Life Cycle Assessment of a Mini Hydro Power Plant in Indonesia: A Case Study in Karai River

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Abstract

Indonesia is a vast archipelago with more than 10,000 islands spread across the nation. One of the challenges to provide better lives for the residents is energy distribution to remote areas. With many rivers in the islands, hydropower plants become the best renewable energy source for these remote areas. This paper aims to assess the life cycle of a mini hydro power plant in Simalungun, Indonesia. Life cycle inventory data were collected and impacts were assessed using SimaPro software. A sensitivity analysis comparing two methods, CML-IA and TRACI 2.1 were conducted. Result shows that carcinogenic, marine aquatic eco-toxicity and freshwater aquatic eco-toxicity are the highest environmental impact, generated from the construction of the mini hydropower plant.

Keywords: Life Cycle Assessment; Renewable energy; Hydropower plant

1. Introduction

Indonesia is a vast archipelago with more than 10,000 islands spread across the nation. Distribution of energy is a major issue in this archipelagic nation, especially in remote islands and rural areas. According to PLN (Perusahaan Listrik Negara), Indonesia's Electric generation company, at the end of December 2013, PT PLN and Subsidiary owned and operated about 5,269 generating units with total installed capacity of 34.2 GW. 78% of the units were installed in Java, whereas, the area of Java island is only 7% of the whole nation [1]. This uneven distribution caused major energy crisis in several areas, including North Sumatera Province, where electricity deficit of 9% is reported by the Ministry of Energy and Mineral Resources [2]. Although Indonesia is abundant with potential renewable energy such as Geothermal and Hydro [3], 78% of the installed capacity are still generated from fossil fuel [1].

To increase the energy production while reducing the fossil fuel utilisation, the Indonesian Government has identified the biggest potential for renewable energy, which is hydropower. It was estimated that Indonesia has 75 GW of potential hydropower. Nevertheless, until 2008 only 5% have been utilised. One of the developments in hydropower technology is through mini hydro power plant, which is suitable to power rural and remote areas [4].

Six provinces in Indonesia has been identified as the source of mini hydropower plants by the Indonesia Ministry of Energy and Mineral Resources in their Masterplan for New Energy, Renewable and Energy Conservation Development (2010-2025). The six provinces are Papua (12 GW), East Borneo (6 GW), South Sulawei, West Borneo, North Sumatera and Aceh [5].

The capacity of a mini hydro power plant usually ranges from 1 to 10 MW, which can provide electricity to remote islands and villages [3]. Small-
Scale hydro, especially “run-of-river”, with no dam or water storage, is one of the most cost-effective and environmentally benign energy technologies. Small scale hydro power plant has been utilised in developing countries [6]–[9] and its installation has been increasing in Europe and United States [10].

Different to fossil fuel, which is evidently producing greenhouse gas emission, the environmental impact associated with mini hydropower plants has not been thoroughly explored. Flury and Frischknecht [11] conducted life cycle inventories of hydroelectric power generation in Europe. Their report showed that marine ecotoxicity, human toxicity and global warming were the highest impact related to the operation of hydropower plants. However, they omitted the infrastructure of the hydropower plant from their study.

Another study on the life cycle of various renewable energy sources was conducted by Pascale et al [6]. They assessed the life cycle of a community hydroelectric power system in rural Thailand. However, Pascale et al only consider on economic and social consideration. The environmental impacts of the rural electrification options were not addressed.

The previous studies have not addressed thoroughly the environmental impact of hydropower plants from the construction to usage phase. Since mini hydropower plants are targeted to be located in rural and remote areas, environmental issues related with the land clearing and the construction of the hydropower plants are also crucial. An assessment of the life cycle of a mini hydropower plant, which includes the construction phase, is required.

This paper aims to present a case study assessing the life cycle of a mini hydro power plant with run-off river system located at Karai River, North Sumatera. Currently North Sumatera is mainly powered by hydro, diesel and steam engine power plants. Although two other mini hydro power plants have been built around Karai River and several others around Indonesia to utilize small rivers, data associated with the life cycle of other power plants were not accessible.

The paper is organized as follows. First, the description of the site is explained. Included in this section is the system boundary and functional unit for the life cycle assessment. Then, the life cycle inventory for the mini hydro power plant is described. Life Cycle Impact Assessment and its interpretation are discussed in Section 4. Section 5 discusses and concludes the findings. Finally, future outlook and recommendation are presented in Section 6.

2. Site Description

The mini hydro power plant studied in this paper is located at Karai River, Simalungun, North Sumatera. With an area of approximately 180,000 m², this mini hydro power plant was designed as a run-of-river. With 2 generators operating all day, following the run-of-river flow, the mini hydro power plant has the capacity of 9 MW. The power plant is interconnected with the local grid to national electricity company. Fig 1 shows the generic site layout of a small or mini hydro power plant (adapted from [12]).

