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

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ABSTRACT

The power generation sector significantly contributes to climate change. Mitigation efforts are crucial to adhering to the global commitment to limit temperature increases below 2°C. One potential solution is retrofitting existing power plants with technologies that integrate renewable energy. This study explores the integration of solar energy into the operational processes of a coal-fired power plant in Central Kalimantan, replacing the extraction steam turbine in the high-pressure feed water heater No. 7. Using STEAG EBSILON for simulation, this research evaluates the power plant's performance before and after retrofitting in both power-boost (PB) and fuel-save (FS) modes under varying load conditions.

The results demonstrate that thermal efficiency in both PB and FS modes increased by up to 2% compared to the base scenario. Specific fuel consumption decreased by 15.05 g/kWh in PB mode and 15.75 g/kWh in FS mode, leading to a reduction in coal consumption and CO_2 emissions by 4.69% and 4.94% respectively. Additionally, the study observed that the solar percentage and solar-to-electricity efficiency increased as the load decreased. In FS mode, the solar electricity proportions at VWO, 100%, 75%, and 50% load rates were 5.23%, 5.53%, 7.76%, and 11.92%, respectively. The levelized cost of energy (LCOE) for solar electricity was calculated to be 431.82 IDR/kWh, with an expected investment return period of 5.87 years

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تحليل الأداء والتقييم الفني والاقتصادي لتحديث الطاقة الشمسية لمحطة توليد الطاقة التي تعمل بالفحم في مقاطعة كاليمانتان الوسطى.

ملخص: يساهم قطاع توليد الطاقة بشكل كبير في تغير المناخ. وتعد جهود التخفيف حاسمة الأهمية بالالتزام العالمي للحد من ارتفاع درجات الحرارة إلى أقل من درجتين مئويتين. أحد الحلول المحتملة هو تحديث محطات الطاقة الحالية بتقنيات ادماج الطاقة المتجددة. تستكشف هذه الدراسة دمج الطاقة الشمسية في العمليات التشغيلية لمحطة توليد الطاقة التي تعمل بالفحم في وسط Kalimantan، لتحل محل توربين البخار المستخرج في سخان المياه عالي الضغط رقم 7. وباستخدام STEAG EBSILON للمحاكاة، يقوم هذا البحث بتقييم أداء محطة توليد الطاقة قبل وبعد التعديل التحديثي في كل من وضعي تعزيز الطاقة (PB) وتوفير الوقود (FS) في ظل ظروف التحميل المختلفة. اوضحت النتائج أن الكفاءة الحرارية في كلا الوضعين PB و FS زادت بنسبة تصل إلى 2% مقارنة بالسيناريو الأساسي وانخفض استهلاك الوقود النوعي بمقدار 15.05 جم/كيلووات ساعة في وضع PB و 15.75 جم/كيلووات ساعة في وضع FS، مما أدى إلى انخفاض استهلاك الفحم وانبعاثات ثاني أكسيد الكربون بنسبة 4.69% و4.94% على التوالي. بالإضافة إلى ذلك، لاحظت الدراسة أن نسبة الطاقة الشمسية وكفاءة تحويل الطاقة الشمسية إلى كهرباء تزداد مع انخفاض الحمل. في وضع FS، كانت نسب الكهرباء الشمسية في معدلات تحميل VWO و100% و75% و50% هي 5.23% و5.53% و7.76% و11.92% على التوالي. تم حساب التكلفة المعيارية للطاقة (LCOE) للكهرباء الشمسية بمبلغ 431.82 روبية إندونيسية/كيلوواط ساعة، مع فترة عائد استثمارية متوقعة تبلغ 5.87 سنة.

الكلمات المفتاحية – جمحطة توليد الكهرباء التي تعمل بالفحم، انبعاثات ثاني أكسيد الكربون، الطاقة الشمسية، سيناريو التحديث، تعزيز الطاقة (PB)، توفير الوقود (FS).

