A LIFE CYCLE ASSESSMENT BASED COMPARISON OF A LARGE & A SMALL SCALE GEO-THERMAL ELECTRICITY PRODUCTION SYSTEM

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ABSTRACT

Greenhouse gas (GHG) emissions from fossil fuel electricity production cause a big problem on global warming. Using renewable energy, such as wind, solar and geothermal energy, is a more sustainable solution to produce electricity. During the operating phase of a geothermal energy power plant, there are much less GHG emissions compared to conventional power plants. But how sustainable are geothermal electricity production systems considering the whole life cycle, from construction, operation to closure of the power plant? Most research on the life cycle assessment (LCA) of geothermal energy (GTE) systems is conducted on large-scale geothermal power plants (installed capacity > 5MW) to assess their environmental performance. Little is known on the LCA of small-scale GTE systems.

In this study the environmental impacts of a large-scale GTE flash system (with an installed capacity of 110MW) is compared with a small-scale binary GTE system (the installed capacity is 500KW) using LCA, for the construction and operation stages.

The results showed that a small-scale binary system is more sustainable when considering the deep well drilling process and power plant building during the construction phase, while a large-scale flash system shows a better environmental performance when considering the process of power plant machinery production and pipeline construction. A small-scale binary system is more sustainable in the operation phase as there are no gas emissions.

Keywords: Geothermal energy systems, life cycle assessment (LCA), life cycle impact assessment (LCIA), sustainable energy systems

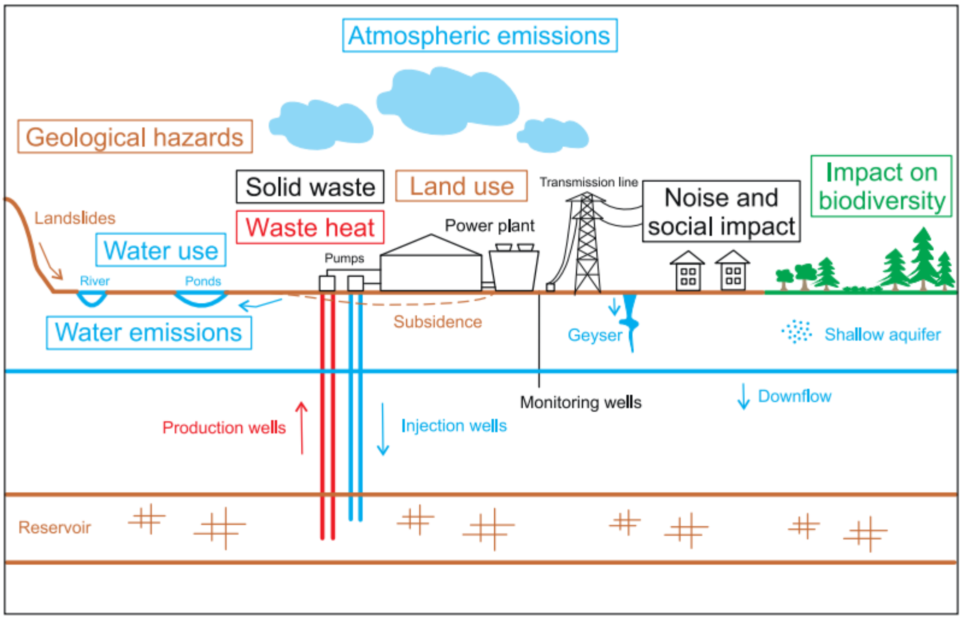
INTRODUCTION

Geothermal electricity production is considered to be more sustainable than the use of fossil fuels. But are they more sustainable if the whole life cycle, from construction, operation to the closure of the geothermal power plant is considered? And is there a difference between different geothermal energy systems: large and small scale systems? These are the questions addressed in this paper.

Burning fossil fuels to generate electricity produces carbon dioxide, one of most important greenhouse gases (GHGs) and therefore driver of climate change observed in the past few decades (Sullivan et al., 2010). Transition from fossil fuels to renewable energy sources is one of the biggest challenges for the coming decades if we wish to reach the agreements of COP21 (Paris Agreement) in view of combating climate change and global warming. Geothermal energy power is one of the sustainable solutions to generate electricity with minor greenhouse gas emissions.

