

Life Cycle Assessment Applications To The Dry Steam Geothermal Power Generation (Case Study: Star Energy Geothermal Wayang Windu, Ltd, Indonesia)

Rina Annisa^{a*}, Benno Rahardyan^b

^{a,b} Master of Environmental Engineering, Faculty of Civil and Environmental Engineering
Institute Technology Bandung
Jl. Ganesha No.10 Bandung 40132, Indonesia

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Abstract

Geothermal potential in Indonesia is estimated can produce 29 GW renewable energy, and until 2016 it was only 5% from its potential converted into electrical power or about 1643 MW and 227 MW of it is produced by Wayang Windu geothermal power plant. The Input was main raw material in dry steam form, energy, chemical, and water consumption. These inputs can produce electricity as the main product, and also other output that relates to the environment such as emission, solid waste, and wastewater. All environmental impacts should be controlled to comply with the environmental standard, and even go beyond compliance and perform continual improvement. This research will use Life Cycle Assessment method based on ISO 14040 and use a cradle to gate concept with boundary from liquid steam production until electricity produced, and Megawatt Hours as the functional unit. Life Cycle Inventory has been done with direct input and output in the boundary and resulted in that subsystem of Non-Condensable Gas and condensate production have the largest environmental impact. LCI also show that every MWh electricity produced, it needed 6.87 Ton dry steam or 8.16 Ton liquid steam. Global Warming Potential (GWP) value is 0.155 Ton CO₂eq./MWh, Acidification Potential (AP) 1.69 kg SO₂eq./MWh, Eutrophication Potential (EP) 5.36 gPO₄ eq./MWh and land use impacts 0.000024 PDF/m². Life Cycle Impact Assessment resulted that AP contribute 78% of environmental impact and 98% resulted from H₂S Non-Condensable Gas. Comparison of LCA study results on GWP and AP value between Wayang Windu power plant with another dry steam geothermal power plant in the world show that impact potential result of the company in a good position and there's a strong relation between gross production, GWP and AP value.

Keywords: *Life cycle assessment; Geothermal; Continual Improvement; Global Warming Potential; Acidification Potential*

* Corresponding author.

E-mail address. rina.annisa@hotmail.com

1. INTRODUCTION

One of the challenges that are very interesting to be researched is a continual improvement that has to be done continuously by the industry as a form of their consistency for the environmental preservation effort. Continual improvement effort can use life cycle assessment method. LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle [1]. In general, LCA is modeling form environmental management that will evaluate the environmental from an activity that has a potential environmental impact. The basic part of LCA is identifying and quantifying energy and material used and wastes released to the environment. LCA assess the environmental impact that related to those flows [21]. Standard that regulated LCA is ISO 14040 and 14044, life cycle perspective also has been stated in ISO 14001 regarding Environmental Management System 2015 [3].

Electricity demands in Indonesia have risen rapidly, so Indonesia is facing an electricity demand challenge. Electrification ratio in 2016 is 91.16% [6]. Geothermal is an industry that has an important role in renewable energy supply to fulfill electricity needs. In Indonesia, the geothermal resource has great value, as its only used 5% at the end of 2016 or 1.634 MW from 29.000 MW geothermal reserves [26]. The target of renewable energy consumption in Indonesia in 2025 is 23% [23] and geothermal contribute 7% [6]. Using geothermal as an energy source has some advantages, such as emission reduction, limited resources consumption reduction and increasing security of energy distribution [5].

Impact calculation result will lead us to determine the highest impact source and to benefit-cost analysis [7]. This value is a calculation of economic valuation from the environmental impact of an activity. After the highest impact source found, the improvement can be done effectively. Research regarding LCA in the geothermal power plant has been done all over the world. Some published research regarding LCA in geothermal power plant showed in Table 1.

These international researches are LCA in the geothermal power plant. It showed that impact evaluation that has been done is GWP (*Global Warming Potential*) calculation because there was greenhouse gas emission, EP (*Eutrophication Potential*) because the activity produces wastewater, and AP (*Acidification Potential*) because there was the emission of H₂S and NH₃, especially from non-

condensable gas. Selection of impact category based on emission characteristic.