Fig. 1 A typical small or mini hydro power plant site layout (adapted from [12]).
The plant consists of dam or weir, carrier channel, spillway and calming pond, rapid pipeline (penstock), powerhouse, exhaust duct, and operator room. The dam is the starting component of the whole plant and acts as a gate to water flow from the river. Its function is to trap water at a certain point where it will manipulate the amount of water flow into the plant. The outlet of the dam is to the carrier channel. Carrier channel serves as way of transporting water to the powerhouse. This plant has 9 water gates to control the water flow.

The calming pond is the last gate before the water enters the rapid pipeline/pennstock. It is designed to level and calm the water before entering the pipeline. Attached to the calming pond is the spillway, which serves as a fail-safe mechanism if the plant has to shutdown or if there is problem with the turbine. Should problem arise, the gate in the pipeline will be closed, which will cause a back flow of water to the calming pond. To prevent the sudden rise of water level in the calming pond and the pipeline steel fatigue, the water will be drained out through the spillway.

Rapid pipeline or penstock is a pressurised conduit that transports water from the calming pond to the water turbine. It is 546 m long with 1.4m in diameter and made of steel. The penstock serves as a medium to transfer the water at a certain hydraulic head, providing potential energy and transfer it to the turbine to kinetically turn the turbine and generate electricity.

The turbines are located in the powerhouse. There are two generators, with the capacity of 4.5 MW each, installed in the powerhouse. Electricity generated in the powerhouse is then connected to the local grid. Currently, the local grid in North Sumatera is mainly powered by combined cycle (41%), hydro (40%), steam and gas power plants (19%) [1]. The water outlet from the generator is then flowed back to the river through the exhaust duct.

2.1. System Boundary

The analysis includes the main life stages of the mini hydro power plant, covering pre-construction stage, construction of the plant and usage. The end-of-life plant is not included in the analysis since the structure will most commonly remain in place and will not be demolished. The mini hydro power plant is built out of concrete and steel, which is durable and provide long-lasting structure. It is considerably a sustainable product[13]. Transportation of material and equipments, manufacturing of construction vehicles/ equipment, and electrical components of the controllers are omitted in this study. The environmental impacts assessed are related to the processing of materials used in the pre construction and construction. Usage stage consists of environmental impacts related to the generation of electricity by the mini hydropower plant and the potential loss due to maintenance and repair. The period of analysis for the mini hydro power plant is 50 years of life. Maintenance and repair of turbine are omitted in this study.

2.2. Functional Unit

The functional unit of used in this study is based on the electricity produced at the plant. The power produced is following the formula for a hydro system:

\[ P = \eta \rho g Q H \]

where P is the mechanical power produced at the turbine shaft (Watts), \( \eta \) is the hydraulic efficiency of the turbine, \( \rho \) is the density of water (kg/m³), g is the acceleration due to gravity (m²/s), Q is the volume flow rate passing through the turbine (m³/s) and H is the effective pressure head of water across the turbine or also known as water head (m). With the flow rate designed at 4 m³/s, 256 m water head or hydraulic head, and an estimate of 80% turbine efficiency, the amount of power produced per hour is 8 MWh.

3. Life Cycle Inventory

The life cycle inventory data for this study are separated into two types, primary data gathered from the site and secondary data gathered from the literature and EcoInvent database. LCA software SimaPro by PRé Sustainability is used in this assessment [14]. The energy and all materials used were calculated from bills of quantities, bills of needs interviewing the head engineer, site visits and manufacturer’s data on similar products/parts.

The mini hydropower plant runs 24 hours per day due to the characteristic of run-of-river system. The power plant uses Pelton Turbine in generating the electricity. Pelton turbine is a type of impulse turbine, which operates with high-pressure head. A Pelton turbine consists of a series of cups or buckets mounted around the periphery of a circular disc. The wheel is driven by jets of high-pressure water, which hit the carbon steel buckets [15]. Due to the high friction and turbulence from the water jet, problem such as broken buckets or erosion often occurred, as it has occurred in this case study. This problem resulted in loss of productivity ranges from 4 to 6 weeks for repair and maintenance, which is around 3000 MWh. Assuming that during that time, only one turbine is working. Therefore, the amount of electricity produced in 50 years is approximately 3312 GWh. This is derived based on the calculation of electricity produced per hour in 24 hour for 50 years.
4. Life Cycle Impact Assessment and Interpretation

The impact assessment was conducted using the CML-IA baseline methodology [16],[17]. The CML-IA impact categories are defined for the midpoint approach. There are 10 impact categories included in the methodology, namely Abiotic depletion, Acidification, Eutrophication, Global warming (GWP100), Ozone layer depletion (ODP), Human toxicity, Fresh water aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity, and Photochemical oxidation [18].

The normalized life cycle impact assessment of the Simalungun mini hydropower plant during construction and usage life is shown in Fig. 2.

The chart shows that the majority of the impact originates from the construction of the hydropower plant. Any contribution to the environmental impact from the electricity generated by the power plant for 50 years was insignificant. Similar finding by the UK Parliament of Science and Technology, during its electricity generation, hydropower plants do not emit any greenhouse gas emission [19].

