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Determining the Environmental Impact of Cradle to Gate in Coal-Fired Power Generation

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ABSTRACT

The analysis of environmental impacts throughout the entire process of coal-fired power plants is imperative to implement effective measures for controlling and reducing pollutant emissions. However, there is still limited research focusing on the cradle-to-gate stage in the life cycle of coal-fired power plants and their environmental impact. This study employs a life cycle assessment (LCA) methodology to assess the environmental impacts of coal-fired power plants in South Sumatra. The primary environmental impact categories of primary emissions include CO_2, SO_2, NO_x, and CH_4. The most significant environmental impacts arise from CO_2 emissions, notably 98.46% from land clearing and preparation and 86.74% from overburden removal and coal extraction. These stages primarily contribute to global warming throughout the cradle-to-gate process. Sulfur dioxide emissions from land clearing activities are the main contributor to acid rain, followed by overburden removal and coal extraction (96.51%) and coal stockpiling (1.48%), which also play a role. The release of NO_x from land clearing and preparation, overburden removal, and coal stockpiling contributes to the potential for eutrophication. Land clearing and preparation have a significant impact on global warming during the coal mining and distribution stages. Practical measures such as enhancing emission reduction facilities and increasing pollutant emission standards for each process are necessary to promote environmentally friendly coal-fired power plants.

Keywords: cradle, gate, coal mining, life cycle assessment, environmental impact, emission.

INTRODUCTION

The global use of coal has increased significantly due to its low cost, wide availability, and stable supply. Coal remains the primary fuel for the electricity sector worldwide. Indonesia's electricity consumption in 2050 is projected to reach 1361 TWh, equivalent to 4319 kWh per capita in the base case demand scenario, and 2565 TWh, equivalent to 7930 kWh per capita in the high demand scenario (Reyseliani and Purwanto, 2021). Coal plays a vital role in the share of electrical energy in the region, contributing around 40% in 2020, and its use is expected to remain above 25% in 2040 (Wang et al., 2021; Zhang et al., 2023). Electricity demand is projected to increase by approximately 4% annually until 2050. In the basic scenario, electricity production could reach 3,388 TWh annually by 2050, with coal contributing around 34% (Do and Burke, 2024).

The high demand for coal has several negative aspects, including significant CO_2 emissions during its use. In 2020, CO_2 emissions from coal power plants reached approximately 500 million tonnes, accounting for around 26–30% of total CO_2 emissions (Lau, 2023). Based on this, several important studies have been conducted that utilize various methodologies to assess environmental impacts. One such methodology is LCA, which is a recognized approach for measuring the environmental impacts associated with processes and products (Wang et al., 2022). As LCA is considered the most effective tool in environmental management, it can be used to conduct a comprehensive and scientific analysis of environmental impacts from start to finish, thereby identifying opportunities for mitigating environmental impacts (Rahn et al., 2024). The aim of LCA in the context of coal-fired power plants is to evaluate environmental impacts and formulate relevant strategies to promote the sustainable development of these power plants.

In recent years, LCA has proven to be an effective tool for promoting cleaner environmental management. It helps measure various environmental impacts at different stages of a process and formulates appropriate solutions (Rasheed et al., 2019). LCA is considered a comprehensive and scientific analysis method that evaluates relevant environmental impacts and assists decision-makers in mitigating these impacts and identifying opportunities for cleaner production (Gaete-Morales et al., 2019).

Research on LCA of coal-fired power plants has been conducted by several previous researchers (Cao et al., 2024; Malode et al., 2023; Wu et al., 2023). For instance, LCA studies of coal-fired power plants in China were conducted by (Wang et al., 2018). The life cycle of a coal power plant is divided into three stages: coal mining, washing, and transportation. These stages help identify the emissions with the most significant environmental impacts. Typically, direct emissions from the electricity generation stage are the main contributors to climate change (Dong et al., 2018; Li et al., 2020; Martín-Gamboa et al., 2018). Research on supercritical pulverized coal power plants has been carried out in Pakistan by (Rasheed et al., 2021), showing that the overall life cycle impact of these power plants on the midpoint index is much lower compared to other conventional pulverized coal power plants.

