CHAPTER 2

LITERATURE REVIEW

2.1 Background

Providing sustainable, secure and continuous energy supply is one the greatest critical concerns facing humanity currently, and STE has recognized itself as one of the most feasible sources of renewable energy. The dispatchability of this promising technology makes it perfectly suitable to form the backbone of a carbon neutral electricity system in future. In the coming years, the solar thermal industry will need to emphasize the exploitation of the diverse possibilities presented by hybridization and thermal energy storage. A hybridization is very prominent opportunity, which combines both solar energy and fossil fuels concomitantly. The integration of STE in electricity generation has notable benefits over solar thermal stand alone power plants, mainly for future markets. These benefits involve the possibility for higher energy efficiency conversion, reduced capital outlay in innovative technology, high quality energy due to dispatchability, and less energy costs. Recognizing the importance of hybrid solar-thermal technology, the chapter attempts to provide an exhaustive review of existing solar thermal energy technologies, emphasizing system integration and evaluation used in the hybrid solar-fossil-fuel power generation system.

During the last two decades, numerous research studies have been performed on the hybridization of concentrated solar thermal energy with existing fossil fuel-based power plants worldwide. Several hybrid power plants in commercial operation worldwide combine power generation from fossil fuels and power generation from concentrated solar energy. The next section presents the review of various studies performed on integration of solar energy with existing fossil fuel based power plants.

2.2 Literature Survey

Zoschak and Wu (1975) evaluated seven approaches of incorporating solar thermal energy into an 800 MW fossil fuel based steam power plant as one of the earliest research in this field. These seven approaches were feedwater heating; evaporation of water, combined evaporation and superheating, superheating of steam, steam reheating, air preheating, and combined air and feedwater preheating. Feedwater preheating using solar heat was one of the approaches recognized as an appropriate option in terms of investment cost, technical design, and functional features.

Griffith and Brandt (1984) carried out performance and economic analysis of the solar-fossil hybrid system using computer code (HYBRID) and central receiver code (STEAEC). The quantity of solar energy directed to thermal storage and the specific load was determined using HYBRID. In the economic evaluation of the solar-fossil hybrid system, fuel consumption was shown to be a dominant variable cost. The study suggested that for the hybrid system to be economically competitive, the present worth of the capital investment for a solar-fossil hybrid system should not exceed 2.5 times the present value of the capital investment for a comparable convention fossil power system.

Pai (1991) performed a study on the retrofit of a 210 MW CFPP for preheating feedwater using solar energy. The results of this study showed that during periods of insolation feedwater heating to a temperature of 241 °C could achieve fuel saving up to 24.5% and the estimated saving in fuel cost was about INR 3 crore and the study suggested that the savings can be doubled by heating feedwater to a higher temperature of 330 °C.

Odeh et al. (1997) proposed solar trough collectors with DSG to improve the performance of SEGS. The study analyzed three different DSG solar collector field arrangements and existing powerhouse backup boiler using the TRNSYS software. All three arrangements are shown in Figures 2.1 to 2.3, respectively. The conclusion of this investigation showed that in the first arrangement (shown in Figure 2.1), the contribution of solar energy is higher, and the specific fuel consumption of the system is lower than the other two arrangements. The case study for a 54000 m^2 array depicted that for a DSG system using the first arrangement, the average solar energy contribution was 36.7%.

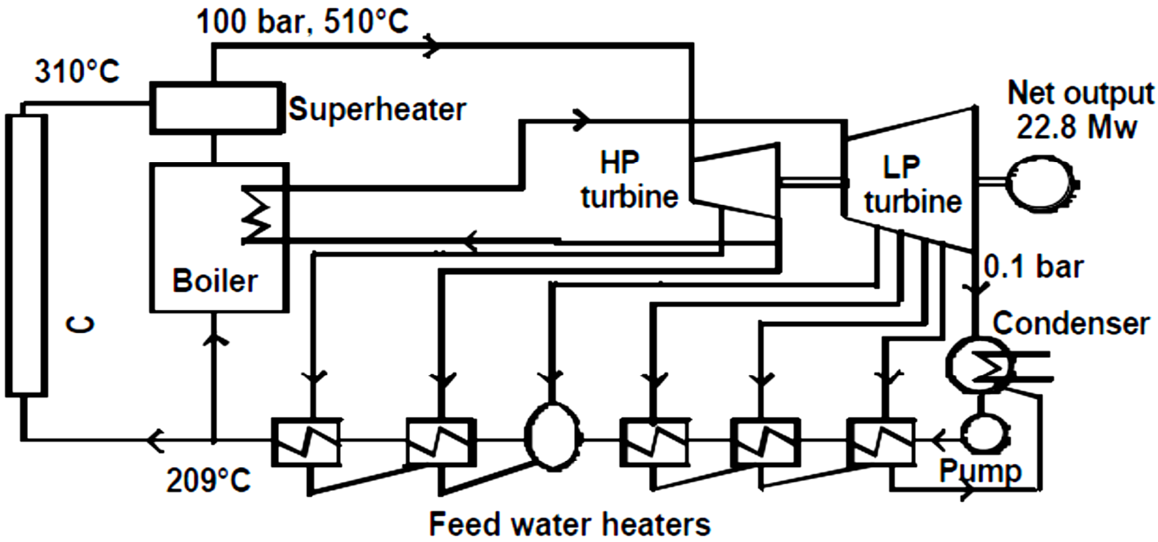

Figure 2.1: Parallel collector boiler and steam FWH (Odeh et al. 1997).

