CHAPTER-5

RESULTS AND DISCUSSION PART-2

5.1 Introduction

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 options. 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.

5.2 System Description

A 660 MW coal-fired supercritical thermal power plant (TPP) has been chosen as a reference plant for establishing the integration of solar thermal energy (STE) into an existing conventional CFPP. The nearest geographic location of the plant under study in India is Delhi. The TPP's main components are condenser, steam generator (SG), turbine, generator, FWHs, and pumps. The system consists of one HPT, one IPT, one BFPT, one LPT, four low-pressure FWHs (LPH), one deaerator, and three high-pressure FWHs (HPH) as presented in Figure 5.1. It has main steam parameters of 242 bar/566 °C with a feedwater temperature of 288.7 °C at SG inlet. The reference plant is assumed to operate at its max continuous rating capacity, and therefore, the plant's output is 670 MW as per the heat balance sheet. Hence, all the calculations have been carried out for 670 MW. In the original power system, coal is the primary external energy source that provides heat to the working fluid to achieve the designed temperature and combustion pressure. Thus, the superheated steam generated in the SG, expands in turbines to produce work and then cooled down in the condenser to its liquid state. Before the integration, to increase the average temperature of the "regenerative Rankine cycle," the feedwater, while passing through eight FWHs is preheated by bled steam extracted from different stages of turbines.

In the solar-coal hybrid system, the new external energy source is solar energy. After integrating CFPP with STE, the bled-off steam from various stages of turbines is partly or completely substituted by a solar-driven FWH that is arranged in parallel with one or more stages of FWHs. In the present investigation, integration of concentrated solar power system with FWHs is considered, and three different replacement options are presented and discussed, as follows:

- High-pressure FWH No.1 is substituted by solar field, as depicted in Figure 5.2.
- Both high-pressure FWHs are substituted by solar field, as depicted in Figure 5.3.
- All high-pressure FWHs are substituted by solar field, as depicted in Figure 5.4.

In Option-1, the 1st stage extraction steam is cut off, and the feedwater is preheated by solar field added in parallel to FWH up to the required inlet temperature. In Option-2, the 1st and 2nd stage extraction steam is cut off, and the feedwater is preheated by solar field added in parallel to FWHs up to the required inlet temperature. In Option-3, the 1st, 2nd, and 3rd stage extraction steam are cut off, and the feedwater is preheated by solar field added in parallel to FWHs up to the required inlet temperature. Such integration will lead to the requirement of reduced steam to generate the rated amount of electricity, and thus coal can be saved in a fuel-saving approach. And in the power boosting approach, such hybridization will lead to augmented power output, keeping the same coal consumption.

5.3 Postulates

The succeeding guesses are considered for the present investigation:

- The integrated plant under study is assumed to operate at full load and at turbine maximum condition rating.
- For a particular FWH under examination, the STE substitutes bled steam completely.
- For remaining FWHs, normal feedwater regeneration using turbine bled steam (TBS) continues.
- When feedwater heating is undergoing in a specific FWH using solar energy, the rise in feedwater temperature across the FWH will be equal to the temperature reached in case of regeneration through TBS.
- During feedwater heating using solar energy, it is supposed that only sensible heating of working fluid and HTF takes place.
- When feedwater heating is done using solar energy in a specific heater, the mass flow rates of extraction steam supplied to other FWHs will vary and can be obtained through first law analysis.
- All calculations are based on steady-state conditions. The temperatures and pressures of steam in the cycle at all points are assumed to be unchanging.
- Three hundred sunny days in a year and 8 hours of daily sunshine are considered in this study.
- DNI is assumed as 500 W/m^2, and the efficiency of solar collectors is considered as 60% (Ahmadi et al. 2017).
- HTF considered in this study is Therminol VP-1.