Several efforts have been made to evaluate the environmental impacts of coal-fired power plants. However, there are still numerous issues that require further study. Most studies focus on specific stages or categories of environmental impacts without comprehensively analyzing the entire life cycle. For instance, aspects such as coal mining, washing, and transportation are often excluded from environmental impact analyses. Therefore, it is essential to conduct further studies to identify the primary sources of environmental impacts through a comprehensive LCA of coal power plants.

This study investigates the life cycle impact of the coal-based power generation system at PT. Bukit Asam, one of the largest coal mining companies in Indonesia, located in South Sumatra Province. The aim is to evaluate the environmental impact across different categories, namely potential climate change, ozone depletion in the stratosphere, and potential acid rain, from cradle to gate. Additionally, the study compares the relative impact scores with previous studies focusing on similar technologies. This research utilizes the latest data to provide a systematic, effective, and realistic assessment of coal-fired power generation systems.

METHODS

Location of study

The research conducted aimed to evaluate the implementation and development strategy of greenhouse gas mitigation through low carbon development measures at the West Banko IUP site of PT. Bukit Asam (Fig. 1), Tanjung Enim Mining Unit, South Sumatra. The research focused on coal extraction steps, including land clearing, overburden stripping, coal extraction, coal processing, and coal transportation. The initial stage was carried out by inventorying data related to emissions generated and identifying potential improvements and emission reductions that can be applied in the coal production process at PT. Bukit Asam. Primary data was collected through direct measurement and calculation of greenhouse gas emissions at Tanjung Enim Mining Unit, West Banko IUP location. Meanwhile, secondary data were obtained through the calculation of greenhouse gas emissions from coal production, overburden removal data, as well as material calorific values and emission factors by IPCC standards and the Ministry of Environment and Forestry’s Greenhouse Gas emission inventory guidelines.

The research implementation steps are by SNI ISO 14040:2016 and SNI ISO 14044:2017 standards. There are four main components carried out in LCA analysis, including the determination of objectives and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation: Once these four key components have been implemented, the next step is to establish Goal and Scope Definition as a key stage for formulating the LCA work plan. This stage involves outlining the objectives and scope of the study. In this study, the scope used is Cradle to Gate with the unit of function defined as per tonne of coal. Cradle to Gate is a life cycle analysis that investigates the process from the raw material evaluation stage, which in this case includes land preparation activities (cradle), to the final operational stage, which is coal transportation (gate). The investigation is limited to this stage due to the limited inventory data in the study, which prevents tracing to the final stage of the waste management process. The unit of function used is per tonne of coal, given that the unit of production commonly used in the coal industry is tonnes per kilowatt-hour (tonnes/Kwh).

Data collection method

The type of data used in this study consists of primary and secondary data. Primary data collection is obtained through direct observation in the field using observation and interviews related to raw material requirements, types of transportation, and types of fuel used in PT. Bukit Asam. Secondary data is obtained from references to research results in the form of journals, and mining process data sets from Simapro software.

Data analysis method

LCA is a data analysis method used in this study based on the SNI ISO 14040: (2016) framework on environmental management, life cycle assessment, principles and framework, and SNI ISO 14044: 2017 on environmental management, life cycle assessment, requirements and guidelines consisting of four stages, namely:

- Determination of objectives and scope: this is the initial stage of the entire LCA in determining a work plan. This stage is carried out by identifying the need for coal raw materials, diesel energy needs and coal distribution routes. The scope includes the distribution of coal raw materials from coal mining to the coal yard of PT Bukit Asam's 3 × 10 MW power plant (Fig. 2). This stage is carried out through a literature review to determine the objectives, impact categories, system boundaries and functional units. The objective set was the assessment of emissions released by coal raw material procurement activities using functional units for 1 ton of coal produced based on 2023–2024 data. The emissions determined are greenhouse gas emissions and acidification. The scope determined is gate to gate starting from coal mining to the West Banko site, West Banko site to stockpile, stockpile to power plant, and power plant to coal yard.