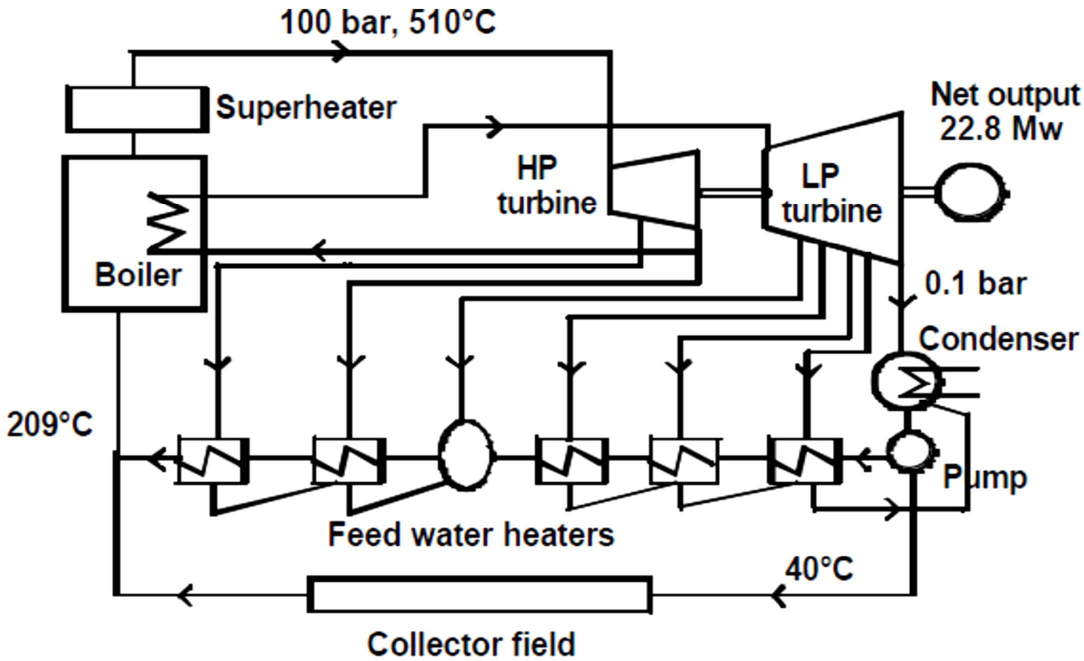

Figure 2.2: Feed-water heating using solar energy (Odeh et al. 1997).

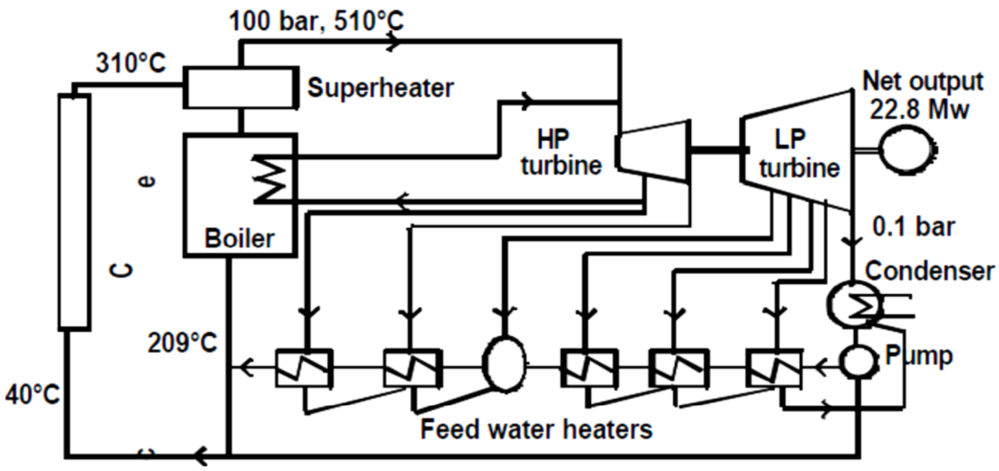

Figure 2.3: Combined parallel collector boiler and solar feedwater heating (Odeh et al. 1997).

Yang et al. (2008) studied the methods and mechanism of integrating solar power with coal-fired power plants. The authors used parabolic trough collectors for collecting solar energy. Their simulation shows that the solar LEC of investigated SACPG system, seeing CO_2 evading, is 0.098 $/kWh, lesser than SEGS, 0.14 $/kWh.

Hu et al. (2010) demonstrated the advantages of solar-aided power generation using THERMOSOLV software. This study examined three different scenarios (100% replacement of all closed FWHs, 10% replacement of all closed FWHs, and 100% replacement of first feedwater heater after reheating process, respectively) for feedwater preheating using solar energy in a 500MWe brown coal-fired power plant. It concluded that the energy and exergy efficiency of the system could be improved. The study also showed that the payback period in fuel-saving mode is relatively long compared to the power-boosting method for all the scenarios. For instance, in the first scenario, 100% replacement of all closed FWHs, the payback period in power-boosting mode is 1.99 years, while the same is 36.8 years in fuel-saving mode.

Suresh et al. (2010) performed a deep 4-E analysis of solar-assisted coal-fired subcritical and supercritical thermal power plant for establishing techno-economic feasibility. The results of this investigation showed that replacing extraction steam to high-pressure feedwater heater alone with solar energy provides 5-6% improvement in coal consumption and additional power generation for fuel-saving and power-boosting modes, respectively, as compared to reference power plants.

Yang et al. (2011) selected a 200 MW CPP as the case study to demonstrate the advantages of SAPG technology in terms of solar to power efficiency, consumption rates of specific fuel and steam under various hybridization schemes. In this case study, four replacement options were investigated in power-boosting and fuel-saving mode, and it was reported that for the solar heat at 260 °C, the solar heat to power conversion efficiency could reach up to 36.5%. The study showed that solar-aided feed water heating seems to be a feasible option to integrate solar thermal energy with CPPs.

Popov (2011) integrated solar field feed water preheating for fast and feasible RES penetration using Thermoflow software. The best outcome was observed when all the HP heaters were replaced and FW temperature exceeds its original design value. It was reported that the share of solar power generation could be reached about 23% of the capacity of the plant, which leads to about 39% improvement as compared to the best solar hour of the year.

Sheu et al. (2012) reviewed hybrid solar-fossil fuel power generation systems mainly aiming towards hybridization schemes and evaluation. The authors concluded that most of the researchers designed the hybrid solar-fossil fuel systems without considering the fluctuations in the supply of solar and selling price of the electricity. Therefore, it was not possible to reach the best yearly performance of the hybrid system.

Ng and Lipiński (2012) carried out thermodynamic analyses for solar thermal gasification of coal (anthracite, bituminous, lignite, and peat). The authors reported replacing a coal-fired Rankine cycle power plant, about 35% efficient, and an integrated gasification power plant, combustion-based, with a hybrid solar-gasification power plant leads to a significant reduction, about 47% and 27%, respectively, in specific CO_2 emissions.

Khanmohammadi et al. (2013) carried out exergy and exergo-economic of a steam power plant in Iran. The study concluded that the highest exergy destruction occurred in a boiler by 360.65 MW and in preheater1 & condenser by 38.81 MW. The corresponding cost destruction for the boiler was 15090.8 US$/h and for preheater1 & condenser was 6056.57 US$/h. The study reported that the final cost of electricity increased from 7.81 US$/GJ to 9.87 US$/GJ when the condenser pressure was decreased from 0.7 bar to 0.05 bar.

Zhai et al. (2013) researched a solar-aided CFPP of 600 MW capacity for understating the advantages of SAPG technology. The study considered solar irradiation and load ratio for investigating the performance of plant under investigation using first and second law analysis. The study concluded that for solar irradiation of 925 W/m^2 and 100% load ratio, the exergy and energy efficiencies of the plant were found to be 44.54% and 46.35%, respectively. The coal savings in the gamut of 8.6 g/kWh to 15.8 g/kWh were obtained at 100% load ratio when solar irradiation was varied from 500 W/m^2 to 1100 W/m^2.

