CHAPTER 1

INTRODUCTION

1.1. Background

Against the backdrop of rapidly increasing worldwide population and increasing electricity demand, the development of novel sustainable energy technologies is of prime significance in the effort to reduce CO_2 and other greenhouse gas (GHG) emissions. Moreover, rapid upsurges in the price of oil, coupled with concerns about the stability and security of the extraction of fossil fuels, have led to a renewed curiosity in the development of indigenous energy resources, thus reducing reliance on foreign suppliers.

Energy is considered a key driver in the generation of wealth and an essential factor in a nation's economic growth. Providing sustainable, stable, secure, and reasonably priced energy is crucial for the fruits of economic development and the industry's rapid growth to reach the bottom of the pyramid. Currently, India is the second-fastest developing economy globally, and this strong economic growth would further accelerate the energy demand. India’s need for secure, affordable, and environmentally sustainable energy has become a significant economic development challenge. Therefore, it is of great concern for India to find a way to safeguard energy and environmental sustainability without negotiating its economic and social development (McKinsey and Company 2009). One possible solution to obviate this concern is to find suitable alternatives and plan a changeover to other energy sources that offer the least environmental impact and are accessible in abundant quantities to satisfy demand and guarantee the security of energy supplies (Jamel et al. 2013).

Pursuant to the above perspective, renewable energy sources are sustainable and have a momentous potential to mitigate global climate change, address local and regional environmental concerns and increase energy security leading to energy independence. Among renewable energy sources and technologies, solar energy systems and technologies hold a pivotal role in meeting the world's future energy needs. Solar thermal energy conversion systems like solar desalination, solar water heating, solar air heaters, solar drying, solar cookers, and solar thermal applications in energy-efficient buildings have already proved their practicalities and have been found suitable for users' need (Ummadisingu and Soni 2011, Sunil et al. 2014). In this context, solar thermal energy will play a very vital role. The foremost challenge in utilizing solar energy for various applications is developing cheaper methods of collection and storage along with thermodynamically efficient systems so that the system's high investment cost can be reduced.

1.2. Indian Power Scenario and Solar Potential

The electricity sector of India is one of the largest markets in the world. During the period 2007-17, India's electricity demand has augmented at an average annual rate of 7%. During the same period, India’s electricity generation has also augmented exponentially, with an average annual growth rate of 6%. Total power generation in the year 2017 was 1532 TWh, with an increase of 86% since 2007. India’s installed capacity has also increased rapidly during the period 2008-2021. In the year 2008, the total installed capacity was 134 GW. It increased to 248 GW in 2013 and further increased to 379 GW as of 28th Feb. 2021. The evolution of installed capacity by fuel source from 2015-2021 (up to Feb. 2021) is given in Table 1.1. The installed capacity by coal includes lignite, hydro includes small hydropower, and biomass includes energy from waste. It can be seen from Table 1.1 that the solar installed capacity has increased rapidly from 6.76 GW in 2015 to 39.08 GW up to Feb. 2021 (Faith 2020, CEA 2021). Recent all India installed capacity has been shown in Figure 1.1, which shows that coal will continue to dominate India's power sector for electricity generation as of 28th Feb. 2021 (CEA, 2021). About 54.78% of power generation in India is obtained from coal-based thermal power plants which are mainly responsible for carbon emissions. India's power sector has the highest potential for emission reduction. It has been estimated that through the use of commercially available clean energy technologies, India could reduce carbon emissions by 30 to 50 percent by 2030 (McKinsey&Company 2009). The total installed capacity as of 28th Feb. 2021 was about 379 GW, in which the share of conventional thermal sources is about 62%, followed by renewable (24.5%) and hydro (12.2%) sectors, as shown in Figure 1.1.

Table 1.1:

Fuel source-wise evolution of installed capacity 2015-21 (MW) (Faith 2020, CEA 2021)

Fuel Source	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Coal	185173	192163	197171	200704	204224	205135	207704
Gas	24509	25329	24897	24937	24937	24992	24957
Diesel	993	838	838	638	638	510	510
Nuclear	5780	6780	6780	6780	6780	6780	6780
Hydro	47057	48858	49779	49992	50047	50382	50992
Wind	26777	32280	34046	35626	37279	37756	38789
Solar	6763	12289	21651	28181	32578	34915	39084
Biomass	8110	8296	8839	9242	9946	10029	10315
Total	**305162**	**326833**	**344001**	**356100**	**365891**	**370499**	**379131**

