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Impact of Small-Scale Geothermal Power Plant Replenishment with A Life Cycle Assessment

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Abstract- Life Cycle Assessment (LCA) is life cycle thinking replenishment in which the targets are environmental aspects and impacts generated in one product life cycle. The benefits of LCA can be taken into consideration in several choices of system, for example, the comparison of the Small-scale geothermal power plant (Unit-SS) replenishment to Unit-1. LCA results in the form of the impact of the production process per product is 1 kWh electricity. The biggest impact on Unit-1 and Unit-SS is acidification. Acidification comes from the release of NCG into the air from the cooling tower. The acidification impact of Unit-1 result is 0.018139 kg SO_{2eq}/kWh. Furthermore, normalizing impact result shows that the acidification impact is much greater than the impact of global warming, toxicity, and other impacts. The contribution impact of the addition of small-scale when compared to the impact of Unit-1 operations has a positive impact or tends to have a lower environmental impact. The Unit-SS has the potential for acidification of 0.002407 kg SO_2eq/kWh lower than Unit-1. In addition, the Unit-SS has more efficient steam consumption by design than Unit-1. Therefore, less impact of Unit-SS can be suspected relate with steam consumption. Another alternative suggestion based on the analysis is an opportunity for further research on the efficiency of the gas removal system which has a positive impact on the distribution of NCG.

Keywords Acidification, Environmental impact, Geothermal, LCA, NCG.

1. Introduction

Indonesia Energy Policy defines that one of the priority developments for renewable energy infrastructure is the development of geothermal utilization for electricity. Geothermal power plant activities which include the use of renewable energy, cause impact on the environment. The development of geothermal energy may cause environmental impacts on the hydrology, geology, microbiology soil surface, air, flora and fauna [1] [2]. Geothermal fluid that emitted to surface water can lead to increasing of some trace elements. The increasing concentration such as aluminium, boron, arsenic, and manganese are related to thermal fluid interference. In addition, this trace elements in surface water increased also related to farming and domestic activities [3]. Nevertheless, the level and distribution trace element from geothermal industry may give impact to toxicity [4]. According to Indonesia Minister of Environment and Forestry Regulation Number 4 of 2021, geothermal exploitation activities at all capacities acquire potential environmental impacts on changes in noise intensity, air quality, local weather conditions, water quantity, water quality declining, flora and fauna, and socio-economic culture, and public health.

Environmental impact studies from geothermal typically is generally based on operational activities partially but it does not examine the product life cycle [5]. Approach methods for assessing the environmental impact of geothermal activities can be developed to gain additional perspectives. One method for assessing environmental impacts is a life cycle assessment (LCA). LCA provides an environmental aspects and impacts assessment through the product life cycle including raw material extraction, production, use, and its disposal or familiarly known as cradle to grave [6]. Life cycle assessment as one of the requirements for environmentally friendly products and services is carried out to demonstrate the company's commitment to making environmentally friendly products by showing information on potential environmental impacts. The collection of environmental impact information with a life cycle study has the advantage of an environmental impact analysis and environmental audit because it covers a wider range of system boundaries from products or processes and does not only focus on the waste [7]. The limitations of the LCA system on geothermal activities start from the construction phase of the geothermal field and power plant as the cradle stage, the operation phase, and the closure of wells and power plants as the end of life/grave stage [8].

The benefits of LCA can be divided into several consideration and methods or materials, for instance, the comparison of geothermal power plant to other renewable generator and energies. A review of the greenhouse gas (GHG) life cycle shows that geothermal has a maximum environmental impact of 78 g CO_2-eq/kWh, smaller than a waste power plant which has a maximum value of 1000 g CO_2-eq/kWh and photovoltaic solar panels of 300 g CO_2-eq/kWh [9]. LCA can be considered when comparing with several types of geothermal power plants, such as dry steam, flash steam, binary on the environmental impacts of land use, emissions to the air, and water use [10] [11].

Life cycle studies can be used for evaluation and optimization considerations as will be carried out in this study on the object of adding small-scale geothermal power plant to geothermal power plant unit-1 as an existing activity. The planned geothermal power plant replenishment is a small-scale geothermal power plant with a capacity of 10 MW (Mega Watt) power to increase the capacity of the existing Unit-1 geothermal power plant with a capacity of 60 MW. Some researches emphasize that the biggest of geothermal life cycle is global warming potential [8], [11]. In the other hand, the biggest impact from small scale and unit-1 geothermal power plant is acidification. Furthermore, this research provides an overview of the positive or negative impacts of small-scale power plants replenishment to the existing geothermal power plant with life cycle assessment.

2. Environmental Impact of Geothermal Power Plant

There are several processes in indirect geothermal utilization activities to generate water vapor as electrical energy. Geothermal power plant is divided into three types which are dry steam plants, flash steam plants, and binary cycle power plants. The dry geothermal steam is directly used to drive turbines in dry steam plants. Geothermal steam could be in the form of hot water with a temperature of more than 200^{0}C which is separated first between the steam and water phases before being used in flash steam plants. Binary cycle power plants utilize hot water to heat lower boiling organic liquids in heat exchangers to produce steam that spins turbines. The most widely used type of geothermal power plant is flash steam plants [12]. In addition, there is the Enhanced Geothermal System technology where injection wells are made to hot rock layers to form a new reservoir network [11].