Shimeles (2014) investigated the possibilities of incorporating solar energy into an existing coal-based power plant. In this regard, the two leading CSP technologies, i.e., PTC and CRS, were employed to integrate solar energy into existing CFPP in five different ways. All these five integration options are shown in Figures 2.4 to 2.8. The integrating option shown in Figure 2.4 improves the performance of the economizer, while that shown in Figures 2.5 and 2.6 boost the output of the super-heater. The integrating options showed in Figures 2.7, and 2.8 increase the power output of intermediate and low-pressure turbines. This study concluded that the introduction of solar energy between HPFWH and economizer using PTC solar field showed superior performance over other integrating options.

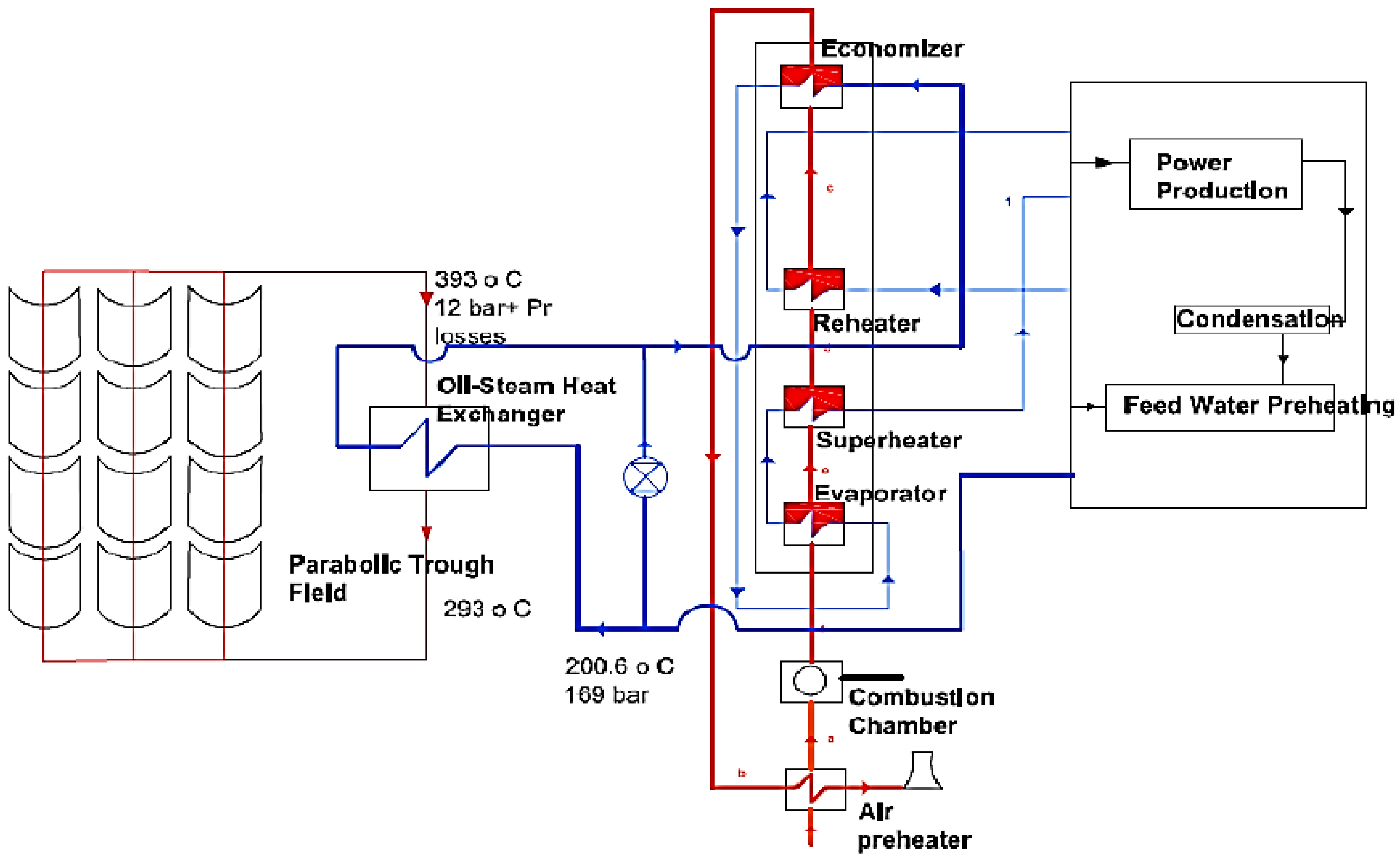

Figure 2.4: Solar energy introduced between HPFWH and Economizer using PTC solar field (Shimeles 2014).