Table 1. LCA Published Research of Geothermal Power Plant

Name	Title	Method	Result
Monte-negro et.al., 2016 [8]	LCA geothermal power generation technologies: An update review	Environmental impact comparison of some geothermal power plant system	GWP, EP and AP value
Martinez-Jorge Isaac., 2016 [9]	Hybrid Life Cycle assessment of a geothermal plant : from physical to Monetary Inventory Accounting	Environmental impact assessment from Geothermal power plant using LCA and input-output analysis	Life cycle calculation in every activity
Heberle, Florian, et.al., 2016 [10]	Life Cycle Assessment of Organic Ranking Cycles for Geothermal Power Generation considering low-GWP working fluids	LCA geothermal power plant in Germany use organic ranking cycle	GHG/ KWh in each stage
Buonoco re, et.al., 2016 [11]	Integrating Life Cycle Assessment and Energy Synthesis for the Evaluation of a Dry Steam Geothermal Power Plant in Italy	LCA of geothermal power generation in Italy with dry steam type	GWP and AP value
Bayer, Peter. Et.al., 2013 [12]	Review on life cycle Environmental Effects of Geothermal Power Generation	Geothermal power plant LCA in USA, data from literature	Potential impact from some plant type

2. METHODS

LCA methods consist of four stages, i.e. goal and scope definition, Life Cycle Inventory, Life Cycle Impact Assessment and Result interpretation. This stages showed in Figure 1. This study conducted in Star Energy Geothermal Ltd (SEGWWL), Wayang Windu, Desa Margamukti, Kecamatan Pangalengan Kabupaten Bandung, ± 40 km south of Bandung City in West Java Province, Indonesia. The functional unit used is Megawatt hours (MWh).

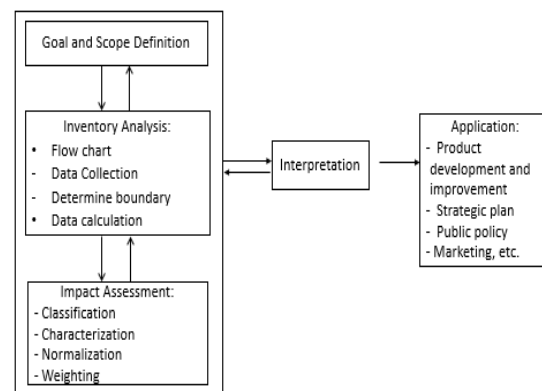


Figure 1. LCA Framework [1]

The product of this company is electricity, with power plant capacity 227 MW that come from power plant unit 1 (110 MW) and unit 2 (117 MW). This electricity will be distributed to PT PLN (Persero) for supplying electricity transmission network Jawa-Madura-Bali [26].

2.1 Initial Identification

This LCA conducted to utilize raw water, energy consumption, wastewater, and solid waste generation, and other material. This research refers to cradle to gate concept, analysis limited from the process in the steam field until the product gate or when electricity supplied to PLN. The boundary consists of four subsystems, where each subsystem consists of some process units that have input and output. The boundary condition is shown in Figure 2.

Dry steam from header steam will control turbine that connected to a generator. The turbine will transform heat from steam to mechanical energy and the generator will transform mechanical energy into electricity. Another steam that passes through the turbine will be condensed in the condenser. Condensation water will be pumped to cooling water. The rest of the cooled water will be recycled to the condenser through a hot well pump, another condensate will flows to the reservoir through

injection well. Non-condensable gas from the condenser will be flowed through Gas Removal System and will be dispersed to the atmosphere by stack in a cooling tower. The supporting system is the subsystem that not includes in geothermal flow but supports the operation.

Those processes determine boundary condition and data collection. Boundary divided into four subsystems. The subsystems are Steam Field subsystem (Production well, separator and scrubber), Power plant (Turbine, Generator, Transformer), NCG and condensate producer (Condenser, Cooling tower, GRS, and Condensate injector) and supporting system subsystem.

2.2 Data Collection

Input data are water consumption, chemical consumption, natural resource consumption, energy consumption, and fuel consumption. Output data are product in the form of electricity, *co-product* in the form of brine water and condensate water that flow into an injection well, and emission from all production system component in the boundary. This research use production data from January 2016 until Quarter 3 2017 and environmental monitoring data from 2012 until Quarter 3 2017.