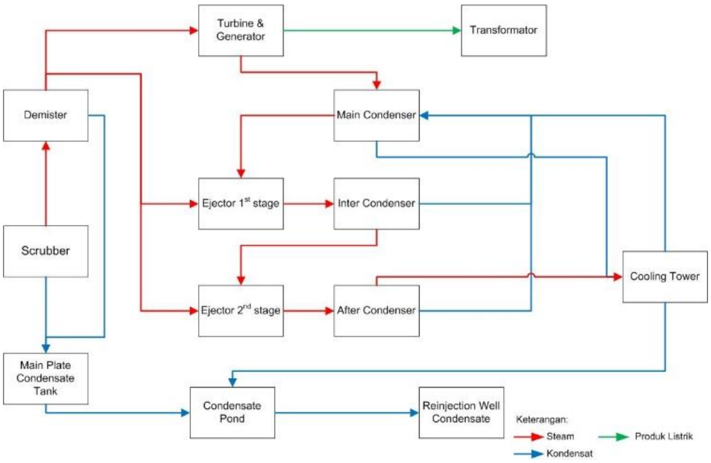

Fig. 1 Unit-1 Gate to Gate Process Diagram

The operational process of the Gate-to-Gate Geothermal Power Plant Process is described in the figure 1. Geothermal power plant generates electricity with filtered steam from the water phase. The power generator produces water and generates residual heat from the cooling system between the condenser and cooling tower. The output of this activity is water and steam emissions that can provide several potential impacts. In addition, Figure 2 shows other impacts of geothermal power plant activities during operation and drilling water use, land use, soil pollution, noise, and social problems, as well as geological hazards such as shifting and the land surface subsidence.

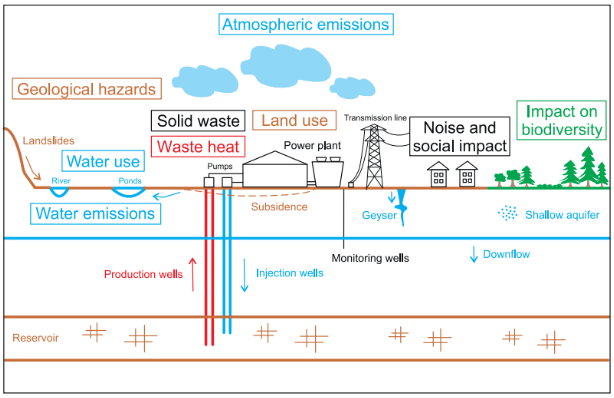

Fig. 2 Geothermal Power Plant Environmental Impact[13]

Also, there are environmental impact issues that can arise from this activity, such as produced water, air emissions, solid waste, explosions of wells and pipes, and water consumption. Water produced from geothermal power plant has a high temperature, acidic pH, and heavy metals. Air emissions that can arise both from well-testing activities and from the outside of the cooling tower are hydrogen sulphide and carbon dioxide. Small amounts of solid waste that can be generated from geothermal power plant activities are in the form of sulphur, silica, and carbonates. Large quantities of water are used for drilling wells, testing well injectivity, and starting up cooling systems [14].

Furthermore, the environmental impact can be seen from three types of geothermal facilities, such as flash steam, binary cycle, and Enhanced Geothermal Systems (EGS).

These three types of facilities have similar environmental impacts such as disturbance of flora and fauna, decrease in surface water quality, geological hazards, noise, thermal pollution, air disturbance, and soil pollution. This impact comes from construction, operational, to post-operation activities [15].

Table 1 Geothermal Power Plant Environmental Impact Classification [1]

Classification	Secondary Classification	Detail
Subsurface Environmental Impact	Hydrology Impact	Groundwater level, temperature, chemical properties, clean water production
	Geology Impact	Structural deformation and subsidence, fracture reactivation, and microearthquake activity
	Microbiology Impact	Microbial diversity
Surface Environmental Impact	-	Land use, landscape change, surface water pollution, damage to ecosystems and agriculture
Air Impact		Air pollution and loudness

Environmental impacts on geothermal power plant activities consist of impacts on the subsurface, surface, and air. The environmental impacts studied using the life cycle method are the impacts that occur on the land, water, biodiversity and air. Every substance released from geothermal power plant activities that interact with the environment or other pollutants can cause environmental impacts [2]. Table 2 shows that each substance or pollutant may cause environmental impacts such as climate change, eutrophication, acidification, respiratory inorganic, photochemical oxidant, and ozone depletion. These impacts detail environmental impacts on the surface and air.

Table 2 LCIA Classification [16]

No	Environmental Impact	Pollutant
1	Climate Change	CO_2, CH_4
2	Eutrophication	BOD, NH_3, NO_x
3	Acidification	H_2S, NO_x, SO_2
4	Inorganic Respirator	NH_3, NO_x, SO_2, CO, PM_{10}
5	Photochemical Oxidants	CH_4, NO_x, SO_2, CO
6	Ozone Depletion	HCFCs dan HFCs
7	Land Use	CO_2

The Regulation of Indonesia Minister of Environment and Forestry Number 01 of 2021 concerning the Company Performance Rating Program in Environmental Management (PROPER) has included a life cycle study as one of the assessment criteria. PROPER regulates companies that follow an assessment beyond compliance to carry out impact assessments for the categories of global warming potential, ozone depletion potential, acid rain potential, eutrophication potential, photochemical oxidant, the potential for abiotic degradation (fossil and non-fossil), ecotoxicity potential, carcinogenic, human toxicity, water footprint, and land-use change.

3. Life Cycle Assessment

Life cycle calculations derived from process chain analysis. The stages of the life cycle of geothermal power plant activities are exploration activities for geothermal steam production, construction of steam fields and power plants, operational activities, and post-operational activities. The boundaries of the system under study for a life cycle study should be defined in geothermal activity. This study carries out life cycle study of the electric kWh product produced from geothermal power plant [17].

