ENVIRONMENTAL IMPACT ASSESSMENT IN HYDROPOWER GENERATION: A LIFE CYCLE ASSESSMENT AT PT PLN NUSANTARA POWER UP CIRATA, PURWAKARTA, INDONESIA

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Abstract

PT PLN Nusantara Power UP Cirata is one of the largest hydropower plants in Indonesia, with an installed capacity of 1.008 MW, and plays a strategic role in supporting national electricity supply security. Although classified as renewable energy, hydropower operations are not entirely free from environmental impacts, including greenhouse gas emissions from biomass decomposition in the reservoir and waste generated from turbine and generator maintenance. This study aims to analyze the environmental impacts of electricity generation using the Life Cycle Assessment method with a cradle-to-gate system boundary. The assessment was conducted using SimaPro 9.5.0.2 with the CML-IA Baseline method, where the functional unit was 1 kWh of electricity. The main hotspot within the cradle boundary is the Cirata Reservoir due to diesel consumption, contributing 1.21E-04 kg CO2-eq/kWh to global warming potential, 2.35E-11 kg CFC-11-eq/kWh to ozone depletion potential, 3.52E-07 kg SO2-eq/kWh to acidification potential, and 3.32E-06 kg PO4-eq/kWh to eutrophication potential. Within the gate boundary, hotspots were identified in the turbine, where used oil contributed 1.91E-05 kg CO2-eq/kWh to global warming potential, turbine oil contributed 2.63E-12 kg CFC-11-eq/kWh to ozone depletion and 3.97E-08 kg SO2-eq/kWh to acidification potential, and the sewage treatment plant contributed 3.49E-07 kg PO4-eq/kWh to eutrophication potential.

Keywords: ***Cradle-to-Gate, Environmental Impact, Hotspot, Hydropower Generation, Life Cycle Assessment***

INTRODUCTION

PT PLN Nusantara Power UP Cirata is one of the largest hydropower generation units in Indonesia, located in Purwakarta Regency, West Java, with an installed capacity of 1,008 MW, making it the largest hydropower plant in the country (Bagaskara et al., 2024). The electricity generated is distributed to the Java, Madura, and Bali regions, thereby playing a strategic role in maintaining national electricity supply security. From a physical perspective, the environmental impacts associated with hydropower are generally lower than those of fossil fuel-based power plants. However, hydropower operations are not entirely free from environmental impacts. Maintenance activities involve the use of materials such as oil and lubricants in turbine and generator units, generating waste that requires collection and transportation to treatment facilities, which indirectly contributes to greenhouse gas emissions (Pant et al., 2016). Changes in land use and human activities in the generation process can increase the entry of sediment and suspended material into water bodies, which has the potential to reduce water quality, increase sedimentation, and affect the balance of aquatic ecosystems (Ridarto et al., 2023; Ayasy et al., 2023). In addition, resource consumption and supporting operational activities may also contribute to various environmental impact categories. One approach that can be employed to comprehensively evaluate these impacts is Life Cycle Assessment (LCA). LCA is a data-based method used to assess the environmental impacts of a system throughout its life cycle, from raw material extraction to the final stage (Jung et al., 2022). Although LCA has been widely applied in the electricity generation sector, specific studies on large-scale hydropower plants in Indonesia, particularly at PT PLN Nusantara Power UP Cirata, remain limited.

This study aims to analyze the potential environmental impacts of the electricity generation process using the LCA method within a cradle-to-gate system boundary and to identify hotspots across impact categories. The cradle-to-gate scope was selected as it represents upstream and core production processes that generally contribute dominantly to environmental impacts, allowing the analysis to focus on the most significant stages. Through this approach, the study is expected not only to enrich the LCA literature on the hydropower sector in Indonesia but also to provide practical contributions toward improving environmental performance and supporting national energy transition and emission reduction agendas.

METHODOLOGY

This study employed a quantitative approach using the Life Cycle Assessment (LCA) method in accordance with ISO 14040 and ISO 14044 standards. The analysis was conducted within a cradle-to-gate system boundary covering upstream and core electricity generation processes. The LCA framework consisted of goal and scope definition, Life Cycle Inventory (LCI) development, Life Cycle Impact Assessment (LCIA), and interpretation of results. Data processing and impact calculations were performed using SimaPro version 9.5.0.2 with the CML-IA Baseline method, adopting 1 kWh of electricity as the functional unit. The impact categories assessed included Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), and Eutrophication Potential (EP). The impact assessment results were subsequently analyzed to identify environmental hotspots at each process unit.