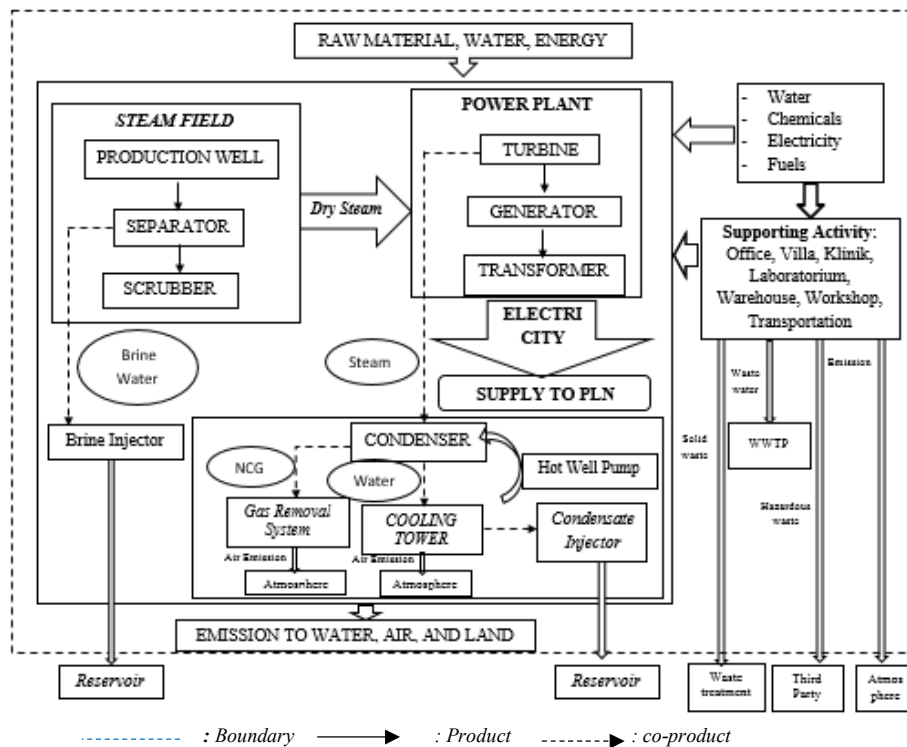


Figure 2. Boundary system

2.3 Implementation of LCA methods

Further step is LCI and LCIA. Life cycle inventory applied to all data that has been collected to be associated with the functional unit. LCI is quantifying the energy and raw material inputs and environmental releases associated with each stage of production. This stage will be continued with characterization which is part of the life cycle impact assessment (LCIA) process. Stages of LCIA showed in Figure 3. Stages of LCIA ^[2] i.e.:

1. Determine the impact category and Classification (*mandatory*)
Determine the environmental impact that appropriate with boundary shall be defined based on data from LCI ^[3].
2. Characterization (*mandatory*)
The impact of each emission and resource consumption modeled depends on impact category. The objective of the impact category is converse emission data to impact value that has been determined ^[28].

$$I_c = \sum_s CF_s \times m_s \quad (1)$$

I_c is indicator result for impact category c , CF_s is characterization factor from compound s to impact category c , and m_s is mass of the compound

3. Normalization (*Optional*)
In this stage, value from characterization divided will result in one value so can be compared ^[13].
4. Weighting (*Optional*)
Weighting will convert all the impact to a single score that can be used for decision making ^[13]. The formula is on equation 2.

$$W = \sum_c WF_c \times I_c \quad (2)$$

W is Weighting, I_c is impact value for impact category c , and WF_c is weighting factor from impact category c .

Characterization factor, Normalization factors, and Weighting factors can be chosen based on methods. There are some methods that can be used, i.e. CML, EPS, EDIP, ILCD, and Recipe. This study also uses software to support the research, i.e. Simapro for impact assessment with an academic license.

LCI and LCIA will lead us to research conclusion getting from LCI and LCIA analysis that will answer research purposes. The last stage of LCA study is result interpretation and conclusion. Subjects that can be identified are resource consumption,

emission generation, emission inventory and identify the stage of activity that will affect environmental impact, and environmental impact potentially.

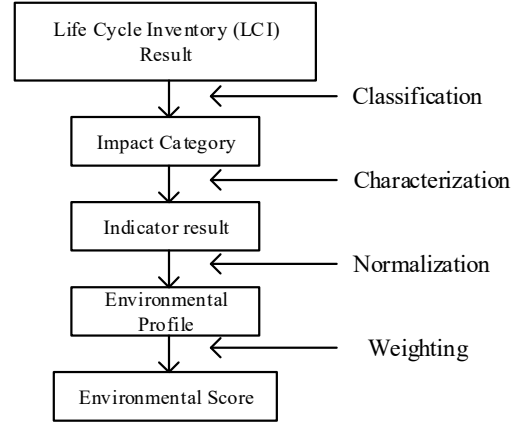


Figure 3. Life Cycle Impact Assessment Stage ^[24]