Geothermal energy production does less damage to the environment than conventional fossil fuel electricity production systems (DiPippo, 2012). However, since geothermal steam and hot water contains hydrogen sulfide and other gases and chemicals that can be harmful in high concentrations, the environmental impacts of them cannot be ignored. Different geothermal energy systems deal with the harmful gases and chemicals differently. For example, in a flash system, the environment impacts of hydrogen sulfide and other gases need to be considered, while binary systems can inject these gases back into the geothermal well (DiPippo, 2012). Therefore, different geothermal energy conversion systems can have different environmental impacts. What's more, the gas emissions during the power generation phase do not completely cover all the environmental impacts of geothermal power plants. Large amount of energy and materials are utilized for the construction of the plant (Lacirignola & Blanc, 2013).This various for different geothermal systems and they in turn cause different environmental impacts. The inputs and outputs, as well as the environmental impacts of the different stages of a geothermal power plant can be assessed using a life cycle assessment (LCA) for different geothermal power production systems (Clark et al., 2012; Bayer et al., 2013; Pehnt, 2006).

LCA is a standard and normalized procedure (ISO 14040, 2006) to explore and assess environmental impacts during the different life cycle stages of a product (Hirschberg S.W. & Burgherr, P., 2015). Using LCA to calculate the total mass and energy consumption based on geothermal energy systems will help identify the environment impacts of the drilling, the construction of the power plant, the buildings and the operation of the power plant itself (Karlsdottir et al., 2010; Frick et al., 2010; Lacirignola & Blanc, 2013).



In this paper, the LCA of a large-scale flash system will be compared with a small-scale binary system, MiniGeo, for the construction and operation stages. The main reason to compare a large scale with a small scale geothermal plant is because little knowledge exists of the LCA of small scale geothermal plants. Wayang Windu is used as an example of a large-scale flash system. Wayang Windu Unit -1 was the first geothermal unit designed with a capacity of more than 100 MW (110 MW) and was therefore the first largest single flash geothermal power station in the world (Purnanto & Purwakusumah, 2015). MiniGeo is a project from IF technology ([c] http://www.iftechnology.nl/off-grid-electricity-production-with-minigeo). It is designed for the undeveloped (off-grid areas) areas, but can also be used in developed areas (with electricity grid). A small-scale system produces 0.5 MW. In this study, one large scale power plant (110MW) will be compared with 220 small scale geothermal power plants (0.5MW) to explore which GTE system performs better in terms of their environmental impacts, given the same electricity production.

Section 2 presents the LCA framework for geothermal energy systems. Section 3 explains the life cycle inventory (LCI) analysis for a large flash and a small scale binary geothermal plant. In Section 4 the environmental impacts of a large-scale flash system are presented for the construction, operation, and disposal phases. In Section 5 the environmental impacts of a large-scale flash system are compared with those of a small-scale binary system (MiniGeo), for the construction and operation phases. Section 6 includes the discussion, conclusions and recommendations.

LCA FRAMEWORK FOR GTE SYSTEMS

Figure 1 represents the goal definition and scope of a LCA of different GTE production system, life cycle inventory analysis and impact assessment.

GTE functional unit and system boundary

The GTE functional unit used in this paper is electricity production (kWh). LCA phases which are included within the system boundary of the considered system are as follow: 1) the production of raw materials and manufacturing of components 2) operational and maintenance phase and 3) end of life phase including the decommissioning and recycling or disposal of the components. The input materials for the GTE system are the materials and fuels used for the construction (such as deep well drilling, pipe construction etc.) and machinery. Maintenance and geothermal fluid are the two components considered for the operation phase. However, as there is hardly information available on maintenance, only geothermal fluid will be considered in this study. The output of the operation phase is electricity and hot water. The end of life stage of the GTE system usually involves the closure (filling up) of the wells and the power plant itself. On average a lifespan of thirty years is considered for a GTE power plant.

