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Environmental Impact Analysis in 3×10 MW Coal Fired Power Plant Through Life Cycle Assessment

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ABSTRACT

The primary energy source in developing countries, including Indonesia, is fossil energy. Therefore, evaluating the environmental impact of coal-fired steam power plants is crucial, but limited. Comprehensive scientific analysis is required to develop appropriate alternative measures. This research aims to analyze the life cycle impact of the coal power plant at the gate, including the coal yard, coal crusher, boiler, turbine, and generator, with the functional unit of 1 kWh of electricity produced. This research provides clear recommendations for mitigating emissions from the main contributing units. The analysis reveals the highest impact in the climate change potential category (1.40×10^{-1} kg CO_2 eq/kWh), while the smallest impact was recorded in the Eutrophication potential category (7.55×10^{-4} kg PO_4 eq/kWh), with no impact on ozone depletion in the stratosphere. The operation of boiler and generator units (gate hotspots) are the main contributors to climate change impacts, including carbon dioxide (9.25×10^{-2} kg CO_2), sulfur dioxide (8.21×10^{-3} kg SO_2), and nitrogen dioxide (7.55×10^{-4} kg PO_4). Alternative programs that may be implemented to reduce emissions include co-firing and installation of flue gas desulfurization and low NO_x burner. The findings of this research provide guidance for developing a policy framework to promote more environmentally friendly coal power plants, thereby achieving greater energy sustainability.

Keywords: LCA, gate, co-firing, flue gas desulphurization, low NO_x burner.

INTRODUCTION

As the global population expands, there is a corresponding rise in economic demands and human living standards. Elevated living standards correlate with heightened energy consumption, with electrical energy being a prominent energy source. Approximately 41% of global electricity generation relies on fossil fuel combustion (Cardoso et al., 2022; Galimova et al., 2023). In Indonesia, the demand for electricity is escalating in tandem with industrial sector advancements and population growth. Statistical data reveals that in 2021, electricity production in Indonesia reached 182,973.884 GWh, with 61.82% sourced from coal-fired steam power plants. Moreover, coal accounted for 66.01% of the total primary energy mix in 2021. The utilization of fossil-based energy sources stands as the primary catalyst for global warming. Within the electricity production sector alone, it represents the largest contributor, responsible for approximately 25% of global greenhouse gas emissions (Bakay and Ağbulut, 2021; Thaker et al., 2019). Mitigation endeavors targeting climate change involve the regulation of greenhouse gas emissions across all sectors. According to data sourced from PT. PLN in 2021, coal-fired steam power plant activities contributed 222.2 million tons of CO_2 emissions, constituting 85.76% of national greenhouse gas emissions. Within coal-fired power plants, greenhouse gases (CO_2, CH_4, N_2O) and air pollutants (SO_x, NO_x, PM) are generated throughout primary processes, spanning from coal bunkering, coal milling, to boiler operation, turbine, and generator utilization. Hence, concerted efforts are imperative to avert environmental repercussions stemming from global warming.

In 2022, the 3×10 MW steam power plant at PT. Bukit Asam is projected to generate 55,954.07 MWh of electricity. While the environmental programs in place are commendable, the ongoing operational activities associated with electricity production continue to exert environmental impacts, notably through emissions and hazardous liquid waste, necessitating adherence to pertinent laws and regulations. In addition to regulatory compliance, PLTU 3×10 MW is tasked with surpassing mandated environmental standards (beyond compliance). Achieving this requires a comprehensive environmental impact assessment to gain deeper insights into potential environmental ramifications. This evaluation should extend beyond the production process, encompassing all facets of electricity production operations, from raw material procurement to final electricity generation.

One method that can be utilized to assess the overall environmental impact of all electricity production activities is the application of life cycle assessment (LCA). LCA has been employed to evaluate environmental impacts across various sectors, including waste treatment, petroleum energy production, and other industrial processes. (Dastjerdi et al., 2021; Liu et al., 2020; Rashid et al., 2023). Research on life cycle assessment (LCA) conducted on coal-fired thermal power plants in India indicates CO_2 emissions ranging from 0.263 to 0.27 CO_2 eq when employing ESP and carbon capture storage (Malode et al., 2023). The potential for global warming is estimated to be approximately 0.603 kg CO_2/kWh based on the findings of an LCA analysis conducted on electricity generation in Iran (Yousefi et al., 2023). According to (Strezov and Cho, 2020), the primary pollutants of concern in thermal power generation technology are greenhouse gas emissions, acid gases like SO_2 and NO_x, and $PM_{2.5}$ particulate matter.

However, the evaluation of environmental impacts in the energy sector, particularly in steam power plants, remains limited. The LCA method can be employed to assess the environmental impact at each stage of the electricity production process (Henriques and Sousa, 2023). LCA offers insights into the environmental impacts associated with the entire product life cycle, spanning from raw material extraction, production processes, product utilization, to waste generated from production activities. Originally devised to evaluate environmental impacts stemming from factories and production processes such as global warming, ecotoxicity, and smog formation, the LCA method yields quantitative values pertaining to impacts or emissions released into the environment, facilitating the analysis and prioritization of improvement program plans. In recent years, life cycle assessment has emerged as an effective tool for promoting environmentally sound management. It aids in quantifying diverse environmental impacts across different stages of processes and devising suitable solutions (Rasheed et al., 2019). LCA is deemed a comprehensive and scientific analysis, not only for quantifying pertinent environmental impacts but also for aiding in effective impact mitigation and identifying cleaner production prospects (Gaete-Morales et al., 2019).