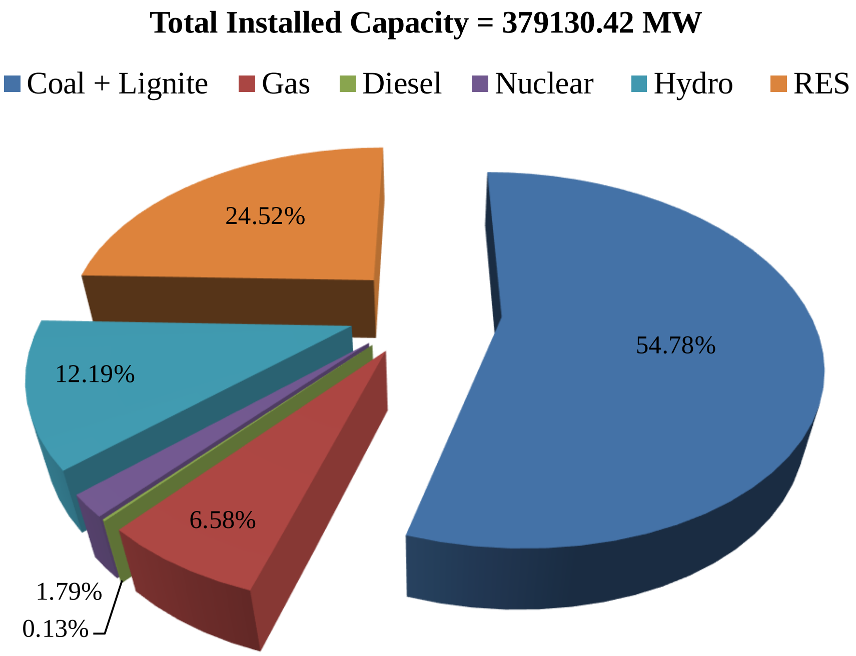

Figure 1.1: All India installed power capacity (CEA 2021).

Solar energy potential based upon land availability and solar radiation in India has been assessed to be around 749 GWp. Figure 1.2 shows the state wise solar energy potential of the entire country as estimated by the National Institute of Solar Energy. In India, Rajasthan has the highest solar energy potential (Thapar et al. 2018).

1.3. Overview of Concentrating Solar Power (CSP) Technologies

Concentrated solar thermal power technologies use concentrated solar radiation as a high-temperature energy source to generate electricity via the thermal route. In this energy conversion process, CSP systems use a combination of mirrors to concentrate incident irradiance to produce useful heat energy, which is further utilized to generate electricity by steam cycle or gas cycle. This section gives an overview of CSP technologies and their operational characteristics. The leading CSP technologies are; parabolic trough collector (PTC), linear Fresnel reflectors (LFR), central receiver (solar tower), and parabolic dish reflectors (PDR). The way of focus geometry classifies these CSP technologies as either line-focusing (parabolic trough collectors and linear Fresnel reflectors) or as point-focusing (solar tower and parabolic dish). The line-focusing CSP technologies are less costly and technically less problematic, but not as efficient as compared to point-focusing. Table 1.2 compares all these CSP technologies on various operating parameters.

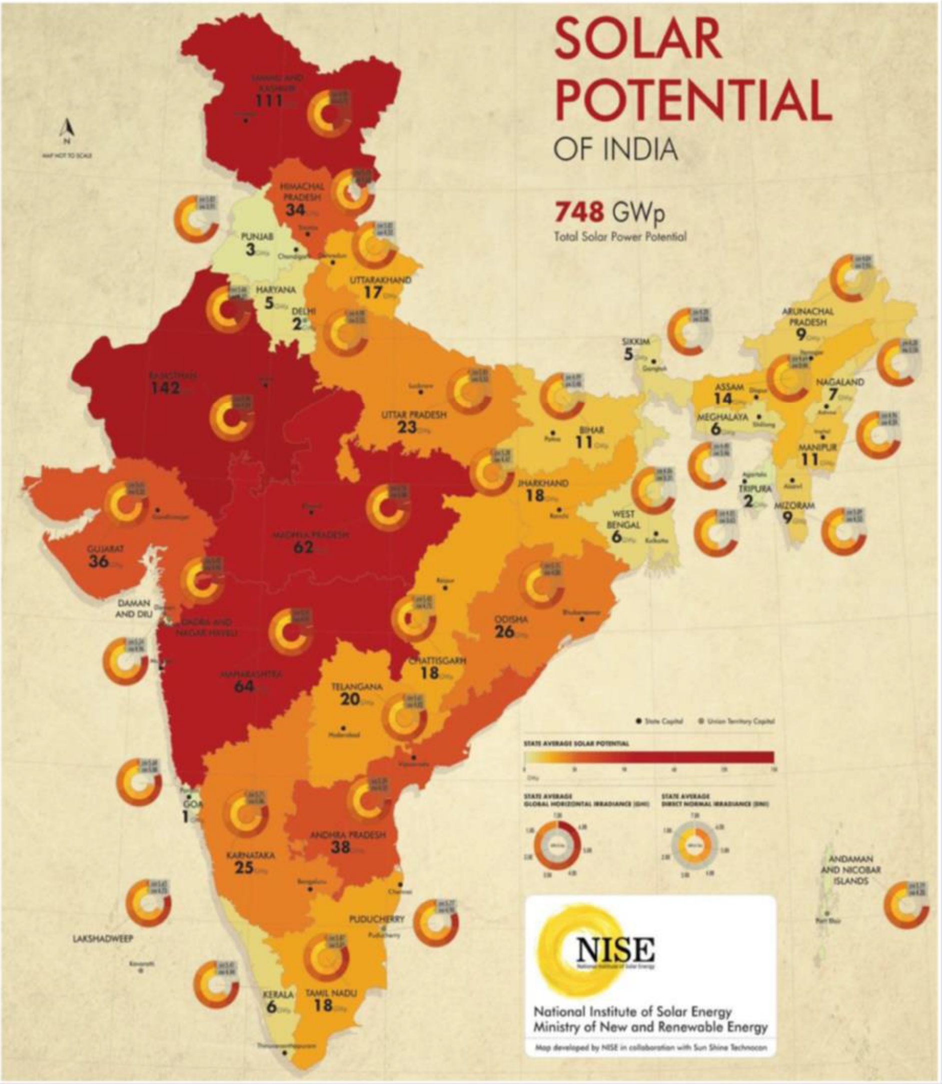

Figure 1.2: State-wise solar potential, India (MNRE 2020).