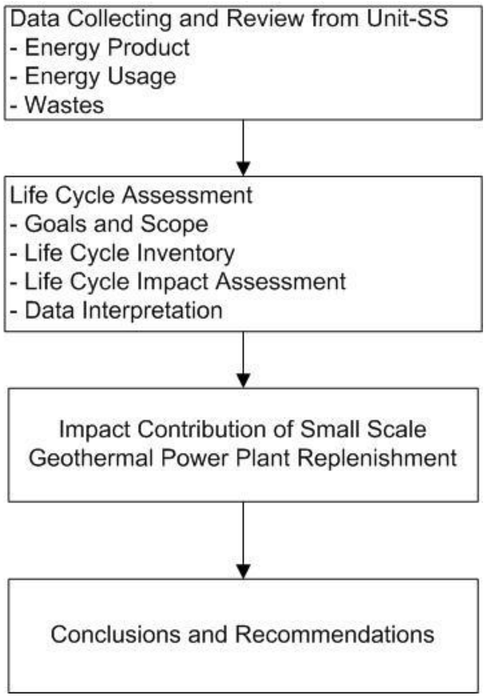

Fig. 3 Impact of Small-Scale Geothermal Power Plant Replenishment with A Life Cycle Assessment Research Framework

Figure 3 defines that impact analysis from each process come from all data record such as fuels, raw materials, chemicals, products, and emissions. The life cycle study consists of four main stages. The first stage is to determine the scope goals or goals & scope. The second stage is life cycle inventory, which contains the product cycle and its inputs and outputs to the environment. The third stage is the Life Cycle Impact Assessment (LCIA) which aims to analyse the relevant environmental impacts of the product cycle. The last stage is the interpretation of the study [18]

3.1 Goals & Scope

The purpose of the life cycle study for geothermal power plant is to develop a geothermal power plant life cycle framework, apply life cycle inventory analysis, assess the impact of construction, drilling, and operational activities, and compare the selection of its technology. The scope of the life cycle for geothermal power plant is system functions & unit system boundaries. Functions and system units are determined to impact each unit product produced. In the geothermal power plant, the unit function specified is electricity production (kWh). The system limits that can be set in the life cycle study are energy balances and raw materials used for construction, operation, and post-operation activities [13] [8].

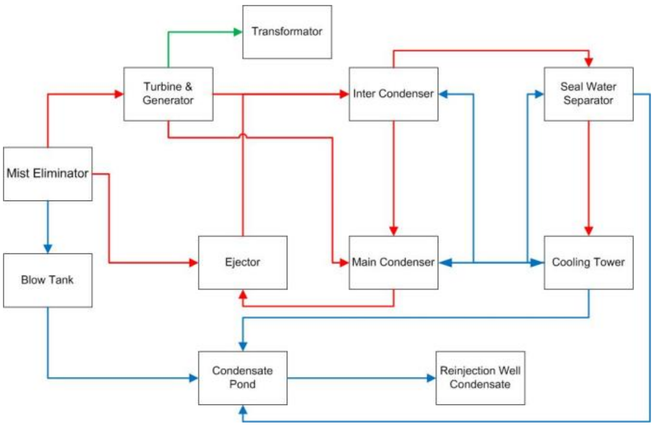

Fig. 4 Small-Scale Geothermal Power Plant Gate to Gate Process

The scope of the life cycle study carried out is gate-to-gate covering the process from the production stage only, used to determine the environmental impact of the production process. This study was conducted to determine the effect of the addition of Small-Scale Unit compared to the operational activities of Unit-1. The scope of the research carried out is Unit-1 and small-scale activities that have just been built and it completes the existing generators. Figure 4 describes the Unit-SS gate-to gate-process. The output of the impact of the life cycle study is the impact of the production process per unit of product. In this study, it generates electricity of 1 kWh.

3.2 Life Cycle Inventory

In the life cycle inventory stage, data on fuel and raw materials are recapitulated, including products, by-products, and emissions generated from each process unit. Life cycle inventories in the power plant construction activities consist of materials used for good drilling, pipe construction, and power plant machinery, electrical, instrument, and civil construction. In the operational stage, inventories are carried out on air emissions such as CO2 and H2S and emissions to water originating from geothermal power plant produced water. At the post-operation stage, the inventory considered is the material used for geothermal power plant closure [13].

Life cycle inventory is the most demanding in life cycle assessment. Data inventory needs site-specific data and it is not always available. Moreover, data inventory will be time consuming and expensive yet [19]. In the geothermal power plant life-cycle data, the data used are raw materials of geothermal steam, electrical energy usage, water usage, also air and water emissions.

