Journal of Renewable Energy, Electrical, and Computer Engineering
Volume 4, Number 2, September 2024. 102-109
eISSN 2776-0049
DOI: https://doi.org/10.29103/jreece.v4i2.16658
Research Original Article

Performance Analysis and Techno-Economic Evaluation of Solar Energy Retrofitting for Coal-Fired Power Plant in Central Kalimantan Province

Irfan Ali✉[1], Hadiyanto[2], Asep Yoyo Wardaya[3]
[1]Master Program of Energy, School of Post Graduate Studies, Diponegoro University, Semarang, Indonesia
[2]Department of Chemical Engineering, Universitas Diponegoro, Semarang, Indonesia
[3]Department of Physics, Faculty of Science and Mathematics, Diponegoro University, Semarang, Indonesia
✉Corresponding Author: irfanali@students.undip.ac.id | Phone: +6281232115377

Received: June 11, 2024 **Revision: August 23, 2024** **Accepted: September 25, 2024**

Abstract
The power generation sector contributes to climate change. Mitigation efforts are essential to ensure that the commitment to limiting the global temperature increase below 2°C stays on course. One option is to retrofit an existing power plant with new technology that allows integration with renewable energy. This study examines the incorporation of solar energy systems into the operational processes of coal-fired power plants. Utilizing solar energy to substitute steam extraction from high-pressure feed water heater No. 7. This study analyzes the performance of the power plant before and after the retrofit scenario within both power-boost (PB) and fuel-save (FS) modes. Performances under different load conditions were also investigated. The results reveal that the thermal efficiency within both FS and power-boost (PB) modes increased up to 2 % compared to the base scenario. In both power-boost and fuel-save (FS) modes, there is a notable reduction in specific fuel consumption, with power-boost mode experiencing a decrease of 15.05 g/kWh and fuel-save mode showing a decrease of 15.75 g/kWh. Thus, the decreasing coal consumption implies reduced CO2 emissions within both FS and power-boost (PB) modes by 4.69 % and 4,94 %, respectively. Results under different loads show that the solar percentage and the rise in solar-to-electricity efficiency with decreasing loads. When operated in fuel-save (FS) mode, the proportions of solar electricity at VWO, 100%, 75%, and 50% load rates are 5.23 %, 5.53 %, 7.76%, and 11.92%, respectively. Moreover, the LCOE for solar electricity for both modes is 0.0267 USD/kWh, with expected investment returns of 5.87 years.
Keywords: Coal-Fired Power Plant; Co2 Emission; Solar Energy; Retrofit Scenario; Power-Boost (PB); Fuel-Save (FS)

Introduction
On April 23, 2016, the Indonesian Minister of Environment and Forestry signed the Paris Agreement on Climate Change. This agreement contains various important provisions, such as the objective of limiting the global temperature rise to 1.5°C or below 2°C, the promotion of achieving net-zero emissions in the long term, the requirement for domestic mitigation actions through Nationally Determined Contributions, and the need for regular evaluations to ensure compliance with these key agreements (Pemerintah Pusat, 2016). Indonesia has implemented measures to reduce emissions across various sectors. In the energy sector, the Indonesian government has established an ambition for transforming the energy supply mix through PP No. 79/2014 on National Energy Policy. One of its ambitions is to increase renewable energy to at least 23% by 2025 and 31% by 2050 (Pemerintah Pusat, 2014). The use of concentrating solar power (CSP) technology for generating electricity faces several technical and economic challenges in Indonesia. Although they encounter challenges like low efficiency, high initial costs, restricted installation capacity, and variable solar resource, solar thermal energy power stations employing CSP technology offer considerable potential as sustainable, long-term energy solutions (Ahmadi et al., 2017), (Adibhatla & Kaushik, 2017).

