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Exergy, Emission, and Operational Cost Analysis of Cofiring Coal-Fired Power Plant Systems

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ABSTRACT

Indonesia's electricity sector remains heavily dependent on coal-fired steam power plants (PLTU), which account for more than 50% of the national energy mix. This study aims to evaluate the impact of biomass cofiring implementation on the thermodynamic, environmental, and economic performance of PLTU Banten 2 Labuan Unit 1, which has a capacity of 300 MW. The methodology involves thermodynamic simulation using Cycle-Tempo software to calculate energy efficiency and exergy, as well as the cost of exergy destruction as part of an exergoeconomic analysis. The results show that the cofiring scenario of 95% coal and 5% biomass is the most optimal configuration. This scenario yields an exergy efficiency of 37.55%, with a reduction in exergy destruction of 7,119 kW compared to 100% coal. Economically, it provides fuel cost savings of 3.2% and a reduction in the cost of exergy destruction of Rp1,623,600 per hour. Environmentally, it reduces CO_2 emissions by 6.25 tons per hour, demonstrating a tangible contribution to emissions reduction in the energy sector. This study concludes that biomass cofiring technology, especially at a 95:5 ratio, offers a viable energy transition solution that can be gradually adopted by existing coal-fired power plants in Indonesia. The results are expected to serve as a technical and strategic reference for developing low-carbon energy policies and optimizing the operation of biomass-cofiring-based power plants.

KEYWORDS *Coal-fired power plants, exergy, exergoeconomic, CO_2 emissions, operating costs,*

INTRODUCTION

Economic growth and increased energy consumption in Indonesia have spurred a massive expansion in power generation capacity (Almogbel et al., 2020; Brueckner & Lederman, 2018; Kawalec et al., 2020; Surya et al., 2021). The national electricity system remains heavily dependent on coal-fired steam power plants (PLTU), which account for more than 50% of the national energy mix. Coal is indeed a reliable and inexpensive energy source, but it has significant environmental impacts, particularly greenhouse gas (GHG) emissions such as carbon dioxide (CO_2). This poses a major challenge to achieving a clean, sustainable national energy system, in line with global emission reduction commitments like the Paris Agreement and Indonesia's Net Zero Emission 2060 target (Finkelman et al., 2021; Ip, 2024; Vig et al., 2023; Zhang et al., 2025).

One strategic approach to balancing high energy demand with emission reduction goals is implementing biomass cofiring technology at coal-fired power plants. Cofiring involves burning a mixture of fossil fuels (coal) and biomass in the same boiler. By incorporating biomass in specific proportions, CO_2 emissions can be reduced, as biomass is considered carbon-neutral (Agoes Noor Sidiq, 2022; Campbell, 2017; Inoue et al., 2015; Kazulis et al., 2018; Pasek et al., 2024). Moreover, this method is more cost-effective than building new renewable energy plants, requiring minimal investment in existing generation infrastructure. Thus, cofiring offers a practical and feasible near-term solution for energy transition.

The biomass used in cofiring typically comes from local agricultural waste such as rice husks, wood industry residues like sawdust, and other readily available organic wastes near the power plant. Utilizing local biomass also boosts regional economic development and reduces reliance on imported fossil fuels (Ertit Tastan, 2016; G S et al., 2023; L.G.POPESCU et al., 2016). However, integrating biomass into existing systems is not straightforward. Technical challenges—including reduced heating value, altered combustion characteristics, slagging, fouling, and impacts on turbine performance—must be thoroughly analyzed to maintain plant reliability and efficiency.

For this reason, a comprehensive performance evaluation method is essential, one that goes beyond conventional assessments of power output and energy efficiency to account for energy quality and thermodynamic irreversibilities. In this context, exergy analysis provides a more precise approach to evaluating energy system efficiency. Exergy quantifies the work potential of energy while pinpointing losses from imperfections in conversion processes. This enables in-depth evaluation of components like boilers, high-pressure turbines, medium-pressure turbines, and condensers to identify major loss sources and improvement opportunities.

Beyond thermodynamics, cost considerations are crucial for cofiring implementation. An exergoeconomic approach integrates exergy analysis with economic evaluation, calculating the cost of exergy losses and destruction in each system component. By quantifying non-beneficial energy losses, it supports strategies to minimize operational costs, boost profitability, and justify cofiring economically. Prior studies indicate that boilers are the primary source of exergy losses, making combustion system enhancements pivotal for overall efficiency and cost reduction.

Environmental impacts must also be addressed in energy planning. Biomass cofiring directly curbs CO_2 emissions due to biomass's carbon-neutral properties. Thus, quantitative assessment of emission reductions across cofiring ratios is vital. Estimating hourly emissions under real operating conditions helps policymakers and operators gauge the technology's role in energy sector decarbonization.

