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A Thermodynamic Study of a Conventional 500 MW Coal Fired Power Plant Hybridized with Solar Energy

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Abstract

In this work, an effort is made to evaluate the performance improvement and harmful emission reduction of a 500 Megawatt conventional coal-fired thermal power plant by installing a parabolic solar trough at the low pressure heater for regeneration. Here, parabolic solar troughs are used in place of LP heaters for heating the feed water before it enters the economizer of the boiler. As a result, the steam flow rate through turbines will increase, which boosts the work output and also decreases the overall coal consumption, resulting in a huge reduction of harmful emissions of various gases as well as a reduction in the investment cost on coal. As an outcome, the objective of this research is to develop a thermodynamic model that can be used to quantify improvements in network output, total thermal efficiency, and daily coal consumption while reducing ash generation, SO_2, and CO_2 emissions.

1.0 Introduction

Nowadays, the increasing demand of energy has been met mostly by coal-fired thermal power plants. The power conversion efficiency of coal to electrical energy in steam power plants is low and toxic pollutants from the combustion of fossil fuels like coal have a major detrimental impact on the environment and humans. Moreover, inefficient use of coal creates different negative impacts on environment. The primary objective in today's world is to harness the power of the sun. The sun's energy is free, and it's also environmentally friendly, meaning it won't pollute the environment significantly. Solar energy can be used in thermal power stations to reduce the need for coal, which will not only save nature but also save us. Therefore, a strategy is taken to use solar energy in a 500 Megawatt conventional coal-fired thermal power plant for regeneration by installing parabolic solar troughs in place of low pressure heaters. As a result steam flow rate through low pressure turbine will increase with the increase of electricity generation as well as reduction of coal requirement.

Some related research literature has been studied in this work initially in order to comprehend the principles of solar hybridising by parabolic solar trough at the position of LP heater and its thermodynamics performance analysis by thermodynamic 1st and 2nd law.

In a study by Sorour Alotaibi et al. [1], the performance of a 300-megawatt traditional steam power plant in Kuwait was analysed after it was fitted with a solar-aided regenerative system using Parabolic Trough Solar Collectors (PTC) with an aperture area of 25,850 m^2 by eliminating low-pressure (LP) turbine extractions without changing other features. The system study showed that removing the LP turbine extractions increased the steam power plant's output by 9.8 MW and cut fuel costs by 56% over a 25-year period compared to a traditional thermal power station. In a natural gas-fired power plant, Tobias Vogel et al. [2] demonstrated several distinct solar hybridization techniques utilizing a parabolic trough collector. They also showed that, in the Californian Mojave Desert, using solar energy in conjunction with a parabolic trough collector increased power output while decreasing expenses by 27.65%. The Integrated Solar Combined Cycle System (ISCCS) with a parabolic trough, designed by J. Dersch et al. [3] is used to generate energy with enhanced efficiency and reduced specific CO_2 emissions. Kapil Rajendra Jadhav [4] proposed replacing LP and HP heaters in thermal power plants with PTC solar fields to heat feed water. LP and HP heater bypassing saves between 23 and 25 tonnes of coal/hr. Hybridizing thermal power plants with solar fields boosts electricity production by 4-5 MW, or 1% of a 500 MW thermal power plant's output. Using solar power with conventional thermal plants reduces fuel usage. This boosts profits. This is also a coal price compensation element. It reduces CO_2 and other greenhouse gases. Emissions of carbon dioxide, carbon monoxide, nitrogen oxide, and sulphur dioxide were quantified by Chakraborty et al. [5]. The thermodynamic First and Second laws based energetic and exergetic efficiency, rate of destruction of exergy, and enhancement of heat rate of coal based steam turbines were examined by Rana and Mehta [6] at different unit load situations (70 per cent and 85 per cent). When the plant is operated at 85 per cent MCR, the heat rate in the turbine improves by 17.01 kJ/kWh, reducing carbon dioxide emissions by 26.89 kg/h, sulphur dioxide emissions by 26.89 kg/h, and ash formation by 41.47 kg per day.