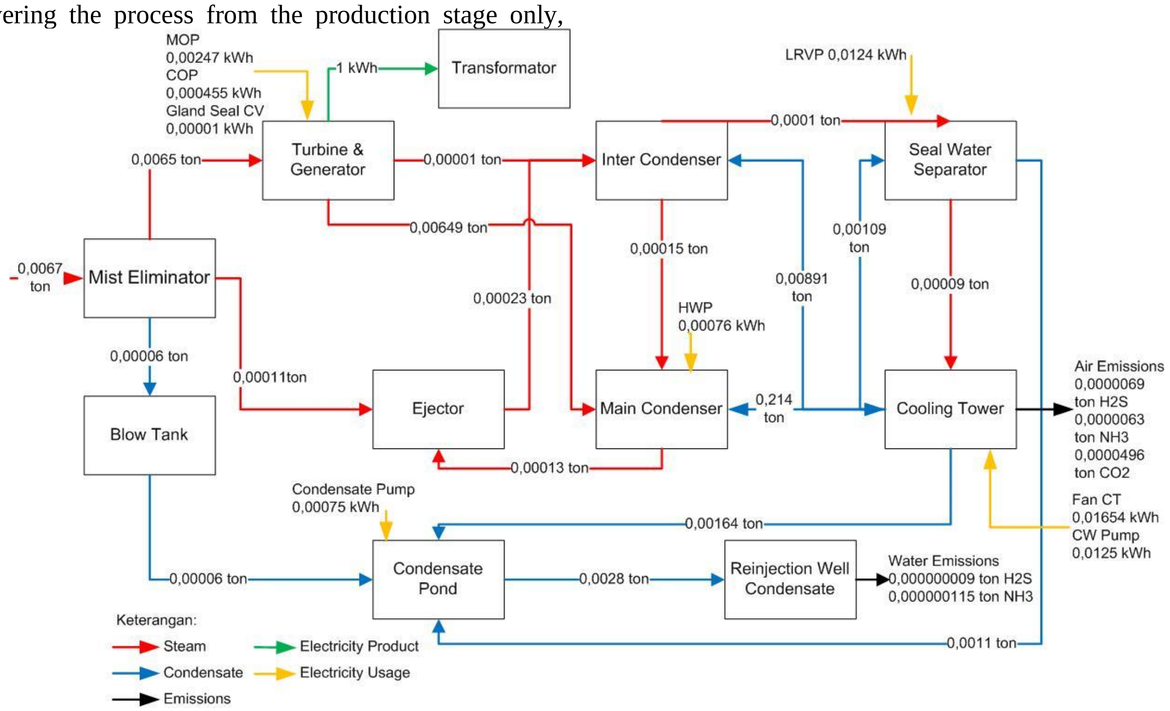

Fig. 5 Small-Scale Geothermal Power Plant Mass Balance (per product 1 kWh) Gate to Gate

Each processing unit in the flow chart has a factor description that affects the input and output. Data collection for each process unit in the system boundary are including data on raw materials, use of electrical energy, emissions to the air, emissions to water, emissions to soil, carried out in 2021. The data collected is divided into primary data and secondary data. Primary data is the data obtained either by measuring or calculating according to the results of company monitoring. Secondary comes from literature studies or journals related to the calculations needed. Based on the inventory that has been carried out, 100% from primary data. Data summary of total inventory within the scope of the gate-to-gate small scale per unit of product produced or according to unit function can be seen in Table 3.

Table 3 Small-Scale Geothermal Power Plant Data Inventory

Category	Data Inventory	Quantity per 1 Period	Unit	Quantity per Function Unit	Unit
Input					
Material	Steam	290.934	Ton	0,006671906	Ton/kWh
Fuel/Electricity	Electricity	2.000.841	kWh	0,045884741	kWh/kWh
Output					
Product	Electricity	43.605.797	kWh	1	kWh/kWh
Air Emission	H_2S	292	Ton	$6,69 \times 10^{-6}$	Ton/kWh
	NH_3	350	Ton	$8,028 \times 10^{-6}$	Ton/kWh
	CO_2	2162	Ton	$4,957 \times 10^{-5}$	Ton/kWh
Water Emission	NH_3	5,00	Ton	$1,147 \times 10^{-7}$	Ton/kWh
	Dissolved H_2S	0,38	Ton	$8,805 \times 10^{-9}$	Ton/kWh

3.3 Life Cycle Impact Assessment and Data Interpretation

Life Cycle Impact Assessment (LCIA) is environmental impacts assessment under the scope of the data inventory and the objectives of the research to be carried out. The methods used in the LCIA assessment process are Recipe 2016 Midpoint (H) V1.03, CML-IA Baseline V3.05, and Cumulative Energy Demand (CED) [20], [21]. These three methods are used together in the framework of a broader impact assessment, because one method with another has a different selection of impact categories, even though there are several categories of the same impact, so that one of the same impacts is chosen. The following impact categories in geothermal LCA study include global warming potential (GWP), ozone depletion, acidification, eutrophication, photochemical oxidation, potential for abiotic degradation (fossil and non-fossil), ecotoxicity potential, carcinogenic, toxicity, water footprint, land use change, and cumulative energy demand (CED) or the impact of energy use [20].

Identification of critical issues is a systematic procedure for identifying, testing, examining, evaluating, and presenting conclusions based on the findings of the LCA, to meet the requirements for application as described in the objectives and scope of the study. The identification of these important issues will discuss the relationship between the inventory data and the impact categories studied, to determine hotspots, conclusions, and recommendations for improvement. In general, the impact assessment on the environment in this study is divided into 2 which are primary impacts and secondary impacts. Primary impacts include the impact of Global Warming Potential (GWP), potential for ozone depletion, acidification, and eutrophication, while secondary impacts include the impact of photochemical oxidation, potential for abiotic decline (fossil and non-fossil), potential for biotic or ecotoxicity decline, carcinogenic, human toxicity, water footprint, and land use change. In addition, an impact assessment is carried out on cumulative energy demand (CED).

3.3.1. Primary Impact

3.3.1.1. Global Warming Potential

Global warming potential of geothermal industry comes out from resource characteristic, construction, drilling, and operation stage. Despite of resource and technology type, most of global warming potential impact from geothermal activities are cause by diesel consumption at drilling and construction stages [11]. Global warming potential mostly comes from cooling tower at the operational stage. The results of the global warming potential of geothermal power plant with a capacity of 110 MW is 4.05 x 10¬-8 kg CO2eq [13]. Another case study of geothermal power plant in China shows a GWP indicator value of 80.49 CO2 eq/kWh [22]. Another study showed that the GWP range in single flash geothermal power plant was 18-24 g CO_2 eq /kWh and in double flash geothermal power plant was 15-23 g CO_2 eq / kWh [8][23]. Overall, the indicator value of geothermal power plant's global warming potential is decreasing as its service life is getting longer. This is due to the intensity of the GWP produced is getting smaller due to greater production even though the GWP generates large amount of power, especially in the construction phase [24]. The largest GWP impact contribution was generated from the Cooling Tower process by 100%. The contributor to the GWP impact 100% comes from the carbon dioxide emissions produced by cooling tower at operation stage. Carbon dioxide emissions produced in the Cooling Tower process are sourced from Non-Condensable Gas (NCG) which is released into the air. Meanwhile, in other processing units, no emissions are produced, so there is no potential GWP impact.