This study evaluates biomass cofiring performance at the Banten 2 Labuan Power Plant (300 MW) via thermodynamic simulations using Cycle-Tempo software. Key parameters analyzed include exergy efficiency, thermal efficiency, heat rate, fuel costs, exergy loss costs, and CO_2 emissions. Scenarios with cofiring ratios of 0%, 3%, 5%, and 7% were examined to identify the optimal balance of efficiency, cost, and emissions. The findings are expected to inform low-carbon energy policies and provide technical guidance for optimizing biomass cofiring at Indonesian PLTU.

METHOD

This study employs a quantitative simulation and modeling approach to evaluate biomass cofiring implementation in a coal-fired power plant. The research is designed as a comparative case study involving scenario analysis of different cofiring ratios to determine optimal configurations based on thermodynamic, economic, and environmental performance indicators.

This research is focused on the Banten 2 Labuan Power Plant with a capacity of 300 MW located in Labuan, Pandeglang Regency, Banten. This unit is one of the subcritical coal-fired power plants in Indonesia that implements biomass cofiring in the national energy transition roadmap.

The data used in this study consisted of:

a. Primary data in the form of data from the performance test results of the power plant unit which includes:
   1) velocity of steam mass,
   2) temperature and pressure at various points of the system,
   3) enthalpy and entropy of working fluids,
   4) types and compositions of fuels (coal and biomass).
b. Secondary data were obtained from the plant's technical documents, operational performance reports, scientific literature, and relevant international journals.

Simulation of the generation system was carried out using the Cycle-Tempo software, which was developed for the thermodynamic analysis of steam cycles and combined cycles. The simulation is carried out in *steady-state conditions*, and reflects the actual operation of the coal-fired power plant in the following fuel scenarios:

a. 100% batu bara (baseline),
b. 97% coal – 3% biomass,
c. 95% coal – 5% biomass,
d. 93% coal – 7% biomass.

The model consists of main components such as boilers, high/medium/low pressure turbines, condensers, pumps, and feed water heating systems (HPH and LPH). Input parameters such as pressure, temperature, and enthalpy are used to calculate the energy efficiency and exergy in each component.

Energy analysis is performed to calculate thermal efficiency based on the ratio between the outgoing energy and the incoming energy. While exergy analysis is used to assess efficiency based on the potential energy that can be used to do work.

Perhitungan exergy:

$$Ex = (h - h_0) - T_0(s - s_0)$$

where:

a. h = enthalpy of the system under certain conditions
b. h_0 = enthalpy of the system at the reference condition (environment)
c. T_0= ambient temperature
d. s = entropy of the system under certain conditions
e. s_0= entropy of the system at the reference condition

Calculation of Exergy Efficiency

$$\eta_{exergy} = \frac{Total\ Exergy\ in}{Total\ Exergy\ out} \times 100\%$$

Exergoeconomic analysis aims to evaluate the cost of energy loss in the system. The main parameters calculated include:

Cost of Exergy Destruction (C_D):

$$C_D = \dot{E}_D \cdot c$$

- $\dot{E}_D$ = exergy damage rate,
- c = cost per unit exergy (Rp/kWh).

Cost Rate of Exergy (C_Ex):

$$C_{Ex} = \dot{E} \cdot c$$

Evaluation was carried out for each component of the plant and compared between scenarios of the cofiring ratio.

The estimated CO_2 emissions are calculated based on the fuel emission factors used. The calculation was carried out using the IPCC standard approach based on the mass and calorific value of the fuel as well as specific emission factors for coal and biomass. Emissions are compared between scenarios to assess emission reductions due to biomass addition.

RESULT AND DISCUSSION

Exergy System Analysis

Exergy analysis was carried out to assess the efficiency of the power generation system from the perspective of advanced thermodynamics by considering the energy quality and the level of irreversibility in the energy conversion processes. In contrast to conventional energy analysis that only pays attention to the quantity of energy, exergy analysis is able to identify where and how much potential loss of energy can be used to do work.

In this study, exergy analysis with the scenario of cofiring variations of coal and biomass, namely: 100% coal, 97% coal–3% biomass, 95% coal–5% biomass, and 93% coal–7% biomass.