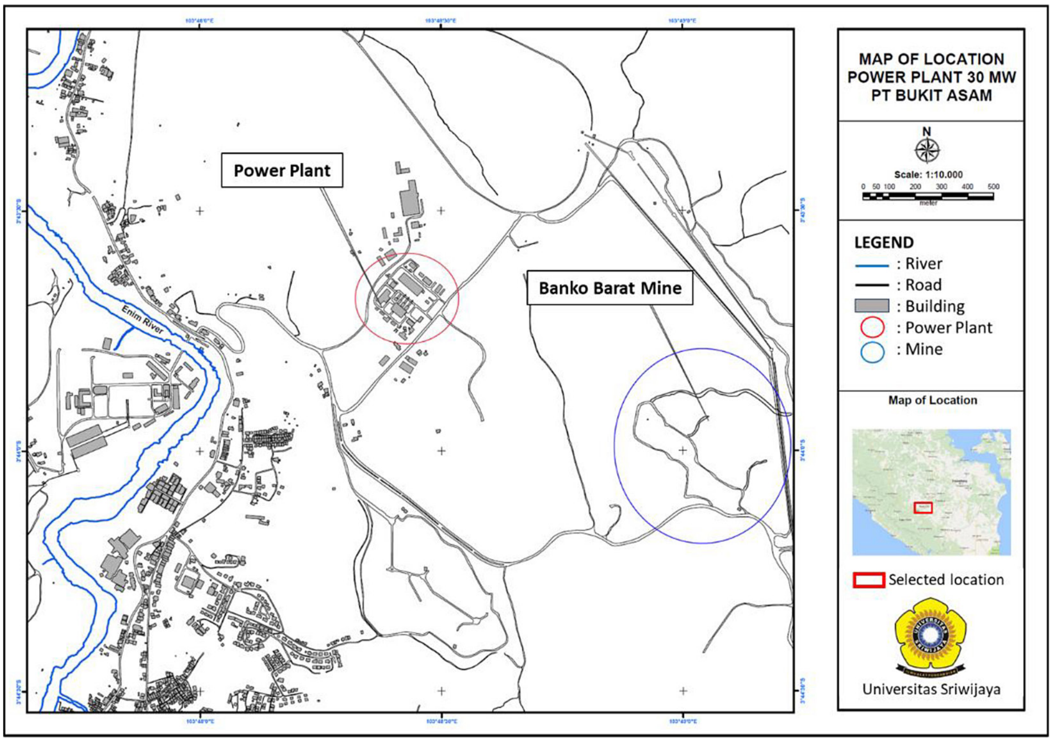

Figure 1. Coal fired power plant 3 × 10 MW study area

- Inventory analysis: is the stage of collecting data on the input-output in the process flow that is passed. This stage is carried out through direct review in the field using observation and expert interviews to obtain detailed information on coal raw material procurement activities.
- Impact analysis: this is the stage of assessing and evaluating potential environmental impacts based on the results of inventory data analysis. This process is carried out by linking the inventory data and the impact categories determined at the objectives and scope stages previously established. 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. Four categories of impact consisting of primary impacts, namely the impact of global warming, potential ozone depletion, potential acid rain, and potential eutrophication.
- Interpretation of results: is the basis of consideration obtained based on the results of inventory analysis and impact assessment to provide recommendations for reducing negative impacts on coal raw material procurement activities. This stage is carried out by evaluating and analysing the impact to determine alternative improvements to the coal raw material procurement process.

RESULTS AND DISCUSSION

The overall mass balance for calculating in LCA is illustrated in Figure 3. Analisis ini menggunakan basis per 1 kWh listrik yang dihasilkan dari process cradle to gate. Pada tahap awal, data dari PLTU 3×10 MW disajikan sebagai data pengukuran dari bagian land clearing and preparation. Kemudian, pengukuran input dan output dilanjutkan pada Proses gate yang dimulai dari overburden removal and coal hingga produk batubara disalurkan ke unit pembangkit listrik.

Purpose and scope

Open-pit coal mining activities have very complex operating units. Mining activities start from land clearing, topsoil removal, overburden removal, overburden disposal, reclamation, excavation and coal getting and hauling, coal processing, coal shipping, and coal utilisation for energy. To organize the scope of the LCA study, it is necessary to define system boundaries so that the impact estimation can match the objectives of the study. Figure 4 shows an example of a system boundary that can be applied in an LCA study. System boundaries in LCA are highly variable, either covering the entire process from start to finish or focusing on a specific aspect to evaluate alternative technology options.