Table 1.2:

Comparison of different CSP technologies on various parameters (Nixon et al. 2010, (Gielen 2012), Shimeles 2014, Barlev et al. 2011)

	Parabolic trough	**Linear Fresnel**	**Solar tower**	**Parabolic dish**
Typical Capacity (MW)	10-300	10-200	10-200	0.01-0.025
Technology maturity	Commercially proven	Mature	Most Recent	Demonstration projects
Technology development risk	Low	Medium	Medium	Medium
Operating temperature (°C)	50-400	50-300	300-2000	150-1500
Annual solar-to electricity Efficiency (net) (%)	15	8-10	20-35	25-31.25
Optical efficiency	Medium	Low	High	Very High
Concentration ratio	30-100	10-100	150-1500	500-1500
Tracking	One-axis	One-axis	Two-axis	Two-axis
Cycle	Superheated Rankine steam cycle	Saturated Rankine steam cycle	Superheated Rankine steam cycle	Stirling
Hybridization	Yes and direct	Yes, direct (steam boiler)	Yes	In limited cases
Relative cost	Low	Very low	High	Very high
Land use (m^2 MWh^{-1} y^{-1})	3.2	1.8	4.6	4.15
Grid stability	Medium to high	Medium	High	Low
Storage with molten salt	Commercially available	Possible, but not proven	Commercially available	Possible, but not proven

1.3.1. Parabolic trough collector

In this CSP technology, parabolic trough-shaped mirrors produce a linear focus on the receiver tube along the parabola's focal axis, as shown in Figure 1.3. Among all technologies, parabolic trough technology is the most mature, advanced, and proven solar technology to produce heat at temperatures around 400 °C for generating electricity or process heat applications. The largest and first commercial application of this technology is the nine solar energy generating systems (SEGS) with a total installed capacity of 354 MWe, built by Luz Company in the Mojave Desert in California, USA (Kalogirou 2004). Ministry of New and Renewable Energy (MNRE), the then Ministry of Non-conventional Energy Sources, installed India’s first solar thermal power plant of 50 kW using PTC technology at the Gwalpahari, Gurugram, which was commissioned in 1989

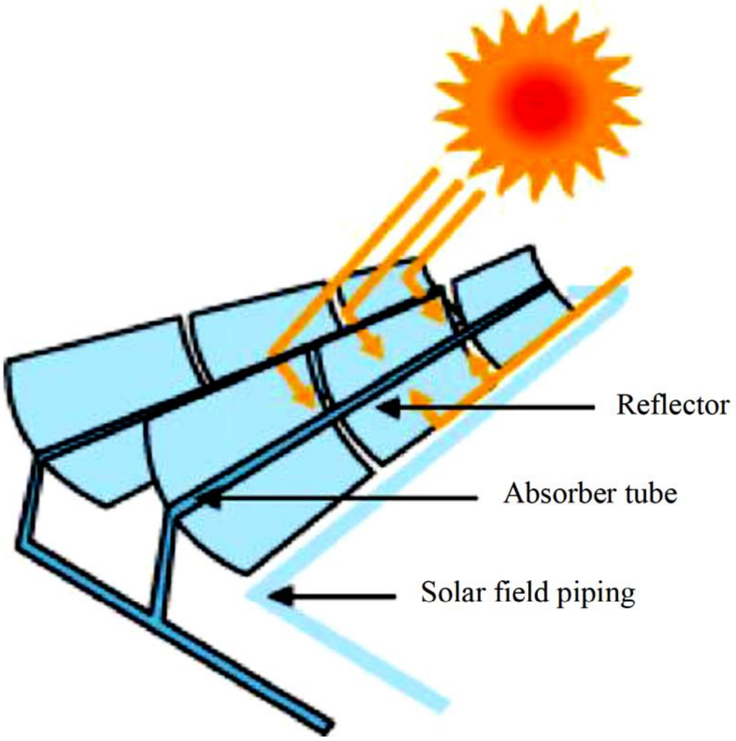

Figure 1.3: Parabolic trough Collector (Ummadisingu and Soni 2011).

(Garud and Purohit 2012). PTC technology is the most widely used CSP technology for solar thermal power plants due to its proven market and commercialization. Almost more than 90% of solar thermal plants worldwide use this technology for electricity generation. Therefore, in this thesis PTC technology has been used for the integration of solar thermal energy with subcritical and supercritical CFPP.

1.3.2. Linear Fresnel

LFR systems also produce a linear focus on downward-facing stationary receiver using an array of mirror strips that concentrate light on the receiver mounted on a linear tower shown in Figure 1.4. In the LFR system, a fixed receiver containing HTF is placed at this focal point. Fresnel reflectors concentrate the solar radiation onto the fixed receiver where HTF is heated to about 300 °C by concentrated sun rays. This high-temperature HTF can be used to generate steam through heat exchanger, which in turn can operate a simple Rankine cycle to produce electricity. With concentrated ratios of about 10-100, the operating temperatures in the gamut of 50-300 °C can be achieved with the help of linear Fresnel reflectors. LFR technology is simple in design and requires less supporting structure because it is mounted close to the ground.

This technology is not commercially proven and less efficient than PTC. The challenges with LFR technology are the problem of shading and blocking between adjacent reflectors. These issues can be resolved either by increasing the receiver tower's height or by enlarging the receiver size. But both these options lead to increased cost and more ground usage. An alternate solution is the advanced design of LFR known as Compact LFR, which can use two separate receiver towers with adjacent reflectors directing their light beam onto opposite receivers. This arrangement also reduces the incident radiation loss (Kalogirou 2004).