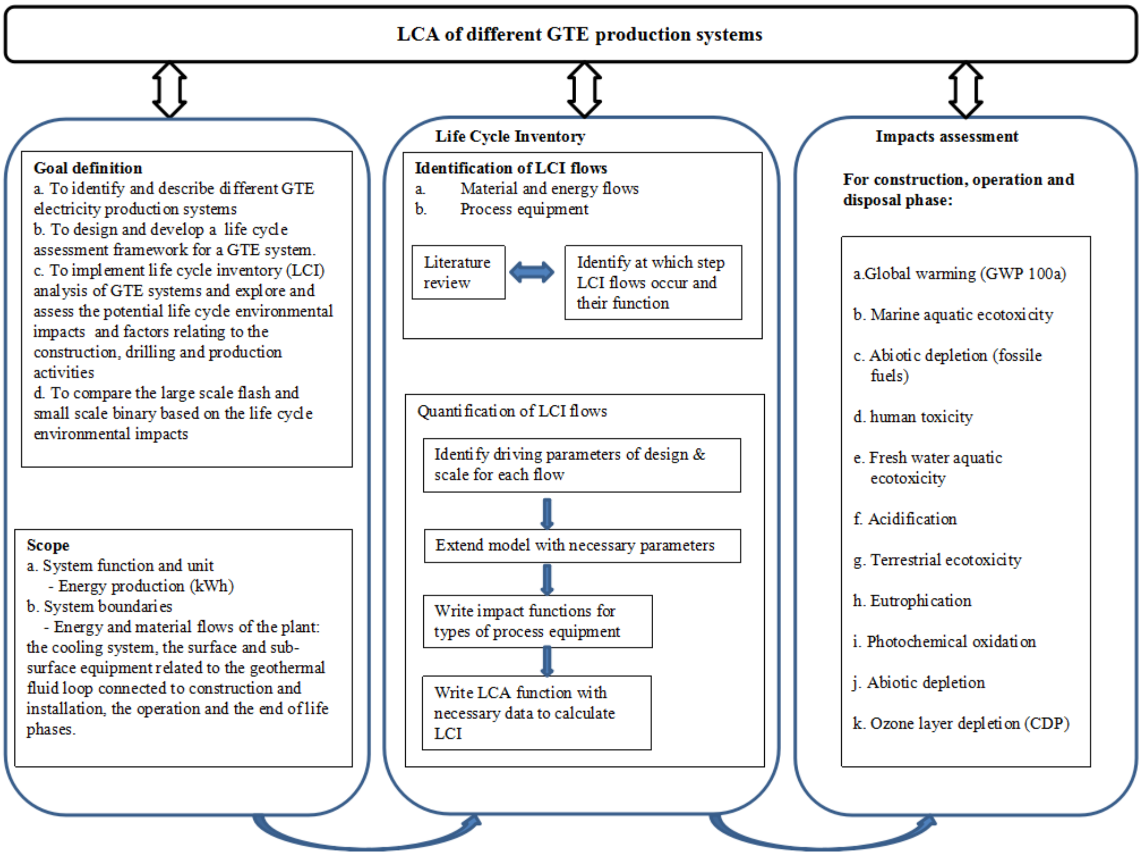


Figure 1 LCA framework for GTE electricity production systems

Life cycle inventory (LCI) analysis for GTE systems

The LCI involves the compilation and quantification of all the inputs and outputs for the construction, operation and disposal phases of the GTE system. The inputs/outputs for the geothermal energy production system includes raw material inputs, energy inputs and outputs, waste to be recycled and/or treated and emissions to the air. LCI is the most time consuming stage for conduction a LCA. The LCI data was obtained based on the literature reviews & expert knowledge. The construction phase includes all the materials (inputs and outputs) used for deep well drilling, pipeline construction, powerplant machinery and power plant buildings. For the operation phase CO_2, H_2S and CH_4, all outputs from geothermal fluid, were considered. Gravel and cement were the main components included in the LCI of the disposal phase. The LCI analysis can be conducted in LCA software, in this case SimaPro was used.

Life cycle impact assessment (LCIA) for GTE systems: impacts and indicators

An overview of possible environmental impact categories as well as specific impacts and emissions for a GTE system is given in Figure 2.

Figure 2 Direct life cycle environmental impacts of a GTE power plant (Source: Bayer et al., 2013)

When the LCIA is applied to geothermal energy systems, a number of impact metrics need to be identified. Table 3 - adapted from (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) shows the eleven impact categories considered in this study for the different LCA-stages.