Based on this premise, this research aims to evaluate the environmental impact of the 3×10 MW Steam Power Plant at PT. Bukit Asam Tbk using LCA. The objective of this analysis is to assess environmental impacts, specifically focusing on the potential for climate change, ozone depletion in the stratosphere, acid rain potential, and eutrophication potential. Additionally, this study proposes alternative programs that could be adopted by the management of coal-fired power plants at PT. Bukit Asam to mitigate environmental impact. Utilizing current data, this study provides a detailed depiction of a systematic, efficient, and realistic coal-fired power generation system. Consequently, this research contributes to filling knowledge gaps in the sector and advocates for the adoption of evidence-based scientific models, which are instrumental for policymakers in attaining energy sustainability objectives.

MATERIALS AND METHODS

The methodology used in conducting this LCA is based on SNI ISO 14040: 2016 and SNI ISO 14044: 2017 which is carried out to measure the impact of the production process on the environment in one product life cycle. There are four main components defined by SNI ISO 14040:

2016 and SNI ISO 14044: 2017 as LCA study materials. The first component is the determination of goals and scope, which consists of the process of receiving coal material that produces energy in the generator. The second component is the determination of the life cycle inventory, consisting of material and energy calculations for each stage in the system. This data is then used to calculate the total emissions, resource consumption, and energy use by the system as a whole. In conducting the inventory analysis, improvement measures are taken to identify opportunities to reduce the system's impact on the environment. This could include changes in the production process, replacement of materials with more environmentally friendly materials, and exploration of the potential for recycling materials.

The third component, life cycle impact assessment (LCIA), is the least developed and most controversial of the three. There are various ways to measure the impact of existing systems on the environment. The impact assessment method that is often the most interesting, is valuation. Valuation is the most attractive impact assessment method. It values each environmental stressor (emissions, resources used, or amount of energy consumed) based on its perceived impact. For each system studied, a total "score" or "set of scores" can be calculated. When assigning scores, the judgment of impact severity depends largely on the analyst's terms of reference or study objectives. Another less debated method is called categorization. Any environmental stressors such as, greenhouse gases, substances that damage the ozone layer, carcinogens, resource depletion, and habitat alteration are some of the categories to give a qualitative picture of the possible environmental impacts. This method can be used in single-system analyses to determine whether design changes made during the refurbishment stage of an assessment reduce environmental damage or for comparative analyses to determine which systems produce lower amounts of a particular stress factor. However, this method cannot distinguish which systems have the greatest effect in situations where they produce different stress factors. For example, it is difficult to determine whether a system that results in the release of higher amounts of greenhouse gases is better or worse than a system that results in the release of carcinogens into the environment.

System limitations and data availability

This LCA system is designed to cover all major processes required to generate electricity from coal, such as mining, equipment manufacture, transport, and production of chemicals used in mining and power generation operations. It also includes material and energy flows from the feedstock extraction process and the production of intermediate feedstocks, as well as waste disposal. The analyzed processes are depicted in Figure 1–2. In these figures, the solid lines show the actual material and energy flows, while

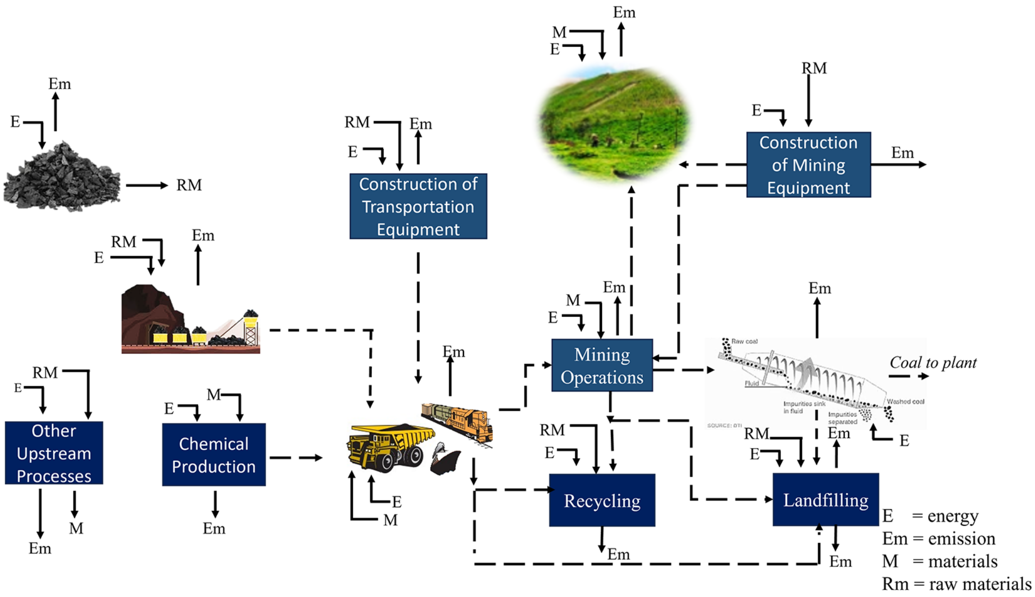

Figure 1. Coal production and transportation – life cycle assessment boundaries

the dashed lines show the logical relationships between the process blocks. The main manufacturing processes required to produce the intermediate raw materials are referred to as "other upstream processes".