There have been few studies on solar hybridization, which involves installing parabolic solar troughs in place of the Low Pressure Heater for Regeneration to improve the performance and lower emissions of a traditional coal-fired thermal power plant. So an effort is made to compare the energetic and exergetic efficiency, as well as coal consumption, ash generation, SO_2 and CO_2 emissions, and heat rate improvement of a 500 megawatt coal-fired thermal power plant of Damodar Valley Corporation in India after and before solar hybridization by deploying parabolic solar troughs at the place of the Low Pressure Heater for regeneration.

1.1 Details of the Problem

The Damodar Valley Corporation, an Indian thermal power plant, has a 500 MW coal-fired steam power plant that is under consideration in this study. Figure 1 depicts the flow diagram, while Table 1 summarises the flow and thermodynamic characteristics for the 500 megawatt load. There are five water heaters used in the regeneration process, three of which are low-pressure feed water heaters (LPH) and two of which are high pressure water heaters (HPH). Steam escapes from the HP, IP, and LP turbines and flows into the HPH and LPH for the regeneration process. Figure 2 depicts the installation of parabolic solar troughs in place of low-pressure feed water heaters. A parabolic solar trough heats the boiler feed water before it passes through the economizer and enters the boiler drum. As a result, it is no longer necessary to perform steam bleeding between the stages of the LP turbine. As a result, both the mass flow rate of steam that passes through the LP turbine and the amount of work produced will increase. Less coal will be used, so less ash will be made and less SO_2 and CO_2 will be released into the air.

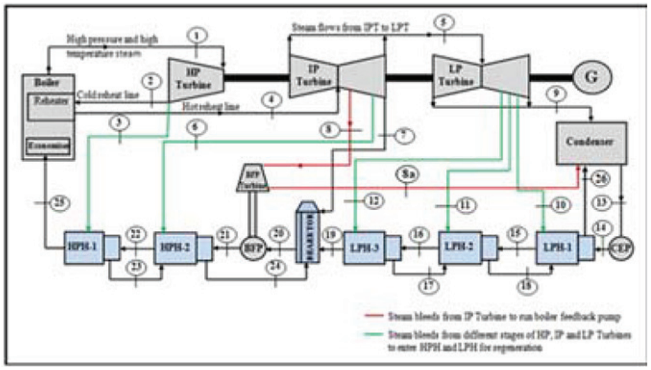

Figure 1: Represents a Flow diagram of the turbine cycle of a 500 megawatts capacity coal-fired thermal power plant

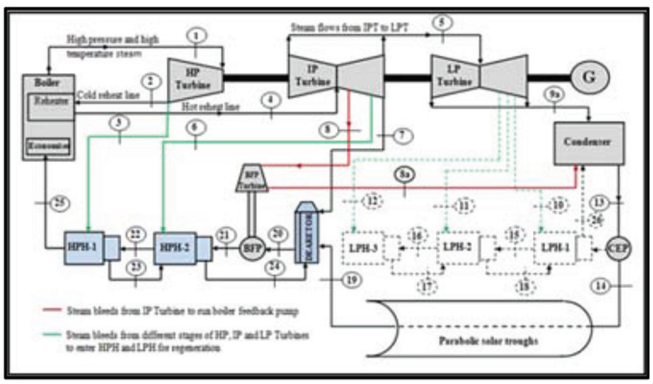

Figure 2: Depicts the turbine cycle of a 500 megawatt coal-fired thermal power plant with parabolic solar troughs installed for regeneration in place of the LP heaters