Today, coal-fired power plants are widely utilized due to their exceptional economics, as they provide electricity at the lowest operating costs when compared to various power generation systems. However, the plant's efficiency is average, their fuel supplies have limitations, and they emit high levels of pollutants (Nasution et al., 2020). Integrating solar heat into conventional systems could be a potential solution to the conflict between coal-fired power stations and concentrating solar power (CSP). This integration concept was called Solar Aided Power Generation (SAPG) by (Hu et al., 2010), but the concept of integration was already proposed by (Mubarak et al., 2020). Numerous studies concerning SAPG systems have been examined in various settings in recent years. (Shagdar et al., 2022) performed assessments of the SAPG in a 300 MW coal-fired station. In fuel-save (FS) mode, the suggested plant can conserve 8.82 tons of coal per hour, while in power-boost (PB) mode, it can produce an extra 20 MW of power. The financial payback period for implementing the SAPG is 5.91 years. (Mehrpooya et al., 2019) Performed a similar analysis was conducted on a 250 MW CNG power plant, which used a solar field collector system with a net aperture area of 120,000 square meters. Integrating solar heat into this system can produce an additional 24 MW of power and decrease annual CO2 emissions by 11,164.3 tons. On different integrating methods, (J. Li et al., 2021) Integrate solar heat for steam reheating within a coal-fired power plant with capacity 600 MW. The power plant absorbs 24,952 kW of solar heat in power-boost (PB) mode and 23,486 kW in fuel-save (FS) mode. Solar-to-electricity efficiency (SEE) in this scenario is at a maximum of 35.17 % and can lead to specific coal consumption of 19.14 g/kWh. In a study by (Xu et al., 2018), solar energy was utilized to heat air for pre-drying coal in a 600 MW coal-fired power plant. This resulted in a reduction of coal's moisture content by 18.24%. As a consequence, the coal's lower heating value (LHV) increased by 5 MJ/kg, contributing to an additional 29.6 MW of electricity generation. The system's levelized cost of electricity (LCOE) was reported at 0.035 USD/kWh (Chen et al., 2021), (Fitria et al., 2024).

Methods

Retrofit Configuration

A coal-fired power plant with a design capacity of 115 MW in Central Kalimantan, Indonesia, was designated as the reference system for analysis. The model specified for the steam turbine is N115-13.24/535/53, characterized by its subcritical nature, single shaft, double cylinders, single-flow exhaust, and reheating, operates according to the heat and mass balance diagram in Figure 1, condenser feed water passes through four low-pressure feed water heaters (LPH1, LPH2, LPH3, and LPH4), a deaerator, and three high-pressure feed water heaters (HPH5, HPH6, and HPH7) before entering the boiler. Within the boiler, the preheated feed water is transformed into superheated steam through coal combustion in the furnace. After entering the HP cylinder of the turbine, the superheated steam undergoes reheating in the boiler. The exhaust steam from the HP cylinder turbine then drives the LP cylinder turbine before finally being condensed in the condenser.

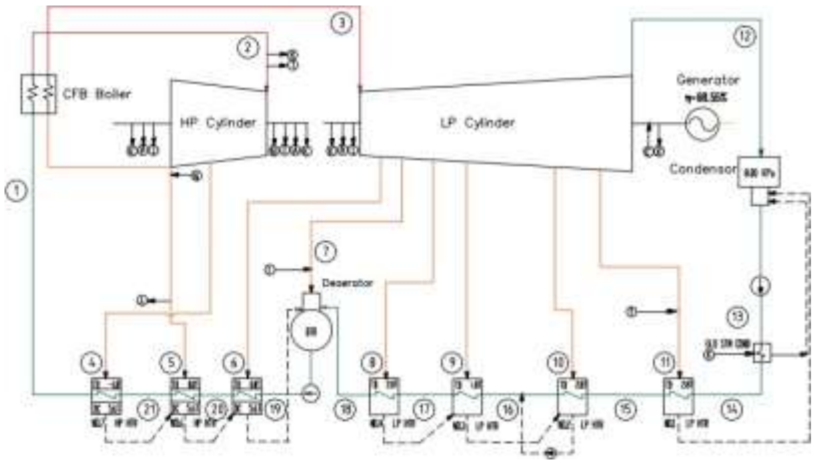


Figure 1. Base scenario coal-fired power plant system

After retrofitting, as illustrated in Figure 2, an oil-water heat exchanger is introduced to use collected solar energy to preheat the feed water. When solar energy is sufficient during peak solar hours, the first stage of steam extraction is shut off, and Solar heat is harnessed within the collector system to elevate the temperature of the feed water as it passes through the oil-water heat exchanger (Han et al., 2021), (Pawellek et al., 2009). To evaluate the performance of the retrofit and the effects of power load, the retrofitted power plant will be simulated at four operational turbine loads (VWO, TMCR, 75% load, and 50% load), considering two main operational modes. The first mode, known as fuel-save (FS) mode, maintains a steady power output while reducing coal consumption (Prosin et al., 2015). The second mode, called power-boost (PB) mode, keeps the coal consumption rate constant while increasing the power output. EBSILON Professional was used to simulate the power plant model for this study. The model was initially confirmed using the original configuration of the coal-fired power plant system before proceeding to simulate the retrofit scenario (C. Li et al., 2020), (Hasibuan et al., n.d.).