Sensitivity analysis

Sensitivity analysis is used to determine the parameters that affect the results the most. It is also done to find out how data estimation and data differences impact the conclusions. In sensitivity analysis, the selected variables are chosen to indicate the parts of the system that inherently have more unknowns in the data, as well as the parts of the system where variations are most likely to occur during normal operation. Each parameter is changed separately from the others to find out how much impact it has on the base case. Therefore, no sensitivity case shows the best or worst state of the system. However, the dependency of the changed variable on other variables is still considered. For example, the amount of coal required for

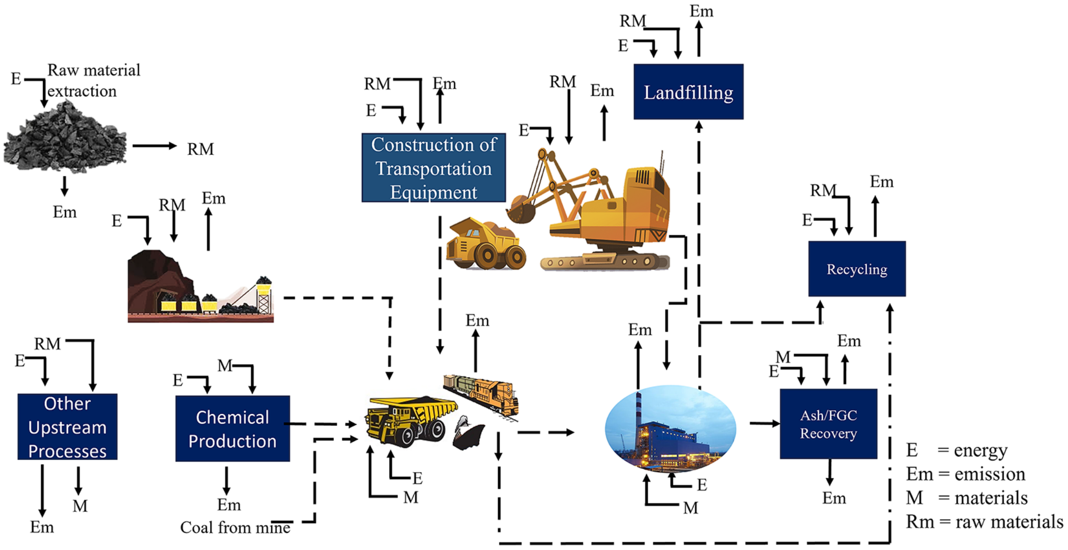

Figure 2. Life cycle assessment guidelines for power generation and transportation

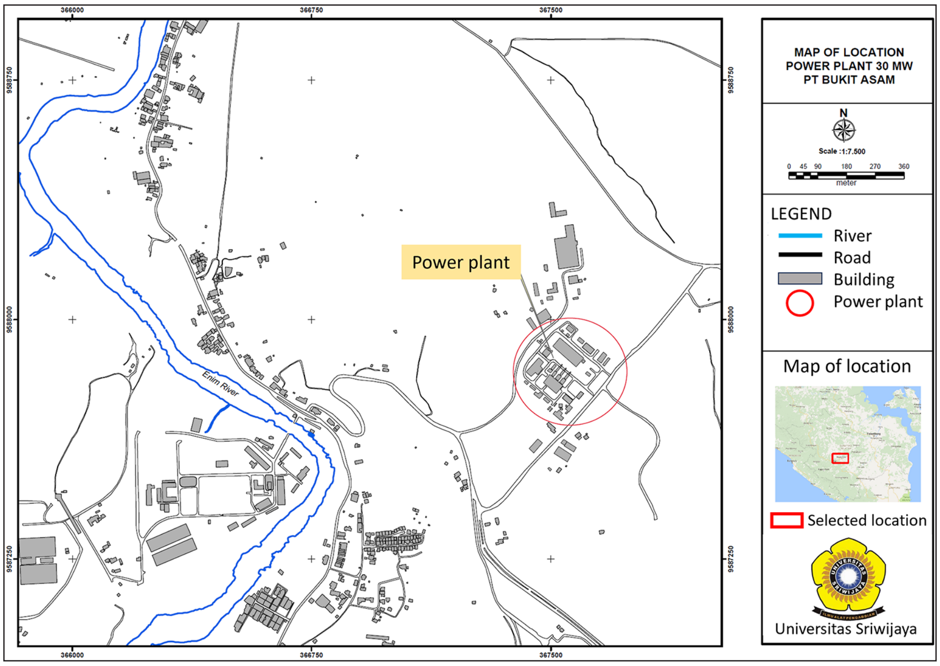

Figure 3. Location of power plant 3×10 MW at PT. Bukit Asam

power generation is affected by changes in power generation efficiency, which in turn affects the amount of coal required.

Location of study

Tanjung Enim City, South Sumatra Province, Indonesia, is well-known as one of the mature coal-based cities (Fig. 3). Prospective reserves of coal fields in Tanjung Enim are recorded at 3.33 billion tonnes with resources reaching 8.17 billion tonnes, where most of the mining is managed by PT. Bukit Asam. In addition to mining activities, PT. Bukit Asam also has a 3×10 MW Steam Power Plant. This PLTU was built to support the need for electrical energy in its operational activities. The electricity industry developed along with the growth of the coal industry and has gradually become one of the dominant industrial categories. The coal used for PLTU 3×10 MW has a calorific content of 4.200–6.000 gross air received (GAR) kcal/kg. PT. Bukit Asam has a land area of approximately ± 4 ha for the PLTU, located approximately ± 5 kilometers from the West Banko mine as the source of coal supply. In addition, the power plant is also located near the Enim River, which is used as a source of raw materials for the power plant.