Table 4 Life Cycle Impact Assessment at the Gate to Gate Stage of Small-Scale Geothermal Power Plant Electricity Production Process

No	Impact Category	Unit	Method	Total	Turbine Generator	Main Condenser	Seal Water Separator	Cooling Tower	Condensate Pond	Reinjection Well - Condensate	Land Use
Primary Impact											
1	**Global warming potential**	kg CO_2 eq/kWh	ReCiPe 2016 *Midpoint* (H) V1.03	0,04958	0	0	0	0,04958	0	0	0
2	**Ozone Depletion**	kg CFC11 eq/kWh	ReCiPe 2016 Midpoint (H) V1.03	0	0	0	0	0	0	0	0
3	**Acidification**	kg SO_2 eq/kWh	ReCiPe 2016 Midpoint (H) V1.03	0,0157	0	0	0	0,0157	0	0	0
4	**Eutrophication**	kg PO4--- eq/kWh	CML-IA *Baseline* V3.05	0,00285	0	0	0	0,00281	0	0,00004	0
Secondary Impact											
5	**Photochemical oxidation**	kg C_2H_4 eq/kWh	CML-IA *Baseline* V3.05	0	0	0	0	0	0	0	0
6	**Potential for Fossil and Non-Fossil Abiotic Decline, which are:**										
	a. Abiotic depletion (fossil fuels)	MJ/kWh	CML-IA *Baseline* V3.05	0	0	0	0	0	0	0	0
	b. Abiotic depletion	kg Sb eq/kWh	CML-IA *Baseline* V3.05	0	0	0	0	0	0	0	0
7	**Potential for Ecotoxicity, which are:**										
	a. Terrestrial ecotoxicity	kg 1,4-DCB/kWh	ReCiPe 2016 Midpoint (H) V1.03	0	0	0	0	0	0	0	0
	b. Freshwater ecotoxicity	kg 1,4-DCB/kWh	ReCiPe 2016 Midpoint (H) V1.03	0	0	0	0	0	0	0	0

No	Impact Category	Unit	Method	Total	Turbine Generator	Main Condenser	Seal Water Separator	Cooling Tower	Condensate Pond	Reinjection Well - Condensate	Land Use
	c. Marine ecotoxicity	kg 1,4-DCB/kWh	ReCiPe 2016 Midpoint (H) V1.03	0	0	0	0	0	0	0	0
8	**Carcinogenic**	kg 1,4-DCB/kWh	ReCiPe 2016 Midpoint (H) V1.03	0	0	0	0	0	0	0	0
9	***Toxicity***	kg 1,4-DB eq/kWh	CML-IA *Baseline* V3.05	0,0022758	0	0	0	0,0022758	0	0	0
10	***Water Footprint***	m3/kWh	ReCiPe 2016 Midpoint (H) V1.03	0	0	0	0	0	0	0	0
11	***Land Use Change***	m2a crop eq/kWh	ReCiPe 2016 Midpoint (H) V1.03	0,002511134	0	0	0	0	0	0	0,002511134
12	**The Impact of Energy Usage**										
	a. Non-renewable	MJ	Cumulative Energy Demand	0	0	0	0	0	0	0	0
	b. Renewable	MJ	Cumulative Energy Demand	0,165185	0,010523	0,002728	0,044654	0,104552	0,0027284	0	0

3.3.1.2. Ozone Depletion

Ozone Layer Depletion appears during the construction phase or drilling. The results of the ozone layer depletion potential of geothermal power plant with a capacity of 110 MW 8.39 kg CFC-11eq [13]. Dry steam geothermal plant in Indonesia has ozone depletion potential by 2.69 x 10^{-8} kg CFC-11eq [16]. Ozone layer depletion potential in operational phase will obtained by binary power plant technology with the percentage of 73% [23]. There is no impact of ozone layer depletion during this gate process because the process unit studied does not produce CFC emissions released into the air. Therefore, ozone layer depletion impact is 0 kg CFC -11eq based on LCIA result.

3.3.1.3. Acidification

Acidification appears during the construction phase or drilling. Geothermal power acidification impacts come out from construction materials that release SO_2 and NO_2, fossil fuel from drilling activity, and H_2S release from geothermal well [5]. The results of the acidification potential of geothermal power plant with a capacity of 110 MW are 1,62 x 10^{-6} kg SO_2 eq/kWh [13]. Other geothermal power plant studies in China showed a acidification indicator value of 2.5 x 10^{-4} kg SO_2 eq [22]. Dry steam geothermal plant in Indonesia has acidification potential by 1.6985 kg SO_2 eq [16]. However, the acidification impact contributor from small scale geothermal power plant 100% comes from cooling tower unit process. Ammonia emissions generated in the Cooling Tower process give acidification impact. It comes from Non-Condensable Gas (NCG) released into the air. NCG is a natural component of geothermal fluids containing carbon dioxide (CO2), ammonia (NH_3), and hydrogen sulfide (H_2S).

3.3.1.4. Eutrophication

Eutrophication impact appears during the construction phase or drilling. The results of the eutrophication potential of geothermal power plant with a capacity of 110 MW are 3.46 x 10^{-5} kg PO_4 eq [13]. Other geothermal power plant studies in China showed a eutrophication indicator value of 3.25 x 10^{-5} kg PO_4 eq [22]. This impact also occurs because of drilling mud activity during drilling stage [11]. The contributor to the potential impact of eutrophication on the scope of the Unit-SS gate comes from the Cooling Tower and Reinjection Well-Condensate process units. The hugest contribution to the potential impact of eutrophication is obtained from the Cooling Tower by 99%. The results of the percentage of impact contributors can be seen in Table 5.