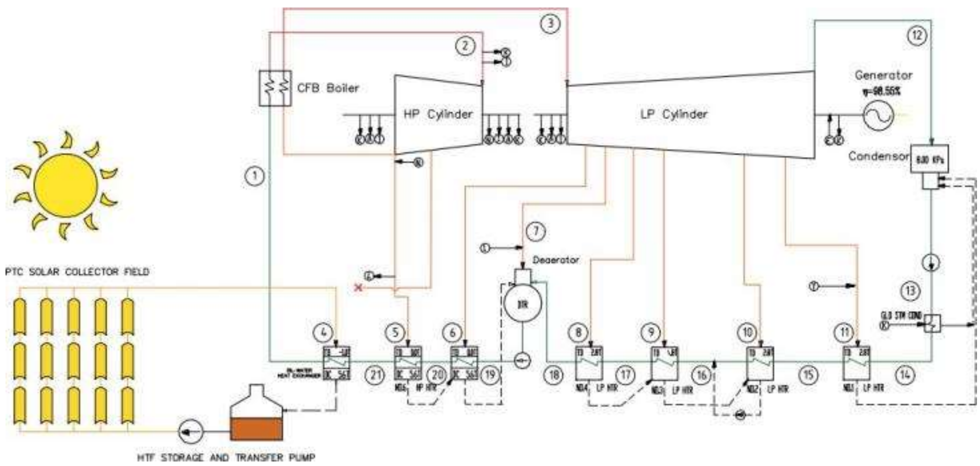


Figure 2. Base scenario coal-fired power plant system

Performance Indicators

A number of performance evaluation indices based on thermodynamic, environmental, and economic performances are proposed in order to assess the advantages of a retrofit scenario power plant (Roeder & Kather, 2014).

a. Thermodynamic performance

The gross efficiency of the retrofit scenario power plant system is defined as:

$$\eta_{th} = \frac{Q_{st}}{P_e}.100 \quad (\%) \tag{1}$$

Where, Q_{st} is the amount of heat produced by steam, in kW, and P_e is the power plant's electric power output, in kW.

The calculation for determining the specific heat consumption rate of the retrofit scenario is as follows:

$$q_s = \frac{P_e}{Q_{st}}. \quad (kg/kWh) \tag{2}$$

In the retrofit scenario, the solar percentage indicates the proportion of solar energy in comparison to the overall energy consumption. This can be computed as follows:

$$P_{Solar} = \frac{Q_{Solar}}{Q_{Boiler} + Q_{Solar}}.100 \quad (\%) \tag{3}$$

Where Q_{Solar} represents the solar heat input to the feed water heater (kW), and Q_{Boiler}denotes the heat supplied to the boiler (kW). The efficiency of converting solar energy into electricity is measured by comparing the electrical power produced to the total amount of solar energy captured in the solar field. The solar to power efficiency calculated by:

$$\eta_{s-p} = \frac{\Delta P_e}{Q_{Solar} \pm \Delta Q_{Boiler}}.100 \quad (\%) \tag{4}$$

Where, ΔP_e is the increase in electricity output after retrofit scenario, (kW); ΔQ_{boiler} is the potential change in heat sent to boiler right after retrofitting scenario, (kW).

The site's solar resource condition and the key design parameters of the solar collector field system are given in tables 3 and 4, respectively.

Table 1. Solar resources condition

Items	Value	Units
Latitude	-1,31	Deg
Longitude	113,58	Deg
DNI	2.692	kWh/m^2 per day
Solar peak hours	4,98	Hours
Amb. temp	27,3	Deg. Celcius
Rainfall	3.011,66	mm

Table 2. Key design parameters of the solar collector field

Items	Value	Units
Collector length	150	m
Gross aperture	5,76	m
Focal length	1,71	m
Row spacing	17,28	m
Number of collector	11	Units
DNI	2.692,00	kW/m^2
Incident angle	4.63	deg
Optical eff	74,75	%
Thermal eff	97,19	%
Net apperture	8991,73	m^2

b. Environment performance

This study assesses the environment performance of the retrofit scenario using the CO2 emission rate and the specific fuel consumption. The emission rate calculated by:

$$E_{CO2} = \frac{3600.V_{CO2}.\rho_{CO2}.Q_{boiler}}{Q_{LHV}.P_e} \quad (g/kWh) \tag{5}$$