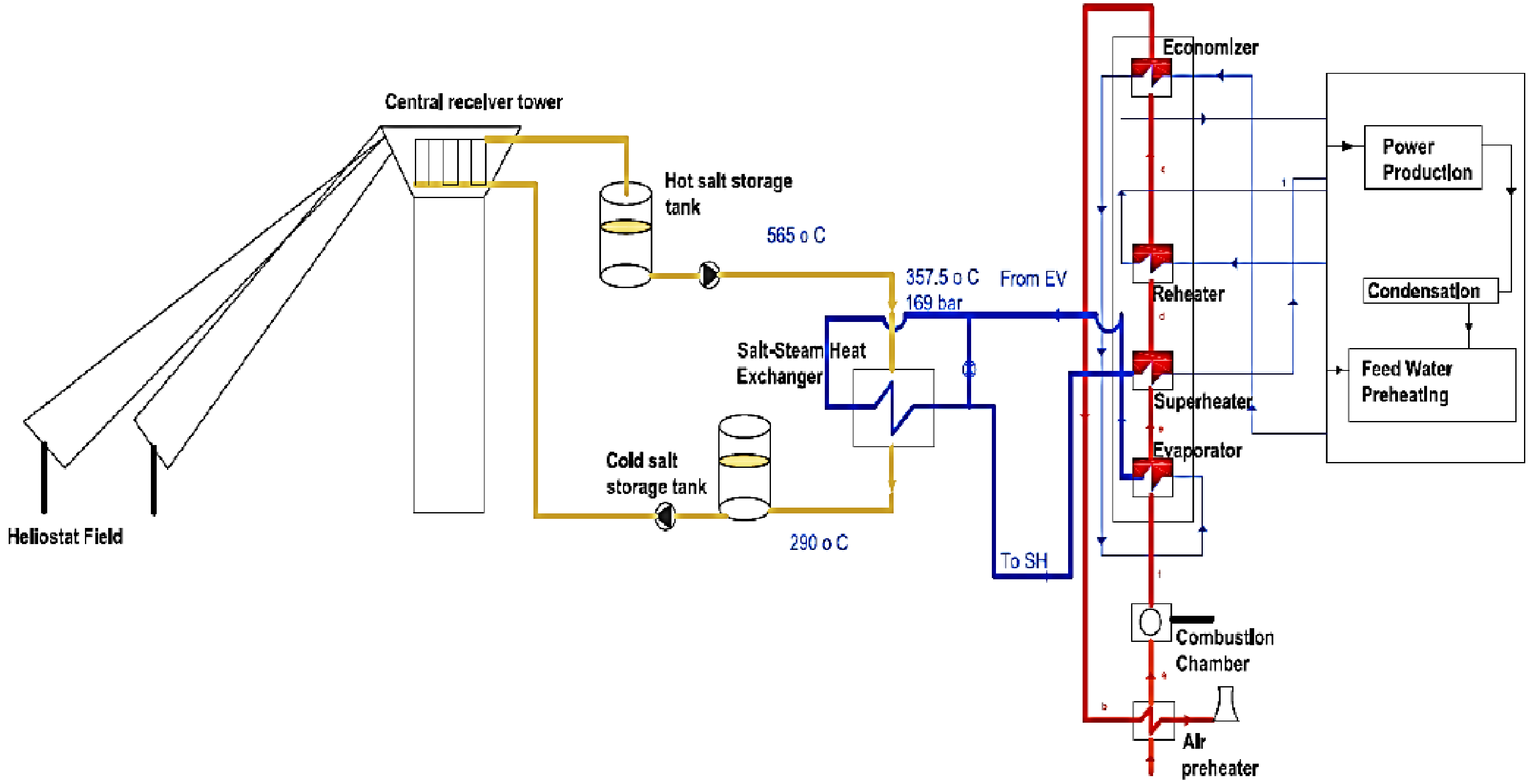

Figure 2.5: Solar energy introduced between the Evaporator and Super-heater using CRS solar field (Shimeles 2014).

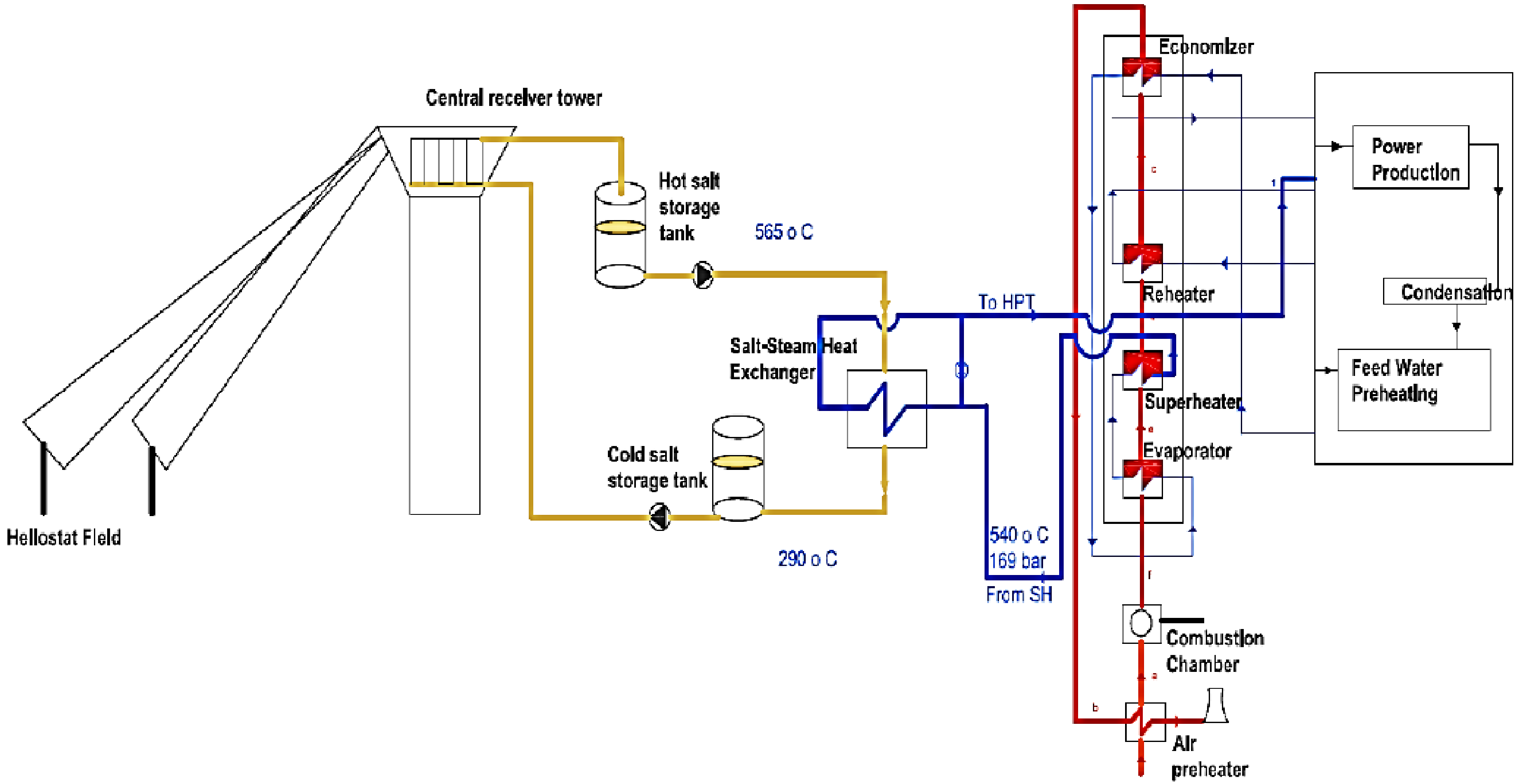

Figure 2.6: Solar energy introduced between Super-heater and HP turbine using CRS solar field (Shimeles 2014).