In LCA studies, coal is a product that is the subject of study and has the potential to cause impacts on the environment. This implies that coal (at one tonne) can be used as the functional unit in an LCA. The use of tonnes of coal as the evaluation standard is similar to the approach used in PROPER assessments for coal mines, where units of tonnes of coal and overburden are used, especially in the benchmarking phase. The function and evaluation standard are important aspects of LCA that need to be clearly

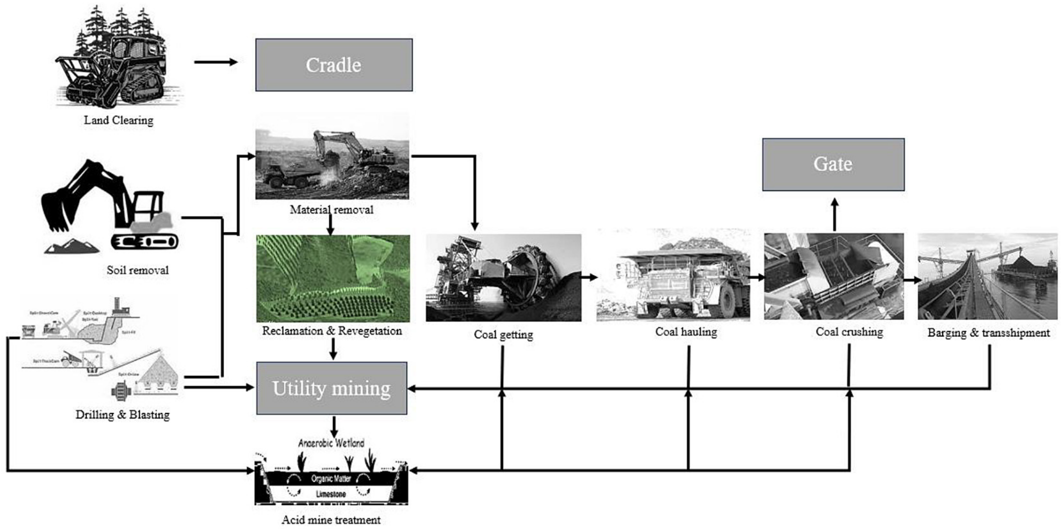

Figure 2. Coal mining flow of PT Bukit Asam Site Banko Barat from cradle to gate

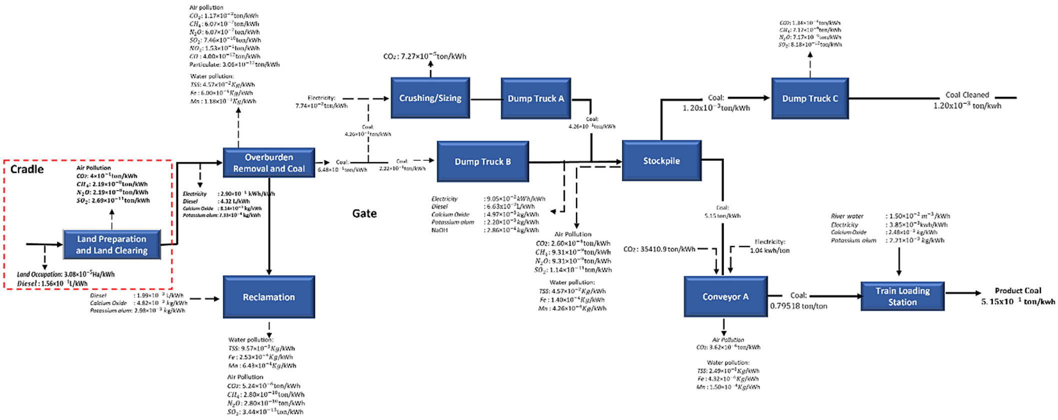

Figure 3. Mass balance in cradle to gate of coal fired power plant 3×10 MW at PT. Bukit Asam

defined from the beginning of the mining process. In the production process of a product, there are several production units with different functions. This function determines the working characteristics of the product system. Meanwhile, the function unit is the measurable performance of the product system that is used as a reference unit.

