Life Cycle Assessment of a combined cycle power plant in Indonesia

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Abstract. This paper presents the Life Cycle Assessment (LCA) of a 640 MW combined cycle power plant located in West Java, Indonesia. The power plant adopts the dual-fuel firing system, in which both natural gas and high-speed diesel fuels are used. The LCA was performed using the open-source LCA software OpenLCA version 1.9. A functional unit of 1 kWh of electricity generation was used in calculating the environmental impacts. The system boundary was modeled using the gate-to-gate system, which includes all inputs and outputs for the following subsystems: fuel storage, water preparation, electricity production, and supporting subsystems. The life cycle inventory (LCI) used data gathered from July 2018 to June 2019. The CML–IA baseline method was used to perform the life cycle impact assessment (LCIA), providing results for ten midpoint impact categories. All impact categories were normalized using World 2000 normalization factors. The result shows that the most significant impact categories are acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP), respectively. The largest acidification source is nitrogen oxide emission from the combustion chamber, with a percentage of 80.32%. Regarding the combustion stage, the post-combustion method is recommended to remove nitrogen oxide from exhaust gases to lower the AP impact category.

1. Introduction

Electricity is a pivotal energy source closely related to the economy and life quality in a country. It is a vital infrastructural component that strengthens production effectiveness, supports business activities, and enhances life quality through products and services [1]. The increase in global electricity demand has reached 3.1% or higher than the overall increase in energy demand [2]. Meanwhile, Indonesia's electricity consumption per capita from 2013 to 2018 increased from 0.84 to 1.06 GWh, where the annual increase average is 4.8% [3]. The rapid increase in electricity consumption is risking electricity demand continues to be fulfilled by burning more fossil fuels and contributes to steady increases in the global concentrations of greenhouse gases (GHGs) [4].

In terms of fulfilling the electricity demand, an electric power system is needed. An electric power system is a network that consists of three major electrical components: electricity generation, a high voltage transmission grid, and a distribution system. More than 60% of the environmental impacts associated with the electricity sector were caused by electricity generation. In contrast, electricity transmission was found to have a 70%-90% lower life cycle impact than electricity generation [5]. The environmental impact percentage of electricity generation may vary among countries depending on the applied electricity scenarios. Applying a renewable energy scenario may decrease global environmental
impacts from fossil energy consumption and greenhouse gas emissions but may increase other local environmental impacts such as acidification and human toxicity [6].

In 2018 the Indonesian power sector still largely depends on thermal power, which accounted for 84.9% of the total electricity production [3]. The steam power plants and combined cycle power plants played the most significant role in generating electricity with a 42.34% and 17.28% percentage. Notwithstanding the growing contribution of renewable technologies in national energy mixes, the current electricity generation is still heavily reliant on fossil fuels, such as coal, natural gas, and oil. The Indonesian Ministry of Energy and Mineral Resources reported that the fuel consumption of power plants was 60,481,244.55 tons of coal; 3,718,749.55 kiloliters of oil; and 454,730.75 MMscf natural gas in 2018 [3]. All coal was used by steam power plants, while combined cycle power plants used 70% of natural gas (319,143.25 MMscf) and 4% of oil (146,545.92 kiloliters) [3].

Even though many studies showed various environmental impacts associated with coal-powered power plants, the need for affordable electricity may cause coal to remain as the primary energy source for electricity generation [7]. One scenario to reduce greenhouse gas emissions from burning coal to generate electricity is to shift to natural gas [8]. Transitioning coal to natural gas can reduce carbon dioxide emissions from the electricity generation sector by 22% [9]. In generating electricity, there are always potential environmental impact regardless of the forms or sources of energy used [6]. A study reveals that natural gas can generate more environmental impacts in freshwater ecotoxicity, marine ecotoxicity, human toxicity, and acidification potential [10]. Thus, it is essential to assess the environmental profile of a power plant or electricity generation system.

Among the wide range of methodologies used to analyze products' environmental profile, Life Cycle Assessment (LCA) is the most comprehensive and extensive method [11]. The basic concept of LCA is to identify and quantify the energy and material used to produce a product and the byproducts that are disposed of or released into the environment [12]. LCA can be used to assess and measure the potential environmental impacts of electricity sources and account for the electricity generation, transmission, and distribution [13]. LCA is appropriate for the electricity sector because it can provide better information for the electricity scenario selection or the right recommendation to improve its environmental performance.