RESULTS AND DISCUSSION

Life Cycle Inventory

The inventory analysis stage involves identifying and documenting all input and output flows from each process unit within the defined system boundary. The system boundary includes raw material extraction from the reservoir, production and transportation of supporting materials, and hydropower plant construction activities, which comprise the powerhouse, intake, headrace tunnel, penstock, turbine, generator, and utilities process. The inventory was conducted by recording all material and energy flows entering and leaving the system. Input data included raw materials, electricity consumption, and water use, while output data comprised emissions, wastewater, hazardous waste, non-hazardous waste, and the electricity generated from the power production process. Life cycle inventory can be seen in figure 1.

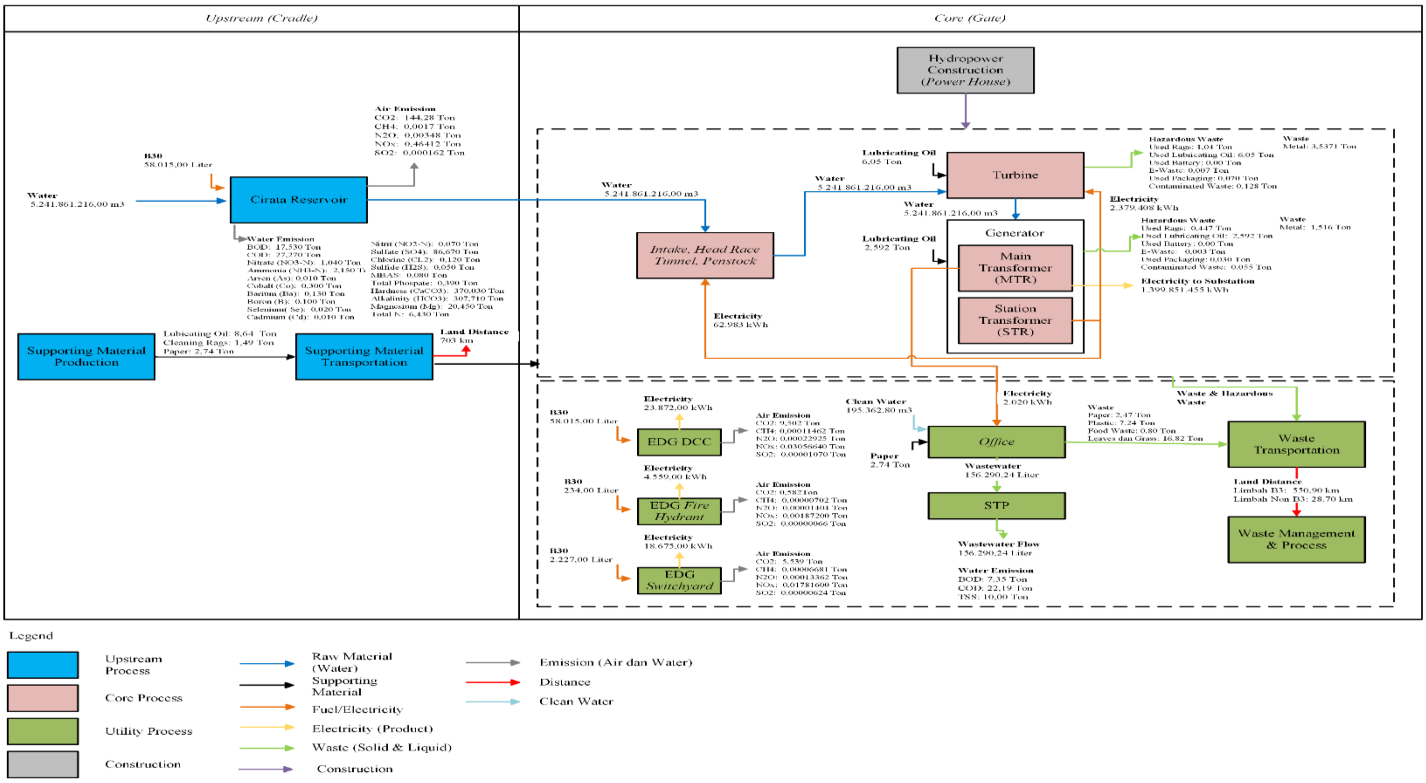

Figure 1. Life Cycle Inventory of The Power Generation Process

Life Cycle Impact Assessment (LCIA)

The impact assessment was conducted using the CML-IA method implemented in SimaPro software for the impact categories of Global Warming Potential, Ozone Depletion Potential, Acidification Potential, and Eutrophication Potential. The CML-IA method was selected because it is a midpoint-based approach widely applied in Life Cycle Assessment studies to quantitatively and systematically evaluate environmental impacts. The characterization stage was carried out by converting all input and output inventory data into equivalent environmental impact units through multiplication by the characterization factors corresponding to each impact category. These characterization factors represent the potential contribution of each substance or flow to a specific impact category. The impact results can be seen in table 1.