Understanding the function of the product and its units helps in defining the potential impacts at each stage. Coal is commonly used as a source of electrical energy through combustion in power plants. There are several types of coal such as lignite, bituminous, and anthracite, which are distinguished by their calorific value. These characteristics are influenced by the geological process of coal formation. The difference in coal types can affect the impact on the mining and combustion stages in the power plant. The study by Roychoudhury and Khanda (2016), shows the different energy flows of each coal type, which impacts the LCA value. The flexibility of LCA makes it suitable for use in the mining industry with many independent variables. The evaluation of environmental impact lacks division into individual units. Electrical products serve as energy sources for industrial activities. The reliability assumption is applied uniformly to all machinery and equipment, hence the calculations are not separated for each generating unit. Limitations in this analysis are primarily focused on the production process and exclude support activities. Each scenario's assessment period spans five months, overlooking supporting facilities and office operations within the production process. Inter-unit losses are not considered, and transportation data for inspection trips, such as employee transport for production monitoring, is unavailable. Additionally, core infrastructure aspects like construction, reinvestment, and decommissioning of energy conversion plants (systems) and related structures, fuel preparation equipment, and on-site roads are not factored into the assessment (Fig. 4).

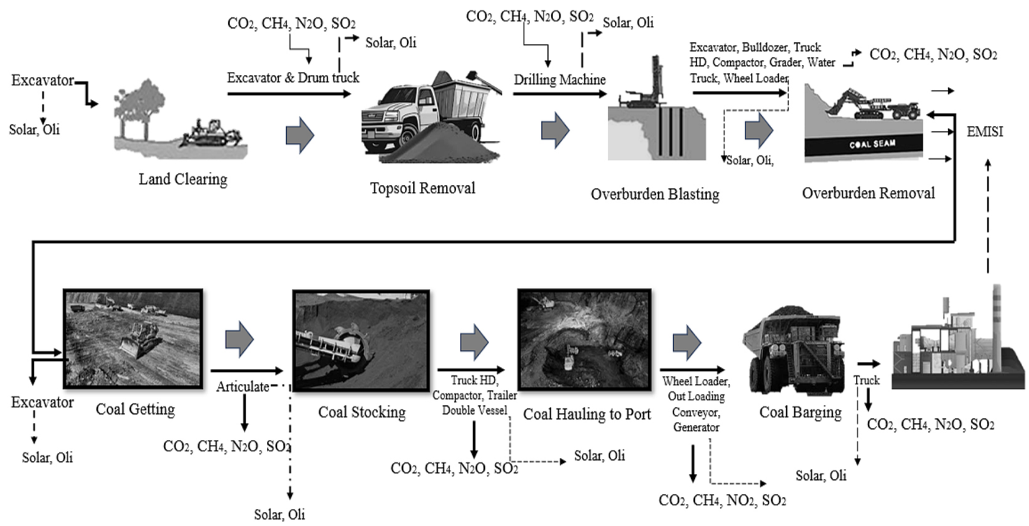

Figure 4. System limitations used in coal mining PT Bukit Asam Site Banko Barat from cradle to gate

In the coal production process at PT Bukit Asam, there are several inputs that are used as data for LCA analysis, data inputs that will be used in this LCA research include the use of diesel fuel, and the use of oil. The total emission value resulting from the calculation of CO_2, CH_4, N_2O, and acidification (SO_2) emissions from the use of materials (Table 1). Cradle data is in the form of coal from the internal mine of PT Bukit Asam at the West Banko site, Tanjung Enim. The inventory data used in the cradle process uses secondary data contained in the SimaPro software, namely the Ecoinvent-3 database, hard coal mine operation and hard coal preparation, as well as data on the amount of coal required by the 3X10 MW PLTU in 2022 of 69,289.26 tonnes. The selected database has included the coal production process consisting of coal mining, coal cleaning and coal transportation processes as well as data on electricity/fuel consumption, water consumption, chemical consumption and emissions generated (Nugraheni et al., 2023).

Impact category assessment result

Based on the results of the inventory analysis, the stages of the coal raw material procurement process to the power plant consist of 3 activities that have the potential to have environmental impacts, namely distribution from coal mining to stockpiles, stockpiles to power plants, and power plants to coal yards. Each stage in each process can produce emissions based on both impact categories per activity, namely:

Table 1. Inventory data input-output coal raw material procurement process

Inventory data	Total 1 Period	Unit	Quantity per unit function	Unit	%
Input					
Raw material					
Coal	36,264,749.56	Ton	0.6.48	ton/Kwh	100
Chemical Ingredients					
Calcium oxide	1,159,390.00	kg	2.07×10^{-2}	kg/Kwh	69.44
Alum	508,300.00	kg	9.08×10^{-3}	kg/Kwh	30.45
Soda ash	1,840.00	kg	3.29×10^{-5}	kg/Kwh	0.11
Fuel					
Diesel	248,659,315.31	L	4.44	L/Kwh	100
Electricity					
Power	92,662,523.64	kWh	1.66	kWh/Kwh	100
Water usage					
River water	2,422,287.00	m^3	4.33×10^{-2}	m^3/Kwh	100
Output					
Product					
Coal (Cleaned)	36,264,749.56	ton	0.648	ton/Kwh	100
Air emissions					
CO_2	741,564.14	ton	1.33×10^{-2}	ton/Kwh	100
CH_4	34.91	ton	6.24×10^{-7}	ton/Kwh	100
N_2O	34.91	ton	6.24×10^{-7}	ton/Kwh	100
SO_2	0.043	ton	7.66×10^{-10}	ton/Kwh	100
CO	0.00022	ton	4.00×10^{-12}	ton/Kwh	100
NO_2	0.00085	ton	1.53×10^{-11}	ton/Kwh	100
Partikulat	0.00017	ton	3.06×10^{-12}	ton/Kwh	100
Water emissions					
Biochemical oxygen demand (BOD)	477.33	kg	8.53×10^{-6}	kg/Kwh	100
Chemical Oxygen Demand (COD)	811.34	kg	1.45×10^{-5}	kg/Kwh	100
Total Suspended Solid (TSS)	2,381,336.90	kg	4.26×10^{-2}	kg/Kwh	100
Iron metal (Fe)	56,979.17	kg	1.02×10^{-3}	kg/Kwh	100
Manganese (Mn)	134,498.12	kg	2.40×10^{-3}	kg/Kwh	100

a) Coal mining activities in the West Banko stockpile function in distributing ready-to-use coal to the PLTU, producing emissions because it uses diesel fuel in the process of distributing coal.
b) Stockpile to 3×10 MW power plant functions to distribute coal using diesel-fuelled trucks, resulting in emissions.
c) 3×10 MW power plant to the coal yard as coal transport during unloading using excavators and trucks to temporary shelters produces emissions because it uses diesel fuel.

Interpretation of LCA results

Interpretation of the results in the LCA study at the 3 × 10 MW power plant is carried out as an effort to analyse improvements to reduce the resulting environmental impacts. Based on Table 1 in the coal raw material procurement process, it can be seen that the largest emission value (hotspot) is when coal distribution activities from the West Banko site to the 3 × 10 MW power plant amounted to 741,564.14 CO_2/ton and 0.043 SO_2/ton. Coal is distributed using trucks used to load coal.

The coal mining activity (subsystem) to the stockpile contributes the second largest emission value because it uses dump trucks as a means of coal transport. Based on Octova and Indra (2019), it is explained that the factors that affect diesel fuel consumption in dump trucks are the characteristics of material transport routes such as road surface, distance travelled, and road slope. The characteristics of the material transport path greatly affect the level of productivity of the equipment used, therefore the use of diesel consumption is directly proportional to the characteristics of the material transport path. The level of road slope causes the speed of the dump truck to be reduced so that the time required is also longer. This condition causes the amount of diesel fuel usage to increase, hence the emissions generated from the combustion process of diesel fuel are higher. The percentage of emission value for each activity is presented in Table 2. The following are three improvement recommendation scenarios as an effort to reduce greenhouse gas emissions and acidification in coal raw material procurement activities.

- Cofiring diesel fuel with biodiesel. Biodiesel can be an alternative to diesel engines, because the low carbon content makes biodiesel an alternative to heating oil, where the use of biodiesel can reduce the potential environmental impact. Thus cofiring diesel fuel with biodiesel is one of the recommended alternatives. According to Gashaw et al (2015), a biodiesel mixture ratio of 20–30% will reduce CO_2 emissions by 15.66%. The carbon dioxide emission value recommended by cofiring biodiesel is assumed to be neutral, or the emission value is equal to zero so that the GHG emissions calculated are CH_4 and N_2O, which are equated to CO_2eq.
- Modernization of dump trucks with overload conveyors (OLC), unloading coal from the stockpile to the coal yard using heavy excavator gear, and dump trucks can be modernized using OLC. The emission value produced using OLC is relatively lower because it uses electricity compared to diesel in excavators and dump trucks. Damanik et al (2021) stated that energy consumption in transportation using trucks is 4 to 12 times greater than transportation using OLC, and CO_2 emissions from truck transportation are three to 10 times greater than OLC transportation. In this way, using OLC can reduce the energy consumption ratio and relatively decrease the resulting emissions.