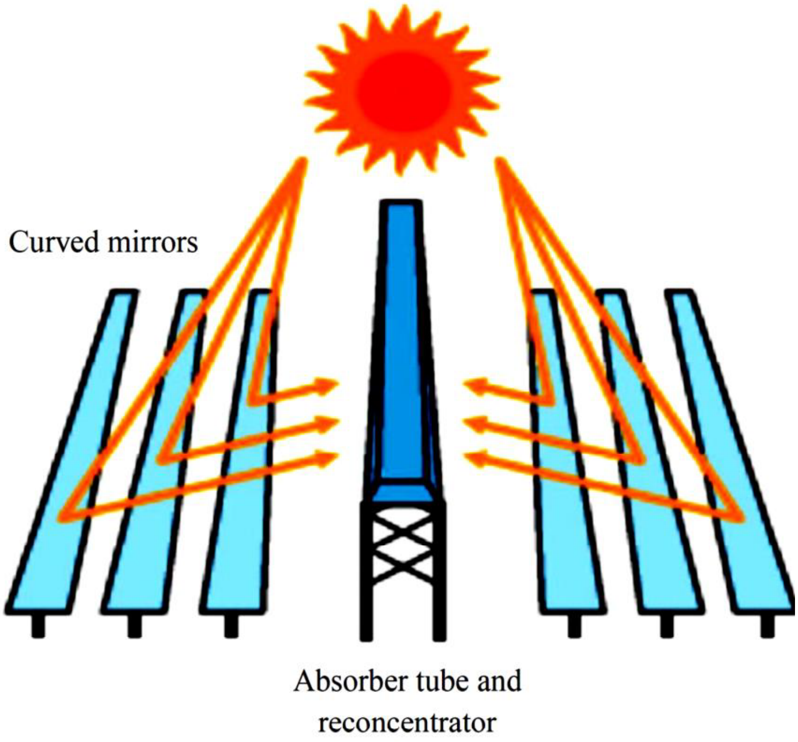

Figure 1.4: Linear Fresnel Reflector (Ummadisingu and Soni 2011).

1.3.3. Central receiver system

This CSP technology involves an array of heliostats that concentrate the incident solar radiation onto a fixed receiver mounted on the top of a tower, as shown in Fig. 1.5. The central receiver systems (CRS) can achieve high concentration ratios (300-1500) compared to line focusing systems, which permits these systems to operate at higher temperatures with reduced losses. CRS have many advantages such as minimum thermal energy transport requirements, highly efficient in collecting energy and in converting it to electricity, store thermal energy conveniently and benefit from economies of scale (Kalogirou 2004). Nevertheless, the CRS have great potential as compared to PTC technology but central receiver technology is not as mature and proven as PTC technology.

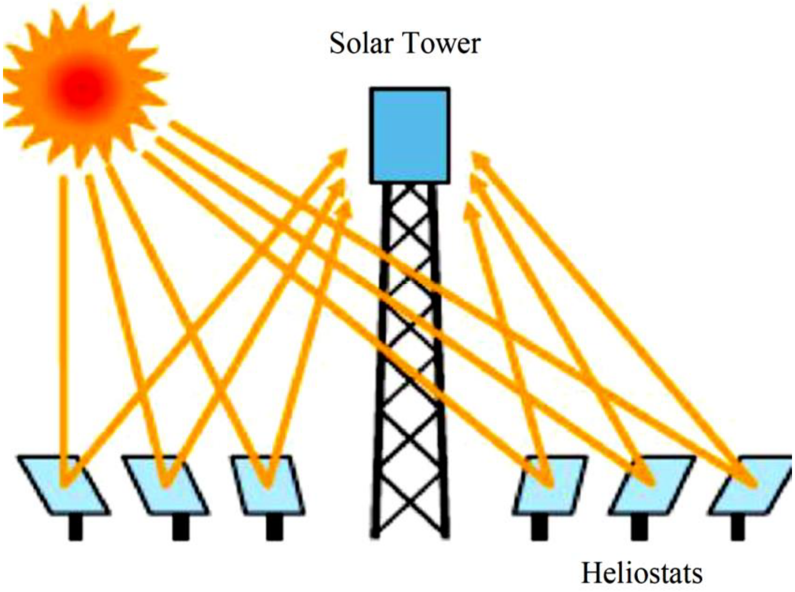

Figure 1.5: Central receiver system (Ummadisingu and Soni 2011).

1.3.4. Parabolic dish

The parabolic dish reflector is also known as the dish engine, is a point focus collector that tracks the sun in two axes for concentrating incident solar energy onto a receiver mounted at the focal point of the dish, as shown in Figure 1.5. In PDR, the receiver absorbs the incident solar energy, converts it into thermal energy via a circulating fluid. This thermal energy can be used directly as heat for thermal application or for electricity generation.

The thermal energy can either be converted directly into electricity through an engine-generator coupled to the receiver or transported using pipes to a central power conversion system. Technically, the PDR systems have the highest potential for converting solar to electricity efficiencies among all CSP technologies because they continuously track the sun on two axes. However, the parabolic dishes are the least commercially mature and are very costly (Kalogirou 2004).