Table 1. Impact Result from Hydropower Generation

Process Unit	Global Warming Potential (kg CO2ek/kWh)	Ozone Depletion Potential (kg CFC-11 ek/kWh)	Acidification Potential (kg SO2ek/kWh)	Eutrophication Potential (kg PO4ek/kWh)
Cradle				
Cirata Reservoir	1.21E-04	2.35E-11	3.52E-07	3.32E-06
Supporting Material Production	2.11E-05	4.19E-12	1.35E-07	1.15E-07
Supporting Material Transportation	5.69E-07	9.89E-14	2.21E-09	3.86E-10
Core				
Hydropower Construction	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Intake, Headrace Tunnel, Penstock	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Turbine	1.91E-05	2.63E-12	3.97E-08	4.80E-09
Generator	8.16E-06	1.12E-12	1.70E-08	2.05E-09
Core Utility				
EDG DCC	7.97E-06	1.55E-12	2.33E-08	4.17E-09
EDG Firehydrant	4.87E-07	9.49E-14	1.43E-09	2.55E-10
EDG Switchyard	4.64E-06	9.03E-13	1.36E-08	2.42E-09
Office	3.78E-06	2.07E-14	1.45E-09	2.20E-09
STP	0.00E+00	0.00E+00	0.00E+00	3.49E-07
Hazardous Waste Management	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Waste Management	0.00E+00	0.00E+00	0.00E+00	0.00E+00

a. Global Warming Potential

In the cradle boundary, the Global Warming Potential (GWP) results show that the largest contribution comes from the Cirata Reservoir unit at 1.21×10^{-4} kg CO_2-eq/kWh, followed by Supporting Material Production at 2.11×10^{-5} kg CO_2-eq/kWh, reflecting the impact of the production of lubricating oil, paper, and rags. Supporting Material Transportation has the lowest impact at 5.69×10^{-7} kg CO_2-eq/kWh, indicating a relatively small role compared to material production. In the downstream boundary (gate boundary), the turbine unit shows the highest GWP value at 1.91×10^{-5} kg CO_2-eq/kWh, followed by the generator at

8.16×10^{-6} kg CO_2-eq/kWh. Among the utility units, EDG DCC contributes the largest GWP (7.97×10^{-6} kg CO_2-eq/kWh), while EDG Switchyard and EDG Firehydrant contribute 4.64×10^{-6} and 4.87×10^{-7} kg CO_2-eq/kWh, respectively, and office units contribute 3.78×10^{-6} kg CO_2-eq/kWh. Meanwhile, hydropower plant construction, inlet–water channel tunnel–penstock, wastewater treatment plant (STP), and hazardous and non-hazardous waste management show zero GWP in the initial stage due to the absence of additional greenhouse gas emissions, energy consumption, or to avoid double counting, as the waste impact has been allocated to the original turbine and generator units.

b. Ozone Depletion Potential

The largest Ozone Depletion Potential (ODP) in the cradle boundary, impact comes from the Cirata Reservoir process unit at 2.35×10^{-11} kg CFC-11 ek/kWh, which arises not from the direct use of ozone-depleting substances, but from the indirect contribution of upstream processes such as the production and distribution of fuel and supporting materials (van den Oever et al., 2024). The Supporting Material Production unit contributes 4.19×10^{-12} kg CFC-11 ek/kWh, while Supporting Material Transportation has the smallest impact on the cradle scope, namely 9.89×10^{-14} kg CFC-11 ek/kWh. At the gate scope, the hydropower construction unit and the intake–headrace tunnel–penstock have a zero value because only water flow occurs without other input or output. The turbine and generator units contribute 2.63E-12 and 1.12E-12 kg CFC-11 ek/kWh, respectively. In the utility group, EDG DCC has an impact of 1.55E-12 kg CFC-11 ek/kWh, EDG Switchyard 9.03E-13 kg CFC-11 ek/kWh, and EDG Firehydrant 9.49E-14 kg CFC-11 ek/kWh. The STP unit does not show an ODP contribution because the inventory is only in the form of liquid waste without an ODP characterization factor in the CML-IA method, while waste transportation provides a very small contribution of 2.92E-14 kg CFC-11 ek/kWh.