This research will conduct LCIA until weighting with impact category Climate Change with characterization factor GWP (Global Warming Potential) caused by greenhouse gas emission from the production process, Eutrophication with characterization factor EP (Eutrophication Potential) that caused by wastewater production, Acidification with characterization factor AP (Acidification Potential) because there were acidification substance production and land use impacts because there was a land use changing. Also, there was another potential impact, i.e. PMFP (Particulate Matter Formation Potential), POCP Photochemical Ozone Creation Potential and ODP (Ozone Depletion Potential).

The next stage is Characterization, where all potential impact from every inventory will be modelled quantitatively using characterization model ^[27]. This research will use characterization model that chosen based on ILCD recommendation ^[28] and previous research ^[28], for midpoint using CML method and for endpoint using Recipe. Beside those characterization models, this research will also use ILCD 2011 and EDIP 2003 as a comparison. Normalization will use the same model with characterization because this model can be used in all selected impact category. Next stage is weighing and will use ILCD (EC-JRC and PROSUITE) and EDIP.

2.4 Result Interpretation and conclusion

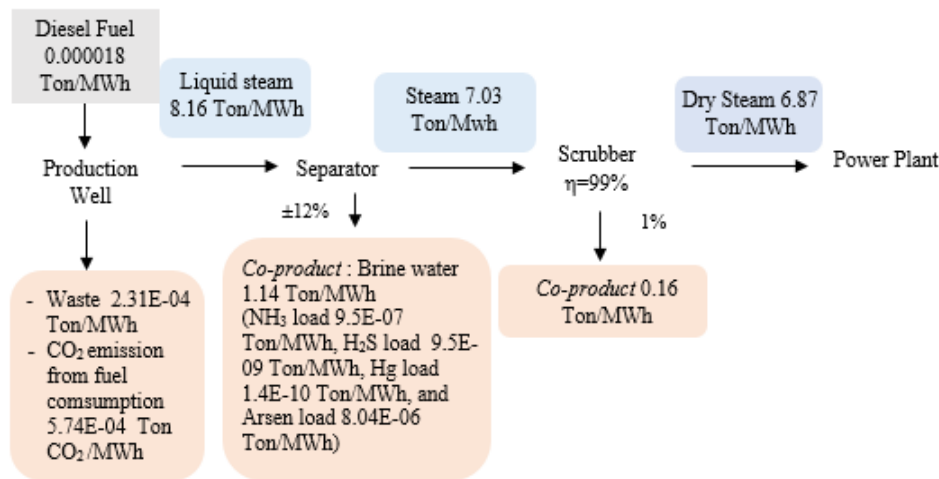
Subjects that will be identified are resource consumption, emission generation, emission inventory and identify the stage of activity that will affect environmental impact, environmental impact potentially, benefit and cost analysis potentially environmental impact with same impact category from other geothermal power generation from literature review.

3. RESULTS AND DISCUSSION

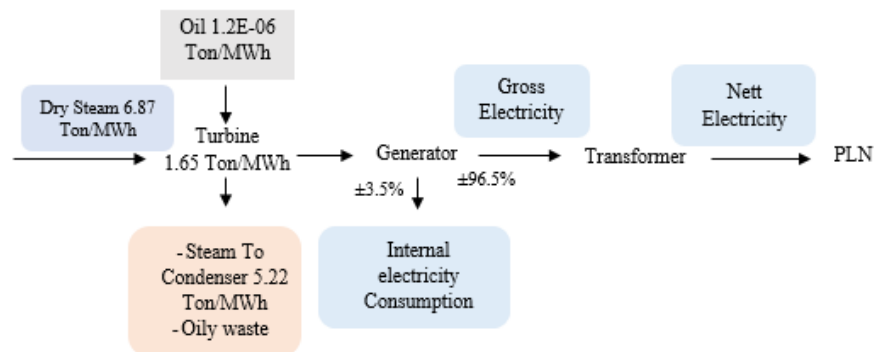
3.1 Life Cycle Inventory

Inventory analysis resulted intensity of liquid steam to electricity production is a 8.16 Ton/MWh. Electricity consumption is about 3.5% from gross