Table 5 Contributors to Potential Impact of Eutrophication

Impact Contributor	Compartment	Cooling Tower	Reinjection Well - Condensate
Ammonia	Air	99%	0%
Ammonia	Water	0%	1%

According to the table 5, the potential impact contributor to eutrophication from the electricity production process comes from ammonia emission released into the air and the water. Ammonia emissions generated in the Cooling Tower process come from Non-Condensable Gas (NCG) released into the air. NCG is a natural component of geothermal fluids containing carbon dioxide (CO2), ammonia (NH_3), and hydrogen sulphide (H_2S). Ammonia emissions produced in the Reinjection Well-Condensate process are obtained from the produced geothermal water phase and it contains dissolved ammonia (NH_3) and hydrogen sulphide (H_2S). Based on the percentage of these impact contributors, it can be seen that the largest contributor to the impact of eutrophication comes from ammonia released into the air with the percentage of 99%. In other process units, no emissions are produced.

3.3.2. Secondary Impact

3.3.2.1. Photochemical Oxidation

In a large scope of the Unit-SS gate, there is no impact of Photochemical Oxidation (PO) generated from the electricity production process because the process unit under study does not produce emissions into the air that have the potential for this impact. The potential for photochemical oxidants in other studies appears in the construction phase, drilling phase, and operational phase of the binary plant. Another research claimed the results of the potential photochemical oxidant from geothermal power plant with a capacity of 110 MW is 8,97 x 10^{-5} kg C_2H_4-eq [13]. Dry steam geothermal plant in Indonesia has photochemical oxidation potential by 1.48 x 10^{-8} kg C_2H_4-eq [16].

3.3.2.2. Abiotic (Fossil and Non-Fossil) Depletion

Within the scope of this gate, there is no potential impact of abiotic decline from fossil and non-fossil materials generated from the electricity production process. This is due to no direct use of fossil and non-fossil materials from nature in the process unit studied. In other studies, the potential for abiotic depletion (fossil and non-fossil) appears during the construction phase or drilling. The results of the potential abiotic depletion from geothermal power plant with a capacity of 110 MW are 4.03 x 10^{-9} MJ for fossils and 1.49 x 10^{-3} Sb for non-fossils[13].

3.3.2.3. Ecotoxicity

Ecotoxicity occurs because of the interference from geothermal fluid traces element such as arsenic, boron, manganese, aluminium, etc. In contrast, this traces elements are related to human activities [3] [5]. Therefore, some of traces elements in surface water increased are not always cause of geothermal industry. Within the scope of this gate, there are no impacts of terrestrial ecotoxicity, marine ecotoxicity, freshwater ecotoxicity resulting from the electricity production process because the process unit studied does not produce emissions released into the air, water, or land.

3.3.2.4. Carcinogenic

Within the scope of this gate, there are no carcinogenic impacts resulting from the electricity production process because the process unit studied does not produce emissions released into the air, water, or soil.

3.3.2.5. Toxicity

Potential toxicities such as marine aquatic eco toxicity, human toxicity, fresh water aquatic eco toxicity, terrestrial eco toxicity arise during the construction phase or drilling. Another research showed the results of the potential toxicity of geothermal power plant with a capacity of 110 MW of 1.97 x 10^{-11} kg 1,4-DB eq for marine aquatic eco toxicity, 5.2 x 10^{-8} kg 1.4- DB eq for human toxicity, 1.27 x 10^{-7} kg 1.4-DB eq for fresh water aquatic eco toxicity, and 1.73 x 10^{-6} Sb for terrestrial eco toxicity [13].

The contributor to the toxicity impact on the gate scope comes from the Cooling Tower process unit. The contribution of the largest toxicity impact is generated from the Cooling Tower by 100%. The results of the percentage of impact contributors can be seen in table 6.

Table 6 Toxicity Impact Contributors

Impact Contributor	Cooling Tower
Ammonia	35%
Hydrogen sulfide	65%

Based on table 6, contributors to the toxicity impact of the electricity production process come from the ammonia emission and hydrogen sulphide released into the air. Ammonia and hydrogen sulphide emissions produced in the Cooling Tower process unit come from Non-Condensable Gas (NCG) released into the air. NCG is a natural component of geothermal fluids containing carbon dioxide (CO_2), ammonia (NH_3), and hydrogen sulphide (H_2S). Based on the percentage of contributors to the impact, it can be seen that the largest contributor to the toxicity impact comes from hydrogen sulphide, which is 65%. In other processing units, no emissions are produced and have the potential to cause toxicity.

3.3.2.6. Water Footprint

At the operational stage, each type of geothermal power plant has a water footprint of 0.29-0.72 gal/kWh for the Enhanced Geothermal System (EGS), 0.27 for binary plants, and 0.01 gal/kWh for flash systems. The accumulated water loss in flash systems due to evaporation and blowdown is 2.7 gal/kWh. The construction phase has a smaller impact on the water footprint, namely 0.001 gal/kWh for binary and flash systems and 0.01 gal/kWh for EGS [25]. Another study mentions that the intensity of water use in geothermal power plant activities is 20 L / MWh [23]. The contributor to the impact of the water footprint does not arise in the scope of the Unit-SS gate. This happens due to the cooling water for the generator comes from circulating condensate-cooling water in the condenser process unit and cooling tower. Water demand comes from circulating cooling water so that there is no use of groundwater or surface water during normal operational activities.

3.3.2.7. Land Use Change

The potential land-use impact from geothermal power plant is 404 m^2 /GWh [23]. Moreover, land use change is estimated by endpoint level with unit reference is PDF (Potentially Disappeared Number of Plant Species). For example, dry steam geothermal power plant in Indonesia has land use impact by 0.000024 PDF/m^2[16]. The potential impact of land-use change resulting from the electricity generation process comes from land use from geothermal power plant operational activities. In general, the contributors to the impact of land-use change from the electricity production process include the main process of generating electricity from geothermal power plant unit-SS. The contribution from the administrative office land is ignored because it has the same value.