c. Acidification Potential

The largest contribution of Acidification Potential (AP) impact in the cradle scope comes from the Cirata Reservoir process unit of 3.52E-07 kg SO2ek/kWh, in the Supporting Material Production process unit it produces an AP impact of 1.35E-07 kg SO2ek/kWh, and the smallest contribution is from the Supporting Material Transportation process unit of 2.21E-09 kg SO2ek/kWh. In the gate scope, it is known that the turbine process unit has the largest impact in the AP impact category, which is 3.97E-08 kg SO2ek/kWh. The second largest impact comes from the EDG DCC process unit with an impact value of 2.33E-08 kg SO2ek/kWh, another process unit, namely the generator, produces an impact of 1.70E-08 kg SO2ek/kWh. In the EDG Switchyard and Firehydrant process units, each produces an AP impact of 1.36E-08 kg SO2ek/kWh and 1.43E-09 kg SO2ek/kWh. In the office process unit, it produces an AP impact of 1.45E-09 kg SO2ek/kWh. In the waste transportation process unit, it produces an AP impact of 6.53E-10 kg SO2ek/kWh.

d. Eutrophication Potential

Eutrophication Potential (EP) value in the cradle scope is dominated by the Cirata Reservoir process unit with a value of 3.32E−06 kg PO_4^{3-} eq/kWh. The second largest impact comes from the Supporting Material Production process unit at 1.15E−07 kg PO_4^{3-} eq/kWh and followed by the third largest impact from the Supporting Material Transportation process unit with an impact of 3.86E−10 kg PO_4^{3-} eq/kWh. The impacts resulting from these two process units are relatively small due to the limited nutrient emissions released. In the gate scope, the largest impact comes from the Sewage Treatment Plant (STP) process unit with a value of 3.49E-07 kg PO_4^{3-} ek/kWh, the turbine and generator process unit also contributes an EP impact of 4.80E-09 kg PO4ek/kWh and 2.05E-09 kg PO4ek/kWh, the Emergency Diesel Generator (EDG) process unit also contributes an EP of 4.17E-09 kg PO4ek/kWh at the EDG DCC, 2.55E-10 kg PO4ek/kWh at the EDG Firehydrant, and 2.42E-09 kg PO4ek/kWh at the EDG Switchyard, and produces an impact of 2.20E-09 kg PO4ek/kWh.

Interpretation (Hotspot Analysis)

Hotspot analysis falls within the interpretation stage of an LCA analysis. Hotspot identification is performed for each impact category. Hotspot identification is performed to identify the impacts that contribute most significantly to each impact category from each process unit. The Impact Contribution Percentage can be seen in the table 2.

Table 2. Impact Contribution Percentage

Process Unit	Global Warming Potential	Ozone Depletion Potential	Acidification Potential	Eutrophication Potential
		Cradle		
Cirata Reservoir	84.84%	84.59%	71.89%	96.63%
Supporting Material Production	14.76%	15.05%	27.65%	3.36%
Supporting Material Transportation	0.40%	0.36%	0.45%	0.01%
		Core		
Hydropower Construction	0.00%	0.00%	0.00%	0.00%
Intake, Headrace Tunnel, Penstock	0.00%	0.00%	0.00%	0.00%
Turbine	43.11%	41.40%	40.86%	1.31%
Generator	18.42%	17.70%	17.48%	0.56%
		Core Utility		
EDG DCC	17.98%	24.40%	24.04%	1.14%
EDG Firehydrant	1.10%	1.49%	1.47%	0.07%
EDG Switchyard	10.48%	14.22%	13.99%	0.66%
Office	8.52%	0.33%	1.49%	0.60%
STP	0.00%	0.00%	0.00%	95.61%
Hazardous Waste Management	0.00%	0.00%	0.00%	0.00%
Waste Management	0.00%	0.00%	0.00%	0.00%