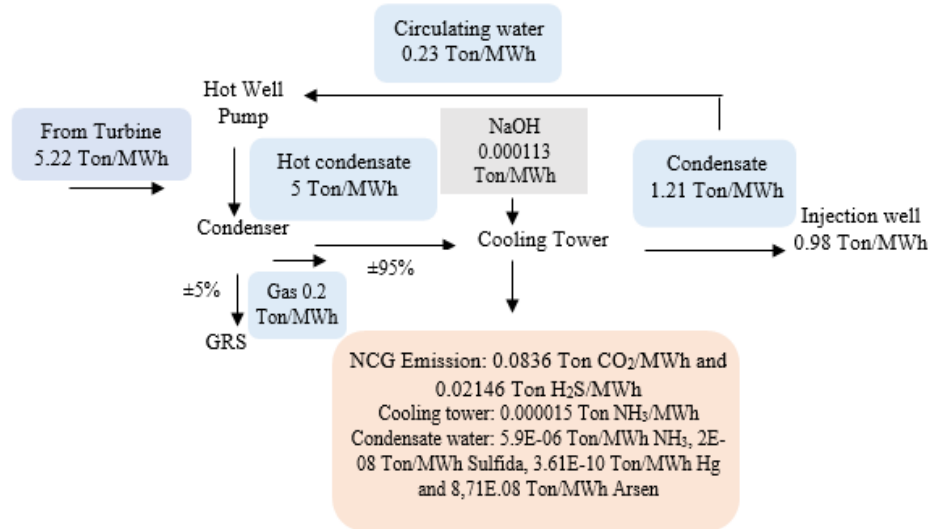
production or 0.0316 Ton/MWh. Intensity calculation of every input and output divided with gross production. Every activity has a contribution to resources, raw material, and energy consumption, also to environmental impact. Inventory analysis resulted that the highest fuel consumption is in subsystem 4 (76.28%), highest chemical consumption is in subsystem 3 (99.98%) and highest CO₂ emission in subsystem 3 (99.83%). In some input and output, e.g. electricity consumption cannot be analyzed in every subsystem because the available data is all consumption, not in each process units. LCI result showed in Figure 4.



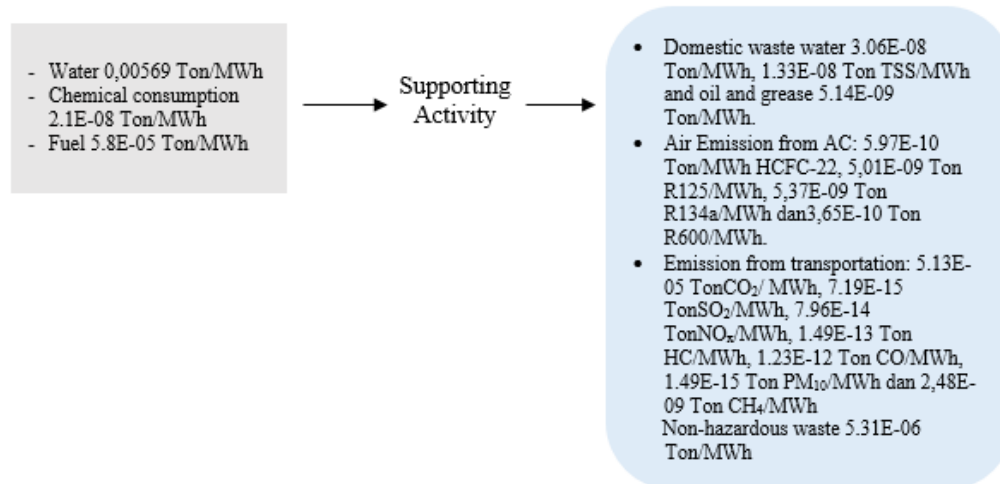
(a) Steam Field



(b) Power Plant



(c) NCG and Condensate Production



(d) Supporting System

Figure 4. Intensity in Subsystem

3.2 Life Cycle Impact Assessment

In this stage, environmental impact as per boundary shall be determined based on LCI result. LCI result combined with impact category based on material that contributed to the environmental problem ^[3]. Determination of impact category or LCIA classification showed in Figure 5.

Potential GWP was calculated by using model of characterization from IPCC 2013, ILCD 2011 and EDIP 2003 using GWP₁₀₀. The unit is CO₂

equivalents. GWP characterization value is 0.115 Ton CO₂eq. /MWh and the biggest greenhouse gas emission source is non-condensable gas.