RESULTS AND DISCUSSION

The overall electricity production system and LCA system limitations within the scope of the study are illustrated in Figure 4. The unit of analysis in this study is per 1 kWh of electricity generated by the plant. At this initial stage, data from PLTU 3×10 MW are presented as measurement or calculation data provided by the company. The electricity production process is subdivided into four process units, namely the coal yard, coal crusher, boiler, and turbine generator.

The coal yard serves as a temporary storage facility for coal before its utilization. Coal is sourced from the West Banko mine and transported via a conveyor belt to the crusher. This LCA analysis does not consider the age of the equipment utilized. Input data for this unit include the quantity of coal as an intermediate material in tons, along with the electrical energy consumption measured in kWh. The outputs from this unit include processed coal products and emissions released into the air, measured in tons (CO_2). A coal crusher is employed to grind coal into smaller sizes, adhering to standard operational procedures for boiler requirements, typically ranging from 8–10 mm. There exists a temporary storage area prior to the coal's introduction into the boiler.

A boiler functions as a device designed to convert water into high-pressure and high-temperature steam, essential for driving steam turbine blades. The system comprises three circulating fluidized bed boilers, each with a capacity of 56 tons, requiring electricity to operate the coal feeder. Input data for this unit include water volume measured in cubic meters, fuel consumption represented by electrical energy in kWh, diesel fuel consumption in liters, and coal quantity in tons. Outputs from this unit consist of steam products directed towards the turbine, measured in MJ units, as well as emissions released into the air, quantified in tonnes (CO_2, CH_4, N_2O, SO_2, NO_2, particulates, and CO).

The turbine functions as the primary mechanism for converting the potential energy stored in steam from the boiler into kinetic energy, which is subsequently transformed into mechanical energy through the rotation of the turbine shaft.

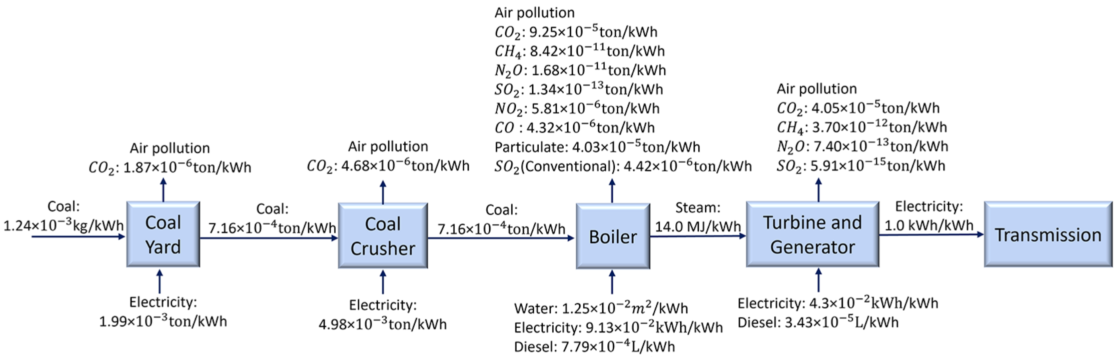

Figure 4. Mass balance of electricity production process of power plant 3 × 10 MW at PT. Bukit Asam

Meanwhile, the generator's role is to convert the mechanical energy generated by the turbine shaft rotation into electrical energy using magnetic field induction. This turbine is designed to handle high-temperature steam. This LCA analysis does not take into account the age of the equipment utilized. Input data for this unit include fuel consumption, represented by electrical energy from the transformer unit measured in kWh, diesel fuel usage measured in liters, and steam from the boiler unit measured in MJ. Outputs from this unit consist of kinetic energy products measured in kWh, which are directed to the generator, as well as emissions released into the air quantified in tons (CO_2, CH_4, N_2O, SO_2).

Data inventory recapitulation

Inventory analysis includes data collection and procedures to calculate the relevant inputs and outputs of the product system. This is done to avoid imbalances in the mass balance. In addition, the possibility of leakage and efficiency in the process is also ignored. The summary data of the total inventory of the 3×10 MW power plant within the scope of cradle and gate per unit of product produced or according to the unit of function can be seen in Table 1.

From the integration of air emission inventory gate data during the electrical energy production process, there are several emissions produced. At the particulate level, CO_2 produced 9.91×10^{-5} ton/kWh, CH_4 4.05×10^{-5} ton/kWh, and N_2O 2.05×10^{-11} ton/kWh. Meanwhile, sulfur dioxide (SO_2) gas emissions were recorded at 8.75×10^{-13} and 4.42×10^{-6} ton/kWh for the conventional type. Nitrogen dioxide (NO_2) gas reached 5.81×10^{-6} ton/kWh, while particulates reached 4.32×10^{-6} ton/kWh. Finally, CO emissions were recorded at 3.03×10^{-5} ton/kWh.

Life cycle impact assessment

The next stage after LCI is the forecasting of potential environmental impacts based on input and output data on each unit of the electricity production process. The LCIA stage aims to make the results of the LCI analysis easier to understand and manage concerning human health, resource availability, and the environment. In this LCA study, a midpoint impact assessment approach is used because the midpoint approach is more specific and emphasizes physical-chemical changes in the environment. The impact assessment stages carried out are characterization, and normalization using the CML-1A baseline method.

