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Energy Performance Analysis and Operational Efficiency Improvement of Steam Power Plant: Energy Audit Case Study

Hanafi Ramadhana [1,2] & Retno Gumilang Dewi[2]

[1]PT PLN (Persero) Unit Induk Distribusi Sumatera Utara
[2] Department of Chemical Engineering, Bandung Institute of Technology, Bandung 40116, Indonesia
E-mail: 23023070@mahasiswa.itb.ac.id, retno@itb.ac.id

Abstract. This study aims to analyze and provide recommendations for increasing energy efficiency at the Labuhan Angin Steam Power Plant (PLTU) by considering technical, economic, and environmental aspects. The Labuhan Angin PLTU, with a capacity of 2×115 MW, uses Circulating Fluidized Bed (CFB) boiler technology that operates the Rankine cycle with high-pressure steam. The method used is a case study with a quantitative and qualitative approach, examining operational data and the thermodynamic system of the power plant during August–December 2024. Quantitative analysis includes measuring cycle efficiency and energy distribution using Aspen HYSYS software, while qualitative analysis assesses operational and technical factors that affect power plant performance. The results of the study show that the thermal efficiency of the PLTU reaches around 22.02%, with steam pressure as the main variable that greatly influences efficiency improvement; the higher the steam pressure, the power plant efficiency increases to more than 23.5%. The study also identified that the efficiency of the boiler, turbine, and air heating system are crucial factors in improving performance, as well as the need for routine maintenance and the use of alternative fuels such as biomass. The application of the regenerative cycle has been proven to reduce boiler energy consumption by up to 22% and heat loss through the condenser by up to 25%, thereby significantly increasing efficiency. These findings provide the basis for technical recommendations for optimizing the operation of the Labuhan Angin PLTU to achieve higher energy efficiency while reducing environmental impacts.

Keywords: *Energy efficiency, coal-fired power plant, energy balance, power loss, combustion optimization*

1 Introduction

The increase in energy consumption is in accordance with population growth and the country's economic growth. In Indonesia, energy consumption is still dominated by fossil fuels (coal, oil, natural gas). The provision of electricity in

Indonesia is currently still dominated by fossil fuels where coal is the most widely used energy source (Lestari, 2021) . Based on the 2020 energy mix data, coal filled the energy mix portion of 38.5% (National Energy Council, 2021). The average growth in coal consumption for power plants for the 2015-2020 period was 8.4%. In 2020, coal consumption for power plants reached 104.8 million tons, influenced by the increase in the capacity of domestic coal-fired power plants (National Energy Council, 2021).

Globally, coal-fired power generation peaked in 2020, and all regions of the world must phase out coal-fired power plants between 2030 and 2040. By 2040, the share of renewable energy in power generation must be increased to at least 75%, and the share of coal without CCS/CCUS technology reduced to zero (Lin & Liu, 2024) .

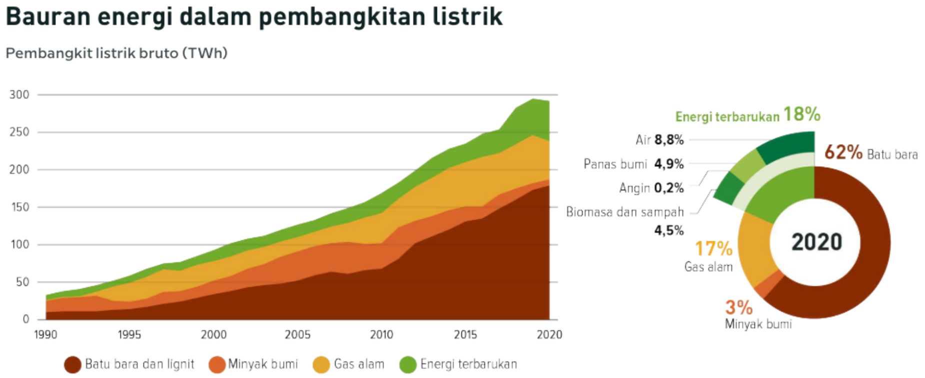


Figure 1 Energy mix in electricity generation Source: (Climate Transparency, 2021)

In 2020, around 82% of electricity in Indonesia was still produced from fossil fuels, mainly coal (62%), while renewable energy only contributed 18%, below the G20 average of 29%, with biomass as one of the main contributors (13%). This condition shows the need for energy conservation as a systematic and planned effort to conserve energy resources and increase the efficiency of their use, both through macro policies such as government regulations (for example, ESDM Regulation No. 14 concerning energy management) and micro methods such as energy audits, considering that energy consumption is projected to increase by 5.6% per year while energy resources are limited (Sinaga, 2024; Di Bella & Tavoni, 2024). Moreover, with the dwindling national oil reserves, because the era of Indonesia's oil glory has passed (Beaton, Lontoh, & Wai-Poi, 2017) .