Where, V_{CO2} represents CO2 specific volume, m3/kg; ρ_{CO2} represents the CO2 density, kg/m3;

The specific fuel consumption rate of the retrofit scenario can be calculated by:

$$b_m = \frac{B_{coal}}{P_e} \quad (kg/kWh) \tag{6}$$

Where, B_{Coal} is the equivalent fuel consumption, calculated by:

$$B_{Coal} = \frac{Q_{st}}{Q_{LHV}\eta_{boiler}} \quad (kg/s) \tag{7}$$

Where Q_{LHV} is the lower heating value of coal (kJ/kg), and η_{boiler} represents the boiler's efficiency (%). Tables 3 and 4 present the characteristics of the coal utilized in this simulation research.

Table 3. Ultimate analyses of coal used in this study

Items	Value	Units
C_{ar}	61,26	Wt%
H_{ar}	4,49	Wt%
O_{ar}	19,14	Wt%
N_{ar}	0,92	Wt%
S_{ar}	0,3	Wt%

ar is an acronym for as-received.

Table 4. Proximate analyses of coal used in this study

Items	Value	Units
A_{ar}	1,93	Wt%
VM_{ar}	44,26	Wt%
FC_{ar}	41,85	Wt%
LHV	23,055	MJ/kg

ar is an acronym for as-received.

c. Economic performance Base scenario

The economic viability of the retrofit scenario project is assessed through two key indicators: the simple payback period and the levelized cost of electricity. Table 5 outlines the primary parameters used to estimate the economic performance of the retrofit scenario.

Table 5. Proximate analyses of coal used in this study

Items	Value	Units
Peak solar hours	4,98	hours
Electricity price	1.818	IDR/kWh
Solar field area	8.992	m2
Direct cost		
Solar collector field	4.054.562,50	IDR/m2
HTF system	810.912,50	IDR/kWh
Oil-water heat exchanger	14.515.333.750	IDR
Contingency cost	10	% of DC
Indirect cost		
EPC	18,5	% of DC
O&M Cost	1,5	% of DC
Discount rate	5	%
Power plant lifespan	30	year

The simple payback period is the number of years needed to return the project investment cost of a retrofit scenario is calculated below:

$$SPP = \frac{C_0}{C_I} \quad (years) \tag{8}$$

Where C_0 is the cost of investing in retrofit scenarios. (IDR); C_I is the annual cash inflow from solar power produced (IDR)

The cash inflow is calculated by:

$$C_I = t_{solar}.E_{solar}.c_{solar} \quad (IDR) \tag{9}$$

Where t_{solar} represents the peak solar hours per year (h), E_{solar} is the hourly solar electricity generation (kWh), and c_{solar} is the revenue from solar electricity (IDR/kWh).

The cost of producing electricity using solar thermal energy is referred to as the levelized cost of electricity (LCOE), calculated by:

$$LCOE = \frac{(C_0.CRF) + O\&M}{E_{Solar}} (IDR/kWh) \tag{10}$$

Where O&M represents the annual operating and maintenance cost (IDR), and CRF is the capital recovery factor calculated by:

$$CRF = \frac{r(r+1)^n}{r(r+1)^n - 1} (\%) \tag{11}$$

Where, n indicates the expected duration of the retrofit scenario, while r represents the discount rate

Results and Discussion

In this study, heat and mass balance simulations will be performed and analyzed under a base scenario and a retrofit scenario. The base scenario simulation model is based on steam turbine type N115-13.24/535/53 technical specifications and parameters. In the retrofit scenario, the power plant uses similarly designed facilities as the base case, except for the additional solar heat from the oil-water heat exchanger, and the first extraction steam will be turned off.

Base scenario

Table 6 presents the simulation results of the basic scenario model, which are then compared to technical specifications issued by the manufacturer. The technical parameters are based on data provided by the manufacturer, and were set for the turbine's maximum continuous rate load. The highest error rate pertains to the mass flow rate and pressure of the reheated steam, reaching up to 0.71%. According to (Wang et al., 2020), an error percentage below 5% is acceptable, indicating that the simulation model meets the necessary requirements.