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

Impact category	Total	Cradle	Gate						
		Land preparation & clearing	OB removal & coal	Reclamation	Dump truck	Crushing/ Sizing	Stockpile	Conveyor	Train loading station
Global warming potential (kg CO_2 eq/kWh)	13.3	0.417	11.8	5.33×10^{-3}	8.30×10^{-2}	7.27×10^{-2}	0.262	0.633	3.62×10^{-3}
Ozone depletion potential (kg CFC-11 eq/kWh)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Acid rain potential (kg SO_2 eq/kWh)	3.23×10^{-8}	3.23×10^{-8}	2.49×10^{-14}	1.14×10^{-17}	1.77×10^{-16}	0.00	3.78×10^{-16}	0.00	0.00
Eutrophication potential (kg PO_4 eq/kWh)	5.91×10^{-6}	5.91×10^{-6}	4.52×10^{-12}	2.08×10^{-15}	3.25×10^{-14}	0.00	6.93×10^{-14}	0.00	0.00

Critical issue identification involves a structured procedure for discerning, testing, assessing, and presenting conclusions derived from the outcomes of a life cycle analysis (LCA), aligning with the objectives and scope delineated in the research. This pivotal step in issue identification aims to elucidate the interplay between inventory data and analyzed impact categories, ultimately establishing focal points, summarizing findings, and proposing enhancement strategies. Broadly, the environmental impact assessment in this study centers on key impacts, encompassing potentialities for global warming, ozone layer depletion, acid rain occurrence, and eutrophication.

The impact categories of electricity production, evaluated from cradle to gate, are outlined in Table 2. These categories encompass the potential for global warming, ozone depletion, acid rain, and eutrophication. In the cradle phase, the impact analysis comprises land preparation and clearing activities. Conversely, the environmental impact assessment at the gate encompasses overburden removal, coal extraction, reclamation, dump truck operations, crushing/sizing procedures, stockpile management, conveyor operations, and train loading station activities. According to the analysis findings, the highest impact category observed is global warming potential, with a cumulative value of 13.3 kg CO_2 eq/kWh. This indicates that the production of 1 kWh of electricity results in emissions equivalent to 13.3 kg of CO_2 from the cradle to the gate stages. Moreover, there is a potential for acid rain and eutrophication, amounting to 3.23×10^{-8} kg SO_2 eq/kWh and 5.91×10^{-6} kg PO_4 eq/kWh, respectively. The analysis findings also indicate the absence of potential for ozone depletion.

The environmental impact percentage at the gate for each impact category is primarily attributed to overburden removal and coal activities. These units contribute to a percentage range of impact categories ranging from 83.99% to 97.34% (Table 3). Overburden removal operations commence with the blasting process in the mining area, followed by the extraction and transport of coal-laden overburden using excavators. Subsequently, heavy-duty vehicles facilitate the transportation of the overburden to the disposal area.

The global warming potential attributed to carbon dioxide stems primarily from land preparation and clearing, as well as overburden removal and coal extraction. Land clearing is the process of removing vegetation, including trees, shrubs, and grasses, from a coal mining site. Typically, coal mining activities commence with clearing the concession area designated for mining. Factors affecting land clearing operations include the types of trees present, soil conditions and stability, topography, rainfall patterns, and weather fluctuations. Additionally, dinitrogen monoxide and methane are generated throughout the cradle-to-gate process (see Table 4). Methane, in particular, becomes entrapped within coal seams and the surrounding soil layers. Under stable conditions, with no geological disturbances compromising methane-containing strata, the gas remains pressurized. However, during mining activities, this pressure is alleviated, resulting in methane release into the atmosphere. Surface mining generally yields lower methane emissions compared to underground operations, as there are no geological layers to confine the gas. Moreover, methane emissions can also occur during coal handling, processing, and transportation, albeit at reduced levels. In longwall mining, the extent of disturbance zones varies based on factors such as longwall dimensions, mining depth, and coal seam thickness