Life cycle assessment has been the most widely used methodology for evaluating the environmental impacts of electricity generation in many countries, namely Turkey [14], Brazil [15], Portugal [16,17], Norway [18], Spain [19], Poland [20], Greece [5], and United Kingdom [21]. This method also has been implemented for evaluating the environmental impacts of 1 MWh electricity generation from a 9 MW mini hydropower plant in North Sumatera, Indonesia [22]. Despite being one of the most significant electricity suppliers in Indonesia and consume a high percentage of fossil fuels to generate electricity, currently, there is no research conducted to investigate the environmental impacts of electricity generation from a natural gas combined cycle power plant in Indonesia. The closest research regarding the environmental impacts of the electricity generation from combined cycle power plant in Indonesia was conducted in 2012 which compared of emission from all types of thermal power plants from 2000-2009 [23].

Therefore, this research was performed to assess the environmental impacts of 1 kWh of electricity generated by a combined cycle power plant using the LCA method. The power plant is a 640 MW combined cycle power plant located in West Java, Indonesia, which adopts the dual-fuel firing system, in which both natural gas and high-speed diesel fuels are used. Using different LCA software tools may lead to different LCA results [24]. In this study, the LCA was performed using the open-source LCA software OpenLCA version 1.9. The CML-IA baseline method was used for the life cycle impact assessment (LCIA) phase, providing ten midpoint impact categories of electricity generation. Each impact category has a different reference [25].

2. Method
In this study, the electricity generation's environmental impacts were assessed using Life Cycle Assessment (LCA) method. According to ISO 14040:2006, an LCA study includes four interrelated
phases: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation [12].

2.1 Goal and Scope Definition
This study evaluates the potential environmental impacts associated with electricity production from a 640 MW combined cycle power plant located in West Java, Indonesia. The power plant used a dual-firing system fueled by high-speed diesel and natural gas. The functional unit chosen to calculate the environmental impacts is 1 kWh of electricity generated. Environmental impacts of four subsystems were portrayed using the gate to gate system boundary (see Figure 1).

2.1.1. Energy source preparation subsystem. Energy source preparation activities include the process of loading and storing fuels. The high-speed diesel was received from the vessel then stored in the bunker. The natural gas was received from the vessel via three gas pipelines and stored in a gas station while a small amount will flow to CNG (Compressed Natural Gas) Plant. Both fuels will flow to the combustion chamber corresponding to the operational needs.

2.1.2. Water preparation subsystem. This subsystem includes the process of preparing seawater as feed water. This production water preparation process begins with taking seawater through a water intake equipped with a bar screen to separate solid waste. The seawater then enters the desalination plant to reduce its salinity. The desalinated water then enters the Water Treatment Plant (WTP), where the raw water from the desalination is treated to obtain the appropriate quality of raw water for the condenser. The condenser serves to condense raw water into feed water to use in the Heat Recovery Steam Generator (HRSG). The WTP’s remaining water will enter the Waste Water Treatment Plant (WWTP) to be treated before being discharged into the sea.

2.1.3. Electricity production subsystem. Electricity production activities include the process of generating electricity through gas turbines and steam turbines. The high-speed diesel and natural gas
will be burned in the combustion chamber with the support of pressurized gas from the compressor. The fast-rotating gas turbine drives a generator that converts some of the rotational energy into electricity. The gas turbine produces exhaust gas, which is then captured by HRSG. HRSG converts as much of the heat as possible from the gas turbine's exhaust gas into steam for a steam turbine. The generator drive shaft converts the steam turbine’s energy into additional electricity.

2.1.4. Supporting subsystem. Supporting activities include office administration, control room, canteen, laboratory, workshop, and warehouse activities.

2.2 Life-Cycle Inventory
Life Cycle Inventory (LCI) phase is the second phase of LCA, which was conducted by collecting data following the initial plan from the goal and scope definition phase [26]. This study's life cycle inventory data were primary data gathered from recorded documents from July 2018 to June 2019, interviews, and field observations. The collected data were calculated and utilized to quantify the inputs and outputs of a unit process within the system boundary. The unit process is a black box that processes inputs, such as natural resources, energy, chemicals, and results from previous processes into the outputs, such as emissions to air, discharges to water and soil, solid waste, hazardous waste, and electricity generated.