1. 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 [1]. 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. The use of concentrating solar power (CSP) technology for generating electricity faces several technical and economic challenges in Indonesia. Due to its intermittent nature, solar energy can create challenges for power grid stability when used on a large scale with grid-connected photovoltaic systems. A promising solution is to convert solar energy into thermal energy using CSP and integrate it into the existing thermal power station [2].

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. 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), a solar thermal hybrid power system which is gaining increasing interest [3]. The concept of integration was first proposed by Zoschak and Wu [4]. The integration of solar energy into coal-fired power plants has garnered significant attention due to its potential to enhance efficiency, reduce emissions, and lower operational costs. Several studies have explored various methods of integrating solar energy into existing coal-fired power plants, demonstrating the benefits and financial viability of these hybrid systems. Shagdar et al., 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 [5]. Wu and Han., conducted a study achieved a solar heat-to-electricity efficiency of 37.1% with 54.45 MW of solar heat, an annual efficiency of 21.5%, and a levelized cost of energy at $0.129/kWh by using solar heat to preheat reheated steam and replace the highest-pressure extraction steam.

The optimal aperture area was 103,620 m², resulting in an annual solar electricity generation of 33.28 GWh. [6].

On different integrating methods, Han et al., study a new solar-aided NOx removal system for a 1000-MW peaking unit operating at 50% load combines solar heat with selective catalytic reduction (SCR) for NOx removal. This system produced 14.6 MWe of solar power with a 30.15% efficiency, significantly improved SCR de-NOx temperature and NOx removal efficiency, and yielded a net yearly benefit of 24.01 million CNY at a low electricity cost of 0.56 CNY/kWh. [7].

Han et al. conducted a study were integrating both non-concentrating and concentrating solar energy for lignite drying achieved high solar energy conversion efficiency. This method efficiently utilizes solar irradiance, particularly diffuse irradiance, at relatively low levels.

For a 600-MW base unit, the system increased electric power output by 26.8 MWe with a solar-to-electricity conversion efficiency of 35.83%.

The low-cost non-concentrating solar collecting device demonstrated excellent thermal performance. The new system's net annual revenue was 63.45 million CNY, with a solar-generated electricity cost of 0.346 CNY/kWh. [8]. Building on these advancements, our study aims to apply the benefits of integrating solar energy into a 115 MW coal-fired power plant in Central Kalimantan, Indonesia. By leveraging solar energy to enhance the efficiency and sustainability of the power plant, we anticipate significant improvements in both economic and environmental performance.

We will focus on the best retrofitting scenario by replacing the extraction steam turbine in the high-pressure feed water heater No. 7. to optimize solar-to-electricity conversion, reduce coal usage, and lower greenhouse gas emissions. This research is expected to significantly enhance both economic and environmental performance, ultimately supporting the region's energy security and environmental goals.

2. METHODS

2.1. 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 sub critical nature, single shaft, double cylinders, single-flow exhaust, and reheating. A coal-fired power plant, in present study operates according to the heat and mass balance diagram as shown in Figure 1. Condenser feed water passes through four low-pressure feed water heaters (LPH1, LPH2, LPH3, and LPH4), a de-aerator, 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.