Eutrophication process in wastewater calculated only in domestic wastewater, because brine water and condensate injected to the reservoir by an injection well. Used characterization model is CML IA Baseline and the parameter is COD, COD intensity is 5.36 gPO_{4eq.} /MWh.

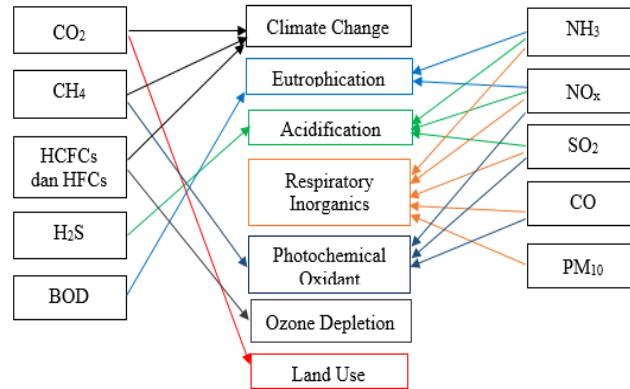


Figure 5. LCIA Classification

Acidification potential in air emission calculated by CML IA Baseline 2001 model, the unit is SO_2 Equivalent. Besides that, as comparison AP also calculated by ILCD, 2011 (mole $\text{H}^+\text{eq.}/\text{MWh}$), EDIP 2003 (m^2/MWh) and Recipe ($\text{kgSO}_2\text{eq.}/\text{MWh}$). The characterization by using all models showed the same result, that the highest emission source is H_2S from NCG, the result from those three models is $\pm 98\%$.

Characterization for another potential impact showed that the value of PMFP is $1.02\text{E-}03 \text{ kgPM}_{2.5}/\text{MWh}$, POCP $1.48\text{E-}08 \text{ kgC}_2\text{H}_4/\text{MWh}$ and ODP $2.98\text{E-}08 \text{ kgCFC}_{11}/\text{MWh}$.

Potentially land use impacts in endpoint level calculated by using area and land use change period. Using characterization mode is Recipe 2007 with unit reference is PDF (Potentially Disappeared Number of Plant Species). This model can be used for LCIA studies in the world, and land use before activity become data. Land use impact value is 0.000024 PDF/m^2 .

Normalization used three model for all midpoint level, i.e. CML IA Baseline (World 2000) and ILCD 2011 (EC-JRC and PROSUITE). For weighting, used model are ILCD and EDIP, because there are no weighting factor in CML.

Normalization value result in all methods used showed that AP is the highest potential impact and GWP is the second one. Normalization result showed in Figure 6. Weighting resulted that from three models used i.e. ILCD (EC-JRC and Prosuite) and EDIP, global warming potential and acidification potential has 99% value from all potential environmental impact in geothermal activity. Acidification potential is the highest with 73% (EC-JRC).

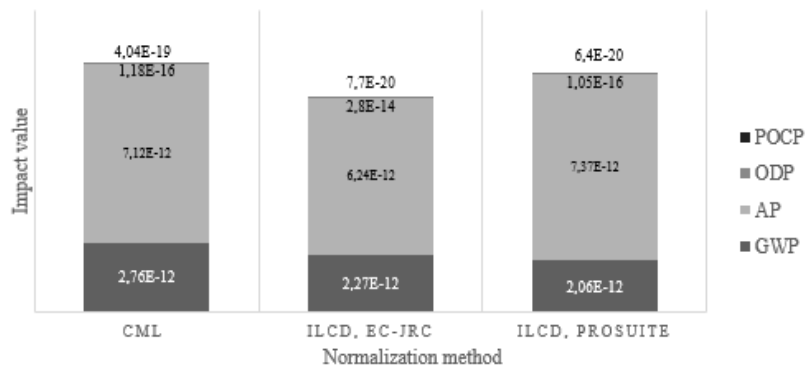


Figure 6. Normalization result

Weighting can lead us into single score (Ecopoints) and monetization to determine environmental cost and conducted benefit and cost analysis. Single score of geothermal activity is $5.69\text{E-}12$ Ecopoints for EC-JRC and $6.33\text{E-}12$ eco points for ILCD-Prosuite.

Monetization is used for benefit cost analysis in this research. Using methods are EPS 2000 and Ecovalue08. EPS calculation based on impact substance and Ecovalue based on potential impact. This calculation is converted into IDR because the cost unit on EPS is ELU (Environmental loading unit) [14] and Ecovalue is in Euro[15]. The conversion rate is IDR 16,824.69/euro and IDR 13,562.45/USD (conversion rate in February 2018). This research resulted that for each MWh electricity produced, environmental cost are IDR 426,165.99 (EPS) and IDR 548,539.32 (Ecovalue).