2.3 Life Cycle Impact Assessment
Life Cycle Impact Assessment (LCIA) phase is the third phase of LCA, where results from the LCI phase were used to evaluate the significance of potential environmental impacts [12]. The LCIA phase included two mandatory steps (classification and characterization) and an optional step (normalization). The chosen method for impact classification and characterization is the CML-IA baseline method, which elaborates on the problem-oriented approach and includes ten midpoint environmental impact categories. The characterization results were obtained by multiplying the characterization factor of the impact category with the mass of the compound from the LCI results. The normalization step was then conducted by dividing the characterization results with selected normalization factors. The normalization factors represent a reference region's total impact for a particular impact category in a reference year. In this study, all impact categories were normalized using CML-IA Baseline World 2000.

2.4 Interpretation
The final phase in this LCA study is the interpretation of results. The results of the LCI and LCIA are summarized and analyzed as a basis for making recommendations following the goal and scope definition. There are three vital elements in interpreting the life cycle: identification of critical issues, evaluation, drawing the conclusion, and making recommendations [27]. In this study, the interpretation phase was done for conceptualizing improvement scenarios that can be applied to manage the most significant environmental impacts of electricity generation from the combined cycle power plant. A sensitivity analysis was conducted by checking the influence of varying data by ±25% of the most significant impact categories obtained from the LCIA phase.

3. Results and discussion

3.1 Life-Cycle Inventory
Inventory analysis involves the collection of the data necessary to meet the goals of the study. Inventory data consists of a stream of input data, process, and output data. Figure 2 shows the inputs and outputs for all unit processes involved in electricity generation within the defined system boundary.
The total electricity generated from July 2018 to June 2019 is 3,102,135461.71 kWh. Table 1 shows all inputs and outputs for each subsystem. The most significant input comes from the fuel consumption of high-speed diesel and natural gas in the energy preparation subsystem. Electricity was used in every subsystem, where it was mostly used to power equipment such as compressors and pumps. Most chemicals such as chlorine, hydrochloric acid, and sodium hydroxide were used in the water preparation subsystem. The main output of the inventory data is the combined cycle power plant product, which is electricity. Carbon dioxide and nitrogen oxides are the top two pollutants released to the air, mostly from energy preparation and electricity production subsystem. In line with chlorine input in the water preparation subsystem, free chlorine was detected in wastewater discharged into the sea.

Table 1. Inventory of 1 kWh Electricity Generation.

| Subsystem          | Sub-1          | Sub-2          | Sub-3          | Sub-4          | Total        | Unit  |
|--------------------|----------------|----------------|----------------|----------------|--------------|-------|
| Fuel Consumption   |                |                |                |                |              |       |
| High-Speed Diesel  | 1.70E-06       | 1.70E-06       | 1.70E-06       | 1.70E-06       | 1.70E-06    | m³    |
| Natural Gas        | 1.02E-03       | 1.02E-03       | 1.02E-03       | 1.02E-03       | 1.02E-03    | m³    |
| Gasoline           | 3.39E-08       | 3.39E-08       | 3.39E-08       | 3.39E-08       | 3.39E-08    | m³    |
| Diesel             | 4.12E-09       | 4.12E-09       | 4.12E-09       | 4.12E-09       | 4.12E-09    | m³    |
| Electricity Consumption | 2.18E-03 | 9.19E-03 | 1.18E-02 | 6.90E-03 | 2.39E-02 | kWh  |
### Water Consumption

| Source                  | Quantity          | Unit       |
|-------------------------|-------------------|------------|
| Seawater                | 6.45E-04          | m³         |
| Drinking water          | 4.89E-05          | m³         |
| Water                   | 6.12E-04          | m³         |

### Chemicals

| Chemical                  | Quantity          | Unit       |
|---------------------------|-------------------|------------|
| Antiscalant               | 7.74E-10          | m³         |
| Anti-foam agent           | 3.87E-10          | m³         |
| Hydrochloric acid         | 1.08E-05          | kg         |
| Sodium hydroxide          | 6.77E-06          | kg         |
| Chlorine                  | 6.45E-05          | kg         |
| Poly-aluminium chloride   | 1.93E-08          | kg         |
| Ferric chloride           | 6.45E-08          | L          |
| Sulfur hexafluoride       | 2.51E-07          | L          |
| Hydrazine                 | 1.61E-08          | L          |
| Phosphate                 | 4.84E-09          | L          |
| Ammonia                   | 1.61E-08          | L          |
| Other liquid chemicals    | 1.94E-06          | L          |
| Other solid chemicals     | 1.57E-07          | kg         |

### Others

| Source                  | Quantity          | Unit       |
|-------------------------|-------------------|------------|
| Lubricant               | 2.31E-06 7.45E-08| kg         |
| Grease                  | 1.68E-10 3.22E-10| kg         |