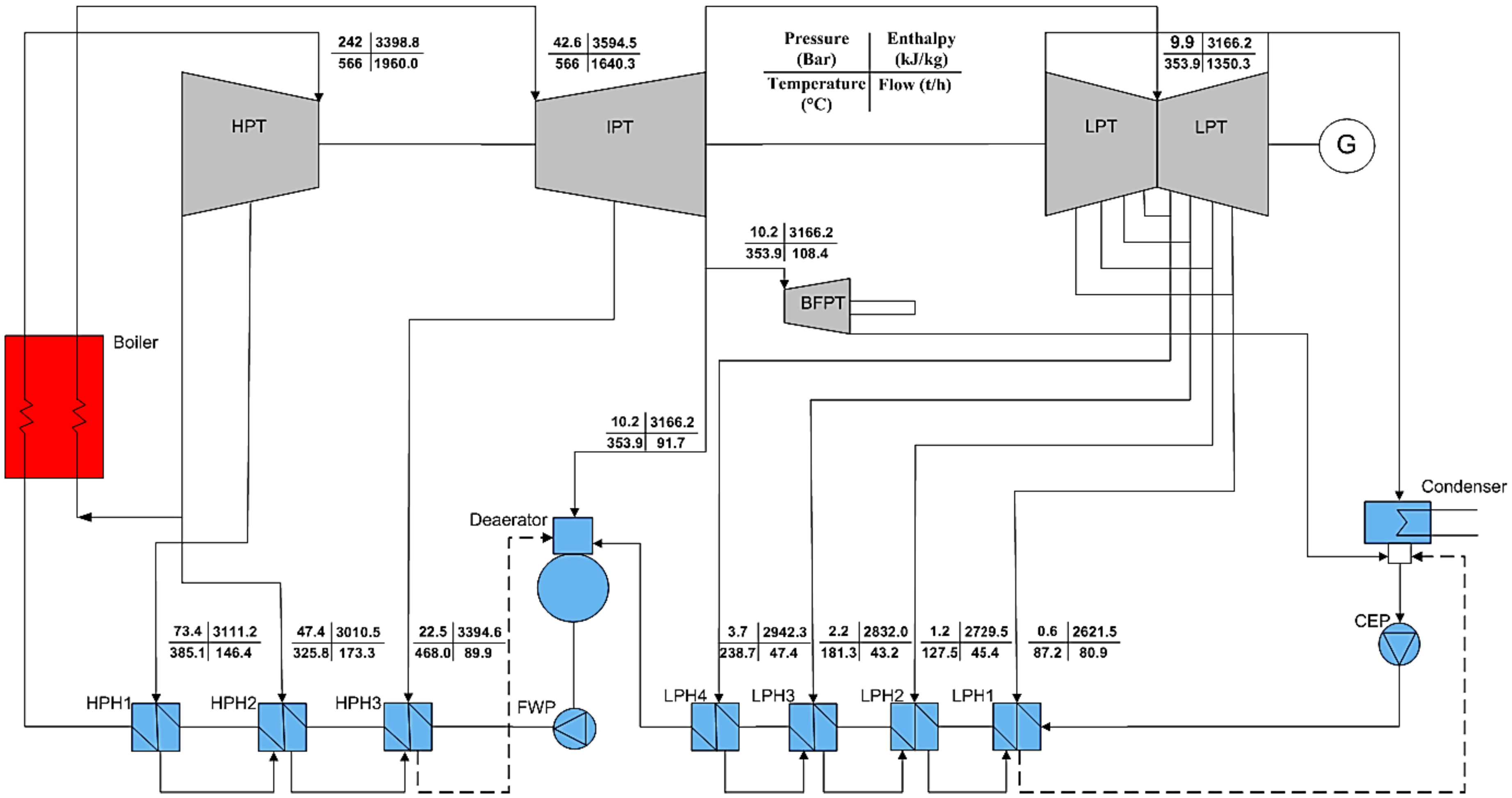


Figure 5.1: Representation of reference plant of 660MWe original CFPP (Base Case).

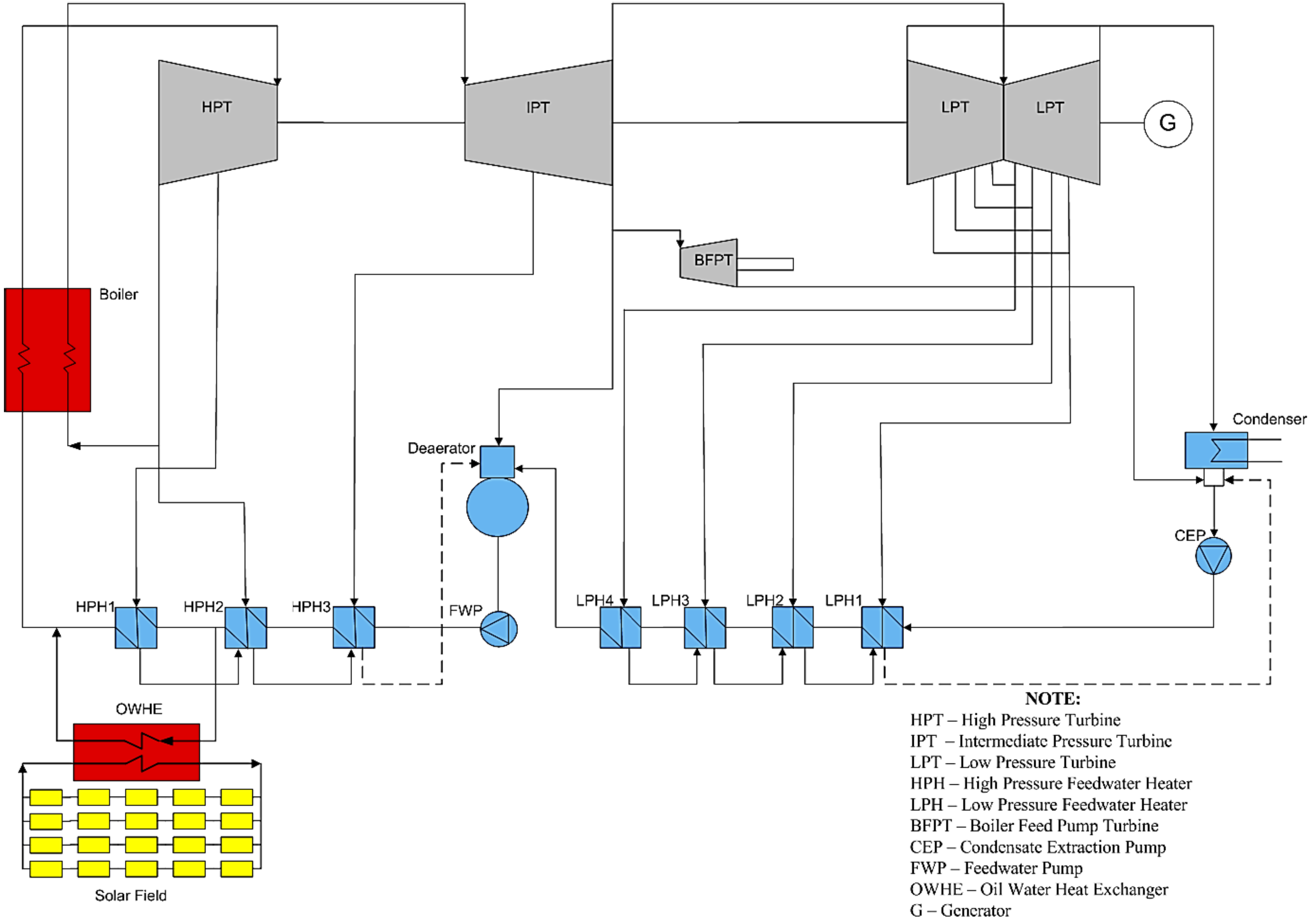
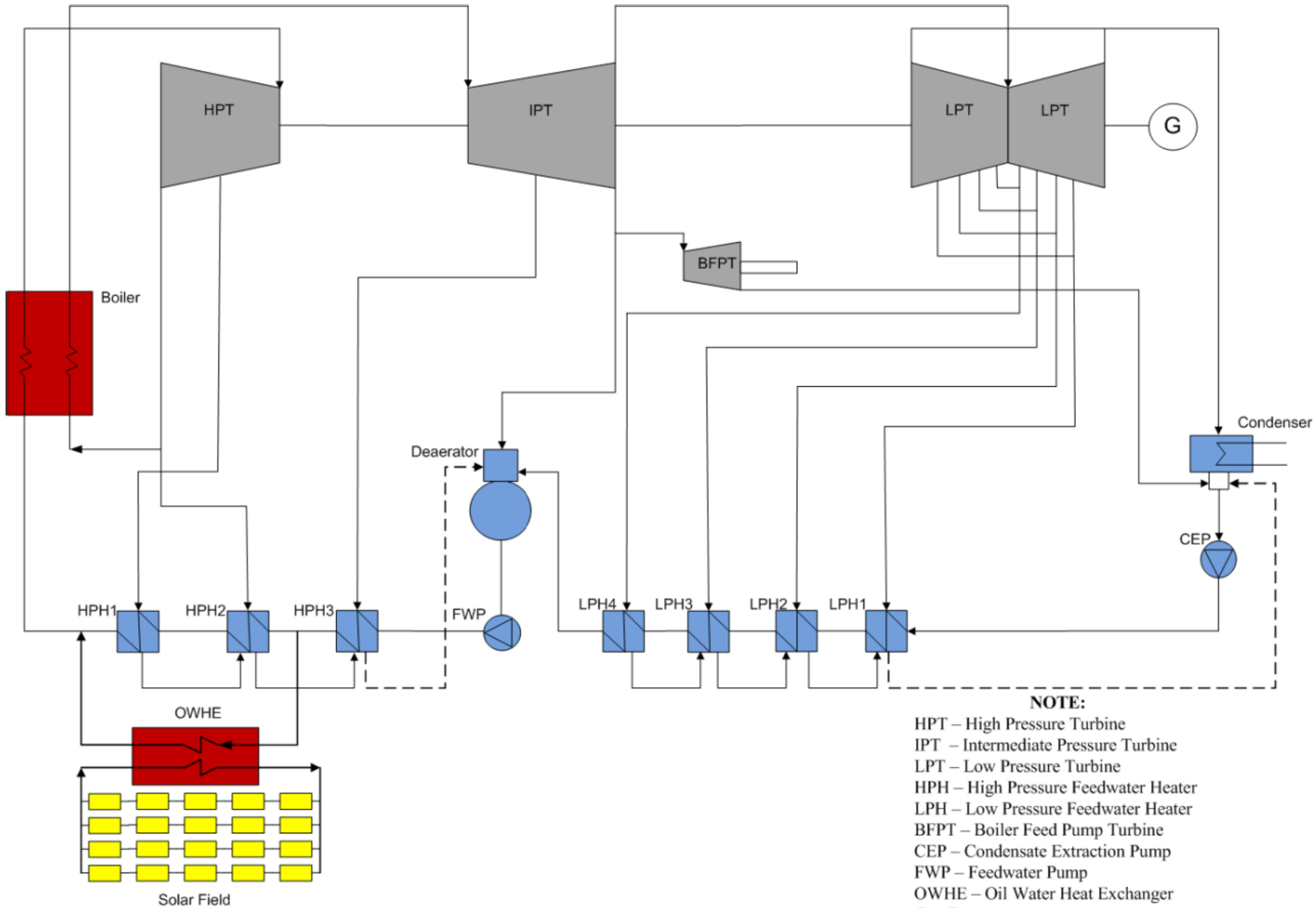