3.3.2.8. Cumulative Energy Demand (CED) or Energy Usage

Energy usage in several studies is the key parameter of LCA alongside global warming potential. Perspective of cradle to gate geothermal stage point out that 95% energy usage are cause by construction and manufacturing activities [11]. In the other hand, the contributors to the impact of Cumulative Energy Demand (CED) in the scope of small-scale gates come from the process units produced in the electricity production process, such as Turbine & Generator, Main Condenser, Inter Condenser, Cooling Tower, and Condensate Pond. The biggest contributor to the CED impact according to the study is the Cooling Tower which has 63% value. The results of the percentage of impact contributors can be seen in Table 7.

Table 1 Impact Contributors of Cumulative Energy Demand

Turbine & Generator	Main Condenser	Seal Water Separator	Cooling Tower	Condensate Pond
6,4%	1,7%	27%	63,3%	1,7%

Based on table 7, 100% of the contributors to the CED impact come from the use of renewable energy for electricity in the Turbine & Generator process unit, Main Condenser, Seal Water Separator, Cooling Tower, and Condensate Pond. The electrical energy used is sourced from the production of the geothermal power plant itself, which is included in the category of renewable energy based on the main raw material for its production, namely geothermal.

4. Data Inventory and Impact Analysis Evaluation

The compiled data from the gate-to-gate process of Unit-1 and Small Scale produces environmental impact data per unit kWh product. Data normalization is also conducted to compare the impact per product between Unit-1 and Small Scale can be seen. In this study, the LCIA (Life Cycle Impact Assessment) stage produces impact category outputs along with characterization values. The output can be in the form of a graph model that shows the impact contribution per production process, bar graphs, and tables, each of which contains impact categories and their impact values. This output can also provide an overview of the biggest impact resulting from the gate-to-gate small-scale process. The following picture is a bar graph of the impact characterization result normalized with the Recipe 2016 Midpoint (H) V1.03, CML-IA Baseline V3.05 method.

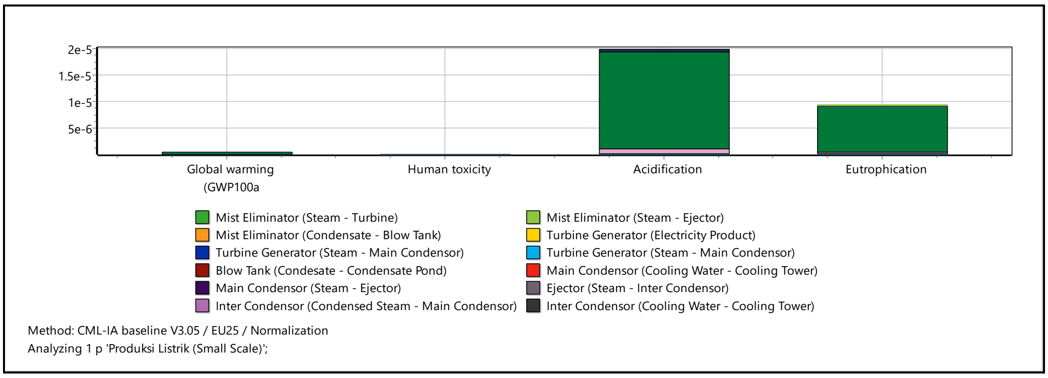

Fig. 6 Normalization of Geothermal Power Plant Unit-SS Method CML-IA Baseline V3.05 Impact

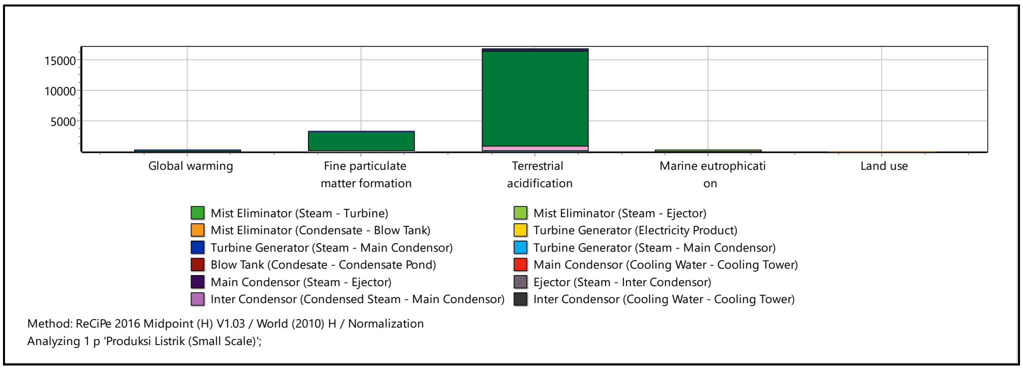

Fig. 7 Normalization of Geothermal Power Plant Unit-Small-Scale Recipe 2016 Midpoint Method (H) v1.03 Impact

Figure 6 and Figure 7 show the greatest impact on all methods. Unit-SS is considered to acquire acidification or terrestrial acidification. The impact of acidification or terrestrial acidification in the LCIA stage comes from the release of NCG into the air from the geothermal power plant cooling tower. The normalizing the impact of both the CML IA and Recipe methods show that the impact of acidification is much greater than the impact of global warming, toxicity, or other impacts. Changes in the impact of acidification which is the dominant impact can show positive or negative results than the development of Unit-SS. The difference in input and output result that has been normalized per unit of electricity kWh between Unit-1 and Unit-SS can result in an initial picture of the impact of using resources (materials and energy) as well as emission outputs generated by the construction of Unit-SS. It can be seen by table 8.