The examination of power plant energy performance and operational efficiency has benefited from the results and improvements published in leading chemical engineering publications. To improve operational efficiency in coal-fired power plants, for example, attention is paid to the use of modern process control systems (Yang, Li, Wang, & Yang, 2019) . The operational efficiency of coal-fired power plants can be improved by conducting an energy audit. To find ways to save energy and make the system more efficient, it is wise to conduct an energy audit (Chauhan, 2015) .

An integral part of the power plant's energy performance is maintenance and care management, which is as important as operational efficiency. Power plants can improve operational efficiency and system availability through the use of artificial intelligence for predictive maintenance in power plants. Reducing downtime and increasing operational dependability can be achieved with the right maintenance strategy (Saputri, Sa'diyah, & Yulianto, 2022) .

Finding the best way to burn coal is a major obstacle to making coal-fired power plants more efficient. Increased efficiency and lower exhaust emissions can be achieved through innovative techniques to optimize coal combustion. Power plants can benefit from the additional knowledge gained by reading reviews of modern methods for energy recovery from exhaust gases, which can help operations run more efficiently (Widhiyanto, 2019) .

To further improve the efficiency of PLTU operations, it is necessary to consider economic factors (Taner & Sivrioglu, 2017) . As mentioned by (Khaleel, Ismail, Ibrahim, & bin Abu Hassan, 2022) , life cycle analysis (LCA) of coal-fired power plants can explain the ecological consequences of PLTU operations (Zhai et al., 2016) . In addition, it can also determine the monetary value of increased efficiency (Duinea, 2019) . Despite numerous studies addressing the macro-level challenges of fossil fuel dependency, few have examined the operational-level energy performance of existing coal-fired power plants in Indonesia using real-time case studies. There is a lack of applied research focusing on system efficiency, combustion optimization, and energy loss diagnosis using audit-based approaches within specific PLTUs such as Labuhan Angin.

This study aims to analyze the energy performance of a steam-fired power plant and improve operational efficiency through a case study of energy audit at Labuan Angin Steam-fired Power Plant, by reviewing the latest research in chemical engineering and related fields. This study will consider technical, economic, and environmental variables in developing recommendations based on existing data and infrastructure for overall energy efficiency improvement.

2 Literature Review

2.1 Energy Analysis of Steam Power Plant (PLTU)

Energy analysis is an important approach in evaluating the performance of a coal-fired power plant (CFPP) and identifying potential efficiency improvements. One of the main methods in CFPP energy analysis is the calculation of an energy balance. An energy balance allows the measurement of energy input, such as the fuel used to produce steam, and energy output, such as the electricity produced by the generator. By comparing energy input and output, an energy balance provides a comprehensive picture of the efficiency of energy use in CFPP operations. In addition, thermodynamic analysis is also used to evaluate CFPP performance. This analysis involves modeling thermodynamic cycles that describe the energy processes in a CFPP. By using thermodynamic concepts such as entropy and thermal efficiency, researchers can identify areas where energy is wasted and design appropriate improvement strategies.

2.2 Optimization of Steam Power Plant (PLTU)

Optimization of a steam power plant (PLTU) is a key step in improving operational efficiency and reducing the cost of electricity production. One common approach used in PLTU optimization is the use of sophisticated control methods. This control method includes setting operational variables such as temperature, pressure, and fuel and air flow using an automatic control system. By continuously monitoring and optimizing these operational variables, the PLTU can achieve higher efficiency and significantly reduce fuel consumption. In addition, mathematical modeling and computer simulation are also important tools in PLTU optimization. Mathematical modeling allows a detailed representation of various processes in the PLTU, while computer simulation allows testing various operational scenarios virtually. By using this modeling and simulation, PLTU operators can identify the most effective improvement strategies and optimize overall system performance.