### Output

#### Emissions to air

| Compound                    | Quantity          | Unit       |
|-----------------------------|-------------------|------------|
| HCFC-R22                    | 1.26E-08          | kg         |
| HFC-R32                     | 1.68E-08          | kg         |
| HFC-R410A                   | 1.26E-08          | kg         |
| Methane (CH₄)               | 5.26E-06 2.22E-05| kg         |
| Carbon dioxide (CO₂)        | 1.02E-03 4.31E-03| kg         |
| Carbon monoxide (CO)        | 3.57E-04 1.32E-05| kg         |
| Nitrogen oxides (NOₓ)       | 4.96E-04 5.80E-05| kg         |
| Nitrous oxide (N₂O)         | 3.98E-12          | kg         |
| Sulfur dioxide (SO₂)        | 2.27E-05 4.41E-10| kg         |
| Sulfur oxides (SOₓ)         | 6.71E-11 3.81E-06| kg         |
| Particulate matter          | 5.23E-05 4.08E-06| kg         |
| Sulfur hexafluoride         | 1.55E-09          | kg         |

#### Emissions to water

| Compound                    | Quantity          | Unit       |
|-----------------------------|-------------------|------------|
| Salinity                    | 1.78E-05          | kg         |
| Suspended solids            | 2.62E-07          | kg         |
| Chlorine (Cl₂)              | 2.33E-05          | kg         |
### 3.2 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) is the third phase of LCA in which LCI results are converted into impact categories. The first mandatory step of the life cycle impact assessment was defining and selecting the impact categories to describe the impacts of natural resource consumption and the emission induced during electricity production. In this study, all inputs and outputs from the life cycle inventory were classified into midpoint impact categories using the CML-IA baseline method as follows: global warming potential (GWP), photochemical ozone creation potential (POCP), acidification potential (AP), ozone layer depletion potential (ODP), eutrophication potential (EP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), freshwater aquatic ecotoxicity potential (FAETP), and abiotic resources depletion potential (ADP).

![Classification of Impact Categories](image)

**Figure 3.** Classification of Impact Categories.

After the impact categories are defined and selected, each input and output's relative contribution within the system boundary was assigned to impact categories (see Figure 3). The relative contribution was then converted into indicators representing the matching impact category by multiplying the result obtained in the inventory phase with each substance's characterization factors within each impact category. The characterization result in Figure 4 shows that the electricity production subsystem is the foremost contributor to the impact categories. Meanwhile, the most prominent impact category generated from the electricity production subsystem is GWP, followed by HTP and AP (see Figure 5).
Both classification and characterization are mandatory steps in LCIA. However, in this study, optional steps such as normalization are applied. Normalizing is a process that normalizes the assessment results obtained by characterizing each impact category to make relative comparisons. In this study, normalization is applied to provide information on the total inputs and outputs using CML-IA Baseline World 2000 data set. The normalization result shows that the three most significant impact categories are AP, EP, and GWP, respectively (see Figure 6).

3.3 Life Cycle Interpretation
Life cycle interpretation is the last phase of an LCA study. Results from the LCI phase or the LCIA phase are evaluated concerning the defined goal and scope. The life cycle interpretation phase includes several elements. The first element is the identification of significant impact categories based on the LCI and LCIA phases. The normalized result of LCIA shows that the most significant impact category is AP. In contrast, the characterization shows that almost 90% of the acidification potential was generated from the electricity production subsystem.

Figure 3 shows that the acidification potential impact category was caused by three gases: sulfur dioxide, sulfur oxides, and nitrogen oxides. Nitrogen oxides emission from the electricity production subsystem contributed the most to the overall acidification potential with a percentage of 80.32%. In the electricity production subsystem, nitrogen oxides were released into the air from the combustion chamber's fuel combustion chamber through the stack.
The second element of the life cycle interpretation is the evaluation. In this study, a sensitivity analysis was conducted by checking the influence of varying assumptions and data by ±25% of the top three most significant impact categories identified (AP, EP, GWP). Figure 7 shows the result of the sensitivity analysis. Since the gap between AP and the other two impact categories is quite far, varying the data by ±25% did not change the result that AP is the most significant impact category. This means that the LCA study's final result is reliable and did not get affected by the uncertainties in the data.