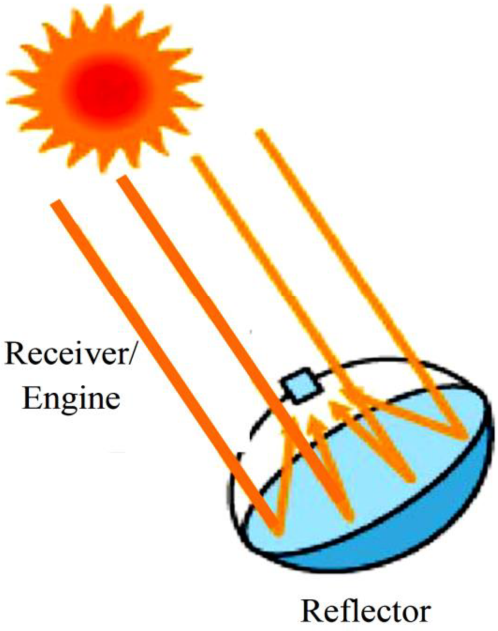

Figure 1.6: Parabolic dish (Ummadisingu and Soni 2011).

1.3.5. Challenges of stand-alone solar thermal plants

The CSP technologies are land and water-intensive; therefore, installing solar thermal only plants using different CSP technologies requires colossal land area and water. The high upfront cost of stand-alone solar thermal power plants is a crucial obstacle to their more significant deployment. The solar thermal only plants can generate power during the day time only when there is sufficient insolation, thus require thermal storage option for continuous operation, which further increases the cost. In the Indian context, the challenges for solar thermal only plants are more pronounced due to technical, market, and environmental concerns. India lacks in technology, awareness, and skilled workforce to install stand-alone solar thermal power plants because no successful demonstration project has tested the techno-commercial feasibility of India's CSP technology. However, Indian government has commissioned two CSP plants of 50 kW and 1 MW capacity at Gowalpahari, Gurugram, and IIT Bombay. But these pilot projects failed to provide sufficient ground-level experience and investor confidence (Bhushan et al., 2015). Therefore, a detailed feasibility study and technology selection accompanied by appropriate solar radiation resource assessment is required to build confidence for setting up solar thermal power plants. In India's context, the present status of international technology, its availability, and financial and commercial feasibility is not clear.

Another key issue for solar-only thermal power plants is dispatchability. The intermittent nature of solar energy sources can be overcome by the use of some form of energy storage. Another viable means of addressing the dispatchability problem is the integration of CSP technologies with a conventional fossil fuel power plant. Hybridization offers excellent potential in allowing the cost-effective deployment of solar thermal energy on a scale commensurate with energy requirements, which is the main focus of this research.

1.4. Issues with Fossil Fuel Power Plants

The world's exponentially growing energy demand depends heavily on fossil fuels because most of the world's primary energy supply is from fossil fuels. Being an economical and reliable energy source, fossil fuels will continue to meet primary energy demands for various sectors like industrial, transportation, and commercial of world economies in the near future. However, contradictory estimates about fossil fuel reserves have been made, but the fact remains that these reserves are exhausting at an alarming pace. This cheap and reliable energy from fossil fuels comes at a cost, such as the release of hazardous pollutants into the atmosphere – a major contributing factor to global warming and climate change. Coal is the world's most copious and extensively distributed fossil fuel and is likely to remain a dominant electricity generation component, particularly in developing countries. As mentioned in previous section, coal is the backbone of India's power sector. After China, India is the 2nd largest producer of coal in the world (Faith 2020).

Nonetheless, coal-based power plants introduce some serious environmental and health problems. More than 100 contaminants (effluents and gaseous emissions) are released into the atmosphere by combustion and coal mining. The most harmful pollutants are CO and CO_2 (responsible for global warming), NO_2 (accountable for smog and asthma attacks), SO_2 (acid rain), and fine soot particles (cause heart and lung disease) (Shimeles 2014). A recent investigation has been carried out on the health costs of coal-fired power plants (CFPP). The study estimated the effects of CFPP on infant mortality in India and reported that a 1 GW increase in coal-fired capacity corresponds to a 14% increase in infant mortality rates (Barrows et al. 2019).

With the above cited problems of environmental pollution and health-related issues associated with fossil fuel power plants and the international pressure on developing countries to limit their carbon emissions, it becomes very important to choose renewable energy sources as an alternative. Among these renewable sources, power generation through concentrated solar thermal energy could be the most promising option for India in the near future. India receives a good amount of solar radiation of 1700-1900 kWh per kilowatt peak for more than 300 clear sky days in a year (Kumar et al. 2017). The biggest obstacle in the path of using solar energy for different purposes is to develop economical ways of solar radiation collection and solar energy storage along with thermodynamically efficient systems so that high initial investment cost of the system can be reduced. India's major economic development challenge is to produce secure, inexpensive, and environmentally sustainable energy for its escalating energy demands. The fast depleting fossil fuel reserves and increasing demand for power in India require the harnessing of solar energy to meet the supply and demand gap. However, the inherent drawbacks of solar energy such as insufficient intensity, availability only during the daytime, intermittent nature, uncertainty, and very high first cost hinder the commercialization of solar thermal energy technologies. As an alternative to overcome these issues, the integration of concentrated solar thermal power into an existing fossil fuel based power cycle can generate cleaner and reasonably priced electricity (elaborated in the subsequent section).

