall efficiency of the solar thermal power plants. The receivers employed in solar fields converts solar energy into thermal energy which is a thermal conversion process and it is widely known as heat transfer. As the solar radiation absorbed at the surface of the receiver, which is in contact with flowing fluid as it passes through it by an appropriate mechanism. While the receiver heats up due to incident solar radiation, the heat is transferred to working fluid which may be oil, water, air and salt. It is challenging to design a receiver wherein extraction of energy with an efficient process with high temperature and it is a challenging as well as complicated task. The selection of receivers depends on the concentration available due to the optical concentrators in the chosen solar field. A detail review of various volumetric receivers was discussed by Ávila-Marín [24] related to solar thermal power plants with central receiver system technology. Ho and Iverson investigated and reviewed central receiver designs which can be operated at high-temperature for concentrating solar power plant applications [25]. Menigault et. al. [26] and Variot et al. [27] have shown by reducing radiative losses thermal efficiencies of near 90% could be attained. Further by introducing nano-sized particles in high-temperature fluids (HTF), observed higher efficiencies were reported by [28].

Han et al. presented paper on Design of 1 MW Heliostat based solar thermal power plant [29]. The aim of the plant is to investigate and optimize thermal performance of receiver. Radosevich and Skin rood presented power plant performance of Solar One [30], pilot plant of USA. They concluded that the plant provided important lessons for design and operation of future solar heliostat plant. Liao et al. discussed about maximum allowable heat flux absorbed by receiver of solar heliostat field plant [31]. The work stated that life-time and economics of receiver highly depends on heat flux falling on receiver. This work concluded that good design of receiver should have small and thin tubes. Rodríguez-Sánchez gave guidelines for thermal design of receiver of solar heliostat plant [32]. They concluded that limiting parameter for receiver design is wall temperature. Small diameter tubes result in low wall temperature however the pressure drop increases because of this. Behar et al. reviewed studies available on receiver of solar heliostat plants [33]. The review concluded that though solar thermal technology reached the commercialized state, it still requires lots of activity to improve its performance. Qaisrani et al. evaluated the thermal losses of an external receiver in windy conditions [34]. Wind blocking walls suggested to reduced heat losses up to 33%. The performance of wall is analysed for different wind velocity and directions. A detailed review of optics of solar central receiver systems were compiled by John Pye, and Wojciech Lipiński [35].

Various optical simulation has been widely used to investigate the central receiver system. A comparison of different software tools were discussed by Ho in his report [36]. Additionally, SolTrace is closed-source proprietary software owned and developed by NREL, being freely available at [37]. These software aims to provide a suitable tool to model CSP systems and analyze their optical behavior. A fast ray tracing tool to provide precise flux density simulation data for the purpose of entire plant simulations were developed by Belhomme [38]. An overview of ray tracing in the context of CSP were discussed by Dilip and Venkatraj [39]. Jafrancesco et al [40] has compared four difference software tools namely: Tonatiuh, SolTrace, TracePro and CRS4-2 for central receiver systems in their investigation. In this thesis we have investigated heliostat field design using ray tracing software Tracepro .

Following is a list of Solar Power Tower in Operation and under construction [41- 43]

Plant Name	Country	Capacity (Mw)	No.of Heliostats	Heliostat aperture area (sqm)	Tower Height (m)	Land Area (sqm)	Receiver	Heat Tranfer fluid used
Operational								
PS 10	Spain	11	624	120	115	550000	Cavity	Water
PS 20	Spain	20	1255	120	165	8000	Cavity	Water
ASME	India	2.5	14280	1.14	46	46500	Cavity	Water
DAHAN	China	1.5	100	100	118	52000	Cavity	Water
SOLUGAS	Spain	4.6	69	121	75	60000	Cavity	Air
ISGES	USA	392	173500	14.08	140	14170000	External Cavity	
Gemsolar	Spain	19.9	2650	120	140	1950000	External Cavity	Molten Salt
Sierra	USA	5	24360	1.136	55	81000	Dual Cavity External	Water
Jülich	Germany	1.5	2153	8.2	60	80000	Volumetric	Air
Under Construction								
EICE SOLAR	USA	150	17170	62.4	165	5710000	External Cylindrical	Molten Salt
CRESCENT DUNED	USA	110	17170	62.4	165	6490000	External Cylindrical	Molten Salt
KHI SOLAR ONE	South Africa	50	4530	128	200	140000	To be decided	Water
SUPCON SOLAR	China	50	217440	2	80	330000	To be decided	