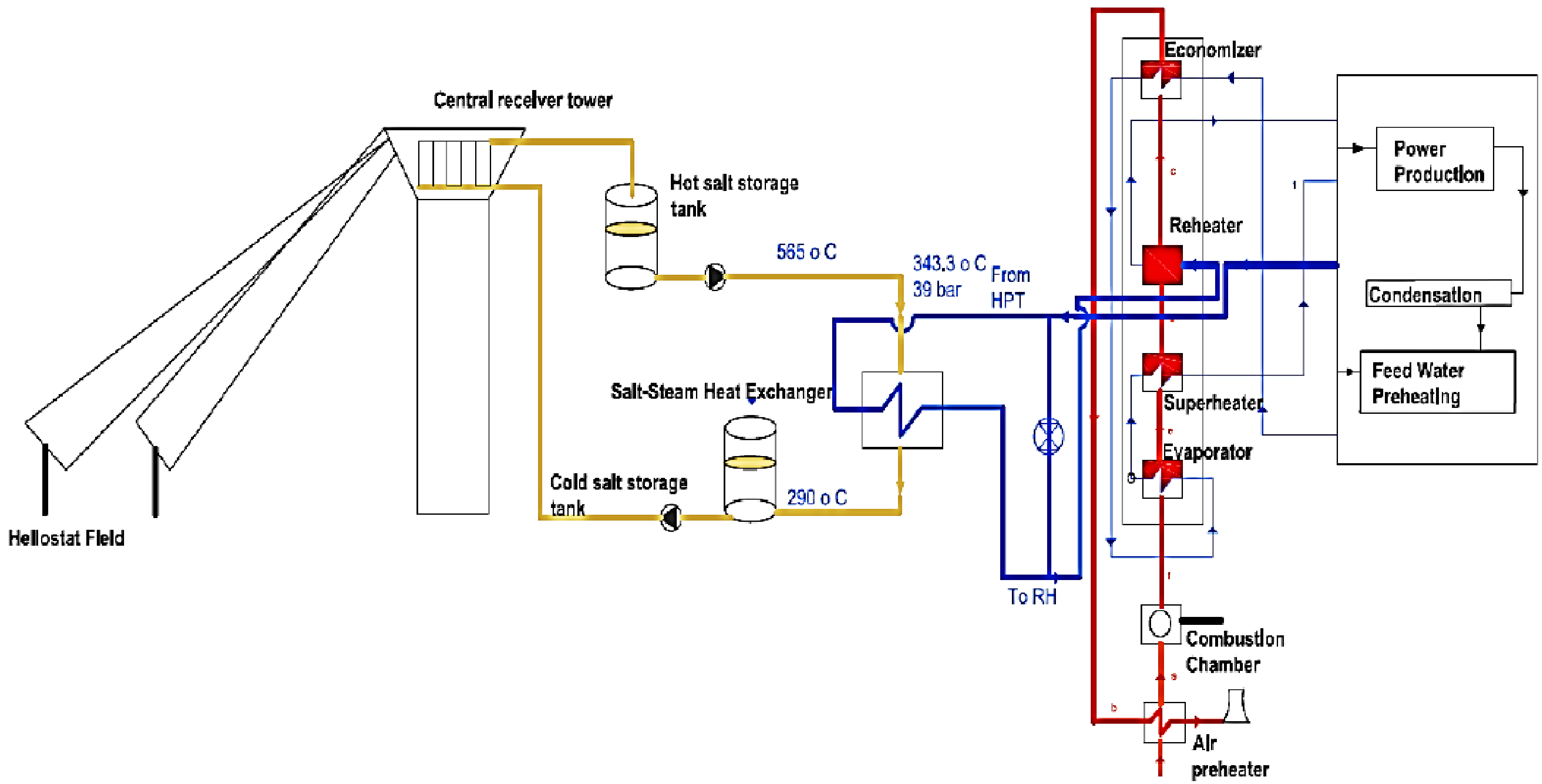

Figure 2.7: Solar energy introduced between HP turbine exit and reheater entry using CRS solar field (Shimeles 2014).

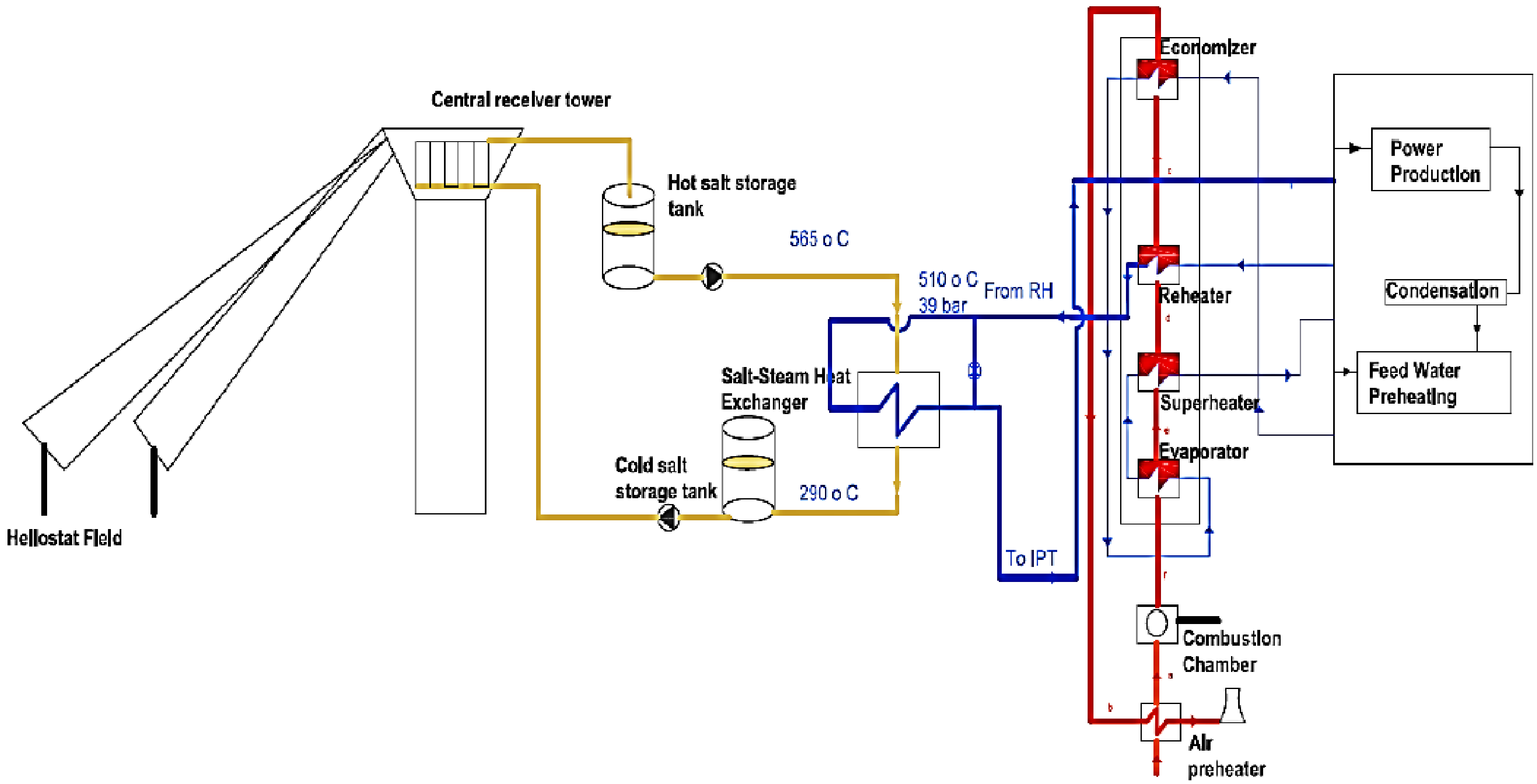

Figure 2.8: Solar energy introduced between reheater exit and IP turbine entry using CRS solar field (Shimeles 2014).