Table 6. Comparison between design value and simulation results

Items	Units	Design Value	Simulation Value	Error (%)
Power output	MW	115,14	115,63	0,42
Main steam pressure	MPa	13,24	13,24	0,00
Main steam temp	Deg. Celcius	535	535	0,00
Main steam mass flow	t/h	348	348	0,00
Reheated steam pressure	MPa	2,9	2,904	0,71
Reheated steam temp	Deg. Celcius	535	535	0,00
Reheated steam mass flow	t/h	296,81	298,93	0,71
Feed water temp	Deg. Celcius	258,9	258,47	0,41
Specific heat consumption	kJ/kWh	8155	8174	0,23
Specific steam consumption	Kg/kWh	3,022	3,01	0,40

Comparing the base mode with the retrofit scenario in PB and FS Mode, Table 7 illustrates that when the main steam mass flow was set to the design parameter, the power output of the retrofit system increased to 120.43 MW from 115.63 MW in power-boost (PB) mode, surpassing the base scenario. Furthermore, the gross thermal efficiency of the retrofit system in both FS and PB modes has seen an improvement of up to 5.18% compared to the base scenario power plant. This indicates that the retrofit system demands less energy input for electricity production. The specific equivalent coal consumption and heat rate of the retrofit system are decreased within both FS and power-boost (PB) modes due to the fact that the chemical energy required by the boiler is diminished by energy from solar heat. The CO_2 emission rate of the retrofit system is decreased following coal consumption; in fuel-save (FS) mode, coal consumption can be reduced by up to 5.35%, thus the CO_2 emission rate is also lower than at the at the base scenario power plant. The simulation results indicate that the retrofit scenario can perform better and provides flexibility during both peak and base load conditions. During peak load, retrofit power plants may employ the use of power-boost (PB) mode, This enables the system to generate increased electricity without consuming additional fuel compared to the basic configuration. However, because power-boost (PB) mode operates over the steam turbine's nominal load, the safety operation condition limits its operation period. In fuel-save (FS) mode during base loads, retrofit power plants notably reduced both fuel consumption and pollutant emissions. At the TMCR load condition, the economic evaluation of the retrofit scenario indicates a payback period of approximately 5.87 years for both power-boost (PB) and fuel-save (FS) modes. Moreover, the levelized cost of electricity (LCOE) for solar thermal energy production is 431.82 IDR/kWh for both modes, significantly lower than that for the solar tower power system, which is at 1,592.99 IDR/kWh (Hong et al., 2014). This difference could be attributed to the excellent thermal efficiency and lower capital cost of the solar thermal energy system.

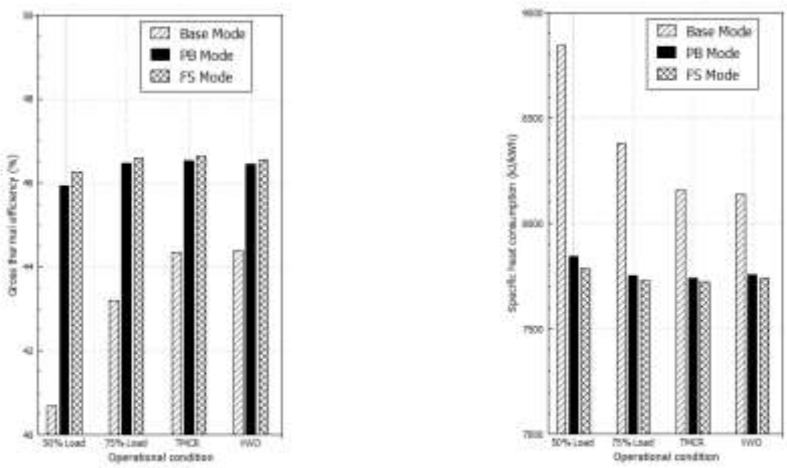
Table 7. Comparison between design value and simulation results.

Items	Units	Base mode	PB Mode	FS Mode
Power output	MW	115,14	120,43	115,14
Gross efficiency	%	44,33	46,51	46,63
Coal consumption	t/h	106,44	105,65	100,74
Specific heat consumption	kJ/kWh	8155	7739,5	7719,60
Specific eq. Fuel consumption	Kg/kWh	3,022	2,889	2,89
CO2 emission rate	g/kWh	28,04	26,72	26,65
Solar percentage	%		5,29	5,53

Solar electricity	MW	6,36	6,36
Solar to power efficiency	%	35,18	35,18
Simple payback period	years	5,87	5,87
Levelized cost of electricity	IDR/kWh	431,82	431,82