3 Methodology

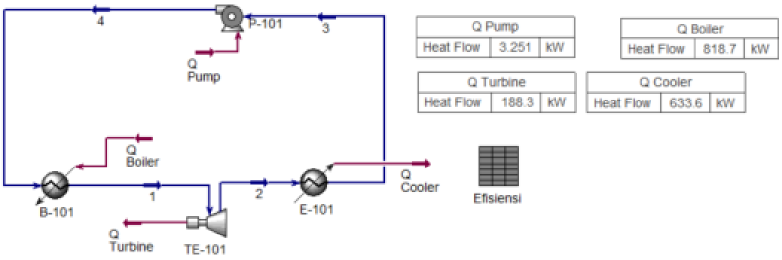
This research method uses a case study approach with a focus on the Labuhan Angin PLTU as the main object. The case study approach was chosen to allow for an in-depth analysis of the complex system in the context of the real operation of the power plant. In this study, two types of analysis were used, namely quantitative and qualitative analysis. Quantitative analysis is carried out by measuring and analyzing numerical data related to the PLTU energy performance, while qualitative analysis includes interpretation of the results and evaluation of non-numerical factors that affect operational efficiency. This research was conducted at the Labuhan Angin PLTU located in Sibolga, North Sumatra, Indonesia, during the period August to December 2024. The selection of the location and time of the study aims to obtain comprehensive and representative data, including seasonal variations that can affect the operation of the power plant.

To support the quantitative analysis, Aspen HYSYS was used as it allows accurate simulation of the Labuhan Angin PLTU's operational conditions. This software enables detailed mass and energy balance calculations, helping assess the impact of various scenarios on plant performance. Its visual and flexible interface also supports qualitative interpretation, aligning with the study's combined analytical approach.

4 Results and discussion

4.1 Analysis of PLTU energy performance

Labuhan Angin PLTU is located in Central Tapanuli, North Sumatra, built in 2004–2006 and has been operating since 2007 with a capacity of 2×115 MW. Using Circulating Fluidized Bed (CFB) technology, this PLTU is capable of burning low-calorie coal with low NO_x and SO_2 emissions. Its operational system includes a conveyor belt for coal filling, dry ash handling, and cooling with seawater from Tapian Nauli Bay. This plant is important for North Sumatra's electricity supply and is connected to the PLN network. This PLTU works with the Rankine cycle, which involves a boiler, steam turbine, condenser, and pump to convert thermal energy into electrical energy repeatedly.



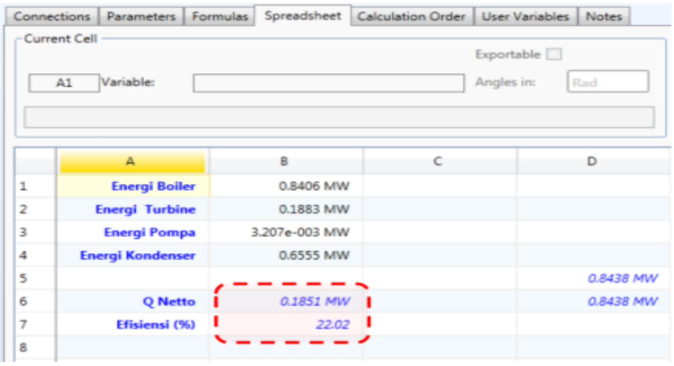
Q Pump
Heat Flow 3.251 kW

Q Boiler
Heat Flow 818.7 kW

Q Turbine
Heat Flow 188.3 kW

Q Cooler
Heat Flow 633.6 kW

Figure 2 Analysis of PLTU efficiency using Aspen HYSYS



A1

Angles in: Rad

	A	B	C	D
1	Energi Boiler	0.8406 MW		
2	Energi Turbine	0.1883 MW		
3	Energi Pompa	3.207e-003 MW		
4	Energi Kondenser	0.6555 MW		
5				0.8438 MW
6	Q Netto	0.1851 MW		0.8438 MW
7	Efisiensi (%)	22.02		
8				