Table 2 Life Cycle Inventory per Products of Unit-1 Geothermal Power Plant and Unit-SS Geothermal Power Plant Comparison and Deviation

Category	Data Inventory	Unit-1 Geothermal Power Plant	Small Scale (SS)	Unit-1 and SS Deviation	Satuan
		Quantity per Function Unit	Quantity per Function Unit		
Input					
Material	Steam	0,007485	0,0067	0,000813	Ton/kWh
Fuel/Electricity	Electricity	0,040888	0,0459	-0,004997	kWh/kWh
Output					
Product	Electricity	1	1	0	kWh/kWh
Air Emission	H2S	0,0000102006	0,000006695	0,000003506	Ton/kWh
	NH3	0,0000092541	0,000008028	0,000001227	Ton/kWh
	CO2	0,0000531274	0,000050912	0,000002215	Ton/kWh
Water Emission	NH3	0,0000000266	0,000000115	-0,000000088	Ton/kWh
	H2S terlarut	0,0000000006	0,000000009	-0,000000008	Ton/kWh

The comparison of Life Cycle Inventory per Unit-1 and Unit-SS products shows an improvement in the output of emissions to the air with the geothermal power plant unit-SS. Another thing to consider is the intensity of emission to water from geothermal power plant unit-SS which has a higher value than geothermal power plant unit -1. The acidification impact category can come from the output of emissions to the air or water, so it is necessary to compare the overall impact value (Life Cycle Impact Assessment) to determine the positive or negative impact of the geothermal power plant unit -SS. The comparison of the overall Life Cycle Impact Assessment can be seen in table 9.

Table 3 Comparison of Impact Value per Product of Unit-1 Geothermal Power Plant and Unit-SS Geothermal Power Plant

Category of Impacts		Unit-1 Geothermal Power Plant	Small Scale (SS)	Unit-1 and SS Deviation	Unit
		Amount per Function Unit	Amount per Function Unit		
Primary Impact	Global warming potential	0,053140	0,0496	0,003560	kg CO2 eq/kWh
	Acidification	0,018139	0,0157	0,002407	kg SO2 eq/kWh
	Eutrophication	0,003248	0,0028	0,000399	kg PO4- eq/kWh
Secondary Impact	Toxicity	0,003170	0,0023	0,000894	kg 1,4-DCB/kWh
	Land Use Change	0,0012883828	0,0025	-0,001223	m2a crop eq/kWh
Cumulative Energy Demand	Renewable Energy	0,1471958163	0,1652	-0,017989	MJ/kWh

Table 9 shows that all primary impacts from Unit-SS are lower than Unit-1. The biggest impact from all power plant, such as acidification, also has a lower value in Unit-SS when compared to Unit-1. The first indication that the value of the primary impact on Unit-SS is lower than Unit-1 is the steam inventory data shows the amount of steam entering the Unit-SS is 0.0067 tons/kWh, which is lower than Unit-1 of 0.007485 tons/kWh. The difference between the steam intensity between Unit-1 and Unit-SS is 0.000813 ton/kWh. The lower steam intensity in the Unit-SS allows lower NCG entering the Unit-SS. Moreover, changes in the primary and secondary impacts (toxicity) of Unit-SS compared to Unit-1, there is no chemical intervention as in the H_2S Abatement. Both Unit-1 and Unit-SS have no H_2S Abatement so that the impact value is only affected by NCG is due to the consumption of steam at the inlet of each generator and the dispersion of gas released from the system (Gas Removal System).

The Gas Removal System functions for the extraction of gas (NCG) contained in geothermal steam. This accumulated NCG in the generation system will cause a heat transfer decrease to the condenser, which will cause pressure increase in the condenser and decrease the power output of the turbine. This is due to the specific calorific value of NCG is lower than that of geothermal steam. On the other hand, Gas Removal System in Unit-SS is different from Unit-1. Unit-SS has a Hybrid Gas Removal System, which are steam jet ejector and liquid ring vacuum pump, meanwhile, Unit-1 has a Gas Removal System which contains two steam jet ejectors. The Steam Jet Ejector System (SJES) has a lower exergy efficiency than the Hybrid System with a larger NCG fraction in SJES. In contrast, steam jet ejectors shown better performance than vacuum pump in lower pressure condition [26] [27].

NCG reinjection by emissions abatement system may be added in the future. However, there are some consideration from NCG absorption. NCG absorption possess high demand for water, high pressure, and loads for gas compressor and water pumps. High water mass flow rate may be doubtful relate to the effectiveness of water absorption for a deep H_2S removal. [28]. Due to its operation, NCG absorption may give additional impact for water footprint and cumulative energy demand. Therefore, NCG reduction is less worth as its mitigation effort based on addition of impact. Otherwise, intermediate pressure reboilers or low pressures turbine can be further solution to NCG extraction. Intermediate pressure reboilers deliver higher heat transfer in condenser because of lower NCG content get in [29].

5. Conclusion

The biggest potential impact from the operation (gate to gate) of Unit-1 Geothermal Power Plant is acidification or terrestrial acidification. The impact of acidification or terrestrial acidification at the LCIA stage comes from the release of NCG into the air from the cooling tower of Unit-1 and Unit-SS Geothermal Power Plant. The potential impact of acid rain (acidification) from Unit-1 is 0.018139 kg SO_2eq/kWh. Therefore, the normalization of the impact results of both the CML IA and Recipe methods show that the impact of acidification is far greater than the impact of global warming, toxicity, and other impacts.

However, the impact of small-scale geothermal power plant replenishment when compared to the impact of Unit-1 Geothermal Power Plant operations is it acquires positive impact or tends to have a lower environmental impact. The biggest impact from all geothermal power plant, namely acidification, also has a lower value in Unit-SS when compared to Unit-1. In Unit-SS, the potential impact of acid rain (acidification) is 0.0157 kg SO_2eq/kWh or 0.002407 kg SO_2*eq*/kWh lower than Unit-1. Furthermore, alternative suggestions based on the analysis of the life cycle study of the addition of small-scale Geothermal Power Plant to the operation of Unit-1 is an opportunity for further research on the efficiency of the gas removal system which has a positive impact on the distribution either the absorption for non-condensable gas.

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