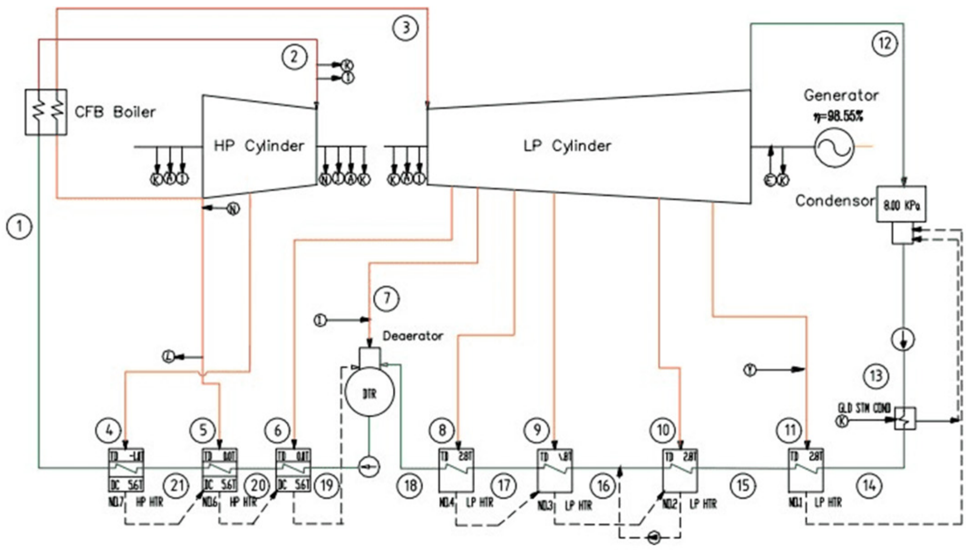


Figure 1. Base scenario coal-fired power plant system.

After retrofitting, an oil-water heat exchanger is introduced to use collected solar energy to preheat the feed water as illustrated in Figure 2. 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. 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. 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 [9] [10]. The model was initially confirmed using the original configuration of the coal-fired power plant system before proceeding to simulate the retrofit scenario [11].

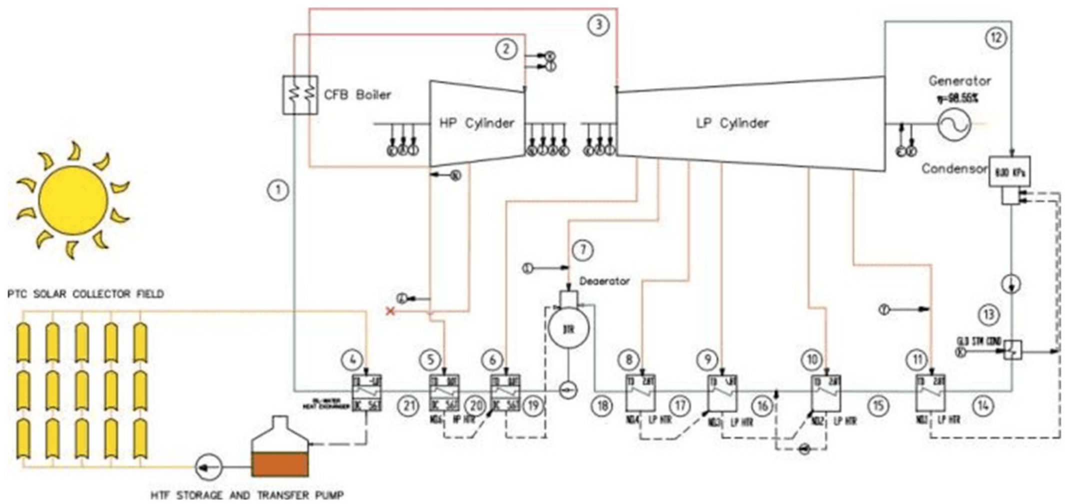


Figure 2. Retrofit scenario coal-fired power plant system.

2.2. Performance Indicators

2.2.1. Thermodynamic performance

The gross efficiency of the retrofit scenario power plant system is defined as Eq. (1).:

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

Where, Q_{st} is the amount of heat produced by steam boiler utilize coal combustion and collected solar heat, 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 defined as Eq. (2).:

$$q_s = \frac{Q_{st}}{P_e} \quad (kJ / kWh) \qquad (2)$$

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 Eq. (3).:

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

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 [12].
The solar-to-power efficiency is calculated by Eq. (4).:

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

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 1 and 2, 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 collectors	11	Units
DNI	2.692,00	kW/m^2

Incident angle	4.63	deg
Optical eff	74,75	%
Thermal eff	97,19	%
Net aperture	8991,73	m^2

2.2.2. Environment performance

This study assesses the environment performance of the retrofit scenario using the CO_2 emission rate and the specific fuel consumption. The emission rate is calculated by Eq. (5).:

$$E_{co_2} = \frac{3600.V_{co_2}.\rho_{co_2}.Q_{Boiler}}{Q_{LHV}.P_e} \quad (g/kWh) \qquad (5)$$