Table 1.1 : A technical detail of existing and coming up projects

As it is understood from the literature study, the research and consequently the applications of solar tower application are limited and in a nascent stage.

1.5 Software and relevant Codes for Analysis of Concentrating Solar Power Technologies

The unique necessity of the CSP plant for thermal energy generation is twofold. Firstly, Large area of vacant land for the spread on the ground. The economic viability of the CSP plant should be duly analyzed. For this reason, it is thought to develop a model of this work with a predetermined power as a target for designed field. In this regard, the following tools are a useful in estimating various parameters involved in the proposed CSP plants.

A. Heliostat performance

MIRVAL

This was developed in 1979 by Leary and Hankins. It was used to simulates the individual heliostats and also a portion of the receiver. It was designed to calculates the optical performance of well-defined solar thermal central receiver power plant [44,45].

HELIOS

HELIOS was designed to determine the solar flux density by using cone optics. It focusses on analysis of the flux density arising from fields of 1 to 559 individual heliostats or 559 cells containing multiple heliostats [44,45].

NS Code

This software was designed in 1978 by University of Houston and multiple CSP like were performed by NS code developed in 1978 [46]. It was used for evaluating the optical performance of a specified central receiver field with the objective of producing flux maps for external surround, cavity and flat plate types of receivers.

HFLCAL

HFLCAL (Heliostat field layout calculations) software was developed Kiera in 1986 for GAST hybrid concept [46]. Later it was applied to other concepts like Phoebus and others.

B. Receiver performance

CAVITY

CAVITY was a software developed to solve the energy balance equation for a solar cavity receiver [47]. This software is designed to couple the solution of radiation exchange in cavity type receivers together with the conduction convection exchange of the working fluid.

DRAC

DRAC , developed by Sandia National Laboratories (Winter) in 1983 was capable be modelboth transient and steady state thermohydraulic phenomena in solar receiver tubes can If time dependent incident heat flux profiles and flow rate changes are specified, DRAC calculates the resulting transient excursions in tube wall temperature and fluid properties. Any receiver fluid can be modeled for which thermodynamic data exists.

RADSOLVER

RADSOLVER was developed by Sandia National Laboratories to calculate the radiation energy transport in arbitrarily shaped solar cavity receivers, In contrast to the common assumption of gray surfaces used in the modeling of radiation transport, this software accounts for the wavelength dependence of emission and reflection using an arbitrary number of wavelength bands.

C. Entire Plant Performance (Including Heliostat, Receiver, Heat Transfer Fluid, Storage)

DELSOL

DELSOL was developed by Kristler in 1986 for evaluate the performance and design optimization software developed by using FORTRAN 77 [45]. It uses Hermite polynomial expansion/convolution of moments method for predicting images from collectors. Time varying effects of insolation, cosine, shadowing and blocking and spillage along with atmospheric attenuation, mirror reflectivity and receiver absorptive.

SOLERGY

The pilot plant Solar One used design proposals compared by solar central receiver annual energy simulation software STEAC [44]. However, the actual energy produced by the plant was different than the results given by STEAC.

System Advisor Model (SAM)

SAM established a connection between market requirement and research and development effort and how research and development efforts improvements contribute to overall system cost and performance. This software can predict the performance and economics of parabolic trough systems. Central receiver solar thermal power plants simulation is under development along with DELSOL and TRNSYS.