Table 1. Gate inventory data electricity production for 3×10 MW power plants PT. Bukit Asam

Inventory data	Quantity	Unit	Quantity per unit function	Unit
Input				
Raw materials				
Water	699.480	m^3	1.25×10^{-2}	m^3/kWh
Fuel				
Solar	1.918	L	3.43×10^{-5}	L/kWh
Coal (cleaned)	40.037	Ton	7.16×10^{-4}	Ton/kWh
Electricity				
Electricity	8.181.713	kWh	0.146	kWh/kWh
Output				
Electricity product	55.954.066	kWh	1.00	kWh/kWh
Emissions to air				
CO_2	5.544	ton	9.91×10^{-5}	ton/kWh
CH_4	2.266.894	ton	4.05×10^{-5}	ton/kWh
N_2O	0.001	ton	2.05×10^{-11}	ton/kWh
SO_2	0.00005	ton	8.75×10^{-13}	ton/kWh
NO_2	325	ton	5.81×10^{-6}	ton/kWh
Particulates	242	ton	4.32×10^{-6}	ton/kWh
CO	1.696	ton	3.03×10^{-5}	ton/kWh
SO_2 (conventional)	247	ton	4.42×10^{-6}	ton/kWh

This impact assessment aims to identify how much a process contributes to the environmental impact resulting from the process.

Characterization is the stage of identifying and classifying input data obtained from the LCI stage into environmental impact categories according to the method and database used. This stage will measure the impact contribution of a product or activity on each impact indicator. The impact categories and characterization values are evaluated using the impact assessment method based on the Ministry of Environment and Forestry Regulation Number 1 of 2021. The characterization value of environmental impacts in the PLTU electricity production process is shown in Table 2. From the characterization stage, it can be concluded that producing 1 kWh of electricity in PLTU creates 4 impact categories consisting of primary impacts, namely global warming impacts, ozone depletion potential, acid rain potential, and eutrophication potential.

Procedure life cycle impact assessment

The steps in conducting a life cycle impact assessment on electricity production activities from the 3 × 10 MW steam power plant (PLTU) using SimaPro software version 9.5.0.2 with the Agrifootprint, Ecoinvent, ELCD, EU and DK Input-Output Database, Industry Data 2.0, methods, swiss input-output database, and USLCI databases are based on:

1. Establish impact categories based on guidelines set by the Ministry of Environment and Forestry of the Republic of Indonesia, including Minister of Environment and Forestry Regulation No. 1 of 2021 and Guidelines for the Preparation of life cycle assessment reports by the PROPER Secretariat. The impact categories analyzed in the LCA study include primary impacts such as global warming potential (GWP), ozone layer depletion potential, acid rain potential, and eutrophication potential.
2. Perform classification by placing the life cycle inventory according to the established potential impact categories.
3. Conduct characterization to quantify the contribution of the life cycle inventory to various impact categories using the CML-IA baseline V3.05 characterisation model.

DISCUSSION

Impact categories and indicators

The LCIA stage aggregates LCI results into impact categories. For each impact category, an appropriate indicator is chosen, and the results for these indicators are computed. The compilation of these indicator results, known as LCIA results, offers insights into environmental concerns associated with the inputs and outputs of a product system. In the environmental impact analysis procedure, the impact assessment method adopts a category-based approach known as midpoint. Conversely, the endpoint approach is more comprehensive, focusing on broader biological alterations.

Life cycle impact assessment results

The life cycle assessment of a coal combustion-based power generation system has been explored. The study shifts focus from the initial impacts related to climate change to various other impacts, including potential acidification and eutrophication. Life cycle impact assessment evaluates environmental impacts quantified during the inventory phase. In the categorization process, the inventory data collected is linked to potential ecological impacts. Power generation systems employing combustion as an energy source consume significant amounts of materials and energy throughout their life cycle. Additionally, this system generates waste such as exhaust gases, wastewater, and solid waste, leading to air, water, and soil pollution. These pollutants have a notable impact on climate change, including CO_2, N_2O, and CH_4. Furthermore, other pollutants such as SO_2, which contributes to acidification, as well as NO_x and phosphate, which contribute to eutrophication, along with various metallic elements, are also present.

The impact assessment process yielded values for each impact category associated with electricity production in each unit, as summarized in Table 2. The assessment evaluated the potential impacts on global warming potential, ozone depletion potential, acid rain potential, and eutrophication potential using the CML-version assessment method IA baseline V3.05. The presentation of values in each impact category has been tailored to the functional unit of 1 kWh of electricity. This study primarily focuses on identifying hotspots within the activities of steam power plants during electricity production. The subsequent analysis of these

Table 2. Results of impact assessment on the gate scope of the electricity production process

Impact category	Unit	Method	Total	Coal yard	Coal crusher	Boiler	Turbine and generator
Global warming potential	kg CO_2 eq/kWh	CML-IA baseline V3.05	1.40×10^{-1}	1.87×10^{-3}	4.68×10^{-3}	9.25×10^{-2}	4.05×10^{-2}
Ozone depletion potential	kg CFC-11 eq/kWh		0	0	0	0	0
Acid rain potential	kg SO_2 eq/kWh		8.21×10^{-3}	0	0	8.21×10^{-3}	7.09×10^{-12}
Eutrophication potential	kg PO_4 eq/kWh		7.55×10^{-4}	0	0	7.55×10^{-4}	2.00×10^{-10}

hotspots informs the development of control programs directly applicable to steam power plants.