LIFE CYCLE IMPACT ASSESSMENT OF A GTE LARGE-SCALE FLASH SYSTEM

In this section, the life cycle impact assessment (LCIA) of a large-scale flash system (Wayang Windu) is described. The impact assessment method and approaches are explained in section 3.1 and section 3.2 presents the life cycle impact assessment results for all GTE stages of a large-scale flash system.

Impact assessment methods

CML-IA (reference) is a LCA method developed by Leiden University. The method is a problem-oriented ('mid-point level') approach, in which eleven environmental impact categories are distinguished. The outcome of the LCIA in SimaPro includes a table showing the actual values for each of the eleven impact categories, for the different LCA processes. It is also possible in SimaPro to calculate the impact % each LCA process contributes to a particular impact, by dividing each impact value by the maximum value of that impact category. This is shown as a bar diagram, of which the first one will be illustrated in figure 3. Since the impact categories have different measurement units, ***normalization*** is used to make those categories more comparable. As there is no specific normalization method for Indonesia, the internationally accepted World 2000 normalization method was selected in SimaPro.

Life cycle impact assessment for all GTE stages

Table 3 shows the construction phase has the highest impact for all impact categories compared to the operation and disposal phases.

Table 3 The LCIA categories and values for the different stages of a large-scale flash system

Impact category	Unit	Total	Construction phase		Operation phase	Disposal phase
			values	%		
Marine aquatic eco-toxicity	kg 1,4-DB eq	1.97E11	1.97E11	99.9	-	8.95E6
Abiotic depletion (fossil fuels)	MJ	4.03E9	4.03E9	99.7	-	3.25E5
Human toxicity	kg 1,4-DB eq	5.2E8	5.18E8	99.6	2.16E6	7.3E3
Global warming (GWP 100a)	Kg CO2 eq	4.05E8	3.65E8	90.2	4.02E7	4.64E4
Fresh water aquatic eco-toxicity	kg 1,4-DB eq	1.27E7	1.27E7	Nearly 100		152
Terrestrial eco-toxicity	kg 1,4-DB eq	1.73E6	1.73E6	Nearly 100		56.8
Acidification	kg SO2 eq	1.62E6	1.61E6	Nearly 100		146
Eutrophication	kg PO4$^-$ eq	3.46E5	3.43E5	99.8		20.5
Photochemical oxidation	kg C2H4 eq	8.97E4	8.92E4	99.9	18.8	6.54
Abiotic depletion	kg Sb eq	1.49E3	1.23E3	99.7		0.0517
Ozone layer depletion (CDP)	kg CFC-11 eq	8.39	8.15	99.9		0.00266

The percentages per impact category for the four different construction processes and for the operation and disposal stages are shown in Figure 3. Deep well-drilling has overall the largest impact. Pipeline construction has a relatively larger impact on human toxicity and abiotic depletion. The impact of power plant buildings is mainly on abiotic depletion. The only significant environmental impact of the operation phase is global warming. Deep well closure (disposal phase) has an impact on marine aquatic eco-toxicity, abiotic depletion (fossil fuels), global warming and human toxicity.

Normalization

After normalization only the impact of deep well drilling on marine aquatic toxicity is prominent (see figure 4). Pipeline construction shows a relatively bigger impact on human toxicity than deep well drilling and has a minor impact on marine aquatic toxicity. The impact on the other environmental impact categories is very low.