Where, V_{co_2} represents CO_2 specific volume, m^3/kg; ρ_{co_2} represents the CO_2 density, kg/m^3; The specific fuel consumption rate of the retrofit scenario can be calculated by Eq. (6).:

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

Where, B_{coal} is the fuel consumption converted to equivalent fuel, calculated by Eq. (7).:

$$B_{coal} = \frac{Q_{st}}{Q_{LHV}.\eta_{boiler}} \quad (kg/s) \qquad (7)$$

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
Car	61,26	Wt%
Har	4,49	Wt%
Oar	19,14	Wt%
Nar	0,92	Wt%
Sar	0,3	Wt%
ar is an acronym for as-received.		

Table 4. Proximate analyses of coal used in this study.

Items	Value	Units
Aar	1,93	Wt%
VMar	44,26	Wt%
FCar	41,85	Wt%
LHV	23,055	MJ/kg
ar is an acronym for as-received.		

2.2.3. Economic performance

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. Economic primary parameters.

Items	Value	Units
Peak solar hours	4,98	hours
Electricity price	1.818	IDR/kWh
Solar field area	8.992	m^2
Direct cost		
Solar collector field	4.054.562,50	IDR/m^2
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 as Eq. (8) [13].:

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

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 Eq. (9).:

$$C_I = t_{Solar}.E_{Solar}.C_{Solar} \quad (IDR) \qquad (9)$$

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 Eq. (10) [13].:

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

Where O&M represents the annual operating and maintenance cost (IDR), and CRF is the capital recovery factor calculated by Eq. (11).:

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

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

3. 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.

3.1. Base and retrofit 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 Xue et al. an error percentage below 2.4% is acceptable, indicating that the simulation model meets the necessary requirements [14].

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	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.	°C	535	535	0,00
Reheated steam mass flow	t/h	296,81	298,93	0,71
Feed water temp.	°C	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, mainly because in a retrofit scenario where solar heat is used to preheat the feedwater, the steam that would have been extracted from the turbine for this purpose is instead left to continue expanding through the turbine. 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. By using solar energy to preheat the feedwater, the plant reduces the amount of coal needed to achieve the same steam temperature and pressure, leading to lower fuel consumption and higher efficiency 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 solar heat is providing part of the thermal energy needed, the boiler requires less energy from coal to achieve the same output. This means less coal is burned for the same amount of electricity produced. 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. This reduction leads to a corresponding decrease in CO_2 emissions, making the retrofit system more environmentally friendly compared to the base scenario power plant. The reduced CO_2 emissions contribute to lower greenhouse gas emissions, supporting climate change mitigation efforts and improving the environmental performance of the 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, although the use of this mode is restricted to ensure the safe operation of the turbine. This balance of efficiency, flexibility, and safety makes the retrofit scenario a valuable improvement over the standard coal-fired power plant [15]. In fuel-

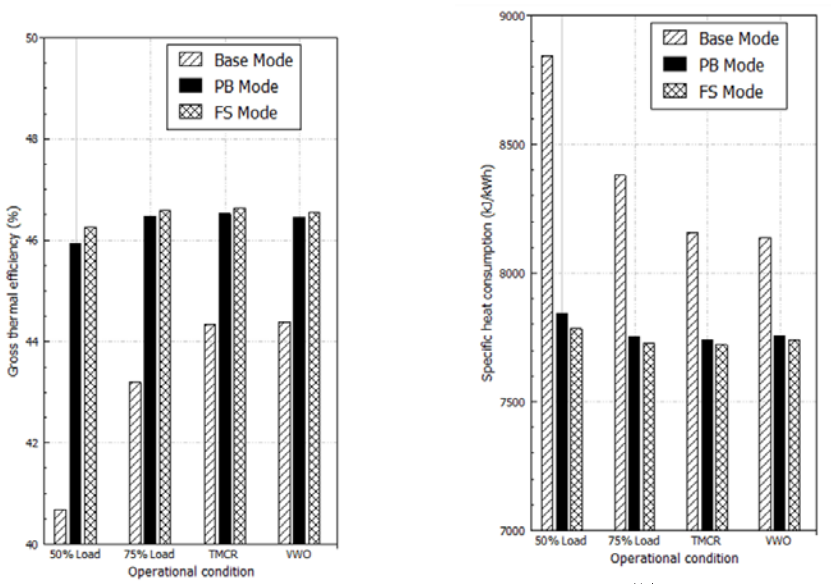
save (FS) mode during base loads, retrofit power plants notably reduced both fuel consumption and pollutant emissions. At the TMCR load condition, the economic evaluation of the retrofit scenario indicates a payback period of approximately 5.87 years for both power-boost (PB) and fuel-save (FS) modes. 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 [16].
This difference could be attributed to the excellent thermal efficiency and lower capital cost of the solar thermal energy system.