Figure 5.2: Representation of 660MWe "Solar-coal hybrid power plant" (Option-1).



NOTE:
HPT – High Pressure Turbine
IPT – Intermediate Pressure Turbine
LPT – Low Pressure Turbine
HPH – High Pressure Feedwater Heater
LPH – Low Pressure Feedwater Heater
BFPT – Boiler Feed Pump Turbine
CEP – Condensate Extraction Pump
FWP – Feedwater Pump
OWHE – Oil Water Heat Exchanger
G – Generator

Figure 5.3: Representation of 660MWe “Solar-coal hybrid power plant” (Option-2).

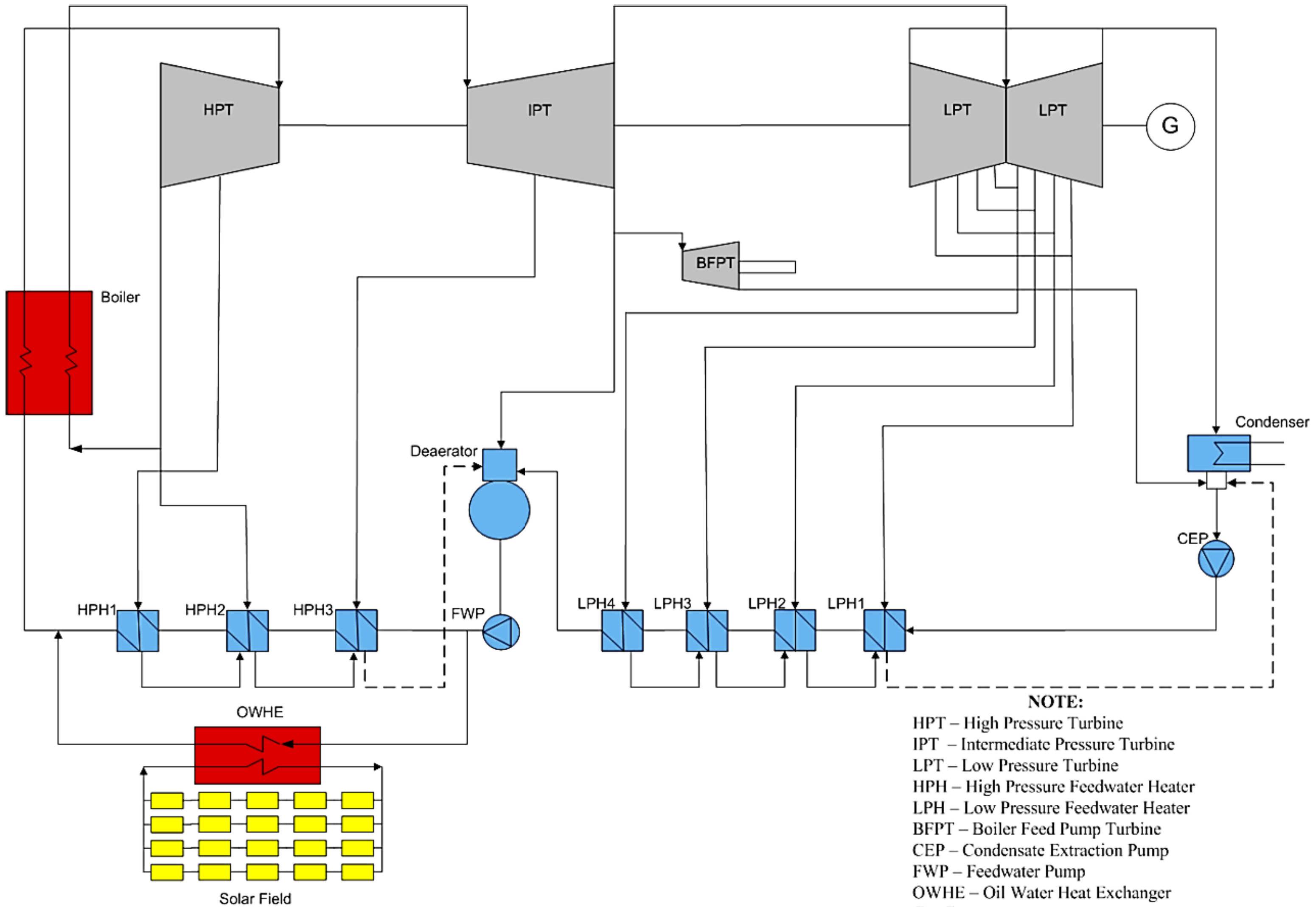


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Figure 5.4: Representation of 660MWe “Solar-coal hybrid power plant” (Option-3).