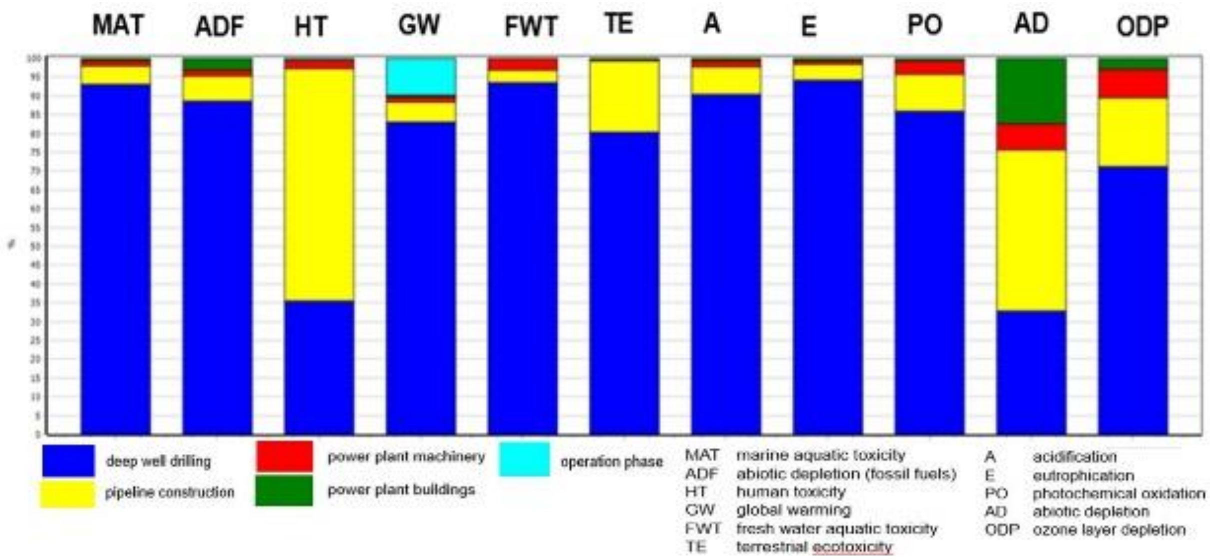


Figure 3 The LCIA for the large-scale flash system - percentage category for the different GTE processes of the construction, operation and disposal phases.