TRaNsient System Simulation (TRNSYS)

TRNSYS software is based on graphical user interface that allows drag and drop construction of the models. Different transient systems can be modeled by using these modular components. Each component represents a physical process or feature in the system and components can be developed as needed to a system model.

Heliostat field layout design (HFLD) with TRNSYS

The modeling and simulation of DAHAN, the 1 MW solar thermal central receiver plant in china is under construction at the foot of The Great Wall near Beijing (Zhihao et.al, 2009). The design and construction of DAHAN will demonstrate the operation of central receiver power plant in China.

1.6 Objective of work

Design and development heliostat based of Concentrated Solar Power [1-5] is a challenging task, as it depends on various parameters like heliostat field, size of heliostat, position of a heliostat in a given location, height of the tower, to name a few. In this thesis, using ray tracing technique, different dimension of heliostats was considered along various distribution of heliostats in a given solar field. Further, two different heliostat configurations were also discussed namely beam-up and beam-down configuration. Additionally, using non-imaging optics introduced between the receiver and secondary reflector, thus increasing higher concentration leading to higher temperature with smaller size of the receiver. By introducing a novel receiver thereby increasing the efficiency of various sub-systems associated with CSP technology. An investigation regarding receiver temperature profile also discussed with the choice of the detectors to monitor it. This method would help its protection from thermal damages due to hot-spots.

The objective of this doctoral work is to establish the feasibility of using solar thermal energy for variety of applications in industry and its related interest. Multiple field designs were performed throughout the day and compared together with possible losses in the heliostat field.

1.7 Justification of work

CSP uses solar resources to generate electricity which produce very low levels of Green House Gases (GHG).It has strong potential to be a key technology for mitigating climate change. In addition, the flexibility of CSP plants enhances energy security.

Unlike solar photovoltaic (PV) technologies, CSP has an inherent capacity to store heat energy for short as well as long periods of time and later conversion to the required form of energy. When combined with thermal storage capacity, CSP plants can continue to produce electricity even when clouds block the sun or after sundown. Thus, CSP plants based on heliostat field ranging from 100 kW to 3 MW optical power outputs were investigated in this thesis using ray tracing techniques. This investigation provides a valuable information about the various parameters that depends on heliostat field for a desired/designed power output.

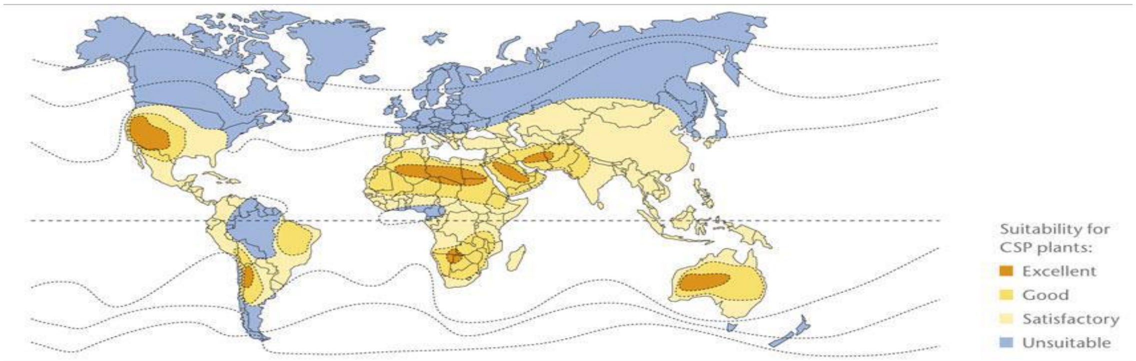

Fig. 1.1Solar resources for CSP technologies [59]

1.8 Solar Thermal Energy generations, the Indian story

Power sector, being one of the key sectors for economic growth of India, needs attention. As per collected data, there is a huge gap existing between the energy generation and consumption. Of the total power generation, currently only 14 % of energy requirement is supplied by renewable sources of which 2% contribution from solar energy. Further, International Energy Agency (IEA) data show that India will become single largest importer of oil, thus contributing to the CO2 emission. Thus, harvesting various forms renewable energy would help in reducing the CO2 emission as well as reducing other polluting resources for energy generation.