Table 7. Comparison between base scenario and retrofit scenario.

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
CO_2 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

3.2. Effects of Power Load

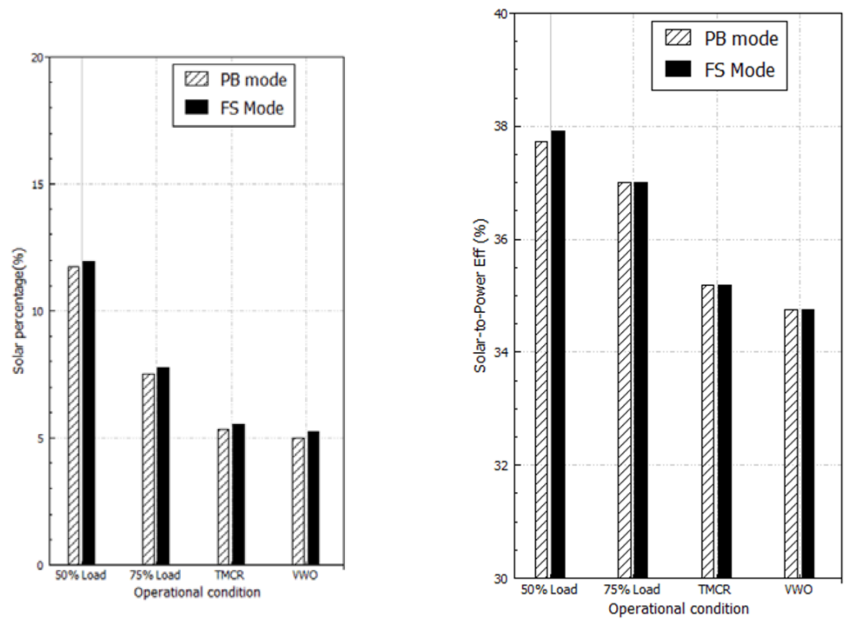
Fluctuations in the electric load on the grid frequently influence the operational efficiency and the power generation system performance [17]. This results in the power plant operating not only at its intended capacity but also at varying loads. As a result, the operational load condition has a direct impact on a thermal power plant's performance and techno-economic indicators [18]. It is required for investigating the steam turbine in partial load condition.



(a) (b)

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

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.
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 [19].



(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 CO_2 emission rate between the base scenario and the retrofit scenario. During the base scenario, the CO_2 emission rate increases when operating with partial loads. The reason is that the that the CO_2 emission rate follows specific fuel consumption, which is higher at low loads. CO_2 emission rate depends on specific fuel consumption [20], 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.