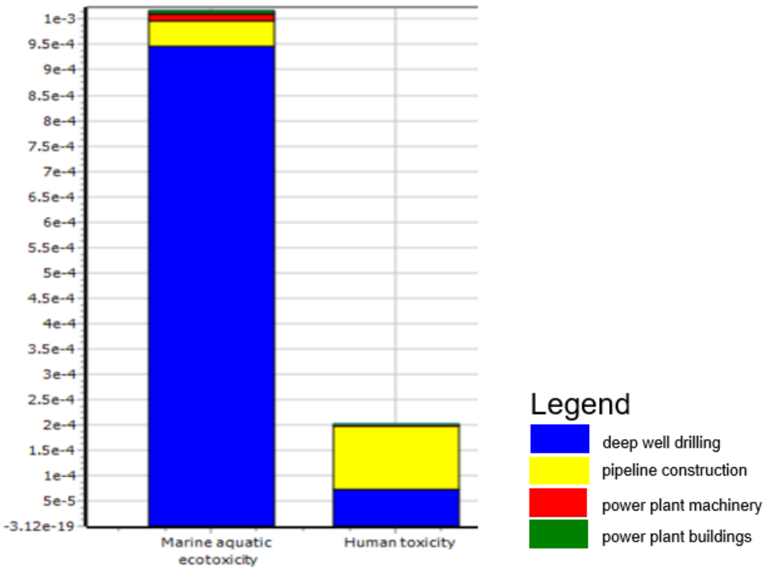


Figure 4 The normalized LCIA values of a large-scale flash system

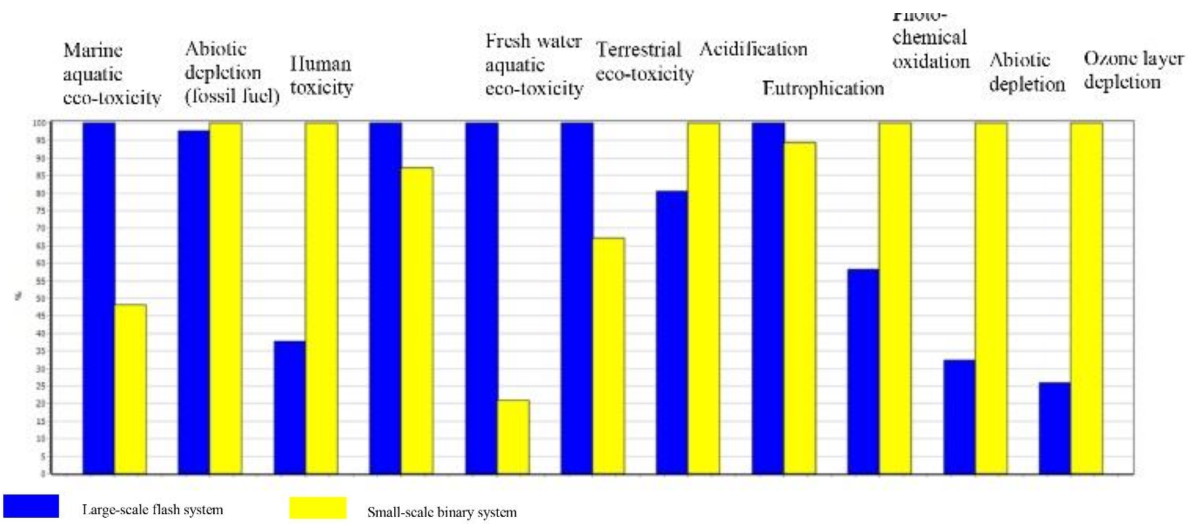


Figure 5 The LCIA of deep well drilling for the large-scale flash system and the small-scale binary system

COMPARISON OF A LARGE-SCALE FLASH WITH A SMALL-SCALE BINARY SYSTEM

For a binary system, there is no gas emitted from geothermal fluids, because a binary system has a closed loop. Therefore, there is no impact expected of the operation phase of a binary system. However, a large-scale flash system has the impacts mentioned in section 3.2. Also, the disposal phase was not considered as MiniGeo is not implemented yet and therefore no information is available on this stage for a binary small-scale system. As deep well-drilling showed overall the largest impact in the construction phase of a large-scale flash system, this phase will be given special attention first, followed by a comparison for all construction phases together.

Deep well drilling

In the process of deep well drilling**,** a large-scale flash system has relatively much more impact on fresh water & marine aquatic eco-toxicity and on terrestrial eco-toxicity and relatively more impact on global warming, abiotic depletion (fossil fuels) and eutrophication than a small-scale binary system. In contrast, the impact of a small-scale binary system is relatively much larger on ozone layer depletion, abiotic depletion and human toxicity, and relatively larger on photochemical oxidation. The impact on acidification is quite similar for both systems (see figure 5).

Comparison of GTE alternatives – all construction phases together

Figure 6 shows a large-scale flash system has more impact on marine aquatic toxicity, on fresh water aquatic eco-toxicity and terrestrial eco-toxicity than a small scale binary one. In contrast, a small-scale binary system has a bigger environmental impact on human toxicity, photochemical oxidation, abiotic depletion and ozone layer depletion than a large scale flash one.

Both systems indicate nearly the same impact on abiotic depletion, eutrophication and global warming.