Effects of Power Load

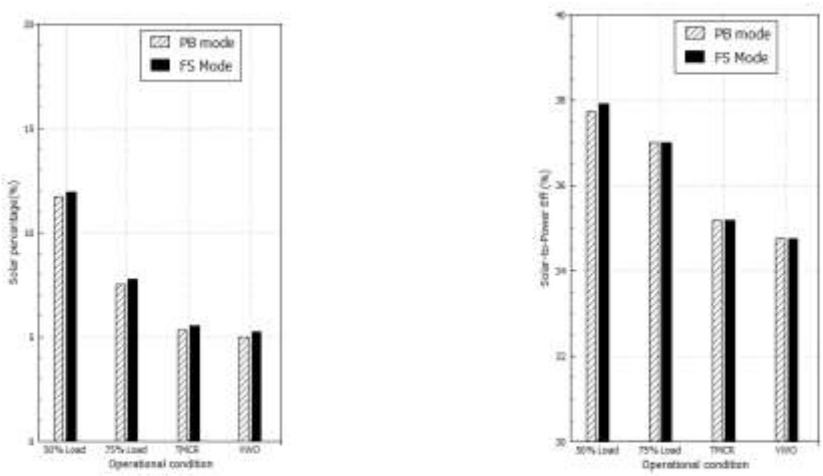
Fluctuations in the electric load on the grid frequently influence the operational efficiency and the power generation system performance. This results in the power plant operating not only at its intended capacity but also at varying loads. As a result, the operational load condition has a direct impact on a thermal power plant's performance and techno-economic indicators. It is required for investigating the steam turbine in partial load condition. The thermodynamic simulation model is carried out under both design and partial load conditions, considering changes in load from valve wide open to 50% of TMCR. Figure 3 illustrates the thermodynamic performance indicators (gross thermal efficiency and specific heat consumption) at various operating loads. The graph shows that a thermal power plant operates most efficiently near its design load. At partial loads, the plant operates with lower operational parameters but maintains relatively the same auxiliary power consumption, leading to a reduction in gross thermal efficiency. When solar heat is introduced to the system at a 100% TMCR operation load, the thermal efficiency in power-boost (PB) mode increases by 4.91% and in fuel-save (FS) mode by 5,18%. The specific heat consumption of base scenario, increase following a decrease in power load. After retrofitting, power plants can utilize the advantage of higher solar heat proportions during partial loads to compensate the needs of heat consumption.



(a) *(b)*

Figure 3. Thermodynamic performance indicators affected by variable power loads;(a) Gross thermal efficiency. (b) Specific heat consumption.

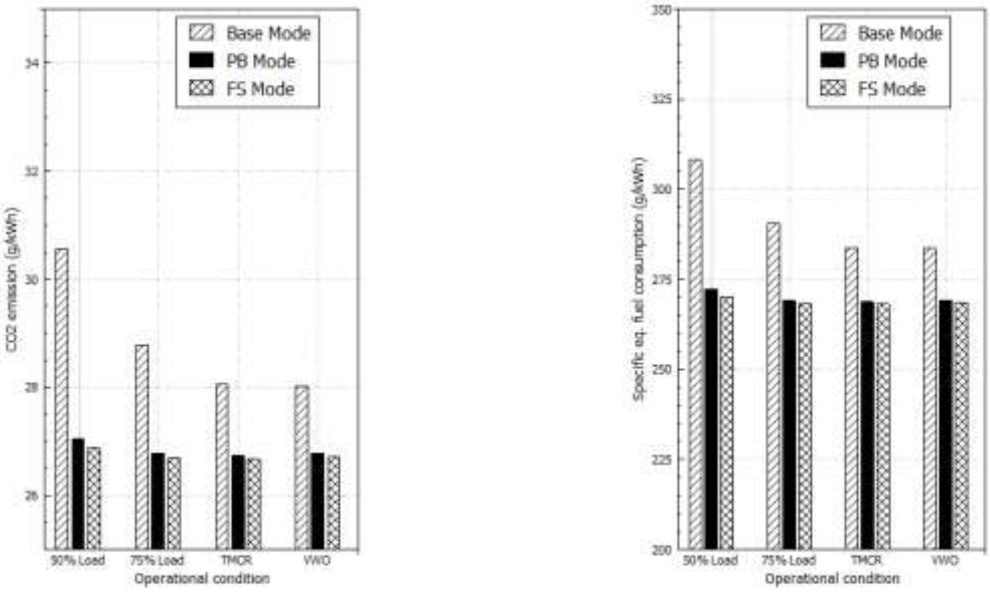
Figure 4. shows the solar thermal energy contribution index (solar energy percentage and solar power generation efficiency) under different operating loads. As the electricity load increases, the share of solar thermal energy shows a downward trend. When solar thermal energy input is constant, and the power plant operates at a partial load, more solar heat is absorbed by the feed water due to heat supplied from turbine extraction for feed water heaters relatively lower.