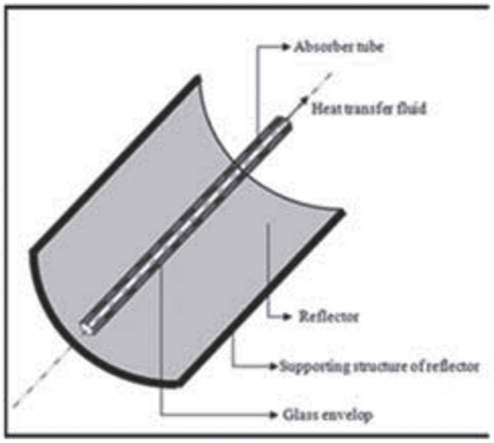

Figure 3: The parabolic solar trough of LS-3 type

1.2 The Parabolic Solar Trough of LS-3 type

LS-3 parabolic trough collectors were chosen for this study because to the fact that these collectors have bigger diameters than the LS-1 and LS-2 kinds, making them more widely used, efficient, and widely available. It can be used in power plants to replace LP heaters. The axis is horizontal and runs north-south. As a result, it may track the sun from east to west. With a special coating, the stainless steel receiver tube is able to absorb more radiation. Conduction heat loss can be prevented with the use of a 66-mm glass tube.

2.0 Thermodynamic Analysis

The following thermodynamic equations are required for thermodynamics 1st law and 2nd law based analysis for before and after hybridization with parabolic solar trough at the place LP heaters.

2.1 A stead State Flow Condition is Considered for Thermodynamic Analysis

The equations of mass, continuity, energy, and then exergy balance are employed for the steady state condition, which are taken from Cengel and Boles [13].

Equation for mass balance

Under the steady state condition, the equation for mass conservation in the control volume [1] is given as

$$\sum\psi_{in} - \sum\psi_{out} = 0 \qquad \text{... (1)}$$

Here ψ is the mass rate (kg/s) of flows.

2.1.1 Equation for Energy balance

Using the first law of thermodynamics, the steady-state energy conservation equation in the control volume can be expressed as follows:

$$\hat{H} - \acute{W} = \sum\psi_{in}\xi_{in} - \sum\psi_{out}\xi_{out} \qquad \text{... (2)}$$

Here $\hat{H}$ and $\acute{W}$ are the heat and work transfer respectively in kJ and ξ is the specific enthalpy in kJ/kg.

2.1.2 Exergy balance equation

On the basis of the 2nd law of thermodynamics, the exergy balance equation in the control volume under steady-state condition is given as

$$Z_{heat} - \acute{W} = \sum\psi_{out}\varepsilon_{out} - \sum\psi_{in}\varepsilon_{in} + \beta \qquad \text{... (3)}$$

Here Z is the exergy transfer and β is the rate of destruction of exergy while e is specific exergy in kJ/Kg.

The net exergy transfer is also presented as

$$Z_{heat} = \sum(1 - \frac{T_0}{T})\hat{H} \qquad \text{... (4)}$$

2.2 The Thermodynamic Analysis is Considered under a Steady Flow Condition

An energy-based analysis is used to determine the turbines' shaft power output rate. After that, exergy flow and exergy destruction are evaluated using the exergy-based analysis. Accordingly,

Actual shaft power output

$$(\acute{W}_{actual}) = \psi_{in}\xi_{in} - \psi_{out}\xi_{out} \qquad \text{... (5)}$$

The energy efficiency of the turbine within control volume is given as follows

$$\eta_I = \frac{\acute{W}_{actual}}{\acute{W}} \qquad \text{... (6)}$$

Therefore heat rate (HR) of turbine is calculated as

$$Heat\ Rate = \{(\psi_s\xi_s - \psi_{fw}\xi_{fw}) \times 3600\}/powergeneration \qquad \text{... (7)}$$

ψ_s and ψ_{fw} are mass flow rate of steam entering HP turbine and feed water entering boiler.

ξ_s and ξ_w are specific enthalpy of steam entering HP turbine and feed water entering boiler.