5.4 Solar Collector Field and Performance Parameters

In this study, PTC solar technology has been considered for integrating STE into a conventional coal-based power plant. The DNI data for the location of the plant under study for a TMY has been obtained from NREL's System Advisor Model (SAM) library (Source: https://sam.nrel.gov/,"). The variation of DNI for all the months of a TMY has been shown in Figure 5.5. Table 5.1 presents the details of geometrical and optical parameters of PTC (ET-150). Therminol VP-1 is HTF in "oil water heat exchanger". The various performance parameters of the solar field have been calculated as under.

Table 5.1:

PTC (ET-150) - Geometrical and optical parameters

Parameters	**Specifications**
Outer diameter of absorber tube (m)	0.07
Inner diameter of absorber tube (m)	0.066
Outer diameter of the glass envelope (m)	0.12
Inner diameter of the glass envelope (m)	0.115
Number of modules/collector	12
Each module length (m)	12.27
Length of the mirror in each module (m)	11.9
Focal length (m)	1.71
Width of aperture (m)	5.77
Intercept factor	92%
Reflectivity of mirror	92%
Transmissivity of glass	94.5%
Absorptivity	94%

The input energy to the solar field ($\dot{Q}_s$) and the output energy of the PTC solar field ($\dot{Q}_c$) are evaluated using equations 3.25 and 3.26 respectively as discussed in Chapter-3. In this study, the collection efficiency of PTC is taken as 60% (Pai 1991).

The collector area needed to transfer the required output energy is evaluated as using equation 3.27 given in Chapter-3. Plant energy efficiency (η_I) is calculated using equation 3.28 as described in Chapter-3. The energy performance index (EnPI) in power boosting mode is defined according to equation 3.29. The solar contribution (%) is obtained using equation 3.30. The exergy efficiency (η_{II}) and the exergy performance index (*ExPI*) have been calculated using equations 4.2 and 4.4 respectively.

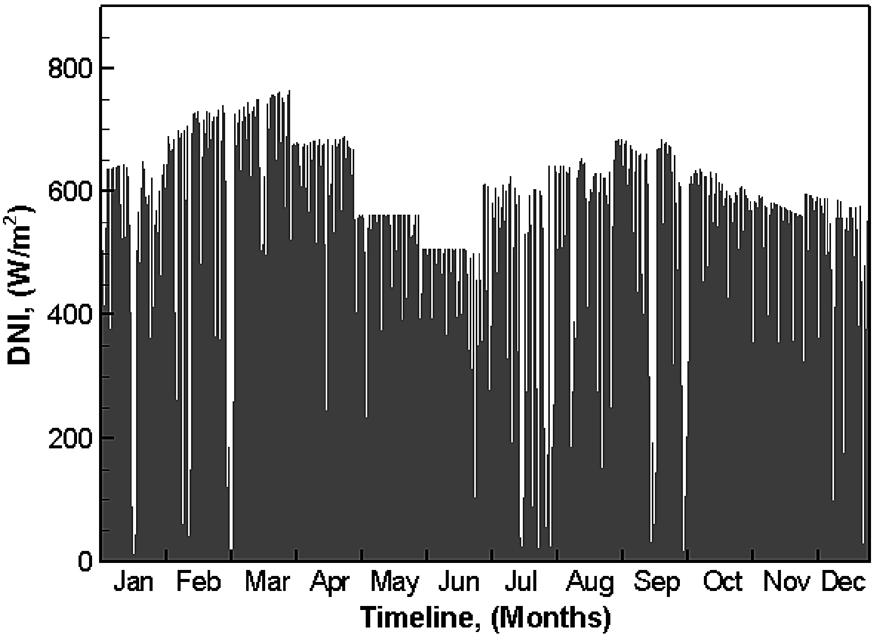

Figure 5.5: Variation of DNI for all the months of a typical meteorological year.

5.5 Economic Parameters

The capital cost of 660 MWe supercritical coal-based power plant with a single unit is about 716 USD/kWe as per norms of CERC “order no: L-1/103/CERC/2012” (Jayaraman et al. 2012). The present study considers the same for economic analysis. The procedure implemented by Ramaswamy et al. (Ramaswamy et al., 2012) is considered for calculating the capital costs of the integrated plant under study. The investment cost of SCHPP has two main components i.e., DCC and ICC. The DCC includes costs of the power block, land, planning of the site, and solar field. While ICC includes costs of “Engineering, Procurement & Construction”, “Project Management”, “Interest during Construction”, and Pre-operative expenses. The detailed procedure for evaluating DCC and ICC of integrated SCHPP is given in Table 5.2. The total capital cost for all studied options has been computed and presented in Table 5.3.

For evaluating the annualized cost of electricity (*ACoE*) and the levelized cost of electricity (LCoE) generation, the procedure followed by Suresh et al. (2010) as described in Chapter-3 is adopted in this study. The discount rate is considered as 12%, and the power plant life is taken as 25 years. The plant capacity factor (*PCF*) has been taken as 0.85 and auxiliary power consumption (*APC*) as 7.5%. The cost of fuel is considered as 32.52 USD/ton (Adibhatla and Kaushik 2017). The cost of capital/unit (*CC*), the capital recovery factor (*CRF*) and the annualized capital cost (*ACC*) per kW have been computed using equations 3.31, 3.32 and 3.33 respectively as mentioned in Chapter-3.

Net energy generated annually (P_{Net}) and the fixed capital cost/unit (*FCC*) are calculated using equations 3.34 and 3.35 of Chapter-3 respectively. In this study, the fixed operation & maintenance cost (*FOM*) is considered as 27.66 USD/kWe as per tariff norms of CERC, 2019 (CERC 2019). The fixed O&M cost/unit, the cost of fuel/unit (C_F) and the total variable cost/unit (C_V) have been obtained using equations 3.36, 3.37 and 3.38 respectively. In the study, the variable O&M cost (C_{VOM}) is considered as 0.00325 USD/kWh (Adibhatla and Kaushik 2017).