1.5. Hybridization of CFPP with Solar Energy

Hybridization of solar thermal energy with fossil fuel based power systems not only overcome the issues of uncertainty and intermittency associated with solar energy but also reduces the high initial investment cost of solar thermal only plants due to sharing of power block and other infrastructural facilities of existing conventional power plant. The hybridization of solar thermal energy with coal-based power plants is a practically feasible option and the most promising technology for developing countries like India, whose primary energy source is coal. Most of the fossil fuel power plants installed in India are situated in the sunny belt. Therefore, the integration of solar energy into CFPP seems to be an attractive option. Introducing concentrated solar energy into an existing CFPP helps reduce coal consumption, thereby mitigating CO2 emissions and employing a steam turbine to convert the concentrated solar energy into power with higher efficiencies.

Hybridization of solar thermal power with CFPP has momentous advantages over solar thermal only plants. The benefits offered by hybridization include the perspective for higher energy conversion efficiency, lower capital investment, higher valued energy due to dispatchability, and lower energy costs. The benefits of hybridization are better summarized in Figure 1.7.

There are two different operation approaches through which the specific objective of power augmentation or emission reduction can be achieved, as shown in Figure 1.8. The first approach "solar augmentation" also known as "Power Boosting Mode" uses the surplus steam (available due to substitution of bled-off steam by solar energy) to generate additional electrical power while maintaining the same level of emissions per unit volume of fuel consumption. For higher electrical output, the power-boosting approach consumes the same amount of fuel.

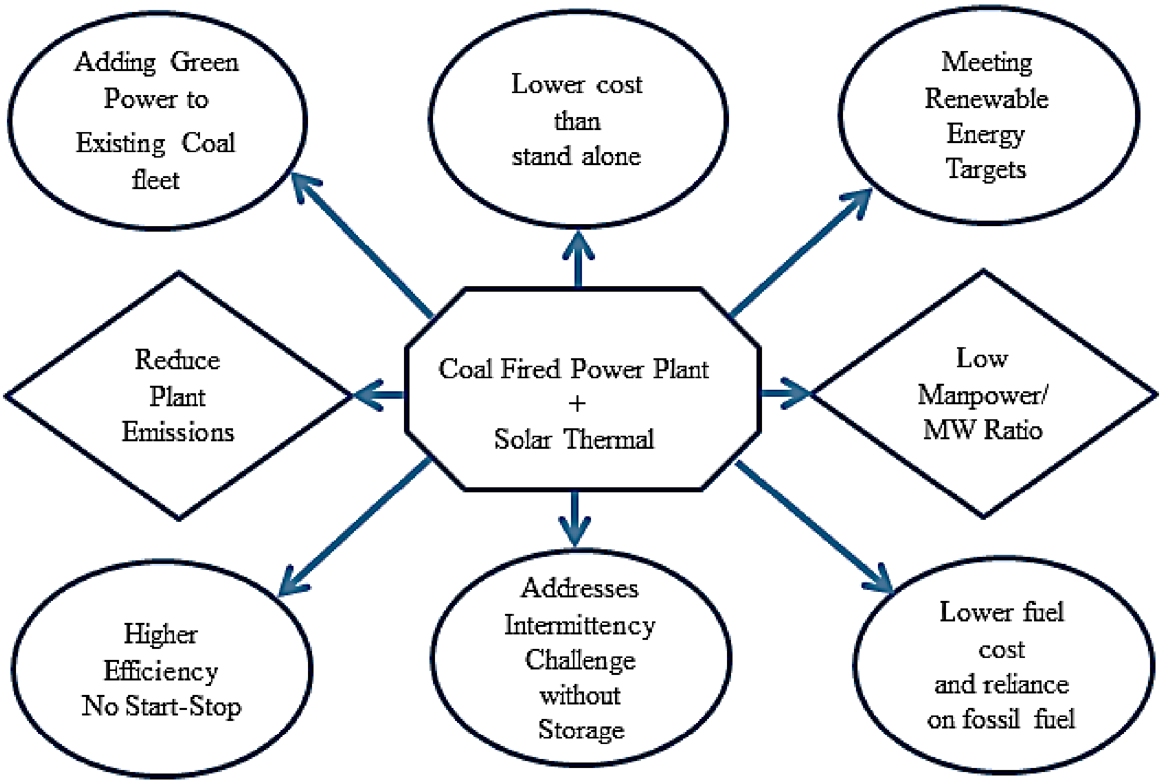

Figure 1.7: Advantages of hybridization of solar thermal energy with CFPP.

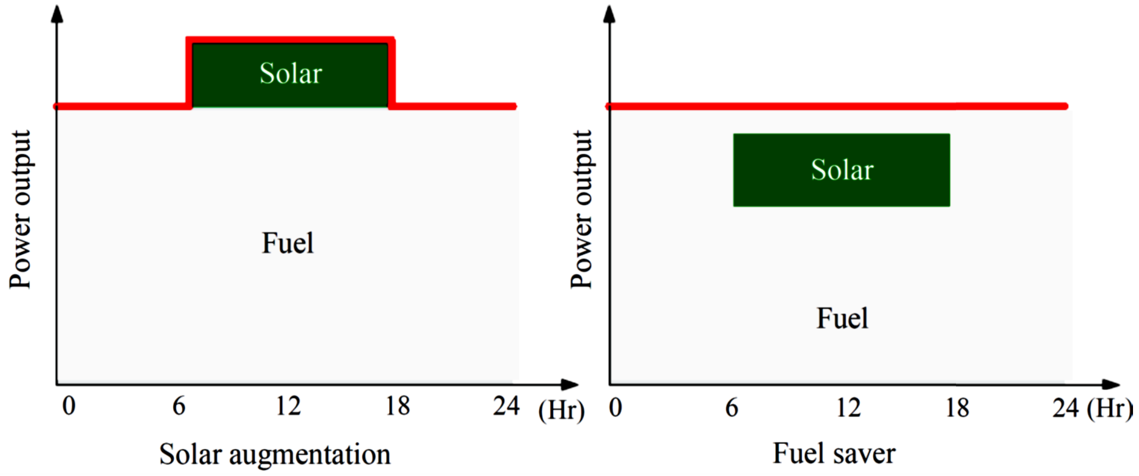

Figure 1.8: Power boosting and fuel-saving concept (De Sousa 2011).