The rate of exergy destruction or irreversibility is calculated as

$$\beta = Z_{in} - Z_{out} + \acute{W} \qquad \text{... (8)}$$

Here, the total exergy flow rate of each fluid stream through the control volume is given by $Z = \sum\psi\varepsilon$

Table 1: Thermodynamic properties of relevant flow at full load of a 500 megawatts capacity coal-fired thermal power plant of Damodar Valley Corporation

Relevant Flow		Rate of Mass flow in kg/s	Tempera-ture in ºC	Dryness fraction (x)	Pressure in bar	Specific enthalpy "h" in kJ/kg	Specific entropy "s" in kJ/kgK	Specific exergy in kJ/kg	Energy flow rate "Ë" in MW	Exergy flow rate "Ës" in MW
1		415.47	537		172.21	3389.77	6.39	1489.6	1408.34	618.88
2		369.9	337.4		45.62	3046.97	6.45	1128.31	1127.07	417.36
3		45.57	337.4		45.62	3046.97	6.45	1138.31	138.84	51.41
4		369.9	537		41.06	3529.43	7.19	1392.6	1305.53	515.12
5		308.59	289.1		7.25	3035.95	7.24	882.4	936.87	272.3
6		23.38	411.1		17.55	3276.44	7.23	1126.6	76.6	26.34
7		11.67	289.1		7.25	3.35.95	7.24	882.4	115.15	33.47
8		26.26	289.1		7.25	3.35.95	7.24	882.4	115.15	33.47
9		264.48	46.71	0.9124	0.1047	2351.48	7.48	127.43	624.08	33.82
9a	When parabolic solar collectors are used, flow "10", "11","12" are eliminated	308.59	46.71	0.9124	0.1047	2351.48	7.48	127.43	725.64	39.32
10		11.67	73.35	0.9536	0.36	2547.14	7.46	328.15	29.73	3.83
11		21.03	133.6		1.55	2739.06	7.33	560.7	57.59	11.79
12		11.41	190.9		2.87	2847.88	7.29	678.98	32.51	7.75
13		334.85	46.1		0.1	194	0.65	5.63	63.73	1.85
14		334.85	46.3		22.27	195.8	0.65	7.43	64.33	2.44
15		334.85	68.6		22.27	288.96	0.94	14.17	94.93	4.66
16		334.85	106.9		22.27	449.79	1.38	43.88	147.77	14.42
17		11.41	190.5		2.73	2847.81	7.32	671.78	32.51	7.67
18		32.44	73.4		0.36	307.27	0.99	17.58	9.97	0.57
19		334.85	126.5		22.27	532.82	1.6	61.35	175.05	20.16
20		415.47	160.8		6.51	679.06	1.95	103.29	282.13	42.91
21		415.47	164.3		207.51	706	1.96	127.25	293.32	52.87
22		415.47	202.3		207.51	870.85	2.32	184.82	355.76	75.5
23		45.57	207		17.96	884.07	2.4	174.2	40.29	7.94
24		68.95	169.1		7.75	715.27	2.03	115.66	49.32	797
25		415.47	253.7		207.51	1104.04	2.79	277.95	451.02	113.55

The efficiency of exergy, also known as 2nd law efficiency, is calculated as

$$\eta_{II} = \acute{W}_{actual}/(Z_{in} - Z_{out}) \quad \text{... (9)}$$

2.3 Overall Enhancement of Work Output due to use of Parabolic Solar Troughs in place of an LP Heater can be Calculated using the following Formula

For regeneration process, steams bleed from LP turbine and enter into the LP feed water heaters. Now LPH have been replaced by parabolic solar trough. As a result, steam flow rate through LP turbine will be increased and the overall efficiency of the thermal power plant will also be increased.

Work output before solar hybridization considering Fig.1 is expressed as on

$$\acute{W}_{bh} = (\psi_1\xi_1 - \psi_2\xi_2 - \psi_3\xi_3) + (\psi_4\xi_4 - \psi_5\xi_5 - \psi_6\xi_6 - \psi_7\xi_7 - \psi_8\xi_8) + (\psi_5\xi_5 - \psi_9\xi_9 - \psi_{10}\xi_{10} - \psi_{11}\xi_{11} - \psi_{12}\xi_{12}) \quad \text{... (10)}$$