Figure 3 Simple efficiency results of PLTU using Aspen HYSYS

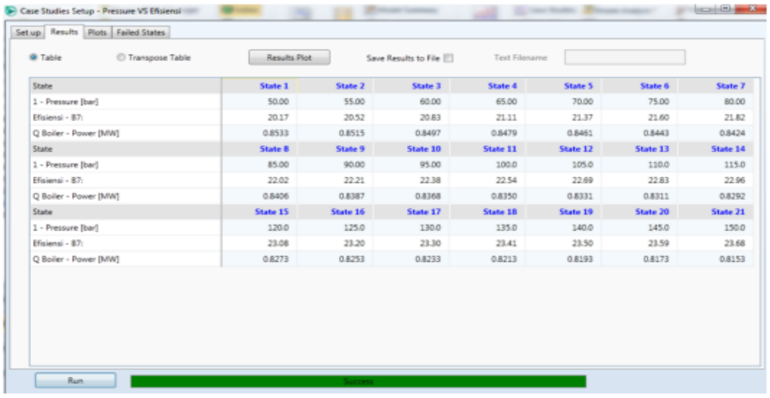
This steam power plant (PLTU) system operates using saturated steam with a mass flow rate of 1 ton per hour (1000 kg/hour) produced by the boiler (B-101) at a pressure of 85 bar and a temperature of 500°C, without a pressure drop during the heating process. This high-pressure steam is channeled to the expansion turbine (TE-101) with a mechanical efficiency of about 75% to convert thermal energy into mechanical energy, while reducing the steam pressure from 85 bar to 1.5 bar, then the mechanical energy is used to drive the electric generator. The low-pressure steam from the turbine is then channeled to the cooling condenser (E-101), where its temperature is reduced to 85°C with a pressure drop of about 5 psi. The condensed water is then channeled to the high-pressure pump (P-101) which has an efficiency of 75% to increase the fluid pressure back to 85 bar, thus forming a closed Rankine cycle. Based on thermodynamic calculations, the total efficiency of this generating system is estimated to be around 22.02%, which reflects the effectiveness of converting heat energy into electrical energy.

According to Putra's research (2015), it provides an overview of energy distribution in the Steam Power Plant (PLTU) system, including incoming energy from coal, outgoing energy used by various components, and energy losses in the energy conversion process. Of the total incoming energy of 1,939,557.49 kW, most of it is allocated to HP Turbine (9.82%), IP Turbine (14.48%), LP Turbine A (5.56%), and LP Turbine B (5.73%), while the largest energy loss occurs in the boiler (36.81%), which shows that the combustion and heat transfer processes have significant inefficiencies. In addition, there is energy loss in the generator (2.57%), turbines (LP, IP, and HP), and supporting systems such as CEP, TFWP, and BWCP, although in smaller amounts. By knowing this energy distribution and loss pattern, further analysis can be carried out to improve the operational efficiency of the PLTU, such as through combustion optimization, heat transfer system improvements, or the application of more efficient technology in the energy conversion system.

Another study by Wahyudi (2023) identified that the decrease in the efficiency of the high pressure turbine (HP) was the main cause of the increase in the net heat rate (Nett Plant Heat Rate), with an average loss of 87.96 kCal/kWh or 24.53% of the total loss. These findings emphasize the importance of maintaining and optimizing key components such as boilers and turbines to minimize energy losses and improve the operational efficiency of the PLTU.

4.2 Factors Affecting the Efficiency of a Steam Power Plant System

Based on the analysis of case studies with variations in steam pressure ranging from 50 bar to 350 bar with an increase of every 5 bar, a number of main factors were found that play an important role in determining the thermodynamic efficiency of the PLTU system.



State	State 1	State 2	State 3	State 4	State 5	State 6	State 7
1 - Pressure [bar]	50.00	55.00	60.00	65.00	70.00	75.00	80.00
Efisiensi - B7:	20.17	20.52	20.83	21.11	21.37	21.60	21.82
Q Boiler - Power [MW]	0.8533	0.8515	0.8497	0.8479	0.8461	0.8443	0.8424
State	State 8	State 9	State 10	State 11	State 12	State 13	State 14
1 - Pressure [bar]	85.00	90.00	95.00	100.0	105.0	110.0	115.0
Efisiensi - B7:	22.02	22.21	22.38	22.54	22.69	22.83	22.96
Q Boiler - Power [MW]	0.8406	0.8387	0.8368	0.8350	0.8331	0.8311	0.8292
State	State 15	State 16	State 17	State 18	State 19	State 20	State 21
1 - Pressure [bar]	120.0	125.0	130.0	135.0	140.0	145.0	150.0
Efisiensi - B7:	23.08	23.20	23.30	23.41	23.50	23.59	23.68
Q Boiler - Power [MW]	0.8273	0.8253	0.8233	0.8213	0.8193	0.8173	0.8153

Figure 4 Results of a case study using pressure as the limiting variable.