(a) *(b)*

Figure 4. Solar thermal energy system performance indicators affected by variable power loads;(a) Solar percentage. (b) Solar-to-Power Efficiency.

Figure 5. shows variations in the CO2 emission rate between the base scenario and the retrofit scenario. During the base scenario, the CO2 emission rate increases when operating with partial loads. The reason is that the that the CO2 emission rate follows specific fuel consumption, which is higher at low loads. CO2 emission rate depends on specific fuel consumption; the lowest reduction occurs when operating in fuel-save (FS) mode, which can reduce up to 4.94% compared with the base scenario at 100% load. which can reduce up to 4.94% compared with the base scenario at 100% load.



(a) *(b)*

Figure 6. Environment performance indicators affected by variable power loads;(a) CO2 emission rate. (b) Specific equivalent fuel consumption.

Conclusions

In this paper, we suggest a retrofitting plan for a coal-fired power station that involves integrating collected solar heat to preheat the boiler feed water. Compared with the base scenario of a coal-fired power plant, the thermal efficiency of the proposed retrofit scenario is increased within both operational modes, implying that solar thermal energy can efficiently improve the performance of a base power plant. Taking into account the potential effects of different operating loads, the analysis and comparison cover the thermodynamic performance of both the base and retrofit coal-fired power plants in power-boost (PB) and fuel-save (FS) modes. The following conclusions are drawn from this study:

1. Compared to the base scenario of a coal-fired power plant, the retrofit scenario power plant produces 4.15 percent more electricity in power-boost (PB) mode while reducing coal consumption by up to 5.35 percent in fuel-save (FS) mode. The retrofit power plant demonstrated a notable enhancement in thermal efficiency, with a 4.9% increase observed in both power-boost (PB) and fuel-save (FS) operational modes. The retrofit scenario reduces specific heat consumption within both FS and power-boost (PB) modes by 415.5 and 435.4 kJ/kWh, respectively.
2. Using the simple payback period indicator, it is projected that the investment in the retrofit scenario will be recovered in approximately 5.87 years. This applies to both operational modes: power-boost (PB) and fuel-save (FS). In both modes, the levelized electricity cost from solar thermal energy amounts to 431.82 IDR/kWh
3. In the retrofit scenario, the shares of heat generated by solar energy in the power plant decrease heat consumption generated by coal firing, leading to a decrease in CO2 emissions.In the power-boost (PB) and fuel-save (FS) modes, CO2 emissions are reduced to 1.317 g/kWh and 1.386 g/kWh, respectively. fuel-save (FS) mode can approximately reduce CO2 emissions by 3.83 tons per day.
4. Under different operational loads, the base scenario power plant will perform better on near design load, while in partial load the power plant will operate less efficient, this can be seen on from the decrease of thermal efficiency and increased of specific equivalent fuel consumption. In a retrofit scenario of a power plant operating under constant solar thermal energy conditions, the system absorbs more solar energy as the load decreases. This will help the power plant during partial load condition to perform better.

References

Adibhatla, S., & Kaushik, S. C. (2017). Energy, exergy, economic and environmental (4E) analyses of a conceptual solar aided coal fired 500 MWe thermal power plant with thermal energy storage option. *Sustainable Energy Technologies and Assessments*, *21*, 89–99.

Ahmadi, G., Toghraie, D., & Akbari, O. A. (2017). Solar parallel feed water heating repowering of a steam power plant: A case study in Iran. *Renewable and Sustainable Energy Reviews*, *77*, 474–485.

Chen, H., Wu, Y., Zeng, Y., Xu, G., & Liu, W. (2021). Performance analysis of a solar-aided waste-to-energy system based on steam reheating. *Applied Thermal Engineering*, *185*, 116445.

Fitria, N., Hasibuan, A., Zulnazri, Z., Azhari, A., Safitri, N., & Ula, M. (2024). Techno-Economic Assessment of the

Development of a Biogas Power Plant Made from Liquid Palm Oil Waste in Rantau Sub-District. *Construction Technologies and Architecture*, *14*, 73–77.