1.8.1 National Review

Being a tropical country with Tropic of Cancer (23.5^0N) passing through it , India is blessed with 240-300 days per year of intense Solar irradiation. Because of this, the amount of solar irradiance is 4-7 kWhr of solar energy per square meter per day as an average which lead to 1200-1820 kWhr per square meter per year. It has an annual average of 2300-3200 Hrs of clear sunny time. As an annual average, India's electrical energy may be met with proper harvesting of 3000 km2 which stand as 0.1 % of total land of the country.

The Solar Thermal Research (STR) group at Indian Institute of Technology Bombay, Mumbai led by Prof. Shireesh Kedare have developed various Solar Concentrators [47], namely Arun Dish having reflective area of 50 -160 m^2 and it being implemented by industries. Prof. Rangan Banerjee of IIT Bombay have investigated various aspects of harnessing the solar energy. Prof. Pradip Dutta along with other co-investigators [48] from Indian Institute of Science (IISc), Bangalore are actively involved in the development of Concentrated Solar Power (CSP) for its implementation in storage and its related applications. Prof. T. Sundarajan and Prof. K. S. Reddy of Indian Institute of Technology Madras, Chennai [49]are involved in the development and implementation of Linear Fresnel Reflector (LFR) technology near Chennai. Prof. Kandepal, Centre for Energy Studies, Indian Institute of Technology-New Delhi, New Delhi is very actively involved in the research domain of Solar Thermal Technologies. The SECI (Solar Energy Corporation of India) has involved in the development of technology demonstration plant in collaboration IIT Bombay and implemented it near New Delhi. In recent years, academic institutes like IIT Ropar, IIT Guwahati have taken lead initiative and actively pursuing research in the domain of STR. Further, Ministry of New and Renewable Energy (MNRE), New Delhi is actively pursuing and supporting the research domain of STR through active participation and by funding. Bhabha Atomic Research Centre (BARC), Mumbai under Department of Atomic Energy (DAE), have taken lead initiative in the direction for furthering the technological development in this domain. Even though, various aspects of Concentrated Solar Power (CSP) technology is being currently pursued by the researchers within the country, optical design and development of heliostat field is currently a gap area, which has an immense potential for technological development.