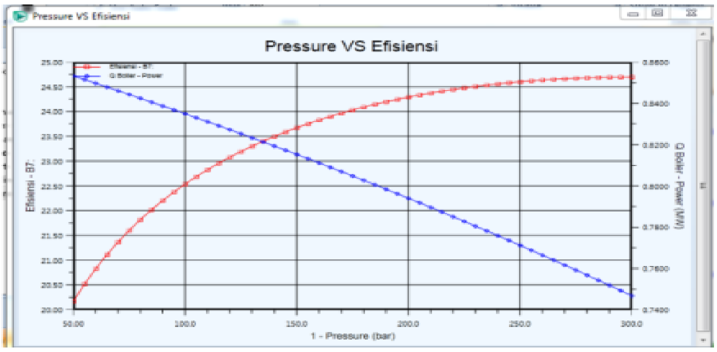


Figure 5 Case study graph using pressure as the limiting variable.

Thermodynamic efficiency in a steam power plant system is greatly influenced by steam pressure, because this pressure determines the saturation temperature and specific enthalpy of steam entering the turbine. Higher pressure results in higher steam temperature and energy, so that the turbine can produce higher mechanical work during expansion. This increases the enthalpy difference between the turbine inlet and outlet, which directly affects the increase in Rankine cycle efficiency. The graph shows that the efficiency increases from about 20% at 50 bar to about 24% at higher pressures, reflecting the positive relationship between steam pressure and system efficiency.

In addition to pressure, efficiency is also affected by superheat temperature, condensing pressure, and isentropic efficiency of the turbine and pump. Higher superheat temperature increases efficiency by increasing the average heat addition temperature, while lower condensing pressure increases the specific work of the turbine. Isentropic efficiency is important because irreversibility in components can reduce net work output. However, from the case study data, increasing steam pressure is proven to be the dominant factor that consistently increases the efficiency of the steam power plant, from 20.17% at 50 bar to more than 23.5% at pressures above 130 bar, confirming that the higher the steam pressure, the higher the efficiency of the power plant system.

Energy efficiency in Steam Power Plants (PLTU) is influenced by various technical and operational factors. Previous research by (Suhardi, Kamriani, Suryanto, & Jamal, 2020) has identified several main aspects that play a role in increasing energy efficiency. One of them is boiler efficiency, where the use of economizers has been shown to increase combustion efficiency, as found in a study at the Jeneponto PLTU. In addition, steam turbine efficiency also plays an important role in converting heat energy into mechanical energy.

Research (Purnomo & Effendy, 2018) at the Tanjung Awar-Awar PLTU showed that turbine efficiency increased from 86.02% at 75% load to 88.64% at 100% load. Another factor that affects efficiency is the performance of the air heater system , which functions to increase the combustion air temperature. A study by Irawan & Mursadin (2019) at the Asam-Asam Unit 2 PLTU showed that optimal air heaters contributed to increasing the overall efficiency of the system. In addition to technical factors, routine maintenance and *overhauls* also play a role in maintaining the thermal efficiency of the PLTU.

Research (Arfiansyah & Hiendro, 2023) shows that after *overhaul* , there is an increase in thermal efficiency and a decrease in specific fuel consumption. In addition, the use of alternative fuels such as biomass is also a strategy that can increase operational efficiency and sustainability. A study (Isarani, 2017) shows that the use of wood waste as fuel can maintain the stability of operating costs and reduce dependence on coal. By understanding and optimizing these aspects, PLTU can increase energy efficiency, reduce fuel consumption, and minimize environmental impacts.

4.3 The PLTU system uses integration with simulation regeneration

Heat integration is an effective strategy to improve the efficiency of steam power plants by reusing the heat of steam after it exits the turbine, thereby reducing heat loss in the condenser and saving heating energy in the boiler. This approach is realized through a regenerative cycle, where steam is extracted from the turbine at several points to heat the boiler feed water before entering the main boiler. Labuhan Angin PLTU, as a coal-fired power plant, applies a water tube boiler system with three pressure stage steam turbines (HP, MP, LP) and other supporting components to generate electricity efficiently.