a. Global Warming Potential
In the cradle scope, it is known that the Cirata Reservoir process unit is a hotspot with a contribution of 84.84%. This is due to the use of diesel fuel of 58,015.00 liters in this process for periodic cleaning of water hyacinth growing in the reservoir using an excavator. This cleaning is carried out to maintain the reliability of the generating system to prevent blockages due to water hyacinth rotting at the bottom of the reservoir. Due to the massive growth of water hyacinth, cleaning activities using excavators must also be carried out frequently so that the use of diesel fuel also increases. The combustion process of this fuel directly produces greenhouse gas emissions such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) which have an impact on global warming (Gentilucci et al., 2025). In the gate scope, it is known that the Turbine process unit is a hotspot with a contribution of 43.11% caused by the accumulation of used oil of 6.05 tons due to routine maintenance in the turbine to maintain the reliability of the generating process. This used oil must be processed, and this process can produce high greenhouse gas emissions. One method for processing used oil is burning it in a kiln or incinerator, which oxidizes the carbon content in the oil and produces CO2, increasing its potential for global warming (Garcia-Gutierrez et al., 2025).

b. Ozone Depletion Potential
In the cradle scope, it is known that the Cirata Reservoir process unit is a hotspot with a contribution of 84.59% due to the use of diesel fuel of 58,015.00. Ozone depletion due to the use of diesel fuel is an impact that appears indirectly. The LCA cycle calculation takes into account upstream stages such as petroleum exploration, refining processes, and the use of chemicals and other auxiliary materials where there is the possibility of emissions of substances with the potential for ozone depletion in very small amounts, so that when calculated using the ODP characterization method, the contribution can still be calculated even though the value is low (Heidari Maleni et al., 2024). In the gate scope, it is known that the turbine process unit is a hotspot with a contribution of 41.40% due to the use of lubricating oil of 6.05 tons. Lubricating oil causes an indirect ODP impact because lubricating oil is a petroleum-based product so that the impact modeling in the LCA analysis starts from crude oil extraction, refining process, to lubricant formulation. This process becomes background emissions which have an ODP characterization factor.

c. Acidification Potential

In the cradle scope, it is known that the Cirata Reservoir process unit is a hotspot with a contribution of 71.89% due to the use of diesel fuel of 58,015.00 liters. The use of diesel fuel can cause an increase in Acidification Potential because the diesel combustion process produces emissions of acidic gases, especially sulfur dioxide (SO_2) and nitrogen oxide (NO_x). These acidic compounds are then deposited onto the surface of the land and water through acid deposition, thus contributing to an increase in the Acidification Potential value (Brambilla and Girardi, 2025). In the gate scope, the turbine process unit is a hotspot with a contribution of 40.86% due to the use of lubricating oil of 6.05 tons. The use of lubricating oil can cause an indirect impact of Acidification Potential. Lubricating oil is a derivative product of petroleum whose production process involves other processes and auxiliary materials that produce acid gas emissions such as sulfur dioxide (SO_2) and nitrogen oxide (NO_x).

d. Eutrophication Potential
In the cradle scope, it is known that the Cirata Reservoir unit is a hotspot with a contribution of 96.63% due to the use of diesel fuel of 58,015.00 liters. The use of diesel fuel will release NO_x emissions that can experience wet deposition (rain) or dry deposition. This nitrogen acts as a nutrient that can increase the productivity of algae and aquatic plants, thereby contributing to eutrophication (Yau et al., 2022). At the gate scope, the STP process unit is a hotspot with a contribution of 95.61% because the wastewater effluent still contains organic matter and nutrients, as indicated by the BOD and COD values. This organic material will be degraded by microorganisms by consuming dissolved oxygen, while releasing nitrogen that encourages algae growth and contributes to eutrophication (Ro'in and Dahalan, 2024).

CONCLUSION

The results of the LCA analysis with a cradle-to-gate scope show several process units that are hotspots. In the cradle scope, the process unit that is a hotspot is Cirata Reservoir with an impact value of 1.21E-04 kg CO2ek/kWh on global warming potential, 2.35E-11 kg CFC-11 ek/kWh on ozone depletion potential, 3.52E-07 kg SO2ek/kWh on acidification potential, and 3.32E-06 kg PO4ek/kWh on eutrophication potential. Meanwhile, in the gate scope, the turbine process unit was found to be a hotspot with an impact value of 1.91E-05 kg CO2ek/kWh global warming potential, 2.63E-12 kg CFC-11 ek/kWh on the ozone depletion potential impact, and 3.97E-08 kg SO2ek/kWh on the acidification potential impact, as well as the STP (sewage treatment plant) process unit with an impact value of 3.49E-07 kg PO4ek/kWh on the eutrophication potential.

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