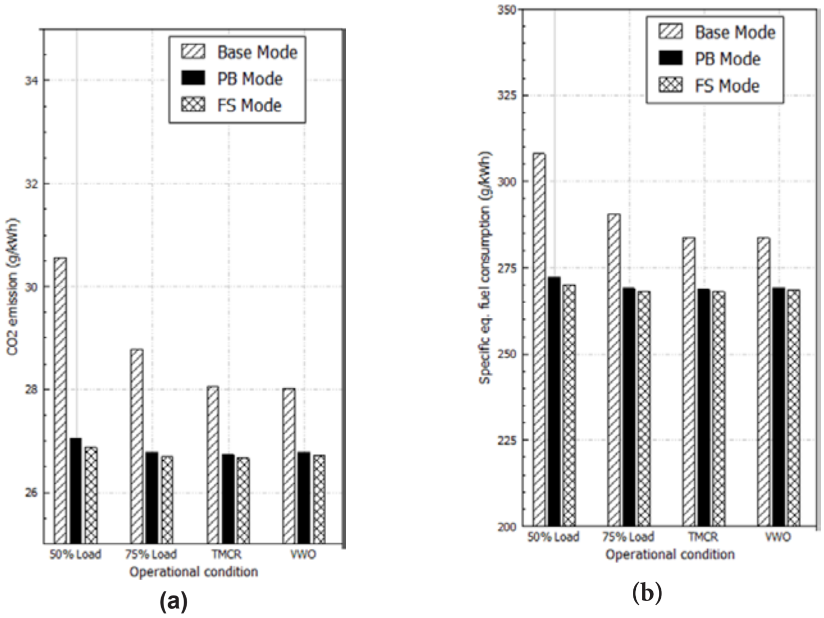


Figure 5. Environment performance indicators affected by variable power loads;(a) CO_2 emission rate. (b) Specific equivalent fuel consumption.

4. 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 conclusions are drawn from this study as follows:

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, the increase in electricity production implies that the power plant can generate more power without proportionally increasing fuel consumption. This improvement is significant for meeting higher energy demands without needing to expand coal usage, thus enhancing the plant's capacity and efficiency. Retrofitting scenario also reducing coal consumption by up to 5.35 percent in fuel-save (FS) mode, means substantial savings on fuel costs and a corresponding reduction in the environmental impact. This reduction is especially important in the context of sustainable energy practices and lowering greenhouse gas emissions. 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 increase signifies that the plant can convert a higher proportion of the input energy into useful electrical energy. This improvement enhances the overall performance and sustainability of the power plant. The retrofit scenario, solar energy contributes to the heat input, reducing the reliance on coal, which typically requires higher heat consumption. The specific heat consumption within both FS and power-boost (PB) modes reduces 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 of both operational modes: power-boost (PB) and fuel-save (FS) will be recovered in

approximately 5.87 years, which is relatively short in the context of power plant investments, which often have long operational lifespans. With a payback period of under six years, the project becomes less vulnerable to long-term changes in market conditions, fuel prices, or policy changes. This short payback period makes the retrofit project financially attractive to investors and stakeholders. In both modes, the levelized electricity cost from solar thermal energy amounts to 431.82 IDR/kWh. An LCOE provides a benchmark for comparing the cost-effectiveness of the retrofit scenario against other energy sources. If this LCOE is lower than the current cost of electricity from coal alone, it indicates a favorable economic outcome.

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 CO_2 emissions. in the power-boost (PB) and fuel-save (FS) modes, CO_2 emissions are reduced to 1.317 g/kWh and 1.386 g/kWh, respectively. fuel-save (FS) mode can approximately reduce CO_2 emissions by 3.83 tons per day. The significant reduction in CO_2 emissions aligns with global efforts to combat climate change by lowering greenhouse gas emissions. This is crucial for meeting international targets, such as those set by the Paris Agreement.

4. Under different operational loads, the base scenario power plant will perform better on near design load, at this load, all systems and components are optimized for maximum performance. 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 constant contribution of solar energy improves the overall thermal efficiency of the plant, even at partial loads. This is because solar energy, being a direct and clean source of heat, compensates for the inefficiencies that typically occur at lower loads.

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REFERENCES

[1] Indonesia, Pemerintah Pusat. 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 Tahun 2016 , No. 115. Sekretariat Negara. Jakarta.

[2] Yan, H., Liu, M., Wang, Z., Zhang, K., Chong, D., & Yan, J. (2023). Flexibility enhancement of solar-aided coal-fired power plant under different direct normal irradiance conditions. Energy, 262, 125349. https://doi.org/10.1016/j.energy.2022.125349.