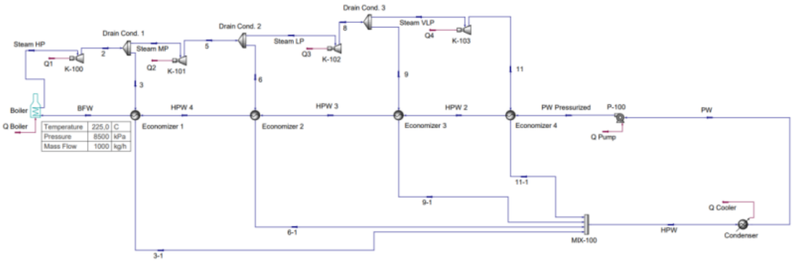


Figure 6. Analysis of regenerative PLTU efficiency using Aspen HYSYS

The regenerative system uses four staged steam turbines from 85 bar to 1.5 bar, each with 75% efficiency, and four economizers that heat the boiler feedwater from 85°C to 225°C with a pressure drop of 5 psi per stage. Steam is generated by the boiler at 500°C and 85 bar without significant pressure drop, supported by a condenser and high-pressure pumps at 85 bar. Compared to a conventional Rankine cycle, the regenerative cycle shows higher efficiency with a reduction in boiler energy requirements of 22% and condenser waste heat of approximately 25.4%, increasing the system efficiency from 22.02% to 25.38%. This improvement is achieved by preheating the feedwater using extracted steam, making the regenerative cycle a more energy-efficient and efficient solution to improve the performance of the power plant.

4.4 Comparison between Rankin PLTU simulation and Integration

In a conventional cycle, all the turbine output steam is condensed, resulting in a large amount of heat energy being wasted to the environment, while the regenerative cycle uses some of the steam to heat the feed water, reducing the amount of steam condensed and reducing the heat loss in the condenser by 25.4%. Although the regenerative cycle causes a slight decrease in the turbine output energy by 7.5% because the steam is extracted before full expansion, the energy savings in the boiler and the reduction in heat rejection are much greater, so the total system efficiency is still significantly increased.

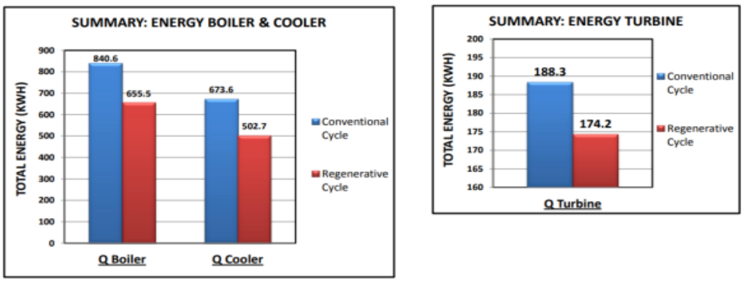


Figure 6 Bar chart comparing Rankin results with regenerative results

The regenerative cycle improves the efficiency of a steam power plant by heating the feed water using extracted steam, which reduces the boiler energy requirement and condenser heat exhaust, increasing the system efficiency from 22.02% to 25.38%. Although the turbine energy is slightly reduced, this cycle is more economically profitable and environmentally friendly, especially for large plants. In addition, technologies such as supercritical, ultra-supercritical, CCGT, and cogeneration cycles are also used for higher efficiency, although they require expensive special materials. In Indonesia, the system design must be adjusted to the fuel conditions and tropical climate for optimal efficiency. The regenerative cycle is an efficient solution for medium to large capacity plants, supporting emission reduction and operational cost optimization amidst the increasing electricity demand.

The comparison between the conventional Rankine cycle and the regenerative cycle highlights significant technical and economic advantages of the latter. Technically, while the Rankine cycle allows full steam expansion for maximum turbine output, it results in considerable energy loss through condensation. In contrast, the regenerative cycle extracts part of the steam before full expansion to preheat the feedwater, reducing boiler fuel demand and condenser heat load achieving a 25.4% reduction in heat rejection despite a 7.5% decrease in turbine power. This leads to an overall system efficiency increase from 22.02% to 25.38%. Economically, although the regenerative system requires additional components like feedwater heaters and extraction lines, it lowers long-term fuel costs and operational expenses. For medium to large-scale coal-fired power plants like Labuhan Angin, the regenerative cycle offers a more cost-effective and practical solution than advanced technologies such as supercritical or cogeneration systems, which demand expensive materials and infrastructure. Therefore, regenerative integration supports better thermal efficiency, reduced emissions, and enhanced economic viability under Indonesia’s tropical and coal-dependent conditions.

4.5 Comparison between Rankin PLTU simulation and Integration

Labuhan Angin PLTU is a coal-fired power plant equipped with a water tube boiler system, which is commonly used in large-scale facilities. The main components of the plant include a boiler, a three-stage steam turbine (high-pressure/HP, medium-pressure/MP, and low-pressure/LP), a generator, and a condenser. With a coal feed rate of 474.3 tons per hour and combustion air supply of 500 tons per hour, the plant generates primary steam at a temperature of 532°C and a pressure of 8.56 MPa, with a steam flow rate of 413 tons per hour. The three-stage steam turbine produces a total electrical output of 110.5 MW, distributed as 62.58 MW from the HP turbine, 15.99 MW from the MP turbine, and 31.91 MW from the LP turbine.