Based on the analysis results, global warming emerges as the impact category with the highest total value, namely 1.40×10^{-1} kg CO_2 eq/kWh. This signifies that in the production of 1 kWh of electricity, 1.40×10^{-1} kg of carbon dioxide is released into the atmosphere. Among the four identified sources, boilers exhibit the highest CO_2 emissions compared to other units. Additionally, turbines and generators also contribute significantly to CO_2 emissions (4.05×10^{-2} kg CO_2 eq/kWh). Within this unit, coal combustion generates steam to power the turbine and generator (Somova et al., 2023). The potential impact value for acid rain is 8.21×10^{-3} kg SO_2 eq/kWh, originating from boilers, turbines, and generators. This value exceeds the terrestrial acidification potential observed in supercritical coal-fired power plants according to other research findings (Rasheed et al., 2021). The global warming potential in this LCA study was determined through simulations using SimaPro software version 9.5.02. The percentage contribution to the global warming impact from the gate process is outlined in Table 3. Potential contributors to global warming include emissions of carbon dioxide, nitrous oxide, and methane. Boilers represent the largest percentage contribution to the global warming impact, accounting for 66.28%. Overall, contributors to the global warming potential impact of the electricity production process primarily stem from coal usage, which generates CO_2 emissions, followed by emissions produced by turbines and generators. The primary contributor to the global warming potential impact is carbon dioxide emissions, accounting for 99.99% (Table 4). Carbon dioxide emissions within the gate scope comprise the company's electricity generation process and diesel fuel usage. Conversely, nitrous oxide and methane emissions stem from coal usage by generators, albeit in relatively small quantities.

Ozone depletion potential

Ozone is a minor constituent, with concentrations varying with latitude and season. Even at its peak, ozone levels never exceed 10 ppmv

Table 3. Percentage of environmental impact assessment of the electricity production process (gate)

Impact category	Unit	Method	Coal yard	Coal crusher	Boiler	Turbine and generator
Global warming potential	%	CML-IA baseline V3.05	1.34	3.35	66.28	29.02
Ozone depletion potential	%		0	0	0	0
Acid rain potential	%		0	0	100	0
Eutrophication potential	%		0	0	100	0

Table 4. Contribution of the impact of global warming potential on the scope of the gate

Contributor	Unit	Total	Coal yard	Coal crusher	Boiler	Turbine and generator
Carbon dioxide	%	99.99	1.34	3.35	66.28	29.02
Dinitrogen monoxide	%	0.003	0	0	0.003	0.0001
Methane	%	0.002	0	0	0.002	0.0001
Total of contributor	%	100	1.34	3.35	66.28	29.02

(parts per million by volume). Despite its low concentration, ozone plays an important role in the troposphere and stratosphere. In the stratosphere, ozone protects the Earth from harmful short-wavelength ultraviolet radiation. Concerns have been raised over the presence of man-made chemicals in the stratosphere, which act as catalysts for ozone depletion. Predictions suggest that a 5% decrease in stratospheric ozone could lead to a 20% increase in skin cancer cases annually in the United States. Among the catalysts of concern are species such as chlorine atoms (Cl), nitric oxide (NO), hydroxyl radicals (OH), and hydrogen atoms (H), all of which have unpaired valence electrons outlining their operation according to a specific mechanism, where x represents odd electron species (Spath et al., 1999).

Chlorofluorocarbons (CFCs), a heat transfer fluid used in refrigeration and air conditioning systems since the 1930s, gradually degrade due to photolysis. This process produces more chlorine, which then undergoes the following reactions:

$$CF_2Cl_2 \rightarrow hv, \lambda < 250\ nm \rightarrow CF_2Cl + Cl \quad (1)$$

In this research gate scope study, there are no potential ozone depletion impacts generated by the power plant. This is because there are no components that cause potential ozone depletion impacts. So based on the results of running using the CML-IA baseline V3.05 method, the result is 0 kg CFC11 eq.

At quantities less than 2 ppm, ozone, a potent oxidizing agent, is a bluish, explosive gas with a pleasant, distinctive odor. At greater doses, ozone is an unpleasant and harmful respiratory toxin. Acute exposure damages and swells lung tissue, whereas persistent exposure can lead to emphysema. Ozone, one of the more active greenhouse gases, contributes to the unpleasant quality of photochemical smog. Ozone also contributes to corrosion processes by accelerating the aging of elastomers and other organic substances often utilized as protective coatings. Although ozone has negative effects in the troposphere, it is necessary in the stratosphere to minimize UV light penetration. UV-B light (280 – 320 nm) is harmful to life as it is easily absorbed by proteins, nucleic acids, and other biological components (Forstner et al., 1997).

Acid rain potential

Rainwater typically has a pH of around 5.6 due to the reaction between water and atmospheric carbon dioxide, resulting in carbonic acid. Rainfall with a pH below 5.0 can be caused by the presence of sulfur oxides, nitrogen oxides, chlorides, and fluorides, which are precursors to sulfuric and nitric acids, respectively. Rainwater typically has a pH of 4 to 4.5, but pH levels as low as 2 have been documented (Forstner et al., 1997). Excess acidity can hurt plants. Precipitation with a pH below 3.5 can harm plant leaves, while less acidic pH levels can still cause soil changes. Soil changes will be most noticeable in poorly buffered soils. While some plants may withstand acidic soil, most prefer an alkaline climate. Soil acidity can limit seed germination and growth, among other impacts (Prakash et al., 2023a). Acid rain is thought to deplete soil minerals like calcium, magnesium, and potassium. Leaching may initially improve cation availability for vegetation, but might lead to nutritional shortage over time. Additionally, acidic water may discharge substantial levels of aluminum.