The operational cost for geothermal operation is 2-10 eurocent/kWh [16], while this research used 7 eurocent/kWh. For selling price, this research used ministry decree of energy and mineral resource Indonesia regarding electricity price from geothermal in 2018 is 13 cent USD/kWh [25]. All those value gathered in benefit cost analysis.

Benefit cost analysis resulted that benefit per cost ratio from geothermal activity is 1.1 (EPS) and 1.02 (Ecovalue). The value is higher than 1, it means that when environmental cost added to cost component, not only operational cost, the industry still have benefit.

3.3 Sensitivity Analysis

Sensitivity analysis will define the effect from differences of potential environmental impact that resulted by geothermal power generation. This analysis is a simulation analysis to predict the result of a study in how changes in one variable affect the outcome. In this research, the highest potential environmental impact is acidification potential, where the highest acidification source is non- condensable gas. The second highest potential impact is global warming, where the highest global warming source also from non-condensable gas.

The result of sensitivity analysis until $\pm 25\%$ differences of acidification value did not affect any changes. Therefore, acidification potential still the highest potential environmental impact. This sensitivity analysis use normalization value of GWP and AP.

3.4 Comparison with other Geothermal Power Generation

The comparison of GWP and AP characterization value in geothermal power plant with dry steam type in some countries with some methods

resulted that this company has a good position. Comparison done to other LCA study in geothermal power plant with same boundary and use same functional unit (MWh). Meanwhile, acidification potential value has a high value compared to other dry steam geothermal power generation. This comparison can be seen in Figure 7.

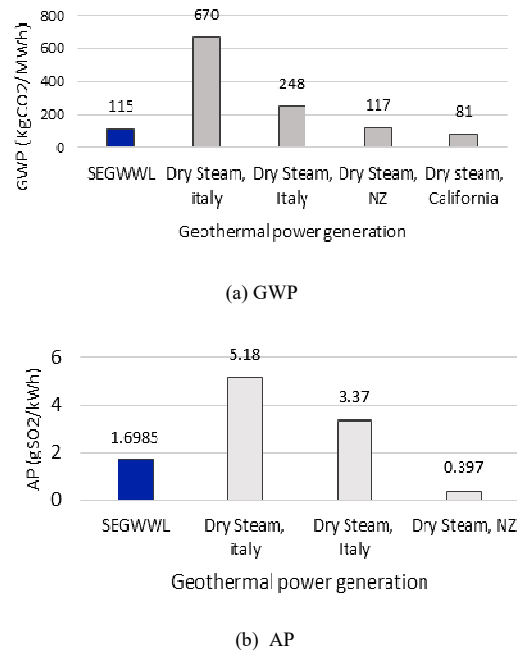


Figure 7. Comparison of Characterization Value with Other Geothermal Power Generation

3.5 Comparison with other Types of Power Generation

The comparison of LCA study result in GWP and AP characterization value between Wayang Windu Geothermal power generation with other types of power generation, such as nuclear, wind, thermal, gas etc. that has a same functional unit with boundary cradle to gate.

This comparison resulted that GWP and AP value of Wayang Windu geothermal power plant is lower than fossil fuel power generation but the highest one if compare with other renewable power generation. Figure 8 showed this comparison, and it's clearly describe that geothermal has a high potential impact compare to other renewable power plant, and it also showed that renewable power generation produce less environmental impact than fossil fuel power generation.