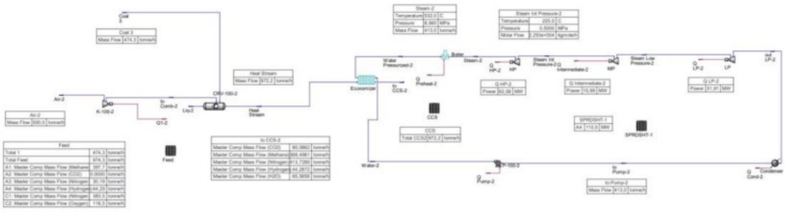


Figure 7 Analysis of the efficiency of regenerative PLTU using Coal

Labuhan Angin PLTU uses a coal-based power generation system with a water tube boiler designed to process Coal 3 type coal with a flow rate of around 474.3 tons per hour. The combustion process is carried out using pulverized coal with excess air to produce high-pressure steam of 8,560 MPa at a temperature of 532°C. The installed steam turbine consists of three pressure levels (HP, MP, LP) which in total are capable of producing 110.5 MW of electrical power with the largest power distribution on the high-pressure turbine (HP).

Boiler performance analysis shows imperfections in the combustion process as seen from the high concentration of methane and hydrogen in the exhaust gas, indicating less than optimal combustion efficiency. This condition can be caused by an imbalance in the air and fuel ratio, uneven air distribution, or problems with the pulverizer system and combustion chamber. Compared to international pulverized coal boiler efficiency standards, this PLTU shows a lower efficiency value so that improvements and operational optimization are needed.

To improve the energy performance of the Labuhan Angin PLTU, strategic steps are needed such as adjusting the air-fuel ratio, improving coal quality, and optimizing combustion chamber parameters. In addition, steam production efficiency can be improved by reducing heat losses through improvements to the economizer, air preheater, and thermal insulation. Increasing turbine efficiency and condenser vacuum is also important to reduce fuel consumption which is currently still relatively high. The implementation of these improvements is expected to improve operational stability, extend equipment life, and reduce overall operational costs.

4.6 Discussion

4.6.1 Energy Performance Analysis

The Labuhan Angin PLTU, which uses Circulating Fluidized Bed (CFB) boiler technology and conventional Rankine cycle, has a thermal efficiency of around 22.02%. However, there is significant energy loss, especially in the boiler (36.81%) and in the turbine and generator due to mechanical and thermal inefficiencies. Maintenance of key components, combustion optimization, and increasing turbine efficiency are key to improving the performance of the PLTU which faces the challenge of low efficiency. Steam pressure also plays a major role in increasing efficiency, with studies showing efficiency increases from 20% at 50 bar pressure to more than 23.5% at pressures above 130 bar.

The implementation of a regenerative cycle that utilizes steam extraction to heat boiler feed water can increase the efficiency of the Labuhan Angin PLTU to 25.38%, an increase of around 15.3%. This system reduces boiler energy requirements by 22% and heat loss in the condenser by 25.4%, although turbine power decreases slightly. A study by Abbas et al. (2019) shows that the distribution of energy entering the PLTU system includes various turbines, but the greatest energy loss occurs in the boiler. By understanding this energy distribution and loss pattern, combustion optimization, heat transfer system improvements, and the application of efficient technology can significantly increase the operational efficiency of the PLTU (Abbas, Jamaluddin, & Amiruddin, 2020) .

Energy efficiency in PLTU is influenced by various technical and operational factors. One of the main aspects that plays a role in increasing efficiency is boiler efficiency. A study conducted by Suhardi et al. (2020) shows that the use of economizers can increase combustion efficiency, as applied to the Jeneponto PLTU. Economizers function to increase the utilization of heat from exhaust gas, thereby reducing fuel consumption and increasing the overall efficiency of the system (Karaeng, Iswandi, Firman, & Nuzul, 2013) .

In addition, steam turbine efficiency is also a key factor in converting heat energy into mechanical energy. Research conducted by Purnomo & Effendy (2018) at the Tanjung Awar-Awar PLTU showed that turbine efficiency increased from 86.02% at 75% load to 88.64% at 100% load. This increase shows that operating the turbine at optimal load can significantly increase energy efficiency.

Another factor that affects efficiency is the performance of the air heater system. A study conducted by Irawan & Mursadin (2019) at the Asam-Asam Unit 2 PLTU showed that optimal air heaters contribute to increasing the overall efficiency of the system. The air heater functions to increase the combustion air temperature, thereby increasing boiler efficiency and reducing fuel consumption (Ahmad, Gaos, & Wiradinata, 2022) .