The second approach, known as "Fuel Saving Mode" consumes less fuel for generating the same electrical output. In this approach, the solar field is used to preheat the feedwater at the boiler inlet and the mass flow of steam across the turbines remains constant, therefore, reducing the boiler load. This approach may be useful for reducing GHG emissions due to less fuel consumption and help in achieving government's sustainable development goals (De Sousa 2011). In this thesis, both power boosting and fuel-saving modes have been studied for solar-coal hybrid power plants.

The integration of concentrated solar energy with CFPP can be done in many ways, such as to preheat the feed-water, superheating of steam, reheating of steam, steam evaporation, steam generation for deaerator and auxiliary equipment, and air preheating (Ahmadi et al. 2017). The different ways of integrating solar thermal energy into fossil fuel power plants can be broadly summarized as generation of high-pressure steam using solar thermal energy, production of intermediate pressure steam, and preheating of feedwater using solar thermal energy (Figure 1.9). The latter is the most widely studied and most effective means of integrating solar thermal energy into existing CFPP (Petrov et al., 2012, Pierce 2013). Therefore, the main focus of this research work is also confined to feedwater preheating using concentrated solar thermal energy.

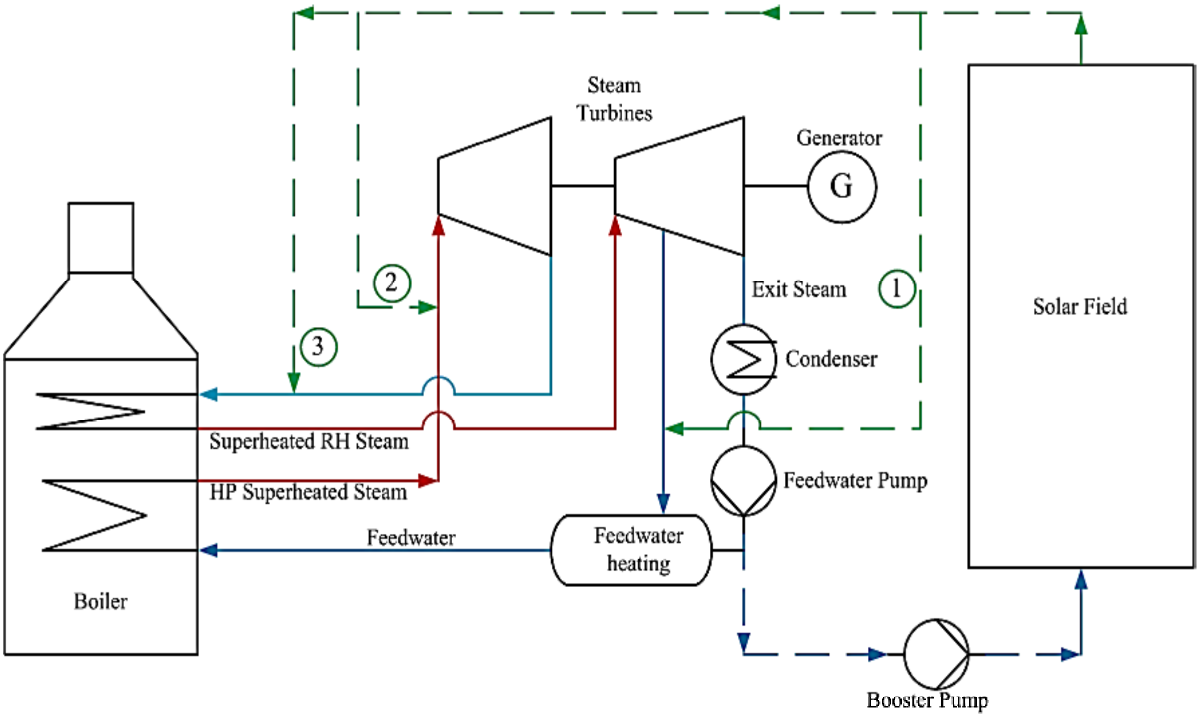

Figure 1.9: Simplified plan of CSP integration options into existing plants. (1) Feedwater preheating; (2) high-pressure steam; and (3) cold reheat line

1.5.1. Successful demonstration of solar-coal hybridization

To meet utility emission goals and achieve sustainable development goals, recently there has been rising interest in implementing solar-coal hybrid projects. The first successful demonstration of the solar-coal hybrid power plant, Cameo generating station by Xcel Energy with a combined capacity of 48 MW at Colorado, USA, became operational in 2010. PTC solar field (4 MW) designed by Abengoa Solar covering 6.4 acres of land area was used to preheat the boiler feedwater before entering into the boiler. The results of this demonstration showed that the use of solar energy achieved lower NO_x emissions and saved 900 tons of coal per year. Xcel further anticipates that the power plant's efficiency will increase by 5%, and the project will bring down the CO_2 emissions by 2000 tons per year (Mills 2011, Shimeles 2014).