[3] Qin, J., Zhang, Q., Liu, Z., Hu, E., & Zhang, H. (2022). A strategy to flexibly operate a solar aided power generation plant for wide irradiation conditions. Applied Thermal Engineering, 213, 118659. https://doi.org/10.1016/j.applthermaleng.2022.118659.

[4] Li, C., Zhai, R., & Sun, Y. (2022). Thermal and economic performances comparison of different

pulverized coal power systems augmented by solar trough or tower technologies. Case Studies in Thermal Engineering, 34, 102009. https://doi.org/10.1016/j.csite.2022.102009.

[5] 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. https://doi.org/10.1016/j.energy.2021.122005.

[6] Wu, J., & Han, Y. (2023). Integration strategy optimization of solar-aided combined heat and power (CHP) system. Energy, 263, 125875. https://doi.org/10.1016/j.energy.2022.125875.

[7] Han, Y., Yan, X., Sun, Y., & Wu, J. (2024). A novel solar-aided NOx removal system in peaking power plants. Energy, 132494. https://doi.org/10.1016/j.energy.2024.132494.

[8] Han, Y., Sun, Y., & Wu, J. (2024). An efficient and low-cost solar-aided lignite drying power generation system based on cascade utilisation of concentrating and non-concentrating solar energy. Energy, 289, 129932. https://doi.org/10.1016/j.energy.2023.129932.

[9] Pawellek, R., Löw, T., & Hirsch, T. (2009). EbsSolar – A solar library for EBSILON®Professional. https://elib.dlr.de/62438/.

[10] 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. https://doi.org/10.1016/j.applthermaleng.2020.116445.

[11] 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 & Sustainable Energy Reviews, 77, 474–485. https://doi.org/10.1016/j.rser.2017.04.019.

[12] Zhai, R., Yang, Y., Zhu, Y., & Chen, D. (2013). The Evaluation of Solar Contribution in Solar Aided Coal-Fired Power Plant. International Journal of Photoenergy, 2013, 1–9. https://doi.org/10.1155/2013/197913.

[13] Yong, Q., Jin, K., Li, X., & Yang, R. (2023). Thermo-economic analysis for a novel grid-scale pumped thermal electricity storage system coupled with a coal-fired power plant. Energy, 280, 128109. https://doi.org/10.1016/j.energy.2023.128109.

[14] Xue, X., Han, W., Wang, Z., Jin, H., & Wang, X. (2023). Proposal and assessment of a solar-coal thermochemical hybrid power generation system. Applied Thermal Engineering, 219, 119584.https://doi.org/10.1016/j.applthermaleng.2022.119584.

[15]Yuanhui, W., Liqiang, D., Shuaiyu, J., Jiaping, G., Hanfei, Z., Ming, Y., & Xingqi, D. (2024). Optimization study of a high-proportion of solar tower aided coal-fired power generation system integrated with thermal energy storage. Energy, 132724. https://doi.org/10.1016/j.energy.2024.132724.

[16] 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. https://doi.org/10.1016/j.egypro.2014.03.188.

[17] Azubuike, U. G., Egbuhuzor, L. C., Njoku, H. O., & Ekechukwu, O. V. (2023). Exergy analysis of a steam power plant at full and partial load conditions. International Journal of Exergy, 40(2), 182. https://doi.org/10.1504/ijex.2023.128784.

[18] 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. https://doi.org/10.1016/j.applthermaleng.2020.115127.

[19] Tong, Y., Duan, L., Jiang, Y., Yang, M., & Pang, L. (2022). Performance study of solar tower aided supercritical CO_2 coal-fired power generation system with different schemes. Energy Conversion and Management, 252, 115113. https://doi.org/10.1016/j.enconman.2021.115113.

[20] Haiping C, Heng Z, Yuegang B, Haowen L, Xuelei Z. The performance analysis and evaluation of C-PV/T aided power generation system. Int J Energy Res 2018;42:863e76.https://doi.org/10.1002/er.3833.