The increased potential for acid rain from power generation activities is due to the combustion of fossil fuels and biomass such as Sulphur dioxide (SO_2), nitrogen oxides (NO_x), NH_3, HC, and HF, which produce acid when reacting with water (Yang et al., 2019). The main contribution to acid rain in the electricity production process comes from boiler units, which produce sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) emissions. SO_2 and NO_2 emissions in all process units come from the use of diesel fuel and coal combustion. From the percentage contribution analysis, it can be seen that the largest contribution comes from SO_2 and NO_2 emissions, which reach 100% when added together (Table 5). According to the Pareto Principle, contributions of more than 80% are considered significant in influencing the analysis results (Prakash et al., 2023b). Meanwhile, in other process units, no emissions are generated and do not have the potential to cause acid rain impacts.

Table 5. Contribution of acid rain impact on gate scope

Contributor	Unit	Boiler
Sulfur dioxide	%	64.64
Nitrogen dioxide	%	35.36
Total all contributors	%	100

Eutrophication potential

Eutrophication is caused by the release of molecular phosphorus and excessive accumulation of nutrients in aquatic habitats, resulting in the uncontrolled development of aquatic plants (Yang et al., 2019). The impact of eutrophication is caused by the supply of biomass in co-burning. Eutrophication is a kind of environmental pollution in which plants grow rapidly in water bodies due to excessive chemical inputs. Coal and boiler water contain nitrogen and phosphorus, both of which contribute to eutrophication. Characterization values on eutrophication contributors from the gate process of electricity production in the boiler process unit, which results in nitrogen dioxide emissions. Nitrogen dioxide emissions across the process units come from the use of diesel fuel and coal. From the analysis of the percentage of contributors, it can be seen that the largest contributor to the eutrophication impact comes from nitrogen dioxide emissions, reaching a percentage of 100% when summed up (Tab. 6). The Pareto Principle, if a contributor is more than 80%, it is considered significant in influencing the analysis results (Prakash et al., 2023b). Meanwhile, in other process units, no emissions are generated and do not have the potential to cause eutrophication impacts.

Table 6. Contributors to eutrophication impact at gate scope

Contributor	Unit	Boiler
Nitrogen dioxide	%	100
Total all contributors	%	100

HOTSPOT ANALYSIS AND PROGRAM RECOMMENDATIONS

Hotspot analysis

The hotspot analysis was carried out after interpreting all potential impacts resulting from the electricity production process of the 3×10 MW steam power plant of PT. Bukit Asam. Hotspot points can be process units or impact categories that have the highest value in a series of production processes. At this stage, an analysis is carried out on process hotspots that have the highest impact value in each impact category. Hotspot analysis is carried out on process units related to electricity production operations (gates) only to serve as a baseline for determining improvement programs for routine production activities. Based on the results of data interpretation, the units with the highest contribution to each impact can be seen (Table 7). The dominant process hotspot is in the boiler unit with the largest contribution to 3 (three) impact categories, namely global warming, potential for acid rain, and potential for eutrophication. In general, the cause of impacts originating from boiler units are pollutant parameters released into the air consisting of carbon dioxide, sulfur dioxide and nitrogen dioxide.

Research tends to focus on pollutant emissions and their impacts. Numerous assessments have been conducted on the life cycle of power generation systems employing combustion as an energy source, and the focus of this research has shifted from the initial impacts associated with climate change to other impacts such as potential acidification and eutrophication. Substantial variations in environmental impacts exist among different types of fuels and technologies utilized in the life cycle of combustion-based power generation systems. Direct emissions from the electricity generation stage of coal-fired power plants life cycle have been identified as significant contributors to climate change (Wang et al., 2022). However, technological advancements and various measures aimed at mitigating their adverse impacts, such as flue gas desulfurization and the utilization of electrostatic precipitators, have effectively reduced the environmental impact of power plants, albeit to some extent.

Program recommendations

Recommendations are based on the results of the Hotspot analysis of the process and the

Table 7. Hotspot process analysis

Contributor	Unit	Method	Impact value	Hotspot process	Cause of impact
Global warming potential	kg CO_2 eq/kWh	CML-IA baseline V3.05	9.25×10^{-2}	boiler and generator	carbon dioxide
Acid rain potential	kg SO_2 eq/kWh		8.21×10^{-3}	boiler	Sulfur dioxide, nitrogen dioxide
Eutrophication potential	kg PO_4 eq/kWh		7.55×10^{-4}	boiler	nitrogen dioxide

resulting impacts. The proposed alternative program was obtained from literature analysis and discussed with the authorities in the electricity production process of the 3×10 MW steam power plant, so that from the results of the discussion 3 alternative programs were obtained that could be implemented. Program alternatives for upstream and downstream processes are listed in Table 8.

Despite having abundant coal reserves as a fuel source, the primary challenge faced by this steam power plant is its high sulfur content. Co-firing technology presents another opportunity to enhance power generation efficiency. Co-firing can reduce greenhouse gas emissions by up to 28% because biomass is a renewable energy source capable of absorbing CO_2 during its growth. Co-firing facilitates the diversification of energy sources by utilizing previously unused biomass waste effectively. Utilizing local biomass waste can generate new economic opportunities and enhance the welfare of local communities. However, challenges may arise, such as the availability of biomass, which can be problematic if the supply is unstable or interrupted. Variations in biomass quality and composition can affect combustion efficiency and resulting emissions. Additionally, the use of biomass in co-firing may have other environmental impacts, such as increased land and water usage and potential conflicts with food production needs. The alternative mitigation programs proposed next are using a flue gas desulfurizer (FGD). FGD typically made from limestone-gypsum to reduce SO_x content, is conducted prior to directing the exhaust gas to an electrostatic precipitator (ESP) via a high-pressure airflow. The flue gas ascends from the bottom of the absorber until it reaches the top, while a continuous spray of the limestone mixture ensures optimal contact with the flue gas. This process efficiently reduces SO_2 levels by up to 90%, yielding gypsum as a by-product (Larki et al., 2023). FGD technology effectively reduces sulfur dioxide (SO_2) emissions from coal-fired power plant exhaust gases by 70–79%, aiding in compliance with stricter emissions regulations and mitigating the impact of air pollution (K.