Work output after installing parabolic solar trough at the place LP heaters considering Fig.2 is expressed as on

$$\acute{W}_{ah} = (\psi_1\xi_1 - \psi_2\xi_2 - \psi_3\xi_3) + (\psi_4\xi_4 - \psi_5\xi_5 - \psi_6\xi_6 - \psi_7\xi_7 - \psi_8\xi_8) + (\psi_5\xi_5 - \psi_{9a}\xi_{9a}) \quad \text{... (11)}$$

Enhancement of power output due to installing parabolic solar troughs at the place LP heater

$$= \acute{W}_{ah} - \acute{W}_{bh} \quad \text{... (12)}$$

2.4 Calculation of Emission Reduction of CO_2, SO_2, Saving of Coal and Reduction of Ash Generation

Here, an effort is made to compute the decrease of different greenhouse gases such as CO_2 and SO_2, as well as the reduction of ash generation, all of which can help to reduce pollution in the environment. The existing literature [1, 2, 3] indicates that solar hybridization by deploying parabolic solar troughs at the place LP heater can reduce hazardous emissions. As a result, the following equations are used to calculate the coal savings, CO_2 and SO_2 emission reductions, and ash generation decrease.

Amount of coal saving = (Heat Rate Improvement x Generator Power)/ Gross Calorific Value ... (13)

Table 2: Ultimate analysis the coal by percentage of weight

Name of the constituents in the coal	percentage of weight
Carbon (C)	42.82
Nitrogen (N)	0.82
Hydrogen (H)	2.65
Sulphur (S)	0.34
Oxygen (O)	7.35
Moisture (M)	6.2
Ash (A)	39.82

Equation for emission reduction of CO_2 is given below

Emission reduction of CO_2 = 3.66 x percentage of carbon in Coal x amount of coal saving ... (14)

Equation for emission reduction of SO_2 is given below

Emission reduction of SO_2 = 2.0 x percentage of Sulphur in Coal x amount of coal saving ... (15)

Reduction in Ash Generation = amount of coal saving x percentage of ash in Coal ... (16)

Chemical constituents of coal, weight per cent-based, are obtained from Mejia thermal power station of DVC in order to determine its Gross Calorific Value (GCV).

The equation to evaluate the Gross Calorific Value of coal in kJ/kg is given as

GCV = 327.8421 x C + 1419.8117 x H – 138.171 x O + 92.5327 x S + 636.424 ... (16)

Table 3: Overall work output of turbines in MW and Overall energy efficiency for before and after hybridization

Condition	Overall work output of turbines in MW	Overall energy efficiency
Beforehybridization	512.3	35.5%
Afterhybridization	548.52	37.62%

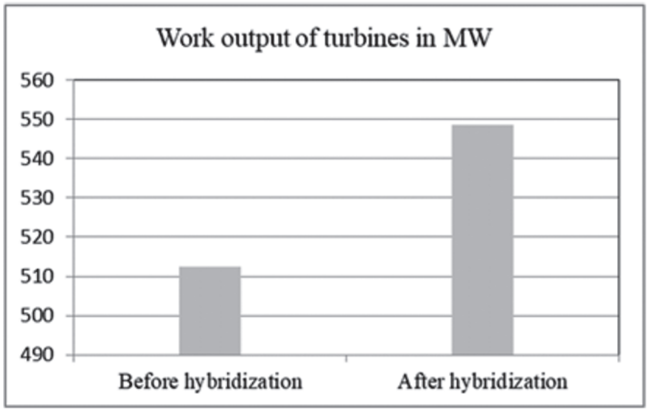

Figure 4: Variation of work output of turbines in MW before and after hybridization