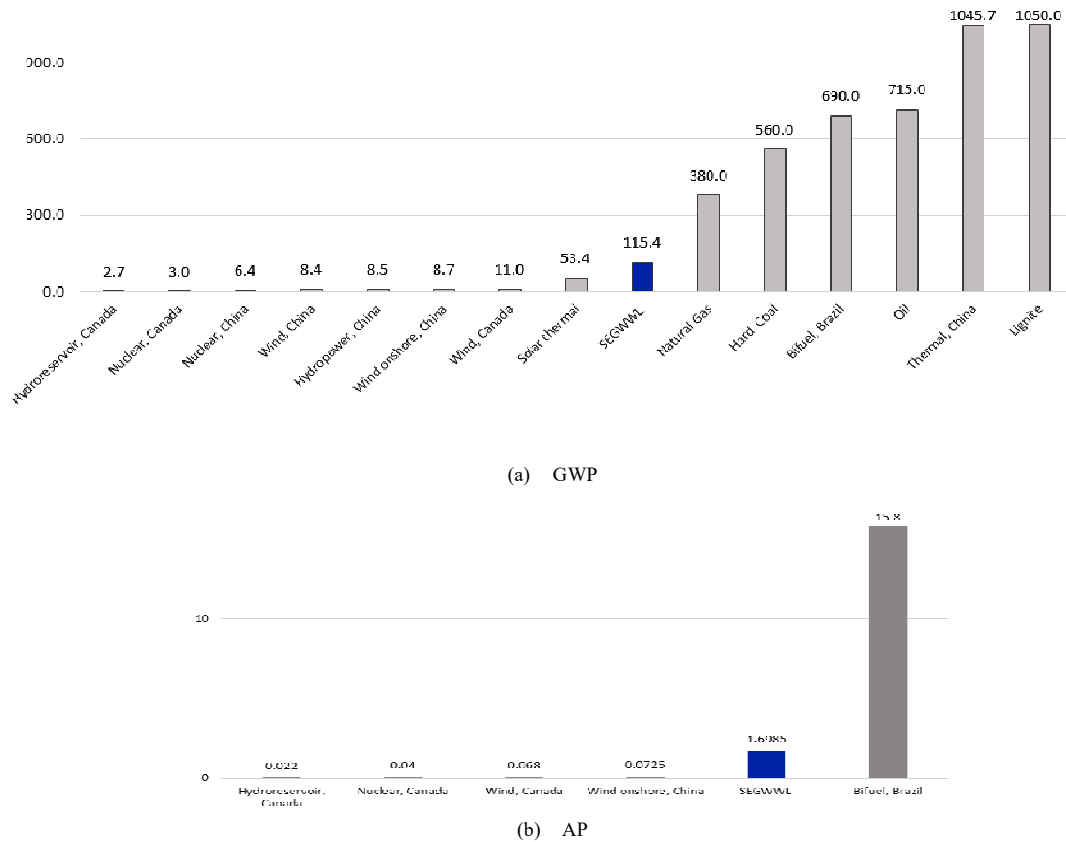


Figure 8. Comparison of Characterization Value with Other Types of Power Generation

3.6 The Relation between Potential Impact and Production

Relation from each category impact with production need to be tested so it can answer research's hypothesis. The hypothesis is the availability of relation between gross production and environmental impact. The strengthens of this relation can be presented by Relation Coefficient (R) value. Potentially impact of global warming has relation coefficient 0.93, acidification 0.56 and eutrophication 0.86. It means that gross production has a strong relation with global warming potential and eutrophication potential, medium relation with acidification potential.

4. CONCLUSIONS

Research hypothesis is there was a relation between production and environmental impact can be accepted because there was strong relation between production and potentially impacts. It shows by the value of relation coefficient, i.e. 0.93 for GWP and 0.86 for EP.

The biggest environmental impact source is subsystem 3 that consist of Condenser, Cooling tower,

and Gas Removal System as process units. The biggest potential impact value is acidification and 98% from all acidification come from H₂S emission Non Condensable Gas.

LCI resulted that for each 1 MWh electricity produced, it needed 8.16 ton liquid steam and 6.87 ton dry steam. Emission that produced are 0.115 Ton CO₂, 2.15E-03 ton H₂S, 1.53E-05 ton NH₃, 6.67E-12 ton SO₂, 7.69E-11 NO_x, 1.49E-13 Ton HC/MWh, 1.23E-12 Ton CO/MWh, 1.49E-15 Ton PM₁₀/MWh, 2.48E-09 Ton CH₄/MWh, and 1.098 Ton/MWh CFCs.

LCIA resulted that for producing 1 MWh electricity it will result an environmental potential impact i.e. GWP 0,115 Ton CO₂eq., EP 5,36 gPO₄ eq., AP 1,6985 kg SO₂eq., POCP 1,48E-08 KgC₂H₄eq. and ODP 2,69E-08 kg CFC₁₁eq. (CML).

The highest potential impact is acidification and followed by global warming potential. Weighting result lead into benefit cost analysis and showed that with includes environmental cost in the activity, the industry still has a benefit.

Characterization, normalization and weighting factor in LCIA mostly still limited on research in Europe, therefore further study in Indonesia is needed to get more accurate impact calculation.

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