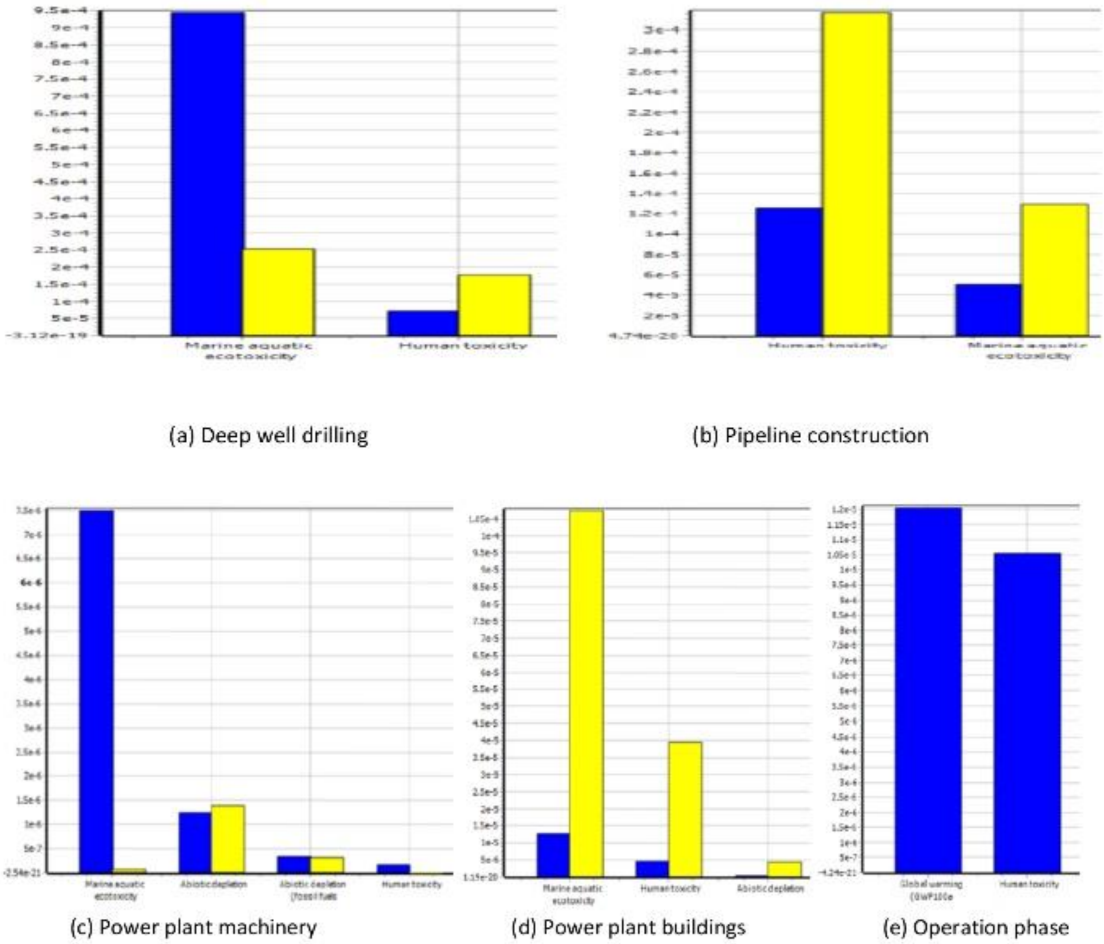


Figure 7 The normalized LCIA values of large-scale flash and small-scale binary system

Normalization

Figure 7 (a-e) shows the normalized LCIA values for the different construction phases (a-d) and the operation phase (7e) for a large-scale flash and small-scale binary system. The results are summarised in table 4.

Table 4 shows a small-scale binary system is overall more sustainable considering the construction and operation phases. Marine aquatic eco-toxicity and human toxicity are the main impacts. In the operation phase of a large-scale flash system global warming & human toxicity are prominent impacts.

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Accuracy assessment

An accuracy assessment was conducted using accuracy percentages between 10-30% for the different elements in the construction and operation phases. Only human toxicity, abiotic depletion and ozone layer depletion showed different impact results and those three impacts might therefore be either under estimated or over-estimated (Yu, 2017).

The LCIA method

Since there are different methods to perform a life cycle assessment, each having its own approach and normalization method, the LCA results can be affected by using a different method. The method chosen for this paper was the CML-IA baseline method. This method was compared with the ReCiPe method. As an example the LCA for deep well drilling in the construction phase of a large- scale flash system was discussed. When using the ReCiPe method, climate change appears to give the highest impact of deep well drilling, while this was marine aquatic eco-toxicity when using the CML-IA baseline method (Yu, 2017).

Comparison with results found in literature

Ketenagalistrikan et al., 2014, conducted LCIA for the process of deep well drilling specifically for the Wayang Windu GTE plant. Their findings showed a global warming potential ranging between 1.4 – 3.1 ton CO2 equivalent. In this research (Yu, 2017) a CO2 equivalent of 3 ton was calculated, which is within the range of the above mentioned research. In the operation phase, global warming potential (GWP) is a very important environmental impact in LCA (Marchand et al., 2015). The greenhouse values from the (Hondo, 2005), (Marchand et al., 2015) and (IPCC, 2011) are compared with the global warming potential results in this research. Their GWP values are between 38.5 and 47 g $CO_{2\,eq}$/kWh. The result in this research is 41.7 g $CO_{2\,eq}$/kWh. According to (IPCC, 2011), the medium value of global warming gas for other renewable energy electricity production systems are: 46 g $CO_{2\,eq}$/kWh (photovoltaic energy) and 12 g $CO_{2\,eq}$/kWh (wind energy). Meanwhile, (IPCC, 2011) also reported the greenhouse gas emissions from non-renewable energy electricity production systems are: 840 g $CO_{2\ eq}$/kWh (fossil oil energy) and 1000g $CO_{2\ eq}$/kWh (coal). The production of geothermal energy seems to be comparable with the one of photovoltaic energy.