In India, the first successful demonstration of the integration of solar thermal energy into a coal-fired power plant has been carried out at NTPC Dadri, Uttar Pradesh, India. In this project demonstration, solar steam produced in a solar steam generator using compact linear Fresnel reflector CSP technology was injected at four different points into a 210 MWe coal-fired unit's existing power cycle. The injection points chosen for solar steam addition were: before high-pressure turbine (HPT) inlet, i.e., BFT-HPT, the HPT outlet, before HPT inlet, i.e., FWH-HPT, and before the intermediate pressure turbine (IPT) inlet, i.e. FWH-IPT, respectively. The simulation results using “Thermoflow” software showed that injection of solar steam before HPT inlet, i.e. BFT-HPT, provided better performance compared to other injection points. This integration could save 16790 tons of fuel and 3213 tons of coal annually (Vir 2012).

The compelling benefits of hybrid power plants are that they generate electricity at the most competitive prices, emit the least carbon dioxide and consume the least possible water. Despite these benefits, currently, there are no solar-coal hybrid power plants in operation in India (Bhushan et al. 2015).

1.6. Objectives of the Present Research Work

Only limited studies have been performed on the hybridization of solar energy with coal-fired power plants. Considering all these notions, it is possible and almost evident to think that hybridization should be the more logical and natural solution for exploiting solar thermal energy in India. Recognizing the aforementioned importance and advantages of solar thermal hybrid technologies the research work undertaken in this thesis is carried out on hybridization of solar thermal energy with existing subcritical and supercritical CFPP emphasizing mainly on feedwater preheating using PTC solar energy technology. This thesis's main focus is to explore the technical and economic feasibility of hybridizing the most mature CSP solar technology, i.e. PTC with subcritical and supercritical CFPP. The broad objectives of the thesis are:

- To identify the technical, environmental, and economic criteria responsible for present status in the field of solar thermal-hybrid technologies (STHT)
- To model the comprehensive usefulness of STHT on technical, environmental, and economic criteria in the present context
- To carry out sensitivity analysis of STHT to investigate its performance with present techno-economic and policy interventions
- To identify the barriers and suggest suitable strategies for further commercialization of STHT in India

Keeping in mind the broad objectives, the study strives to reach the following specific objectives with regard to solar-coal hybrid power plants:

- To develop the solar field and economic model of solar-coal hybrid power plant.
- To carry out energetic, exergetic, economic, and environmental analysis of a Subcritical Solar-Coal Hybrid Power Plant through a case study

- To investigate the techno-economic, energetic, exergetic, and environmental performance of a Supercritical Solar-Coal Hybrid Power Plant through another case study
- To highlight policy interventions, to identify barriers, and provide suggestions for further commercialization of solar thermal hybrid technologies in India.

1.7. Organization of Thesis

Keeping in mind the research objectives, the thesis consists of seven chapters.

Chapter 1 Introduction

In this chapter, the background of solar energy, India's power scenario and solar potential, and overview of CSP technologies is presented. The challenges and issues with solar only and coal-based power plants are addressed. The advantages of hybridization alongwith successful demonstration are discussed in this chapter. This chapter exposes the scope of the work carried out, the concept of solar augmentation and the basic idea behind this thesis. Finally, the broad and specific objectives of this thesis are defined in this chapter.

Chapter 2 Literature Review

In this chapter exhaustive literature survey on integration of solar energy with fossil fuel based power generation systems is presented. The different integrating options and the components of convetional steam power plant integrated with solar energy are discussed. Based on the detailed review the research gaps are identified in this chapter.

Chapter 3 Solar-Coal Hybrid Power Plant Modeling

In this chapter, the general equations for solar field modeling, thermodynamic modeling and the economic modeling of the solar-coal hybrid power plant are presented and discussed. The problem description is also given in this chapter.

Chapter 4 Results and Discussion Part-1

This chapter examines the hybridization of an existing sub-critical coal-fired power plant (CFPP) with concentrated solar thermal energy on technical, environmental, and economic criteria under three different integration scenarios. The 4-E analysis (energetic, exergetic, economical, and environmental) of a 330 MWe sub-critical coal-fired thermal power plant integrated with concentrated solar thermal energy is presented in this chapter. The economic factors (ACoE, LCoE, and simple payback period) and the environmental factors such as annual reductions in coal consumption, CO_2 emissions, and solar contribution have been computed and discussed in this chapter. Exergetic analysis is also performed in this study.

Chapter 5 Results and Discussion Part-2

This chapter examines the hybridization of an existing supercritical coal-based power plant with concentrated solar thermal energy on technical, environmental, and economic criteria under three different integration options. The 4-E analysis (energetic, exergetic, economical, and environmental) of a 660 MWe supercritical coal-fired thermal power plant integrated with concentrated solar thermal energy is presented in this chapter. In this study, a solar field consisting of PTC arrays is integrated with an existing 660 MW supercritical CFPP for feedwater preheating. The economic factors (LCoE and simple payback period) and the environmental factors such as annual reductions in coal consumption, CO_2 emissions, and solar contribution have been discussed in this chapter.

Chapter 6 Policy Intervention

This chapter discusses the current policies of various states focusing on solar energy and presents a state-wise analysis of renewable purchase obligations (RPOs) and renewable energy certificates (RECs). Further, suggestions have been provided to promote the integration of solar energy with thermal power plants to augment the power output of the existing plant. This chapter also provides future recommendations for promoting solar thermal power in India through appropriate policy enablers.

Chapter 7 Conclusion and Future Scope

This chapter concludes the thesis by providing a summary of results, reccomendations and the future scope of the work.