Table 5.2:

Methodology adopted for economic analysis of plant under study

Item Description	Unit	Cost	Formula Used
A. "Direct Capital Costs" (DCC)			
i. Solar			
Land	USD/m^2	2.44	$A_a \times LM_r \times L$and cost/ unit area
Site Preparation	USD/m^2	2.33	$A_a \times LM_r \times$ Site preparation cost/unit area
ii. Solar Field			
Mirrors	USD/m^2	51.79	$A_a \times M$irror cost/unit area
Support Structure Weight/aperture area Fabrication	 Kg/m^2 USD/kg	 19 3.17	$A_a \times Cost\ of\ material\ \&\ fabrication\ per\ kg \times support\ structure\ weight\ in\ kg$ per unit area
Foundation	USD/m^2	4.23	$A_a \times F$oundation cost/unit area
Absorber Tubes	USD/m	325	$Total\ length\ of\ absorber\ tube \times$ Cost/unit length
Swivel Joints	USD/unit	1479.67	$(A_a \times\ Cost\ of\ swivel\ joint\ per\ unit) / mirror\ area$ per swivel joint
HTF	USD/litre	4.23	$Cost\ of\ HTF\ per\ litre \times volume\ of$ HTF
HTF System	USD/m^2	40.16	$Cost\ of\ HTF\ sytem\ per\ unit\ area \times\ A_a$
Hydraulic Drives & Electric Motors	USD/unit	2747.97	Cost/unit $\times\ Total\ length\ of\ absorber\ tube/ T$rough length for each drive unit
ECE System	USD/m^2	21.14	$A_a \times S$ystem cost/unit aperture area
B. "Indirect Capital Costs" (ICC)			
"Engineering, Procurement and Construction" (EPC) Cost			10% of DCC excluding land & site preparation cost
"Project Management" (PM) Cost			5% of DCC excluding land & site preparation cost
"Interest During Construction" (IDC)			DCC excluding land & site preparation cost $\times$ $debt$ (%) $\times$ debt cost $\times$ 0.5
Pre-Operative Expenses			DCC excluding land & site preparation cost $\times$ $debt$ (%) $\times$ debt cost $\times$ 0.01

*Absorber tube length = [actual aperture area (A_a)/chord length]

*Land to mirror area ratio (LM_r) = 3.92

Table 5.3:

Various costs related with economic analysis of plant under investigation

Costs	**Base Case**	**Replacement Options**		
		Option 1 (FWH #1)	**Option 2 (FWH #1+2)**	**Option 3 (FWH #1+2+3)**
A. Direct Capital Cost (in Million USD)				
Power Block	473.00	473.00	473.00	473.00
Solar				
Land	0	2.49	5.86	8.29
Site Preparation	0	2.38	5.59	7.92
Sub Total	0	4.87	11.45	16.21
Solar Field				
Mirrors	0	13.49	31.72	44.89
Support Structure	0	15.69	36.89	52.20
Foundation	0	1.10	2.59	3.67
Absorber Tubes	0	14.67	34.50	48.82
Swivel Joints	0	1.40	3.28	4.65
Hydraulic Drives & Electric Motors	0	0.83	1.94	2.75
ECE System	0	5.51	12.95	18.32
Sub Total	0	52.67	123.88	175.30
Total Direct Capital Cost	473.00	530.54	608.33	664.51
B. Indirect Capital Cost (in Million USD)				
EPC cost	47.30	52.57	59.69	64.83
PM cost	23.65	26.28	29.84	32.42
Interest during construction (IDC)	23.177	25.76	29.25	31.77
Pre-operative expenses	0.473	0.53	0.60	0.65
Total Indirect Capital Cost	94.60	105.13	119.38	129.66
Total Capital Cost	**567.6**	**635.67**	**727.71**	**794.17**

The effect of escalation in annual fuel and O&M cost using levelizing factor (*LF*) is taken into account for calculating ACoE. The equations 3.39, 3.40 and 3.41 as described in Chapter-3 are used to determine the annualized cost of electricity generation (*ACoE*), the equivalent discount rate with escalation (d_e) and the levelizing factor (*LF*) respectively. An escalation rate (e) of 2% in variable cost and fuel/O&M-fixed is taken into account for economic investigation (Suresh et al. 2010).

The levelized fuel and O&M cost (C_L), the levelized cost of electricity generation (*LCoE*) and the simple payback period (*SPP*) of the plant under study have been calculated using equations 3.42, 3.43 and 3.44 respectively.

5.6 Results and Discussion

The main parameters of turbine bled steam, and the reference plant's thermal performance parameters for different options considered in this study are given in Table 5.4. For the base case, the design energy efficiency of the 660 MWe CFPP is 41.7%. The results presented in Tables 5.4, Table 5.5 and Figure 5.6 showed that for Option-1 (TBS to HPH1 is replaced with solar energy), Option-2 (TBS to HPH1 and HPH2 is replaced with solar energy) and Option-3 (TBS to HPH1 to HPH3 is replaced with solar energy) the improvement in energy efficiency over the base case is 6.37%, 13.69% and 16.83% respectively. And the improvement in exergy efficiency over the base case is 6.27%, 13.58%, and 16.72% for all three considered options, respectively. The improvement for Option-2 is more than twice that of Option-1. This is because, in Option-2, the steam saved (ton/h) and thus thermal energy saved is about 2.18 and 2.14 times more than Option-1, respectively.

In power boosting mode, the generator power output of the solar-coal hybrid power plant is increased from the generator's rated power output for all three options by 42/91/112 MW, respectively, as presented in Table 5.6. The solar collector area of about 26/61.2/86.7 ha is required for all three options considered in this study, respectively. The requirement of land for the solar field is about three times the collector area (Pai 1991).

Table 5.4:

Thermal performance parameters for various FWH replacement options

Replacement Option		**Option 1 (FWH #1)**	**Option 2 (FWH #1+2)**		**Option 3 (FWH #1+2+3)**		
Steam saved (ton/h)		146.38	#1	#2	#1	#2	#3
			146.38	173.28	146.38	173.28	89.87
			319.66		409.53		
Steam Inlet Temperature (°C)		385.1	385.1	325.8	385.1	325.8	468.0
Steam Outlet Temperature (°C)		264.3	264.3	221.5	264.3	221.5	189.4
Steam Inlet Pressure (bar)		73.38	73.38	47.37	73.38	47.37	22.55
Thermal Energy Rate (kJ/h)		455414344.8	977061742.8		1282137839		
Thermal Energy (MW)		126.5	271.4		356.2		
$W_{Turbine}$ (MW)	**HP**	207	207		207		
	IP	207	227		227		
	LP	298	327		348		
	Overall	712	761		782		
Cycle Efficiency, η (%)		44.36	47.41		48.72		

The results presented in Table 5.6 showed that the unit heat rate decreases with an increase in solar contribution for all studied options. Figure 5.7 displays the variation of energy performance index (*EnPI*) and exergy performance index (*ExPI*) for all replacement options. From Figure 5.7, it can be clearly observed that the value of ExPI is greater than EnPI for all replacement options. Both EnPI and ExPI are maximum for Option-2, and it can also be seen that the highest ExPI is obtained for Option-2. This clearly shows that the exergetic solar energy utilization for feedwater heating is higher than the energetic utilization of solar energy for feedwater heating at higher temperatures. The percentage solar contribution and percentage power-boosting for all replacement options are shown in Figure 5.8. It can be seen from Figure 5.8 that the solar contribution for Option-3 is the highest (19.35%), followed by Option-2 (15.46%), and the solar contribution is the least for Option-1 (7.85%). The biggest improvement in power-boosting mode is witnessed for Option-3 (16.72%), followed by Option-2 (13.58%) and Option-1 (6.27%).