The normalized result shows that the highest environmental impact category is marine aquatic ecotoxicity, fresh water ecotoxicity and abiotic depletion from fossil fuel. However, marine aquatic ecotoxicity shows a significant impact compared to the others.

The main source of marine ecotoxicity and fresh water ecotoxicity is the rapid pipeline (59%), main building construction (20.5%) and carrier channel (10.5%). The construction of the rapid pipeline, which consists of concrete, steel reinforcement and metal work, utilizes nickel ion to prevent corrosion and product temperature resistance alloys. The nickel ion contained in the process is emitted to the waters. Nickel is easily accumulated in the biota, particularly in the phytoplankton or other aquatic plants, which are sensitive to bioindicators of water pollution. It can be deposited in the sediment by such processes as precipitation, complexation and adsorption on clay particles [20]. Therefore, in this case, contributed to marine aquatic ecotoxicity and fresh water ecotoxicity.

Impact assessment using TRACI 2.1 method is also conducted as sensitivity analysis. There are 10 impact categories in TRACI 2.1, which are ozone depletion, global warming, smog, acidification, eutrophication, carcinogens, non-carcinogens, respiratory effects, ecotoxicity and fossil fuel depletion.

The environmental impact for the construction of the mini hydropower plant was carcinogenic and ecotoxicity. However, carcinogenic impact is more significant compared to the others (Fig.3.). This carcinogenic impact is caused by rapid pipeline (46%) and main building construction/powerhouse (39%). These carcinogenic impacts are caused by the use of Steel Pipe in the penstock and Reinforced Steel for the concrete.
The global warming potential, which is usually the main concern, is barely significant comparing to other impacts. It is still contributed from the rapid pipeline construction stage. However, the total emission of GHG for this run-of-river mini hydro power plant is 9.61 kg CO₂ equivalent/8 MWh, which is around 1.2 kg CO₂-eq/MWh. It is still under the life cycle emission of GHG reported by Turconi et al [22], which is in the range of 2-5 kg CO₂-eq/MWh for run-of-river systems.

5. Discussion and Conclusion

Based on the life cycle assessment performed on the mini hydro power plant in North Sumatera, it is found that the construction phase contributes to the environmental impact to the whole life cycle of the hydropower plant. Within the construction phase, the rapid pipeline construction stage is the major source of environmental impact.

The topography of the site has required a long pipeline (536 m), almost doubled the distance from the water head (256m). The site consists of terrains, which are prone to terrestrial changes. One example is from the sudden soil erosions that changes the terrain. Therefore, the rapid pipeline is designed to follow certain measures:
- The material of the pipeline has to be strong to withstand the water pressure.
- A slope protection is required to prevent the damage of the pipe.
- The position of the slope protection has to specific as to prevent from soil deformation caused by the uncertainty of the soil rigidity and the sudden erosion caused by heavy rainfall.

Thus, environmental impact associated with the rapid pipeline is mainly caused by its design, installation location and material.

Generally, the optimum penstock is as short, straight and steep as practical and has a continuous downward gradient [8]. The penstock used in this plant was installed above the ground. Above-ground pipe indeed has lower construction cost, may allow for more direct routing, as in the case in this plant site, and is more accessible for inspection of repair. However, since above the ground installation is exposed to ultraviolet radiation, thermal expansion, and physical damage to the pipe from falling rocks and tress, steel pipe is the best option for the penstock material selection, as used in this plant. Other common penstock materials such as PVC, Polyethylene, Fiber reinforced epoxy and transite (asbestos cement) could be assessed for further consideration and improvement.

However, although there are some impacts resulted from the construction of the mini hydro power plant, in the long run, the run-of-river hydro power plant has virtually no hazardous components.
Its benefit of producing electricity for the nearby villages is far greater than the environmental impact. The findings in this case study accord to the findings by Flury and Frischknacht [11]. Low contribution to GHG is also confirmed with Raadal et al. [23]. Raadal et al. compared the life cycle GHG emission from renewable resources and fossil fuel technology. Compared to fossil electricity generation technologies, wind and hydropower represented low GHG emissions. The LCA conducted shows that the construction of the power plant contributes to the GHG emission, especially on concrete production and transportation of rocks in the construction of dams and tunnels. Similarly with the results in this paper, the biggest impact is contributed by the construction of the rapid pipeline.

6. Recommendations and outlook

To perform a good assessment of a life cycle of a product, an extensive data is required, from the manufacturing to the usage and end-of-life of the product. Further information on the unit processes gathered from the Indonesian industry is required. Currently the Indonesia government is developing an inventory database of GHG emission based on industrial reports. An LCA study like the one conducted in this paper should benefit the inventory database and vice versa. In the future, it is expected that Indonesia can generate her own database for life cycle assessment and conduct life cycle assessment of other types of energy, renewable and non-renewable sources.

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