Table 8. Alternative mitigation programs

Program	Unit	Method	Strength	Weakness
Utilization of biomass-based fuel (cofiring). Reduces carbon dioxide	Boiler	Utilizing biomass-based alternative fuels used together (co-firing).	• Co-firing can reduce greenhouse gas emissions by up to 28%. • Use of local biomass waste can create new economic opportunities	• Unstable biomass supply • Biomass quality and content varies • The use of biomass in co-firing can also have other impacts on the environment (such as excessive use of land and water) • Potential conflict with food needs
Flue gas desulphurization (FGD) technology. Reduces sulfur dioxide	Boiler	Reducing SO_x gas from coal combustion so that SO_x emissions into the environment are below emission quality standards.	• FGD effectively reduces emissions (SO_2) from coal fired power plant exhaust gas (70–79%) • Can be applied to various types of coal fired power plants • Development of various types of absorbents can increase efficiency and reduce FGD operational costs	• FGD investment and operational costs are high • Produces solid (gypsum) and liquid waste (FGD wastewater) which requires special handling • Requires additional energy consumption for operation • FGD requires intensive care and maintenance • Requires significant adjustments to existing exhaust gas removal systems
Low NO_x burner (LNB) technology. Reduces nitrogen dioxide	Boiler	Controlling NO_x formation by optimizing the mixture of fuel and air in the combustion furnace	• Effectively reduces nitrogen oxide (NOx) emissions by up to 40–50% compared to conventional burners • LNB integration with other emission control technologies, such as Selective Catalytic Reduction (SCR), can increase NO_x emission reduction efficiency by up to 70–80%. • LNB technology can also reduce particulate emissions (PM) by 20–30%.	• Increase fuel consumption by around 1–2% • Increases emissions of other gases (CO and hydrocarbons) • Requires proper maintenance and operation • LNB technology needs to be integrated with other emission control technologies such as SCR

Zhao et al., 2021). FGD can be implemented in various types of power plants (Rahmanta et al., 2024). Ongoing development of diverse absorbents aims to enhance efficiency and reduce operational costs of FGD systems, rendering them more economically viable and sustainable (Li et al., 2022). However, the implementation of FGD necessitates significant upfront investment and ongoing operational costs, particularly for equipment procurement and absorbent chemicals (Zhang et al., 2020). The FGD process generates solid waste (gypsum) and wastewater that require specialized handling to mitigate adverse environmental impacts. Additionally, the application of FGD technology demands extra energy consumption for operations, potentially increasing fuel consumption and greenhouse gas emissions from coal-fired power plants. FGD systems require meticulous care and maintenance to sustain their performance, leading to heightened operational costs and downtime for coal-fired power plants, along with substantial modifications to existing exhaust gas disposal systems.

The final alternative mitigation program proposed for application in coal-fired power plants involves technology aimed at reducing nitrogen oxide (NO_x) emissions by up to 40–50% compared to conventional burners (Li et al., 2015). Integrating LNB with other emission control technologies, such as Selective Catalytic Reduction (SCR), can enhance NO_x emission reduction efficiency by up to 70–80% (S. Zhao et al., 2022). LNB can also reduce particulate matter by 20–30% (Svinterikos et al., 2019). However, it may increase fuel consumption by around 1–2%, thereby potentially affecting coal-fired power plant operations and costs. Additionally, it could lead to increased emissions of other gases, such as carbon monoxide (CO) and hydrocarbons (HC), which necessitate careful management (Kim et al., 2020). To achieve optimal emissions reductions, LNBs should be integrated with other emissions control technologies, such as SCR, which may entail additional investment. Upon analyzing the advantages and disadvantages based on cost, technical aspects, and environmental impact, the recommended program for addressing the operational hotspot conditions of the 3×10 MW coal-fired power plant involves utilizing biomass fuel (co-firing) and installing flue gas desulphurization (FGD), along with low NO_x Burner (LNB) technology.

CONCLUSIONS

This LCA research has assessed the ecological footprint of the 3×10 MW steam power plant at PT. Bukit Asam. The highest life cycle impact score was recorded for climate change potential. Potential environmental impacts arising from the electricity production process of the 3×10 MW steam power plant at PT. Bukit Asam at the gate point include global warming potential, potential for acid rain, and potential for eutrophication. Gate process hotspots are identified in units such as the boiler unit, with environmental impacts including carbon dioxide (9.25×10^{-2} kg CO_2), sulfur dioxide (8.21×10^{-3} kg SO_2), and nitrogen dioxide (7.55×10^{-4} kg PO_4). Acid rain impact is caused by the contribution of sulfur dioxide (64.64%). Nitrogen dioxide released from the boiler fully contributes to the eutrophication. After analyzing the advantages and disadvantages in terms of cost, technical feasibility, and environmental impact, recommended programs for the operational hotspots of the 3×10 MW coal-fired power plant include the use of biomass fuel (co-firing), installation of flue gas desulfurization (FGD), and implementation of low NO_x burner (LNB) technology.

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