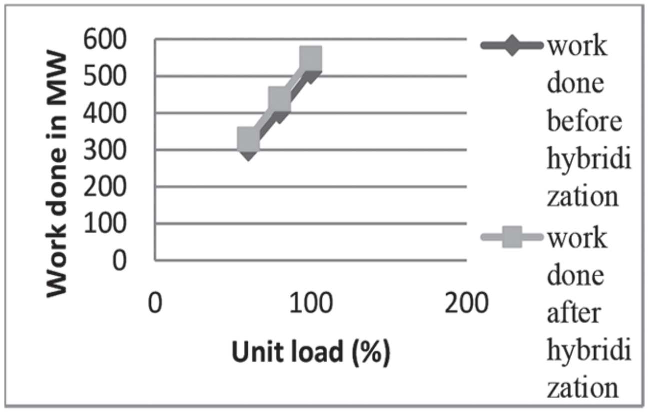

Figure 6: Variation of thermal power plant's work output under varying unit loads prior to and after its solar hybridization with parabolic

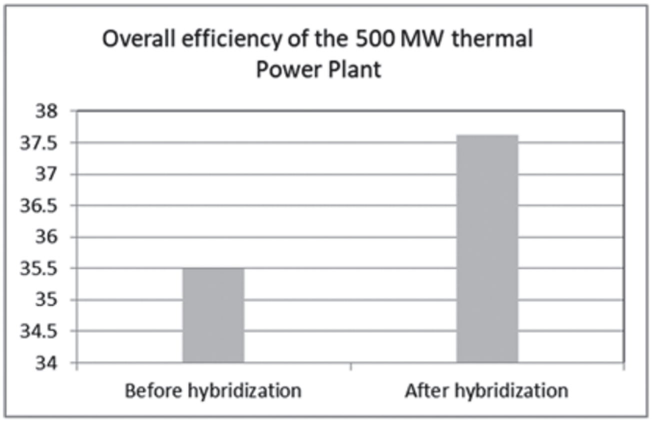

Figure 5: Comparison of the overall efficiency of the 500-MW coal-fired power station before and after the installation of parabolic solar troughs for solar hybridization at the locations of LP heaters

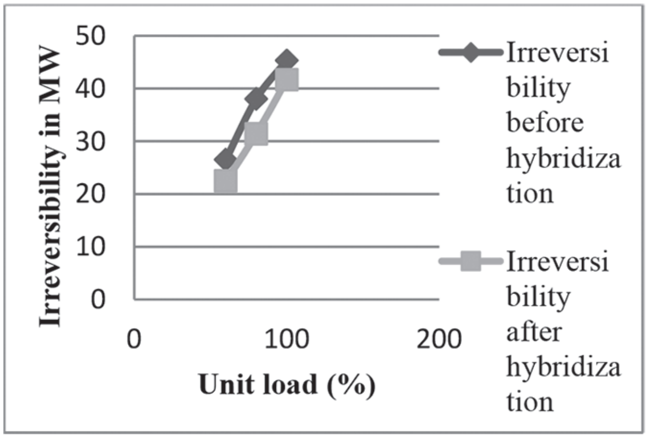

Figure 7: Variation in irreversibility of the 500 megawatt thermal power plant before and after hybridization with a parabolic solar trough at varied unit loads

3.0 Result and Discussions

The steam mass flow rate through the LP turbine is improved due to the deletion of the LP heater and the elimination of steam bleeding from different stages of the LP turbine by employing a parabolic solar trough. As a result of the hybridization with the parabolic solar trough, the work output of turbines as well as total energy efficiency will improve.

According to Figs.5 and 6, as a result of hybridization with a parabolic solar trough by substituting LP heater for regeneration, the amount of work done increases while the amount of irreversibility decreases under various unit load circumstances such as 100%, 80%, and 60%.

Due to solar hybridization by parabolic solar trough, heat rate is also improved more than before hybridization. As a result, coal consumption rate as well as harmful CO_2, SO_2 emission and ash generation will be decreased more due to solar hybridization.