Previous research has been conducted for evaluating the environmental impacts of 1 MWh electricity generation from a 9 MW mini hydropower plant in North Sumatera, Indonesia [22]. Both the previous research and this research used CML-IA baseline as the characterization method but used different normalization factors where the previous research used EU25 data set. There are significant differences regarding the environmental impacts of electricity generation from a combined cycle power plant and mini hydropower plant. The results of the previous research shows that the most significant environmental impact category for generating 1 MWh of electricity is MAETP and almost no AP, GWP, or EP [22].

### 3.4 Recommendations for Environmental Improvement

Based on the LCA study's interpretation phase, the most significant impact category of 1 kWh of electricity generated by the combined cycle power plant is acidification potential, where the largest source of acidification is nitrogen oxide emission from the combustion chamber with a percentage of 80.32%. Combusting HC at low temperatures within a short resistance time and under fuel-rich conditions. Regarding the combustion stage, there are three different methods to control NOX emission [29]. The first method is the pre-combustion method, which aims to lower the nitrogen level in fuel to reduce NOX emissions. This can be done by selecting fuel with low nitrogen content. The second method is the combustion method which relates to furnaces and burners' design. This method regulates residence time in the combustion chamber, control temperature, and optimize the air to fuel ratio. Both pre-combustion and combustion methods are reported to decrease the NOX emission by <50%. Based on interviews and field observation, it is known that the combined cycle power plant had used low nitrogen content natural gas (<0.5% molar content) and utilized the Dry Low Emission Combustor, which allowed low nitrogen oxide emission. Thus, both pre-combustion and combustion methods were not recommended.

The third method is the post-combustion method, which eliminates NOX from flue gases. Post-combustion methods were reported to decrease the NOX emission with high efficiency of >80%. There are two main approaches in post-combustion methods: NOX destruction, which transform NOX into...
harmless products and NOX removal from flue gas. Several methods included in post-combustion methods are electrochemical reduction, adsorption, and non-thermal plasma selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), electron beam, and wet scrubbing [29].

Among different post-combustion NOX removal methods, SCR is the most broadly used because of its high efficiency, reasonable operating cost, and fairly uncomplicated installation. In the SCR system, a nitrogenous reductant is added nonstop to the flue gas that contains nitrogen oxide. The reductant agent and NOX react through a catalytic chemical reaction to form nitrogen and water. There are several reductant agents, such as NH3, HC, CO, and H2, that are used in the SCR method to reduce NOX emissions. The NH3-SCR has been employed in many industrial sectors because of its high stability and high NOX removal efficiency of >90% [30]. The SCR system is essentially depending on the reductant agent. Thus the high expense of the catalyst, equipment corrosion, and limited catalyst life span can be a few disadvantages of the SCR system. Further research needs to be conducted to investigate which post-combustion method is best to reduce NOX emission in this combined cycle power plant.

4. Conclusion
Being one of the most significant electricity suppliers in Indonesia and consume a high percentage of fossil fuels to generate electricity, it is essential to investigate the environmental impacts of electricity generation from natural gas combined cycle power plants in Indonesia. One of the most comprehensive and extensive methods to analyze electricity generation’s environmental profile is Life Cycle Assessment. This paper presents the Life Cycle Assessment of a 640 MW combined cycle power plant located in West Java, Indonesia.

The characterization result shows that the electricity production subsystem is the foremost contributor to the impact categories. In this study, an optional step such as normalization is applied to provide information on the total inputs and outputs using CML-1A Baseline World 2000 data set. The normalization result shows that the most significant impact category of 1 kWh of electricity generated by the combined cycle power plant is acidification potential. Almost 90% of the acidification potential was generated from the electricity production subsystem, where the largest source of acidification is nitrogen oxide emission from the combustion chamber with a percentage of 80.32%. The sensitivity analysis was conducted by checking the influence of varying data by +25% of the top three most significant impact categories identified (AP, EP, GWP). The sensitivity analysis result shows that varying the data by +25% did not change the result that AP is the most significant impact category. This means that the LCA study’s final result is reliable and did not get affected by the uncertainties in the data.

There are three different methods to control nitrogen oxides emission: pre-combustion, combustion, and post-combustion. Since the combined cycle power plant had used low nitrogen content natural gas (<0.5% molar content) and utilized the Dry Low Emission Combustor, both pre-combustion and combustion methods are not recommended for this study. Post-combustion methods were reported to decrease the NOX emission with high efficiency of >80%. Among different post-combustion nitrogen oxides removal methods, SCR is the most broadly used because of its high efficiency, reasonable operating cost, and fairly uncomplicated installation. Further research needs to be conducted to investigate which post-combustion method is best to reduce nitrogen oxides emission in this combined cycle power plant.

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