Site specific issues and parameters

The results of the LCA of GTE systems vary for different locations. For example, in Indonesia, materials used to drill wells are different from the materials used in Iceland. In addition, GTE power plants in developed countries, such as Switzerland and Germany, may use more sustainable materials than those in Indonesia. This may explain why e.g. carbon dioxide emissions are lower (Frick et al., 2010) than the ones presented for Indonesia. In some LCA studies, such as (Marchand et al., 2015), for GTE development, land use conversion (by the construction of wells, pipelines and power plant) as part of the construction phase, is included in the LCI.

The same is for the stimulation of wells to test the well performance. The stimulation process happens after the drilling of boreholes. As no information was available on those components, they could not be included in the LCA of this study.

In the operation stage, maintenance of the wells, machinery and the power station are important components in a LCA. Corrosion and geothermal scales are a problem, but could not be included in this study due to lack of data.Many LCA studies provide information on transport, which is an important component for all LCA stages. However, transport of materials to and from the site was not included in this research as no information was available on transport means, nor distances to transport materials and equipment. This, of course, will particularly increase the global warming values.

Table 4 Summarised comparison of a large-scale flash and small-scale binary system

	Large-scale Flash	Small-scale Binary
Construction phase		
Deep well drilling	**1**	2
Pipeline construction		1 & **2**
Power plant machinery		**1,** 2 & 3
Power plant buildings	**1** & 2	3
Operation phase	**4 & 2**	

1 = Marine aquatic eco-toxicity, 2 = Human toxicity, 3 = Abiotic depletion, 4 = Global warming potential

Conclusions

Geothermal deep well drilling is the most polluting phase during the whole life cycle of a large-scale flash GTE electricity production system, giving a high impact on marine aquatic eco-toxicity. Human toxicity is mainly caused by pipeline construction (also as part of the construction phase). The amount of abiotic depletion (fossil fuel) is large in absolute amount, but at a worldwide level, abiotic depletion is less of a concern.

Global warming is the only significant environmental impact in the operation phase, followed by human toxicity. This is mainly caused by gas emissions from geothermal fluid. The disposal phase shows very little environmental impacts in this research. The geothermal well drilling process in the construction phase of a large-scale flash system shows more environmental impact on marine aquatic eco-toxicity and fresh water aquatic eco-toxicity than a binary system.

A small-scale binary system can cause more acidification, photochemical oxidation, abiotic depletion and ozone layer depletion problems because more material are used while downscaling the power plant machineries of a small-scale binary system. Abiotic depletion and eutrophication impacts are nearly equivalent in both systems.

In the operation phase, this research assumed for a GTE system, the most environmental concern is from gas emitted from geothermal fluids. Since no gas will emit from a binary system in the operation phase, no impacts occur in this phase and therefore the operation phase of a small-scale binary system is considered more sustainable than of a large-scale flash system.

Summarized, a small-scale binary system is more sustainable when considering the deep well drilling process. In contrast, a large-scale flash system shows a better environmental performance when considering the process of power plant machinery production and pipeline construction. A small-scale binary system is more sustainable in the power plant building construction and operation phases.

Recommendations and suggestions for future research

Marchand et al., 2015 classified GTE systems into 3 categories: the type of energy produced (electricity or combined district heat and electricity), the type of reservoirs (conventional or unconventional) and the type of conversion technology. In future research, also a large-scale binary system and a small-scale flash system could be assessed. It would also be interesting to include different conversion technology scenarios. Also, different electricity production systems in Indonesia can be compared to figure out which is the most sustainable electricity production system.

Transportation should be included in all phases in a LCA research. The global warming potential values will be higher if also transportation is considered in a LCA study.

Finally, it would be nice to test how representative this research is when applied in another country or for other cases.

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