Table 3. Percentage of environmental impact assessment of the cradle to gate

Impact category	Cradle	Gate						
	Land preparation & Land clearing	OB removal & coal	Reclamation	Dump truck	Crushing/ Sizing	Stockpile	Conveyor	Train loading station
Global warming potential (%)	100	83.99	0.04	0.59	0.52	1.86	4.49	0.03
Ozone depletion potential (%)	0	0	0	0	0	0	0	0
Acid rain potential (%)	100	97.34	0.04	0.69	0	1.48	0	0
Eutrophication potential (%)	100	97.05	0.04	0.70	0	1.49	0	0

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

Impact category	Cradle	Gate						
	Land preparation & Land clearing	OB removal & coal	Reclamation	Dump truck	Crushing/ Sizing	Stockpile	Conveyor	Train loading station
Carbon dioxide	98.46	86.74	0.04	0.61	0.54	1.93	4.71	0.03
Dinitrogen monoxide	1.39	1.20	0.0006	0	0	0.018	0	0
Methane	0.15	0.13	0.0001	0	0	0.002	0	0
Total contributor	100.00	88.07	0.04	0.61	0.54	1.95	4.71	0.03

Table 5. Contribution of acid rain impact on the scope of the cradle to gate

Impact category	Cradle	Gate						
	Land preparation & Land clearing	OB removal & coal	Reclamation	Dump truck	Crushing/ Sizing	Stockpile	Conveyor	Train loading station
Sulfur dioxide	100	96.51	0.04	0.69	0	1.48	0	0
Nitrogen dioxide	0	0.82	0	0	0	0	0	0
Total contributors	0	97.34	0.04	0.69	0	1.48	0	0

Table 6. Contributors to eutrophication impact at gate scope

Impact category	Cradle	Gate						
	Land preparation & Land clearing	OB removal & coal	Reclamation	Dump truck	Crushing/ Sizing	Stockpile	Conveyor	Train loading station
Dinitrogen monoxide	100	97.04	0.04	0.7	0	1.49	0	0

(Dunmade et al., 2019). Importantly, methane emissions persist beyond the coal extraction phase. During coal handling, CH_4 continues to be emitted, from several hours to potentially several days after coal extraction. Emissions arising from the transportation and distribution of coal encompass coal dust, originating both from coal fines and diesel combustion, which emits carbon dioxide, sulfur dioxide, and nitrogen oxide. Concerning the potential for acid rain, sulfur dioxide emissions from cradle activities solely account for acid rain occurrence. Conversely, at the gate stage, overburden removal and coal extraction (96.51%) and coal stockpiling (1.48%) constitute the primary contributors (Table 5). Sulfate compounds primarily drive the escalation of acid rain potential, with a more substantial contribution stemming from land clearing and preparation activities.

A comparable trend in impact value was likewise noted in the contribution to eutrophication (Table 6). Eutrophication manifests during coal mining, transportation, and power generation phases. Nitrate compounds, inherent in coal composition (Petrescu et al., 2017), are the primary drivers of eutrophication. Beyond its implications for global warming, the combustion of coal also heightens the propensity for eutrophication.

CONCLUSIONS

This study applies the LCA methodology to assess the coal-fired power plant technology at PT. Bukit Asam, one of Indonesia's largest coal mines. Emissions with significant environmental impacts include CO_2, SO_2, NO_x, and CH_4. Environmental impacts vary across different stages of the coal-fired power plant's life cycle. The highest contribution to environmental impacts stems from CO_2 emissions, notably 98.46% from land clearing and preparation, and 86.74% from overburden removal and coal extraction. These stages primarily contribute to global warming throughout the cradle-to-gate process. Sulfur dioxide emissions from land clearing activities are the primary source of acid rain, followed by overburden removal and coal extraction (96.51%), and coal stockpiling (1.48%), which also contribute. Similarly, the release of NO_x from land clearing and preparation, overburden removal, and coal stockpiling contributes to the potential for eutrophication. Land clearing and preparation have the most substantial impact on global warming during the coal mining and distribution stages. Emissions result not only from coal but also from gasoline, diesel, and water. Enhancing the implementation of new emission reduction facilities and improving pollutant emission standards are effective strategies for reducing the environmental burden associated with these factors. Robust policies integrating environmental protection, energy, and industrial regulations are essential to continue supporting environmentally friendly coal technology initiatives.

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