4.0 Conclusion

The current study reported that installing a parabolic solar trough at the Low Pressure Heater for regeneration at a conventional coal-fired thermal power plant with a capacity of 500 megawatts (MW) improved both the plant's performance and its emissions. It was noticed that the output of the cycle

Table 4: The rate of flow of energy, exergy flow and irreversibility at various unit loads, such as 100%, 80%, and 60% before hybridization

Unit load	Energy input in Megawatts	Energy output in Megawatts	Exergy input in Megawatts	Exergy output in Megawatts	Work done in Megawatts	Irreversibilit in Megawatts	Actual work done in Megawatts
100	3651.75	3139.44	1405.33	847.71	512.31	45.31	497.37
80	2929.48	2524.78	1156.02	713.31	404.7	38.01	397.19
60	2233.35	1929.98	886.93	557.05	303.37	26.51	297.65

Table 5: The rate of flow of energy, exergetic flow and irreversibility at various unit loads, such as 100%, 80%, and 60% after hybridization

Unit load	Energy input in Megawatts	Energy output in Megawatts	Exergy input in Megawatts	Exergy output in Megawatts	Work done in Megawatts	Irreversibilit in Megawatts	Actual work done in Megawatts
100	3651.74	3103.22	1405.30	815.1	548.52	41.68	531.46
80	2929.48	2490.68	1155.02	684.82	438.8	31.40	427.33
60	2233.35	1904.1	885.93	553.08	329.25	22.48	321.91

Table 6: Prior to hybridization, increasing the unit load improves the turbine heat rate (HR) and reduces the emission characteristics

	Parameters	Unit Load		
		Unit load increases from 50% to 60%	Unit load increases from 60% to 80%	Unit load increases from 80% to 100%
1	Improvement of Heat Rate in KJ/kWh	17.45	48.35	105.98
2	Reduction of daily consumption of coal expressed in kg per day	267.86	762.52	1230.68
3	Carbon dioxide emission reduction in Kg/day	419.92	1195.32	1929.28
4	SO2emission reduction in Kg/day	1.81	4.86	7.82
5	Reduction of ash production reduction in Kg/day	107.15	304.97	492.3

Table 7: After hybridization, increasing the unit load improves the turbine heat rate (HR) and reduces the emission characteristics

	Parameters	Unit Load		
		Unit load increases from 50% to 60%	Unit load increases from 60% to 80%	Unit load increases from 80% to 100%
1	Improvement of Heat Rate in KJ/kWh	18.59	51.13	112.37
2	Reduction of daily consumption of coal expressed in kg per day	283.7	805.55	1301.63
3	Carbon dioxide emission reduction in Kg/day	443.12	1254.42	2042.18
4	SO2emission reduction in Kg/day	1.92	5.13	8.25
5	Reduction of ash production reduction in Kg/day	113.51	321.85	519.02

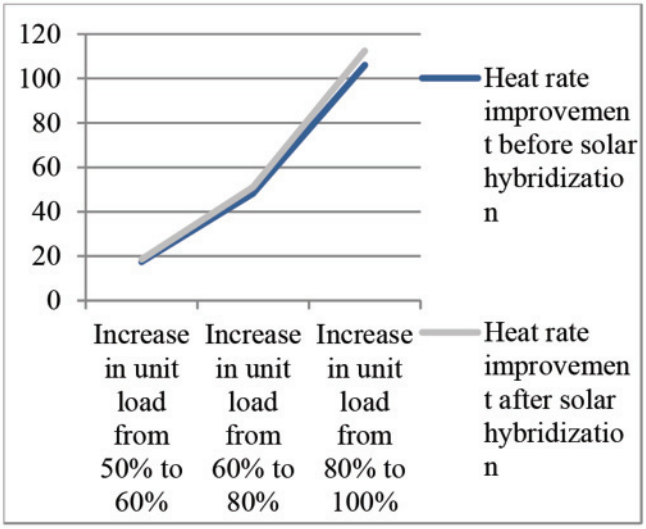

Figure 8: Heat rate improvement due to increase of unit load before and after hybridization