Zhai et al. (2014) proposed an optimization study of integration strategies in solar-assisted coal-fired power plants. The maximum amount of coal saving during the whole year was considered as an optimization function. In addition to this, optimization parameters selected for this research include solar collector area, the method of coupling the power plant, the storage capacity, and whether storage is required or not. The study concluded that the amount of coal saved was higher in the thermal storage system than the without thermal storage system.

Peng et al. (2014) carried out exergetic analysis of a 330 MW solar-hybrid coal-fired thermal power plant and compared a solar-only thermal power plant. The Energy-utilization diagram method was used to compare the off-design performance of both the plants. The study concluded that the off-design and economic performance of the solar-hybrid plant are better than a solar-only thermal power plant. For solar-coal hybrid plants, lower exergy destruction was found in the solar FWH and steam turbine. As compared to solar thermal only plant, the LCoE of solar-hybrid coal plant was reduced to 0.8-1.0 ¥/kWh.

Deng (2014) proposed a hybrid solar-coal-power plant in which secondary air is preheated. The author modeled a total of five cases by GateCycle™. A comparison between fuel-saving mode and power-boost mode has been made. The simulation results show that the solar-to-power efficiency of the hybrid system is about 5.5-6.5% more than HP systems.

Hou et al. (2015) studied solar-aided 330 MW power plant performance in fuel-saving mode. Matrix thermal balance equation (MTBE) method was used for calculations. Results showed that in a SAPG system, when high-pressure extraction steam is partially replaced, with the introduction of increasing solar energy, the temperature of exhaust flue gas reduces; boiler efficiency increases, and the consumption rate of coal decreases.

Wang et al. (2016) integrated solar thermal energy into a 300 MWe subcritical coal-fired power plant and studied seven different configurations. The results depicted that combining solar energy with post-combustion carbon capture can increase power generation and reduce the penalty on electrical efficiency caused due to CO_2 capture. Further, the study also concluded that configuration 6 has the lowest LCoE for new plants and the highest net present value for existing power plants.

Wu et al. (2016) analyzed the annual economic performance of a 600 MW solar-aided coal-fired power plant under different tracking modes, solar multiple, aperture areas, and storage capacities. In this study, high-pressure bled steam is substituted using PTC solar technology for preheating feedwater. The performance parameters in this research, such as thermal energy storage, solar multiple and row spacing to aperture width ratio, have been optimized from the thermodynamic and economic point of view. The simulation results were obtained using the MTBE approach.

Feng et al. (2016) evaluated the thermo-economic performance of a 600 MW coal-fired power plant integrated with solar direct steam generation (DSG) technology. In this hybrid system, the different stages of extraction steam for feedwater heating in the original coal-fired power plant were substituted by steam injected from solar DSG. This research reported an improvement of 1.5 to 7.5 % in thermal efficiency of SAPG system compared to the original CFPP, and the amount of coal saved was 7798 tons to 36577 tons.

Rahmeh et al. (2016) investigated the techno-economic and environmental aspects of integrating PTC with existing 33 MW thermal power plant in Jordan. The study considered 8 different scenarios of replacing feedwater heaters. They concluded that the efficiency of the original power plant augmented by 3% because of higher turbine output as a consequence of increased steam flow rate at later stages of the turbine.

Zhai et al. (2015) used a Genetic algorithm to optimize the solar thermal storage system (TSS) for improving the performance of a hybrid solar-coal power generation system. The authors suggested that the best integration tactic of the system, the collector area, and the corresponding TSS to replace each HP extraction have been achieved when the amount of coal saving in unit solar investment per hour is at its largest. Their findings demonstrate that the improvement of the TSS efficiently increases the economic benefit.

Zhai et al. (2016) carried out a life cycle assessment of solar-assisted coal-fired power plant with and without heat storage. The uncertainty analysis depicted that with longer plant life, the power plant have improved performance; with increased coal price, the power plant will have poor performance; with a lower cost of the solar field, the solar-assisted coal-fired power plant will be more profitable as compared to the original coal-fired power plant.

Zhai et al. (2016a) replaced first-stage extraction from the turbine to heat feedwater with solar energy. Results based on thermo-economic structural theory showed that the coal consumption rate was reduced by 15.04 g/kWh in fuel-saving mode. The power output was 57.2 MW higher in power-boosting mode. The study also reported that the unit cost of electricity was enhanced by 16.9 to 21.6% because of the significant investment of the solar field. The power-boosting approach performed economically better than the fuel-saving approach due to a larger share of coal exergy.

Qin et al. (2017) studied the impact of non-displaced FWHs on the performance of a 300 MW solar-assisted power generation plant. This investigation discussed two operation strategies; constant temperature strategy and constant mass flow rate strategy. The study examined the effect of both the strategy on the plant's overall performance in power-boosting mode. The comparison of annual performance for high, medium, and low solar resource areas showed that the constant temperature strategy provided higher annual performance than the constant mass strategy. It was concluded that the constant temperature strategy is better than constant mass flow rate strategy.

Economic optimization of the solar multiple (SM) is presented by Zhao et al. (2017) for solar–coal parabolic trough plants (200–600 MW). For the considered cases, the optimum SM and the lowest LCoE have been predicted as 1.4 and 0.56 RMB/kW h for a 200 MW, 1.3 and 0.53 RMB/kW h for a 330 MW, and 1.3 and 0.49 RMB/kW h for a 600 MW level solar–coal hybrid system. Additionally, it has been concluded that the location of the site and turbine operational loads strongly affects the performance of a solar hybrid system.

Wang et al. (2017) analyzed a developed power block and solar field model for examining the thermodynamic and economic performance of a typical solar hybrid coal-fired power generation system under different operating conditions. The study concluded that the efficiencies can be achieved in the range of 13-20% and LCoE in the region of 0.7-1.1¥/kWhe, depending upon the solar multiple and substitution method.

Ahmadi et al. (2017) performed a case study in Iran to repower a steam power plant with solar parallel feedwater heating. This case study investigated the preheat project of feedwater on seven separate scenarios. The study results showed that substituting all high-pressure FWHs with solar energy increases the net energy and exergy efficiencies of the power plant by 18.3%.

Further, Ahmadi et al. (2017a) employed solar energy for parallel feedwater heating to repower the Isfahan Mohammad Montazeri power plant and reported that by substituting all HP FWHs with solar collectors, the net energy and the exergy yields improved by 9.5% with respect to the simple cycle, reaching about 35.21% and 36.85%, respectively. Ahmadi et al. (2017b) further investigated full repowering with integrating solar energy in 200 MW Montazeri steam plant in Iran. A gas turbine of 400 MW is employed for repowering and found that for only repowered cycle, the energy and exergy performances have been enhanced by 76.8% and 73%, respectively. In power boosting mode, for a mass flow rate of 31.3 kg/s in the solar field, about 16.8 MW improvements in the power of the steam turbines have been witnessed. The authors reported the rewarded profit of about 8,635,440 USD per year due to reduced fuel consumption and CO_2 emission.