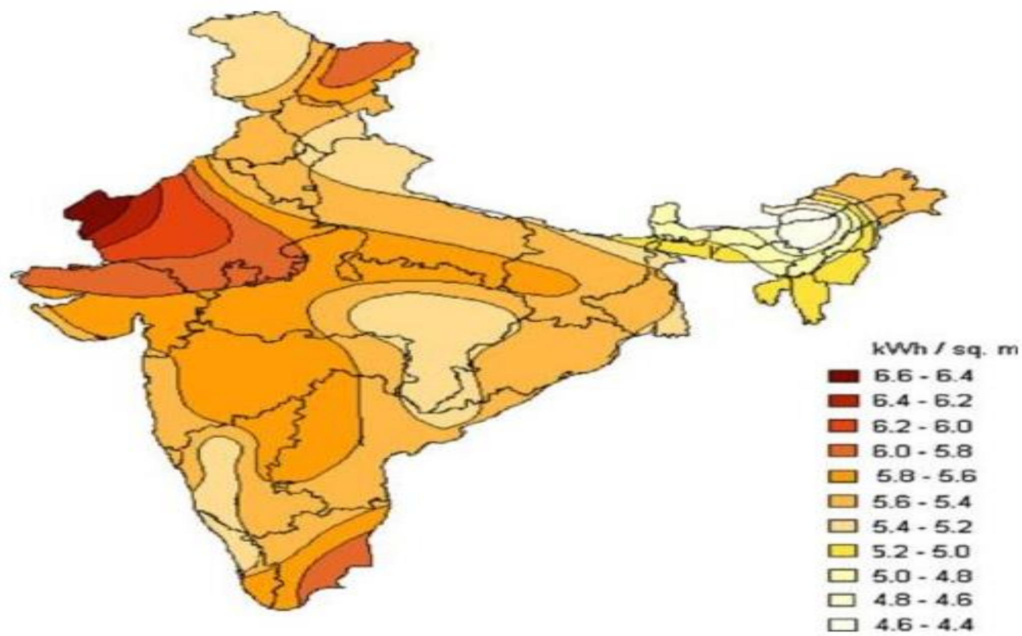

Fig. 1.2 :Solar resources for CSP technologies in India[60]

The above figure is a map representing the Solar irradiance map with an annual average and potential usage of solar energy on various parts of the country. Although Geographical land area is more than 3 million km^2 only 12.5 % of it may be considered for CSP based technology.

The work presented here may be utilized for Micro Small Medium Enterprises (MSME) industries, as they are energy intensive. The energy requirement of these industries can be met by harvesting solar energy based on CSP technologies.

1.9 The research gap areas in the heliostat field design using optical ray tracing approach

Although open literature talks of procedure for field design but there is a lack of information on the details of an optimized field layout. The used software, additionally have indicated the shadow area of the mirrors used, month wise. Likewise being a Monte Carlo ray tracing software, it specifics which area of the field has high shadowing and blocking area by virtue of number of rays trapped in the area.

In the Concentrated Solar Power, heliostat fields wherein large number of mirror collectors (heliostats) are arranged in a given land area along with a Central Receiver Systems (CRS). The incident sunrays are tracked by large-sized heliostats which concentrate the energy flux on radiative/convective heat exchangers called solar receivers that are situated atop a tower where energy is transferred to a working thermal fluid. The available energies in the working thermal fluids are converted into electricity by appropriate mechanism and their by generating power based on Solar Thermal Energy. The tower based heliostat field holds unique advantage due to their higher efficiencies. However, the constrains associated with design and development of development of new solar tower schemes needs to incorporate advanced geometries of solar receivers and heliostats, multi-reflection optics and multi-aiming-point strategies, make it necessary to develop a software tools for the optimization of field layouts and the analysis of their energy performance. The efficiency of a heliostat field depends proportionally on the product of the following factors: cosine, shadowing, blocking, atmospheric attenuation and spillage. Further the additional factors depends on a given heliostat fields are Heliostat spacing, size, number of heliostats, receiver optical height, and receiver length and diameter were all treated as design variables. With thermal energy storage, solar thermal energy is an attractive solution for future power generation [50]. Optimization studies focus on a given heliostat design and seek to optimize the field layout for maximum collection efficiency. Lipps and Van't Hull , who concluded that the overall collection efficiency of staggered heliostat fields is usually higher than that of a cornfield lay-out [9]. Sanchez and Romero [51] suggested the use of a growth based algorithm to design the heliostat field lay-out.

Various software tools (HFLCAL, DELSOL3, CAMPO, SOLTRACE, SAM, SolarPILOT, etc.) have been developed to analyze /optimize either a heliostat field and/or the entire solar thermal plant. Many of these codes are available as freeware, and allow the user greater/lesser freedom of choice in the variables to be optimized. Although some allow user specified field lay-outs, it would appear that their optimization capabilities are currently restricted to radial staggered or cornfield lay-outs. A biomimetic layout, similar to the petals on a sunflower, yields a continuous density function across the entire field. More significantly, it is amenable to mathematical optimization. his has led Noone et al [52] to sacrifice a little on blocking and shading efficiency in return for a higher density layout close to the tower. The overall result is a smaller plant footprint and a more efficient heliostat field.