Table 1. Calculation of total exergy in, exergy out, and exergy efficiency

100% Coal

Parameter	Score
Total Energy Flow In	938,583.62 kW
Total Energy Flow Out	352,919.46 kW
Total Energy Destruction	585,664.17 kW
Energy System Efficiency	37.60%

97% Coal 3% Biomass

Parameter	Score
Total Energy Flow In	931,269.70 kW
Total Energy Flow Out	349,876.87 kW
Total Energy Destruction	581,392.84 kW
Energy System Efficiency	37.57%

95% Coal 3% Biomass

Parameter	Score
Total Energy Flow In	926,393.75 kW
Total Energy Flow Out	347,848.47 kW
Total Energy Destruction	578,545.28 kW
Energy System Efficiency	37.55%

93% Coal 7% Biomass

Parameter	Score
Total Energy Flow In	921,517.81 kW
Total Energy Flow Out	345,820.08 kW
Total Energy Destruction	575,697.73 kW
Energy System Efficiency	37.53%

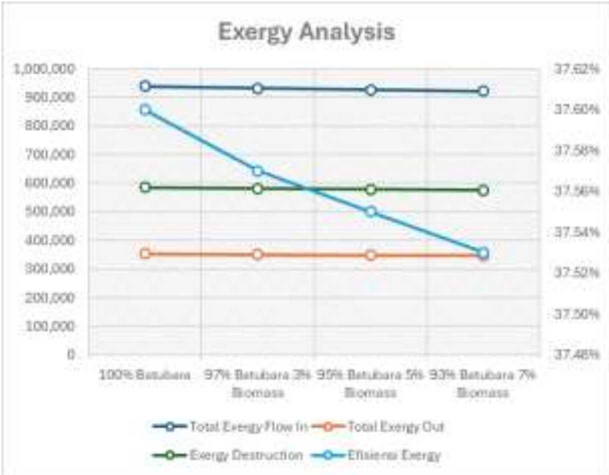

Figure 1. Comparison of Exergy In, Out, Exergy Efficiency of each scenario

The table shows that the larger the proportion of biomass, the total exergy input of the system decreases. This is due to the calorific value of biomass which is generally lower than coal. However, the exergy output remains relatively constant, indicating that the turbine's work is not disrupted by a change in fuel type of up to 7%.

Exergy Analysis of Each Component

1) Boiler

The boiler is the component with the largest input exergy, but also the highest contributor to exergy destruction. This is due to:

a. Extreme temperature difference between flame and working fluid.
b. Irreversibility of the combustion process.

The efficiency of the boiler is relatively stable, but exergy losses tend to decrease as the biomass portion increases. This indicates a positive influence of biomass combustion characteristics that tend to be more reactive and ignite quickly (Zhang et al., 2019).

2) Steam Turbines (HP, IP, LP)

High Pressure Turbines have low exergy efficiency (~5–6%), as most of the energy is stored for expansion in the IP and LP stages. LP Turbine records exergy efficiency of < 2%, as it works with low pressure and small temperature difference. The decrease in exergy destruction in the LP Turbine during cofiring can be interpreted as an indication of improved temperature gradient and steam entropy adjustment.

3) Condenser

Condensers are places of high irreversibility because they convert steam into water through isobaric heat transfer to the environment at much lower temperatures. Although the absolute exergy value is low, the condenser does not produce an exergy output, so it is considered a "waste" of thermal energy.

4) Feed Pumps and Heaters

The exergy efficiency of the pump is generally high (>20%) because the liquid water compression process is quite reversible. LPH and HPH have moderate exergy efficiency (~19%), but better temperature distribution in cofiring scenarios provides a slight increase in efficiency.

Kotas (2013) showed that the exergy efficiency of subcritical plants is in the range of 35–45%. The value of 42–42.4% in this simulation confirms that the Banten 2 Labuan PLTU is in good performance condition.

In a study by Shoaei et al. (2021), the exergy efficiency of a hybrid energy system with biomass and solar increased from 41.1% to 43.6% after optimizing temperature and fuel distribution. A decrease in exercise losses in LP Turbine and heat exchanger also occurred in this simulation.

Exergoeconomic Analysis and Fuel Costs

Calculations were made for four scenarios, taking into account the mixed HHV value, fuel cost per kilogram, exergy destruction, and unit cost of exergy destruction.

Tabel 2. Perhitungan cost of exergy destruction

Biomass Percentage	Exergy Destruction (kW)	Fuel Cost (Rp/kg)	Unit Cost Exergy (Rp/kWh)	Cost of Exergy Destruction (Rp/hour)
100% Coal	585,664	1,037.32	318.81	186,717,600
97% Coal 3% Biomass	581,393	1,031.91	319.48	185,743,800
95% Coal 5% Biomass	578,545	1,028.30	319.93	185,094,000
93% Coal 7% Biomass	575,698	1,024.70	320.39	184,446,000