Han et al. (2017) proposed a flexible solar-aided power generation system for improving selective catalytic reduction (SCR) de-NO_x efficiency and coal-based energy efficiency of coal-fired power plants. The proposed concept selected a 1000 MW coal-fired power plant as a case study. The results indicated that the SCR de-NO_x efficiency could improve by 3.1% and 7.9% under medium load and low load conditions, respectively, compared with the reference plant. The proposed SAPG study further revealed that the standard coal consumption rate could decrease by 2.68g/kWh, 4.05 g/kWh, and 6.31 g/kWh for high, medium, and low loads, respectively.

Suojanen et al. (2017) studied three integration schemes such as feedwater preheating, cold reheat line, and high-pressure turbine concepts for CSP and conventional steam power plants. The authors used a linear Fresnel collector solar field for generating steam parallel with the steam boiler. They have done the modeling using dynamic simulation software Apros®. It was concluded that if the amount of solar steam provided to the system is increased, then there are more imbalanced in the turbine sections and heat surfaces of the steam boiler, thereby leading to many challenges in the system design. The optimized hybrid system design leads to about 20% savings in fuel and emissions.

Duan et al. (2017) investigated the performance of a 660 MW supercritical coal-fired power plant integrated with a solar tower to save conventional fuel and protect the environment. The study used TRNSYS software for simulation of the proposed plant model and studied the system's performance in coal-saving mode. In this work, two integration schemes have been proposed for coal-saving using solar energy. In the first scheme, the solar heater was used to heat the part of extraction steam from the boiler steam-water separator, which then was mixed steam at the outlet of the steam generator super-heater resulting in coal-saving. The second solar heater was used to heat the steam at the outlet of the high-temperature reheater in the coal-saving mode of operation. The heliostat field area with maximum solar-to-electric efficiency was chosen as an optimal point considering the economic costs. The study concluded that the maximum solar-to-electric efficiency was obtained as 16.74%, and corresponding optimal heliostat field area was 101400 m^2. The standard coal consumption rate of the proposed integrated system was reduced by 7 g/kWh compared to the conventional reference power plant under the optimal condition.

Hong et al. (2017) developed an explicit correlation for explaining solar-to-power efficiency using a typical hybrid solar system with 330 MW CFPP. It was found that at 75% and 50% turbine load, integration makes the steam flow rate reach the rated flow, thereby enhancing the turbine efficiency. Eventually, the net solar-to-power performance initially remains constant and then drops at a typical value of DNI = 600 W/m^2 and incident angle = 30°.

Zhai et al. (2017) proposed three integration schemes (PP + Solar + PCC) of 1000 MW CFPP coupled with solar energy and post-combustion CO_2 capture system both in thermal and economic analysis, where solar energy is employed to substitute the 1st extraction to heat the feedwater. The authors compared six systems and concluded that the amalgamation of solar energy for replacing the 1st HP extraction and taking a portion of intermediate pressure cylinder exhaust to provide the reboiler heat demand is the best among the proposed schemes of PP + Solar + PCC.

Wu et al. (2018) carried out performance improvement of the coal-fired power plant by integrating solar energy for preheating feedwater and reheating steam. A 600 MW, supercritical solar-aided coal-fired power plant operating in fuel saving mode was used as a reference plant. In this case study, using solar energy for preheating feedwater and reheated steam could improve cycle efficiency and solar-to-electricity efficiency by 1.91% and 6.01%, respectively.

Qin et al. (2018) proposed a mixed-mode operation of a solar-aided power generation system. The study reported that the profitability of the mixed-mode operation could be up to 12.1% higher than that of a single mode of operation (fuel-saving or power-boosting mode). The study demonstrated the superiority of mixed-mode operation via a case study of 300 MW CFPP where high-temperature FWHs were replaced by solar preheater.

Li et al. (2016) analyzed hybridization of supercritical coal-fired power plant with PTC using MATLAB Simulink in fuel-saving mode. It was found that the intense fluctuation of DNI has a significant impact on the quality of solar-assisted coal-fired power plants. To cut pollutants, greenhouse gas emissions and solar energy investment, Li et al. (2018) tested three schemes of adding $53\ MW_{th}$ solar energy to a $600\ MW_e$ supercritical Coal-fired Power Plant in both fuel saving and power-boosting modes. The coal consumption rate in fuel saving mode is comparatively lower for studied hybridization schemes than in power-boosting mode. Based on the standard coal consumption rate and efficiency, the scheme integrating solar energy to heat superheat steam and subcooled feedwater is found to be the best integration option. The saving of coal consumption rate for the best hybridization option is reached around $11.15\ g/kWh$ and $11.11\ g/kWh$, respectively, for fuel-saving and power-boosting modes than that of a coal-fired plant only.

Further, Li et al. (2019) studied the annual performance of a solar tower coupled with a coal-fired power plant. Additionally, the authors examined the impact of varying thermal storage capacity on the annual solar power generation and solar-to-electricity efficiency. Their results reveal that the hybrid option leads to a significant reduction, about 5.79, 4.52, and 3.22 g/kWh, respectively, in the annual coal consumption rate in the case of high, medium, and low DNI. The LCoE for high, medium, and low values of direct normal irradiance are fairly similar, i.e., 6.37, 6.40, and 6.41 ¢/kWh, respectively. The results of optimization analysis revealed that the optimal thermal storage capacity for high, medium, and low DNIs is 6.73, 4.42, and 2.21 h, respectively.

Recently, Li et al. (2020) discussed and compared the thermodynamic, environmental, and economic performances of solar tower aided coal-fired power plant systems in both power-boosting and fuel-saving modes. The results showed that for a 300 MWe coal-fired power plant, the solar energy used in power boosting and fuel-saving modes is 81.82 and 71.69 MW, respectively. The thermal efficiency of the hybrid system for both modes is 39.42% and 39.30%, respectively, and the cost of electricity for power generated by solar energy for both modes is 3.37 cents/kWh.

Acar and Arslan (2019) performed energy and exergy analysis of the "solar and geothermal powered" organic Rankine cycle for different system configurations. The study concluded that the energy and exergy efficiency of the "*solar and geothermal powered*" organic Rankine cycle increase by the decrease in the area of solar collector. It was also reported that the energy generation of the proposed system was calculated up to 305,713.5 kWh.

Wang et al. (2019) developed a general system integration optimization model. They studied a solar aided power generation system based on a Solar Two plant and a 600 MWe supercritical coal-fired power plant. The results depicted that at higher heliostat field power work conditions, the heat energy should be added to the highest pressure FWHs as a priority.