In additional to the above, heliostat fields with application towards solar thermochemical reactors for fuels production operating at above 1000 K are being designed. The thermochemical reactors based on solar power requires high solar flux densities and high-temperature. Robert Pitz-Paal et. al. designed heliostat fields with 1MW, 10 MW and 100 MW designed power for baseline design parameters [53]. Recently, Besarati and Goswami optimized a biomimetic heliostat field lay-out for a 50 MWt plant at Dagget, California, using maximum field efficiency as target function for a fixed tower height and heliostat size [54]. In addition to the above, SIALA proposed the no-blocking loss radial stagger field layout and derived the mathematical formulations [13]. M. SANCHEZ proposed the methodology for generation of heliostat field layout [51]. In this method, the optimization using iterative algorithm is avoided. The layout with high efficiency can be got directly. The design of the 1 MWe solar tower power plant which will be built in Beijing using the ray tracing calculation and estimated optical efficiency of field. WEI et al. developed the procedure for design and optimization of the heliostat field layout was developed and HFLD code was used [55]. In this, the layout of heliostat satisfies no-blocking loss condition and the heliostats are located at the positions where the annual incident cosine value is higher. We briefly discuss the solar plants with storage in the following paragraph.

Burgelata et al., 2011 have given an overview of the Gemasolar plant, the first commercial tower plant with molten storage [56]. Zunft et al., 2011 have done an experimental evaluation of the storage subsystem and performance calculation of the Jülich Solar Power Tower [57]. They set up a test facility at the plant to monitor performance as well as the storage subsystem of the plant. The results from the analysis carried out affirm that the plant (including the storage system) is functioning to its full capacity. They also confirmed that cycling can be done at high discharge rates of heat transfer accompanied by low heat losses [57]. Koli et al., 2009 have done an analysis of the Jülich Tower plant [58]. Xu et al., 2010 have performed the modelling and simulation of the 1 MW Dahan ST plant [59]. They discuss the generation of response curves for various solar irradiance changes and have shown that the receiver outlet pressure and flow change moderately, regardless of radiation changes. However, the receiver response is more rapid to outlet temperature and power [59]. Quero et al., 2013 have studied the operation experience of the Solugas ST plant, which is the first solar hybrid gas turbine system developed at the MW scale [60]. They concluded that while the plant is operating satisfactorily in its capacity, further modifications like incorporation of storage, turbine improvements and receiver distribution can be incorporated [60]. Tyner et al, 2013 have designed a reference plant using eSolar's modular, scalable molten salt power tower. They proposed a thermal modular design for a plant using these heliostats after performing a detailed risk assessment [61]. Meduri et al., 2010 carried out the performance characterization and operation of eSolar's Sierra Suntower plant [62]. Siva Reddy et al., 2013 have done a review of the various state of the art solar thermal plants worldwide [63]. They have performed a comparative study of the parabolic trough, parabolic dish and solar tower systems in terms of economic viability. Zhang et al., 2013 have performed a review of CSP technologies and talks about the advantage of the power tower technology. They also give a method to estimate the hourly beam radiation flux from available monthly radiation data [64]. M. Romero *et. al*., 2002 have presented a review of the existing central receiver technologies [65].