Routine maintenance and overhaul play an important role in maintaining the thermal efficiency of the PLTU. Reseazrch by Arfiansyah & Hiendro (2023) shows that after overhaul, thermal efficiency increases and specific fuel consumption decreases, due to repair of degraded components. In addition, the use of alternative fuels such as wood waste, according to Isarani (2017), can maintain the stability of operational costs, reduce dependence on coal, and reduce carbon emissions. The use of biomass also increases the sustainability of PLTU operations. With combustion optimization, routine maintenance, and efficient technology, PLTU can increase energy efficiency, reduce fuel consumption, and minimize environmental impacts for future operational sustainability.

4.6.2 Limitations and Challenges

- Boiler Efficiency: Although the boiler system at the Labuhan Angin PLTU is designed for efficiency, there are imperfections in combustion that cause high concentrations of methane and hydrogen in the exhaust gas. This indicates a potential for suboptimal combustion.

- Energy Losses: Most of the energy is lost in the combustion process in the boiler (36.81%), as well as in the generator and turbine, which reduces the overall efficiency. This indicates the need for improvements in the combustion and heat transfer systems to reduce energy losses.

- Technical Limitations: Although the regenerative cycle increases efficiency, the turbine energy reduction of about 7.5% causes a slight decrease in work output. This requires a balance between energy savings in the boiler and the resulting output.

4.6.3 Comparison with Previous Studies

This study not only aligns with but also builds upon previous research examining PLTU operational efficiency, offering further evidence on where and how performance losses occur and can be mitigated. For instance, while Putra (2015) identified the boiler as the primary source of energy loss (36.81%), this study reinforces that observation through similar inefficiencies found in the Labuhan Angin PLTU's combustion process especially due to suboptimal air-fuel ratios and exhaust gas composition. However, unlike Wahyudi (2023), who attributes the increase in net heat rate solely to the decline in high-pressure (HP) turbine efficiency, our findings suggest that system-wide factors including boiler inefficiencies and inadequate regenerative integration also contribute significantly. Moreover, although Suhardi et al. (2020) reported improved boiler efficiency through economizer enhancements at the Jeneponto PLTU, this study demonstrates that further gains in system efficiency (from 22.02% to 25.38%) are achievable through the adoption of regenerative cycles, which address both boiler and turbine inefficiencies simultaneously. The efficiency increase observed mirrors the findings of Arfiansyah & Hiendro (2023), yet this study adds nuance by highlighting the balance between efficiency improvement and minor losses in turbine output due to steam extraction. Overall, the comparison underscores that while individual component improvements (boiler, turbine) are valuable, integrated approaches like regeneration deliver more substantial and sustainable efficiency gains in coal-fired power plants.

5 Conclusion

This study aims to analyze the technical performance and emission characteristics of the application of biomass co-firing technology with palm shell and sawdust fuels at the Labuhan Angin PLTU. Based on the results of the analysis, it can be concluded that the application of co-firing with biomass can be carried out efficiently even though there are several technical changes, especially in the temperature and pressure parameters in the boiler combustion system.

In co-firing with palm kernel shells, although there is a decrease in combustion temperature and fluctuation in furnace pressure, these parameters remain within the safe range and do not significantly affect operational performance. Combustion efficiency can be maintained by adjusting the combustion system and adjusting the air ratio. Likewise, with co-firing with sawdust, although there is a decrease in thermal efficiency and fluctuation in furnace temperature, proper control of the combustion system can maintain the stability of the PLTU performance. Overall, co-firing of biomass, both palm kernel shells and sawdust, can be carried out effectively within the range of 5% without disrupting the stability of the operational system, although further monitoring and adjustment of several operational parameters are needed.

In conclusion, this study confirms that the application of biomass co-firing using palm kernel shells and sawdust at Labuhan Angin PLTU can be implemented effectively with manageable technical adjustments. Quantitatively, co-firing at a 5% ratio results in slight decreases in combustion temperature and thermal efficiency, but operational stability remains intact with proper air ratio and combustion control. These findings align with the study's objective to evaluate the technical feasibility and emission impacts of biomass integration. As a practical recommendation, it is advised to implement routine monitoring and optimization of combustion parameters particularly air-fuel ratios and furnace pressure to maintain performance and reduce emissions. For future research, broader co-firing ratios, long-term performance impacts, and techno-economic assessments should be explored to enhance scalability and support Indonesia's transition to cleaner energy.

6 References

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