Table 5.5:

Energetic and Exergetic performance comparison of 660 MWe solar-coal hybrid power plant

Replacement Options	**Power Boosting Mode**				
	Gross power output (MWe)	**Energy Efficiency (%)**	**Improve-ment over base case (%)**	**Exergy Efficiency (%)**	**Improve-ment over base case (%)**
Base Case	670	41.7	-	40.18	-
Option 1 (FWH #1)	712	44.36	6.37	42.70	6.27
Option 2 (FWH #1+2)	761	47.41	13.69	45.64	13.58
Option 3 (FWH #1+2+3)	782	48.72	16.83	46.90	16.72

Table 5.6:

Performance indicators of the solar-coal hybrid power plant

Performance parameters	**Replacement Options**		
	Option 1 **(FWH #1)**	**Option 2** **(FWH #1+2)**	**Option 3** **(FWH #1+2+3)**
Net Heat Rate (kJ/kWh)	8115.32	7592.79	7388.89
Power Boosting (MW)	42	91	112
Solar Collector Area (m^2)	260424	612495	866749
Solar Contribution (%)	7.85	15.46	19.35

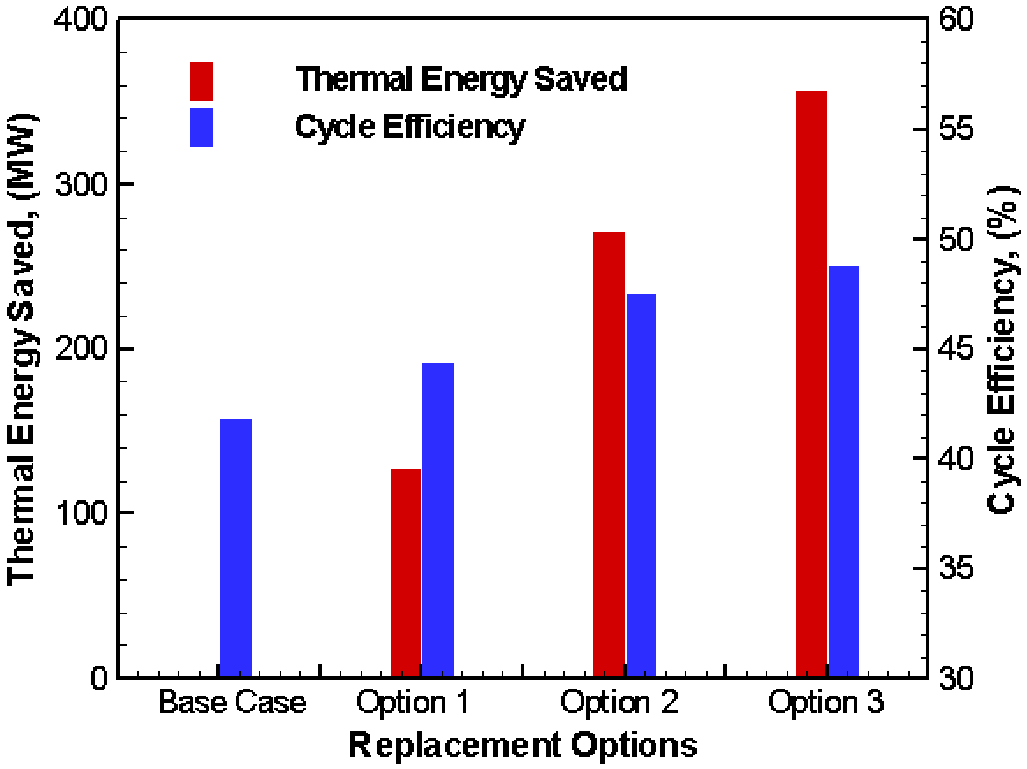

Figure 5.6: Thermal energy saved and cycle efficiency for different replacement options.

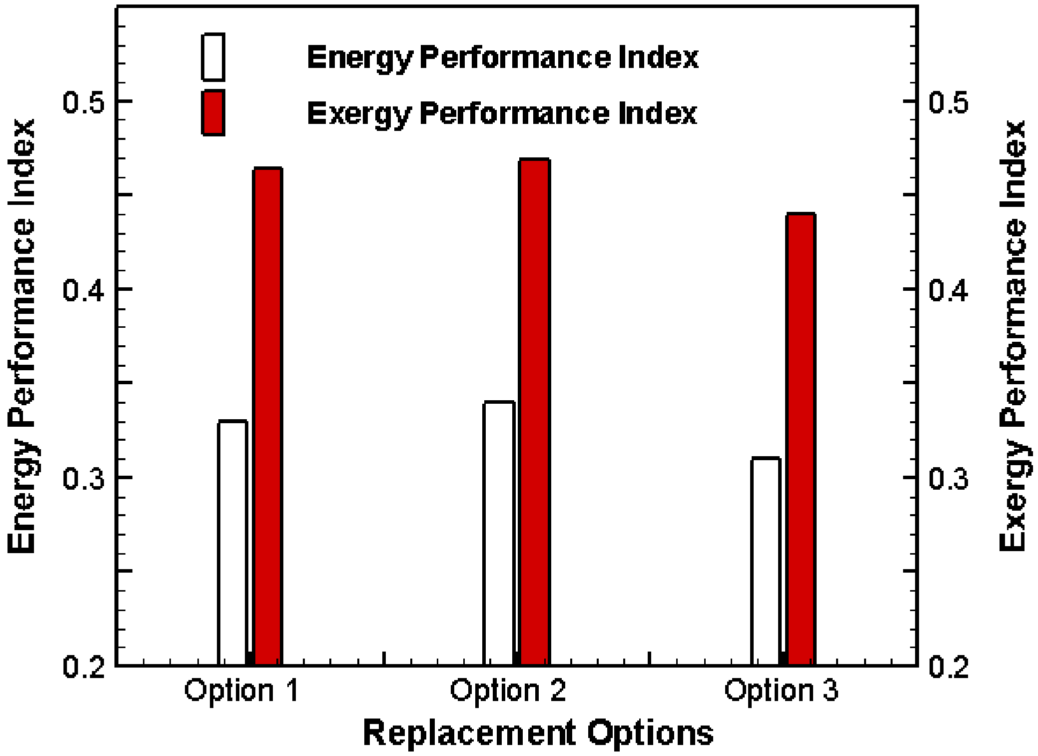

Figure 5.7: Energy performance and Exergy performance index for different scenarios.