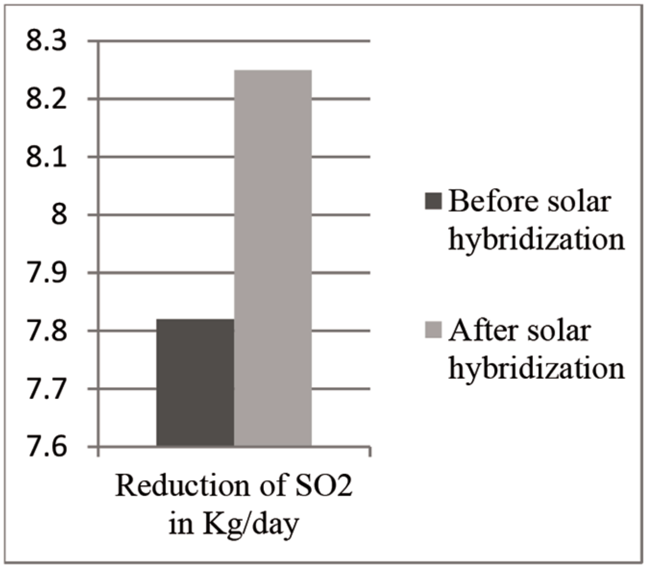

Figure 10: Comparison among reduction of SO_2 emission at 100% of unit load before and after solar hybridization with parabolic solar collector

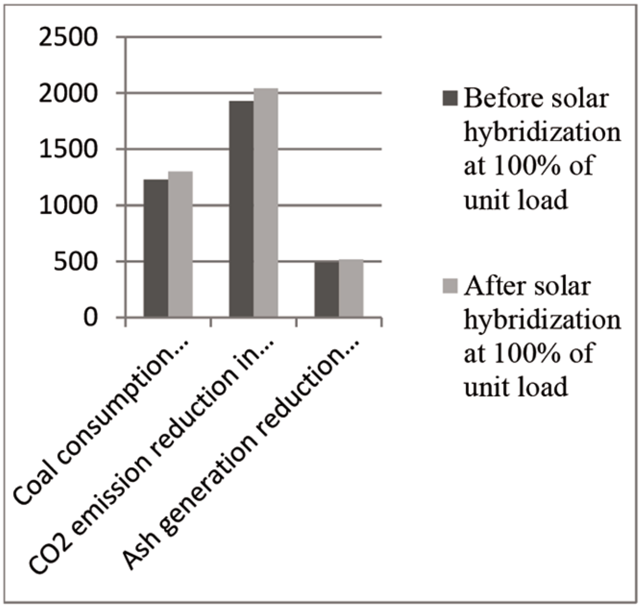

Figure 9: Comparison among reduction of coal consumption, CO_2 emission and Ash generation at 100% of unit load before and after solar hybridization with parabolic solar trough

could be increased by 36.22 megawatts and the overall thermal efficiency could be improved by 2.12% simply by exchanging the LP heater for a parabolic solar trough for the regeneration process. This was accomplished without affecting any of the other components of the cycle. After hybridising the power plant with the parabolic solar trough, the results indicate that the coal consumption rate, emission rate of CO_2 and SO_2 and ash generation rate are decreased by 70.94 Kg/day, 112.9 Kg/day, 0.43 Kg/day and 26.72 Kg/day, respectively, when unit load increases from 80% to 100%. 26.72 Kg/day, respectively, when unit load increases from 80% to 100%. The utilization of solar energy in conventional thermal power plants brings about a reduction in both the effects of greenhouse gas emissions and pollutants on the surrounding environment.

Acknowledgment

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Nomenclatures

ψ	Mass flow rate in Kg/s
ξ	Specific enthalpy in kJ/kg
HPT	High-Pressure Turbine
HR	Turbine heat rate in kJ/kWh
IPT	Intermediate PressureTurbine
β	Rate of irreversibility in MW
LPT	Low-Pressure Turbine
$\hat{H}$	Rate of heat transfer in MW
T	Temperature in K
$\acute{W}$	Rate of work transfer in MW
Z_{heat}	Net exergy transfer due to heat in MW

Greek Symbols

ε	Specific exergyin kJ/kg
η	Efficiency