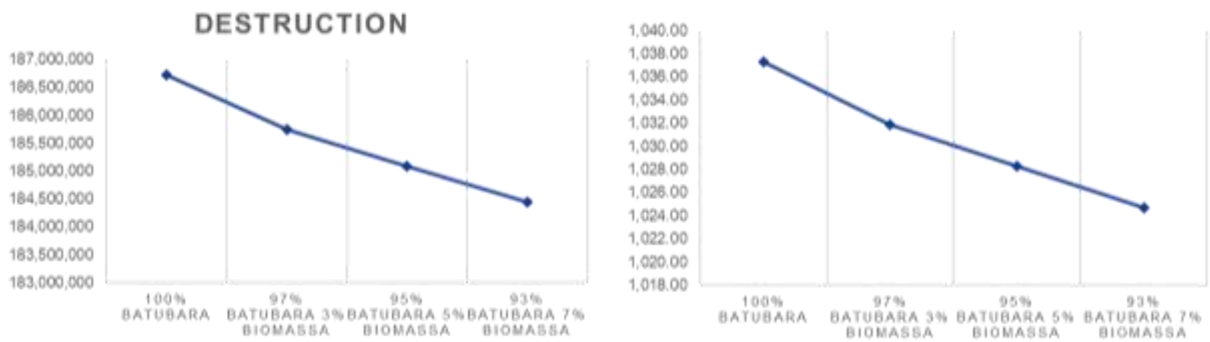

Figure 2. Comparison chart of fuel cost and cost of exergy destruction

a) Fuel Cost

The decrease in fuel costs is evident as the biomass portion increases:

1) From Rp 1,037.32/kg (100% coal) to Rp 1,024.70/kg (7% biomass).
2) This decrease occurs because the price per kg of biomass is lower, so even though the energy per kg is smaller, the mixture still results in cost efficiency.

b) Exergy Destruction

Exergy destruction decreased from 585,664 kW to 575,698 kW. This decrease is consistent with the exergy results and shows that the use of biomass in small amounts does not exacerbate the irreversibility losses of the system, but rather reduces it slightly.

c) Unit Cost of Exergy dan Cost of Exergy Destruction

Although exergy destruction decreased, the unit cost of exergy increased slightly from Rp 318.81/kWh to Rp 320.39/kWh, indicating that the price per kWh of available energy increased slightly. This is a logical trade-off due to the declining HHV of the mixture.

However, the value of the cost of exergy destruction (Rp/hour) shows a downward trend: The total cost of exergy destruction from IDR 186.7 million/hour to IDR 184.4 million/hour, shows a saving of around IDR 2.3 million/hour or around 1.2%.

CO2 Emission Analysis

Table 3. Estimated CO_2 Emissions of Coal and Biomass per Scenario

Coal Ratio	Coal Consumption (t/hour)	Coal CO_2 Emissions (t/h)	Biomass Consumption (t/h)	Biomass CO_2 Emissions (t/h)	Total CO_2 Emissions (t/h)
100%	180.0	298.03	0.0	0.000	298.03
97%	174.6	289.09	5.4	6.264	295.35
95%	171.0	283.12	9.0	10.44	293.56
93%	167.4	277.16	12.6	14.616	291.78

Based on the data above, it can be seen that the trend of decreasing CO_2 emissions as the biomass ratio increases:

a. From 298.03 tons/h (100% coal) to 291.78 tons/h (93% coal),
b. Absolute decrease of 6.25 tonnes CO_2/hour or 2.1%.

Although biomass produces CO_2 emissions during combustion, these emissions are not counted as additional net carbon because they come from short carbon cycles that are reabsorbed by biomass plants. This is because:

a. The carbon content in coal produces fossil CO_2, is non-renewable and causes increased atmospheric emissions.
b. Biomass is considered carbon neutral because the CO_2 released will be reabsorbed during its growth period.
c. Thus, although total biomass CO_2 emissions (e.g. 14.6 tons/hour in the 7% scenario) are still calculated in the inventory, this value is not recorded in the net emission calculation scheme in the GHG (greenhouse gas) emission reporting system.

CONCLUSION

In conclusion, this study demonstrates that implementing a 95% coal and 5% biomass cofiring configuration in a 300 MW subcritical power plant yields an optimal balance of thermodynamic, economic, and environmental benefits, achieving an exergy efficiency of 37.55%, reducing exergy destruction by 7,119 kW, lowering fuel costs by 3.2%, and cutting CO_2 emissions by 6.25 tons per hour compared to the baseline 100% coal scenario. For future research, it is recommended to investigate the long-term operational impacts of higher biomass ratios (e.g., 10–20%) on boiler fouling, slagging, and component degradation, to conduct a comprehensive life-cycle assessment (LCA) encompassing biomass supply chain emissions and sustainability, and to explore the integration of advanced biomass pretreatment methods (e.g., torrefaction, pelletization) and hybrid renewable systems (e.g., solar-thermal) to further enhance efficiency and decarbonization potential in existing coal-fired power plants.

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