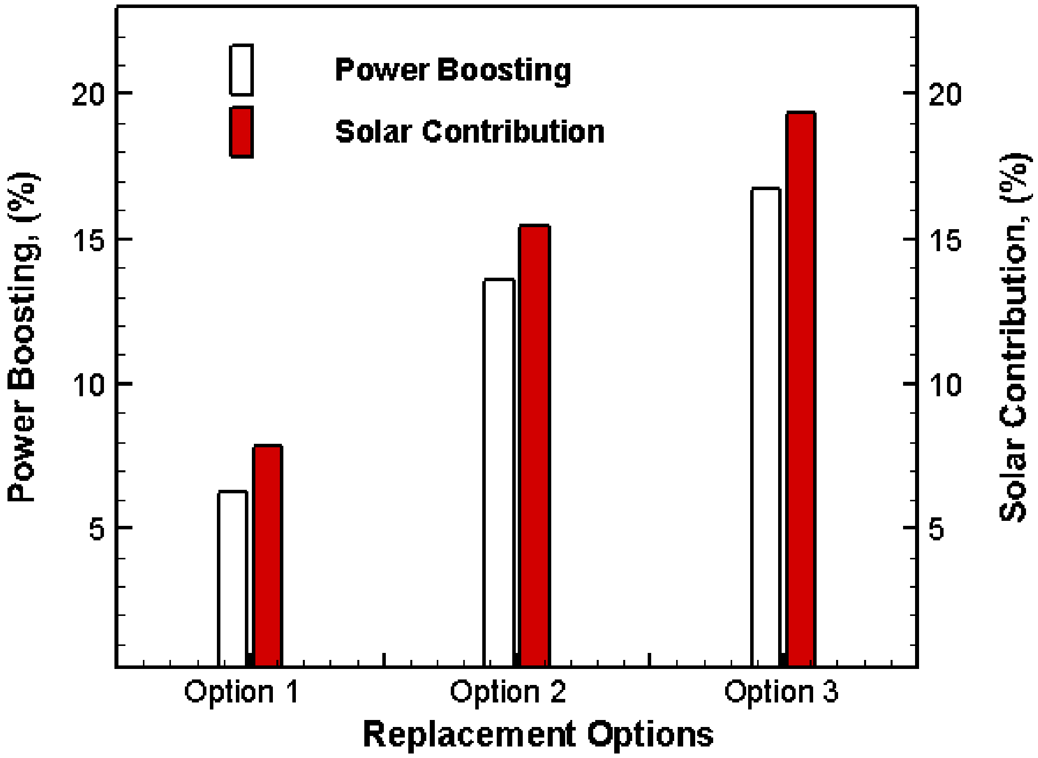

Figure 5.8: Power-boosting and solar contribution for different replacement options.

5.6.1 Environmental analysis

The coal-based thermal power plants release various pollutants into the atmosphere and hence cause environmental degradation. Among these pollutants, CO_2 emissions are the major contributors to environmental pollution. Therefore, in the present investigation, solar energy is integrated under different scenarios into 660 MWe supercritical coal-based TPP to reduce coal consumption and reduce CO_2 emissions. In this study, the annual coal saving is calculated for all three options using thermodynamic energy analysis for solar-coal hybrid power plant (Fuel saving approach). Corresponding to annual coal saving, the annual reduction in CO_2 emissions is evaluated using the methodology adopted by Sunil and Soni (Sunil and Soni 2019a, Sunil and Soni 2019b, Sunil and Soni 2020).

The annual coal saving and annual reductions in CO_2 emissions for all three replacement options considered are shown in Figure 5.9. Option-1 results in annual coal saving and the corresponding reduction in CO_2 emissions of about 47496 tons and 68486 tons, respectively. For Option-2, the annual coal saving and the corresponding reduction in CO_2 emissions are 96744 tons and 139500 tons, respectively. In Option-3, the annual coal saving and the corresponding reduction in CO_2 emissions are 116256 tons and 167635 tons, respectively. This can be inferred from Figure 5.9 that the fuel-saving and reduction in CO_2 emissions are proportionate with solar contribution for all three options discussed in this study. Considering the cost of fuel as 32.52 USD/ton, the annual savings in the fuel cost are 1.5/3.1/3.8 million USD for Option-1, Option-2, and Option-3, respectively.

5.6.2 Economic analysis

For economic analysis, the various economic parameters have been calculated using equations 3.31 to 3.44 as described in Chapter-3. The methodology given in Table 5.2 and various costs associated with reference and hybrid plant given in Table 5.3 have been adopted for the economic investigation. The exhaustive economic analysis of the present study is given in Table 5.7. The results presented in Table 5.7 show that the increase in total capital costs over the base case for Option-1 is 11.99%, for Option-2 is 28.2%, and for Option-3, it is 39.92%.

The LCoE and SPP for all three replacement options are shown in Figure 5.10. Figure 5.10 shows that LCoE increases from the base case scenario to all three replacement options. Similarly, the simple payback period also increases. The economic analysis results in Table 5.7 show that LCoE (USD/kWh) for the base case and three replacement options are 0.045/0.046/0.047/0.048 and simple payback period (years) are 3.03/3.33/3.68/3.88, respectively. The results of energetic, environmental, and economic analysis discussed in the present investigation are in accordance with the previous studies available in the literature (Suresh et al. 2010, Adibhatla and Kaushik 2017).

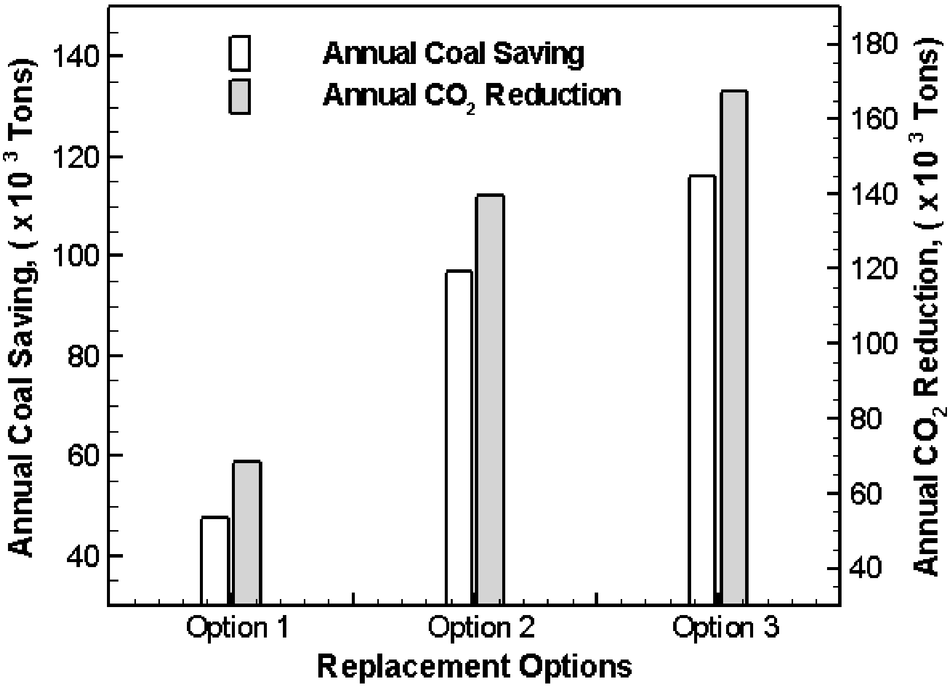

Figure 5.9: Annual coal saving and CO$_2$ reduction for various replacement options.