Han, Y., Sun, Y., & Wu, J. (2021). A low-cost and efficient solar/coal hybrid power generation mode: Integration of non-concentrating solar energy and air preheating process. *Energy*, *235*, 121367.

Hasibuan, A., Daud, M., Marjuli, H., & Isa, M. (n.d.). *Analysis of the Effect of Solar Temperature and Radiation on Characteristics IV on 170 WP Photovoltaic Module Based on Matlab Simulink*.

Hong, H., Peng, S., Zhao, Y., Liu, Q., & Jin, H. (2014). A typical solar-coal hybrid power plant in China. *Energy Procedia*, *49*, 1777–1783.

Hu, E., Yang, Y., Nishimura, A., Yilmaz, F., & Kouzani, A. (2010). Solar thermal aided power generation. *Applied Energy*, *87*(9), 2881–2885.

Li, C., Zhai, R., Zhang, B., & Chen, W. (2020). Thermodynamic performance of a novel solar tower aided coal-fired power system. *Applied Thermal Engineering*, *171*, 115127.

Li, J., Xin, Y., Hu, B., Zeng, K., Wu, Z., Fan, S., Li, Y., Chen, Y., Wang, S., Wang, J., & others. (2021). Safety and thermal efficiency performance assessment of solar aided coal-fired power plant based on turbine steam double reheat. *Energy*, *226*, 120277.

Mehrpooya, M., Taromi, M., & Ghorbani, B. (2019). Thermo-economic assessment and retrofitting of an existing electrical power plant with solar energy under different operational modes and part load conditions. *Energy Reports*, *5*, 1137–1150.

Mubarak, H., Hasibuan, A., Setiawan, A., & Daud, M. (2020). Optimal Power Analysis for the Installation of On-Grid Rooftop Photovoltaic Solar Systems (RPVSS) in the Industrial Engineering Laboraturiom Building, Bukit Indah Universitas Malikussaleh Lhokseumawe Aceh. *2020 4rd International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM)*, 44–47.

Nasution, E. S., Hasibuan, A., Siregar, W. V., & Ismail, R. (2020). Solar power generation system design: Case study of north sumatra muhammadiyah university building. *2020 4rd International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM)*, 191–194.

Pawellek, R., Löw, T., & Hirsch, T. (2009). EbsSolar--A solar library for EBSILON®Professional. *Proceedings of the SolarPACES 2009 Conference*.

Pemerintah Pusat, I. (2014). Peraturan Pemerintah (PP) Nomor 79 Tahun 2014 tentang Kebijakan Energi Nasional. Lembaran Negara RI Tahun 2014, No. 300. *Sekretariat Negara*.

Pemerintah Pusat, I. (2016). Undang-undang (UU) Nomor 16 Tahun 2016 tentang Pengesahan Paris Agreement to The United Nations Framework Convention On Climate Change (Persetujuan Paris Atas Konvensi Kerangka Kerja Perserikatan Bangsa-Bangsa mengenai Perubahan Iklim). Lembaran Negara RI. *Sekretaroiat Negara*.

Prosin, T., Pryor, T., Creagh, C., Amsbeck, L., & Buck, R. (2015). Hybrid solar and coal-fired steam power plant with air preheating using a centrifugal solid particle receiver. *Energy Procedia*, *69*, 1371–1381.

Roeder, V., & Kather, A. (2014). Part load behaviour of power plants with a retrofitted post-combustion CO2 capture process. *Energy Procedia*, *51*, 207–216.

Shagdar, E., Shuai, Y., Lougou, B. G., Mustafa, A., Choidorj, D., & Tan, H. (2022). New integration mechanism of solar energy into 300 MW coal-fired power plant: performance and techno-economic analysis. *Energy*, *238*, 122005.

Wang, J., Liu, W., Meng, X., Liu, X., Gao, Y., Yu, Z., Bai, Y., & Yang, X. (2020). Study on the coupling effect of a solar-coal unit thermodynamic system with carbon capture. *Energies*, *13*(18), 4779.

Xu, C., Li, X., Xu, G., Xin, T., Yang, Y., Liu, W., & Wang, M. (2018). Energy, exergy and economic analyses of a novel solar-lignite hybrid power generation process using lignite pre-drying. *Energy Conversion and Management*, *170*, 19–33.