The exergy and energy analysis of a 35 MW solar-fossil fuel power plant, located in California's Mojave Desert, has been performed by Vakilabadi et al. (2019). The authors reported that the condenser is the crucial part that wastes energy, 47% of the cumulative energy, through energy analysis. The collector and then boiler are the significant units destroying exergy, about 68.32% total exergy loss, for the integrated scheme.

Liu et al. (2020) proposed combining PTC and solar towers to collect solar energy for introducing into the preheaters and boilers of coal-fired power plants. The study showed that the prospective for a 660 MWe power plant integrated with a combined solar field allows the highest solar exergy share of 8.51% to be reached. Further, the study reported that a maximum available solar exergy of 69.43 MW_{th} is provided by combined solar field, which is 7.83%-11.88% higher than the alternative compared systems.

Aliyu et al. (2020) presented the energy and exergy analyses of a combined cycle power plant provided with a reheat facility. Their findings showed that the exergetic efficiency for the turbine is the maximum, about 92%, while minimum, about 63%, for the condenser. It has also been reported that the parameters such as reheat pressure, superheat pressure, and steam quality considerably affect the turbine's performance.

Zhang et al. (2020) studied continuous operation behaviors of a 330 MW solar-aided power generation system in a full day, according to the transient models of a solar-aided thermal power plant. The results of this study showed that during a full day, the essential parameters of the solar-aided power generation system could operate within safety ranges, and the system generates almost 330 MW constant power. The solar output power and CO_2 emissions reductions are 207.7 MWh and 186.7 Ton/day, respectively.

Pang et al. (2020) studied the dynamic characteristics of SAPG system under DNI feedwater control strategy for a 600 MW subcritical CFPP. The study used TRNSYS software for transient simulation of the established SAPG model. The high-temperature superheated steam extracted from the platen super-heater was heated up using a solar tower field mixed with superheated steam at the high-temperature super-heater outlet before entering the high-pressure steam turbine. The fuel-saving mode was adopted in this study, and according to DNI input, the coal consumption was reduced. The study reported a 4.9% reduction in coal consumption in the considered SAPG system using steam temperature control system with a DNI feedwater control strategy in fuel-saving operation mode. It was also concluded that solar-to-electricity efficiency reached up to 22.5%, and the fluctuation in power generation was less than 10 MW.

Shuai et al. (2021) investigated the performance of a solar-coal-hybrid power generation (SCHPG) system using a 200 MW CFPP. The study used IPSEpro software based on off-design mode and heat balance design method for numerical simulation. In SCHPG system, the PTC solar field with an aperture area of 35970 m^2 was used to replace the first high-pressure heater for preheating the feedwater. In fuel-saving operating mode at design-point condition, the reduction in fuel consumption was reported as 4.15 tons/hour, while in power-boosting operation mode, the increase in power output was found as 7.4 MW/hour. In the SCHPG system, the estimated annual reduction in coal consumption was obtained as 9910 tons, and the corresponding yearly reduction in CO_2 emissions was found as 11000 tons. In conclusion, the study exposed that for protecting the environment and mitigating climate change, the SCHPG system can contribute considerably.

A brief summary of essential studies performed on the hybridization of solar energy with existing steam power plants is given in Table 2.1.

Table 2.1:

Integrated solar technology and component of steam power plant of some major works

Author(s)	Integrated solar technology	Integrated power plant component
Zoschak and Wu (1975)	SCR-DSG	FWH (HP+IP), EV, SH, EV+SH, RH, APH, APH+FWH
Griffith and Brandt (1984)	SCR + TSS	Boiler
Pai (1991)	PTC-HTF	All FWHs (add shell and tube heat exchanger before each one)
Odeh et al. (1997)	PTC-DSG	All FWHs, EV and All FWH+EV
Ying and Hu (1999)	FPC-HTF, PTC-HTF	All FWHs, LPFWH
Yang et al. (2008)	PTC-DSG	All FWHs, Economizer and All FWH+Economizer
Gupta and Kaushik (2010)	PTC-DSG	FWHs (replacing single separated heaters) and de-aerator
Hu et al. (2010)	CLFR-HTF, FPC-HTF, ETC-HTF	FWHs (replacing single and groups heaters at multi-integration levels)
Yan et al. (2010)	PTC-DSG, SD, SCR-HTF	FWHs(replacing single heater at multi-integration levels)
Suresh et al. (2010)	PTC-DSG, PTC-HTF	All FWHs including deaerator, HP and LP FWHs, LP FWHs
Popov (2011)	CLFC-DSG	LPFWHs, HPFWH, and HPFWH+Economizer
Yang et al. (2011)	PTC-HTF, FPC-HTF	FHWs (replacing single and groups heaters) and de-aerator
Hou et al. (2012)	PTC-HTF	FWHs
Zhai et al. (2015)	PTC-HTF	HPFWH
Qin et al. (2016)	PTC-HTF	All HPFWHs
Adibhatla and Kaushik (2017)	PTC-HTF	HPFWHs and LPFWHs
Wu et al. (2018)	PTC-HTF, PTC-DSG	All HPFWHs and HPFWHs+between HP turbine outlet and boiler inlet
Wang et al. (2019)	PTC-HTF, PTC-DSG	Economizer and SH
Li et al. (2020)	SCR-DSG	RH at IP turbine exit
Shuai et al. 2021)	PTC-HTF	HPFWH

2.3 Research Gaps Identified

The literature cited above clearly establishes the importance and need to integrate solar energy with existing and new CFPP. Many practical studies have been carried out on solar-assisted gas-based combined cycle power plants throughout the world. Recently, there has been a growing interest in hybridizing coal-based thermal power plants with solar energy because of global warming, climate change, and environmental degradation. The challenge of environmental protection and sustainable development goals is far more compelling for developing countries like China and India. In the purview of this, the following literature gaps have been identified:

- A very few studies have been performed on solar-coal hybridization in the Indian context. Therefore, there is a lack of confidence in power producers, which hinders the implementation of solar thermal hybrid technologies.

- The literature survey suggests that the most appropriate, economic, most accessible and practically feasible method of integrating solar energy with CFPP is replacing extraction steam used for feedwater heating with solar energy. This is because of the fact that it does not require any change in the existing coal-based power plant.

- The best and most efficient way to introduce solar energy into regenerative Rankine cycle is to substitute high-pressure extraction steam.

- The other integrating options such as DSG and introducing high-pressure and high-temperature steam into the existing Rankine cycle requires some modification in the boiler/turbine system, thereby complicating the process.

- Hybridization of coal-based thermal power plants is the most economical and feasible solution for mitigating climate change and achieving sustainable development goals for developing countries.

- There is a lack of government support and policies which are responsible for the present status of solar thermal hybrid technologies.

In light of the above-mentioned literature gaps, this research work's broad and specific objectives have been defined in Chapter-1, 'Introduction'.