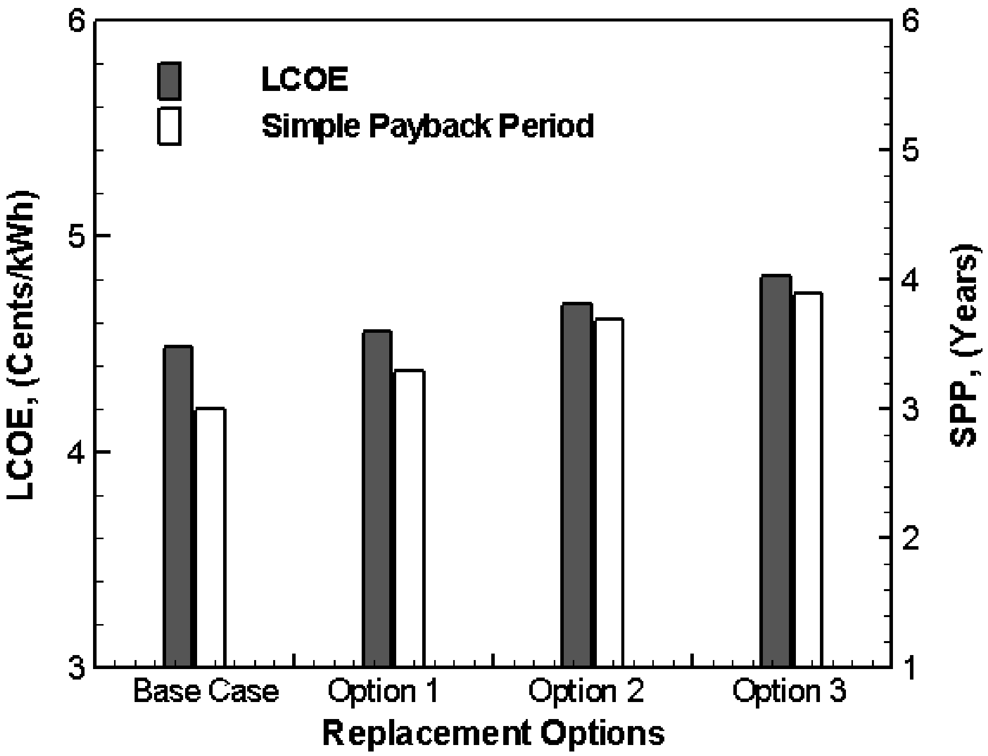

Figure 5.10: LCoE and SPP for different replacement options.

5.7 Summary

In this chapter, the energetic, environmental, and economic investigation of a 660 MWe supercritical coal-fired thermal power plant integrated with concentrated solar thermal energy has been carried out. The integration of solar energy into the existing 660 MWe supercritical coal-fired thermal power plant is done using three replacement options. The energetic analysis results show that the highest energy efficiency of 48.7% is obtained for Option-3. Similarly, the results of exergetic analysis show that the highest exergy efficiency of 46.90% is attained for Option-3. The environmental analysis shows that the maximum reduction in coal consumption (116256 tons of coal) and CO_2 emissions (167635 tons of CO_2) is also for Option-3. This is because of the maximum solar contribution (19.35%) in Option-3.

Table 5.7:

Economic analysis of 660 MWe supercritical Solar-Coal hybrid power plant

Item Description	**Unit**	**Base Case**	**Replacement Options**		
			Option 1 (FWH#1)	**Option 2 (FWH#1+2)**	**Option 3 (FWH#1+2+3)**
Total Capital Cost	Million USD	567.60	635.67	727.71	794.17
Generator Power Output	MW	670	670	670	670
Capital Cost/Unit	USD/kWe	847.16	948.76	1086.13	1185.33
Power Plant Life	Years	25	25	25	25
Discount Rate	Fraction	0.12	0.12	0.12	0.12
CRF	Fraction	0.13	0.13	0.13	0.13
ACC	USD/kW	108.01	120.97	138.48	151.13
Annually Net Energy Generated (P_{Net})	kWh/kW	6887.55	6887.55	6887.55	6887.55
FCC/unit	USD/kWh	0.016	0.018	0.020	0.022
C_{FOM}/unit	USD/kWh	0.004	0.004	0.004	0.004
GCV	kJ/kg	15907	15907	15907	15907
Net Unit Heat Rate (UHR_{Net})	kJ/kWh	8624.05	8115.32	7592.79	7388.89
Fuel Cost (C_F)/unit	USD/kWh	0.0176	0.0166	0.0155	0.0151
C_V/unit	USD/kWh	0.0208	0.0199	0.0188	0.0184
ACoE	USD/kWh	0.0406	0.0414	0.0429	0.0443
Escalation Rate (e)	Fraction	0.02	0.02	0.02	0.02
Equivalent Discount Rate with Escalation (d_e)	Fraction	0.098	0.098	0.098	0.098
LF	Fraction	1.17	1.17	1.17	1.17
Levelized Fuel and O&M Cost (C_L)	USD/kWh	0.029	0.028	0.027	0.026
LCoE	USD/kWh	0.045	0.046	0.047	0.048
SPP	Years	3.03	3.33	3.68	3.88

Similarly, the annual saving in fuel cost (3.8 million USD) for Option-3 is the highest. In power boosting mode, the augmentation in generator power output is maximum for Option-3, followed by Option-2 and Option-1. The economic analysis results show that LCoE and simple payback period increase slightly with an increase in solar contribution. The simple payback periods for all replacement options are seemingly attractive. The investigation carried out in this chapter suggests that hybridization of coal-fired thermal power plants with solar thermal energy is a very lucrative alternative. Such hybridization will reduce environmental degradation and help developing countries in clean power generation and achieve their sustainable development goals.