Further we briefly discuss some of existing solar plants with heliostat mirror area as well as land area. Dahan Power Plant plant is situated in Beijing, China which is is a 1 MW e plant for experimentation and demonstration [59]. It uses 100 heliostats each of 100 m 2 area. Each heliostat has 64 facets. The tower height is 118 m. It uses a cavity receiver with water as the HTF. Solugas Plant located in Spain is 4.6 MW e capacity plant. It is built over a land of area 60000 m 2 [60]. It uses 69 heliostats of 121 m 2 area each. It has a 75 m high tower. France has constructed Themis Solar Tower, which has a capacity of 2 MW e for research and development purposes. It has 201 mirrors to concentrate the solar energy on top of a concrete tower of 101 m height [66]. The Planta Solar 10 (PS 10) plant is the world's first commercial ST plant to be constructed near Seville in Spain [41-43]. The plant uses 55 ha (550000 m 2) of land area with 624 heliostats. Each heliostat has an aperture area of 120 m2 . Jülich Power Tower is designed for 1.5 MWe power with central tower in Germany is an experimental solar thermal plant with central tower of 60m height [41-43]. It uses 2153 heliostats each of 8.2 m 2 area. The heliostats and tower are spread across a land area of 80000 m 2. Planta Solar 20 (PS 20), a tower plant which started operation in 2009 is beside PS 10 at Seville in Spain. It is a 20 MW e capacity plant with a tower 165m high. This plant occupies 80 ha (800000 m 2) of land are and 1255 heliostats with each made up of 120m 2 area [41-43,60]. Sierra Sun Tower solar plant, which is located in Lancaster, California, USA. The 5 MW e capacity project site occupies 8.1 hectares (81000 m 2. It has 24360 heliostats of 1.136m 2 each. It uses a tower height of 55 meter and the heat transfer fluid is HTF used is water [41-43]. Ivanpah Solar Electric Generating Station (ISEGS) This project is a 392 MW e capacity plant in Ivanpah, California. It is a commercial plant which covers 14170000 m^2 with 173500 heliostats, each with an area of 15 m . The tower height is 140 m [41-43]. Thus, most of the existing solar power plants uses large heliostat areas ranging from 80,000 to 20,00,000 m^2 and along with central tower height ranging from 55 meter to 200 meter. In the literature, the central tower with heliostats having small to medium mirror areas are not duly investigated. The small to medium heliostat areas could play significant role for industrial applications and which needs to be explored. In this thesis, we have considered heliostat areas ranging from 800 to 16,000 m^2 which would be beneficial to industries.

1.9.1 General review regarding Solar Thermal Power in India

Mahtta et al. (2014) published a technical note on solar power potential across different states of India. They used remote sensing data and environmental parameters [65]. They have compared district-wise potential for solar photovoltaic and solar thermal power. The study shows that the Rajasthan state has highest potential with total 1571 GW for solar thermal power plants in INDIA. In Rajasthan, Jaisalmer district has solar thermal power potential of 858 GW and Bikaner has 340 GW. Solar thermal power potential for these two districts is more than rest of India. Sharma (2011) presented comprehensive report on solar thermal power in India and world [66]. He told that in present time, solar power is one of the hottest areas in energy investment. He discussed various government policies, incentive and technologies for solar power. He concluded that economically exploitable potential for solar power technology of India is quite high. Pandey et al. (2012) discuss the factors which decisively affect the success for promoting solar energy in Rajasthan, India [67]. Ummadisingu and Soni (2011), discussed different aspect related to solar power in India [68].

1.10 Outline of this thesis

The thesis has been organized chapter-wise to make clarification of work, necessary details, methodology and the findings clear and vivid.

Chapter One **(Introduction)** is an introductory note on the relevance of this work together with motivation and justification of work. The scenario of the world status, especially India is elaborated.

Chapter Two **(Optics, related Thermodynamic, ray tracing and SunShape)** dealswith Earth - Sun geometry and how the Geocentric calculations help in calculating the apparent position of Sun in sky throughout the day and year. Sun, being considered as an source of heat in this work, Thermodynamic basics is dealt with in this chapter. Together with that the necessary ray tracing facts which are used are also elaborated.

Chapter Three (**Concentrating Solar Power (CSP) field, losses and mathematics involved**) deals with the various field setup on the ground for the purpose of CSP. The losses that the radiation faces in their path from the solar source to the receiver and the mathematics of the work are dealt with in this chapter.

Chapter Four (**Heliostat Field Per**form**ances**) deal with the work that was done for the thesis mathematically, simulation wise and otherwise.

Chapter Five (**Temperature profile of the receiver**) deal with the effect of high temperature generated, on the receiver and studies the corresponding hot-spots generated on the receiver.

Appendix, as the name suggests, are a set of work which was done and are written as supplementary to the above chapters.

To develop a fossil fuel free society!