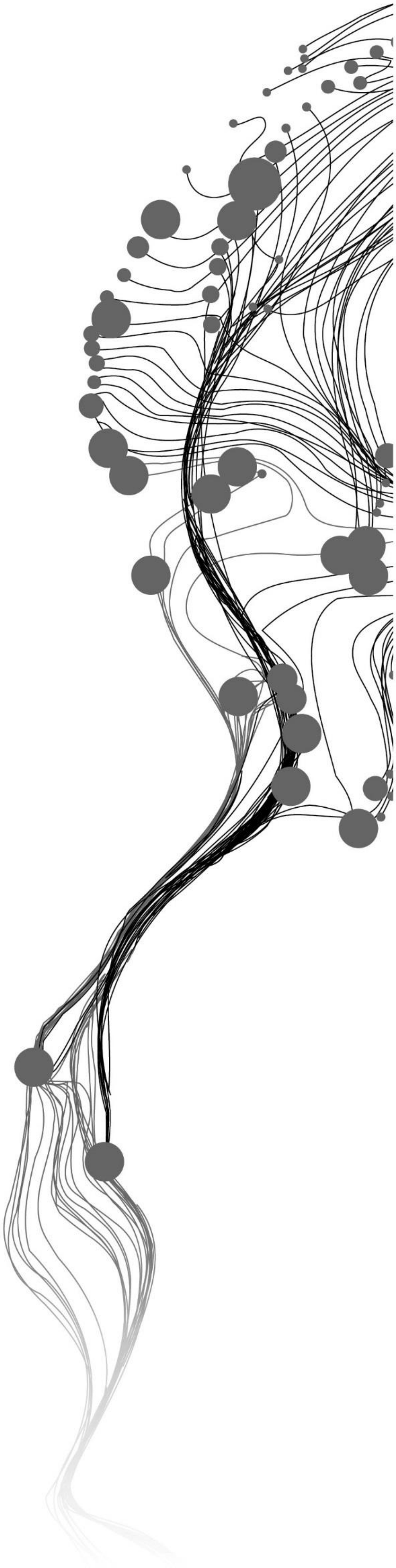
A life cycle assessment based comparison of large & small scale geo-thermal electricity production systems

TIANQI YU
February, 2017

SUPERVISORS:
Drs. J.M. Looijen (1st supervisor)
Prof. Dr. F.D. van der Meer (2st supervisor)



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Enschede, The Netherlands, February, 2017

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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SUPERVISORS:
Drs. J.M. Looijen (1st supervisor)
Prof. Dr. Freek van der Meer (2st supervisor)

THESIS ASSESSMENT BOARD:
Dr. A.G. Toxopeus (Chair, ITC, The Netherlands)
N. Willemsen, MSc (External Examiner, IF Technology)
Drs. J.M. Looijen (1st supervisor, ITC, The Netherlands)
Prof. Dr. F.D. van der Meer (2st supervisor, ITC, The Netherlands)

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.
The main aim of this research was therefore to compare the environmental impacts of a large-scale GTE flash system (the installed capacity is 110MW) and a small-scale binary GTE system (the installed capacity is 500KW) using LCA, for the construction and operation stages.

The results shows that marine aquatic eco-toxicity caused by deep well drilling is the most significant environmental impact in a life cycle aspect for a large-scale flash system, followed by human toxicity and abiotic depletion (fossil fuel). A small-scale binary system is more sustainable related to deep well drilling. Considering the process of power plant machinery and pipeline production, a large-scale flash system is more sustainable than a small-scale binary as overall less materials are required to produce the same amount of electricity. A small-scale binary system performs better in the power plant building phase.
The same can be said for the operation phase as there are zero gas emissions from a small-scale binary system while a large-scale flash system has a large impact on marine aquatic toxicity and to a lesser extent on global warming and human toxicity.

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Last but not least, I would like to address my gratitude to my parents and partner for their endless support and love.

ABBREVIATIONS

ISO: International Organization for Standardization
GTE: Geothermal energy
GWP: Global Warming Potential
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact assessment
ORC: Organic Rankine Cycle

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1. INTRODUCTION

Geothermal electricity production is considered to be more sustainable than the use of fossil fuels. But how do they perform 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?
In this chapter first an overview is given of general geothermal energy systems (chapter 1.1). Chapter 1.2 introduces what the life cycle assessment (LCA) is about. Chapter 1.3 explains the reason for doing a LCA for geothermal energy systems in this research, leading in chapter 1.4 to the main aims and objectives of this study. The thesis outline is shown in Chapter 1.5.

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). The demand for energy will still increase with a growing population and economy (Sullivan et al., 2010). Exploring and implementing renewable energy to generate electricity in a sustainable way is essential. Also, transition from fossil fuels to renewable energy sources is one of the biggest challenges and game changers for the coming decades but an essential one if we wish to reach the agreements of COP21 (Paris Agreement) in view of combating climate change and global warming. In COP 21, for the first time in over 20 years of UN negotiations, countries ratified an agreement 'to achieve a legally binding and universal agreement on climate, with the aim of keeping global warming below 2°C. Geothermal energy power is one of the sustainable solutions to generate electricity with minor greenhouse gas emissions.

Geothermal power generation has rapidly grown in the past few decades (Heberle et al., 2016; Lund & Boyd, 2015). The installed geothermal power capacity around the world increased by about 16% between 2010 and 2015 (Bertani, 2015). Geothermal energy provides power from a renewable energy, which is sufficiently stored in the earth on worldwide scale. Geothermal energy is an independent from season & time, and has the convenience of base load capability (Heberle et al., 2016; Bayer et al., 2013; Frick et al., 2010; Stefansson, 2005; Frick et al., 2007). Due to those advantages, geothermal energy is regarded as a renewable energy with sustainable future potential (Heberle et al., 2016; Bayer et al., 2013; Frick et al., 2007).

1.1. Geothermal energy systems

There are three traditional kinds of geothermal power generating systems: flash-steam, binary and dry-steam (DiPippo, 2012).

Single flash and double flash are the two types of flash steam systems. The single-flash steam power plant is the base of the geothermal energy industry (DiPippo, 2012). It is a liquid dominated system, in which fluids flash to steam, either in the well, or at specific separators. In this way a she single-flash plant is a simple way to convert geothermal energy into power (DiPippo, 2012). Until 2011, there were 168 units of single flash plant in operation in 16 countries around the world (DiPippo, 2012). Around 29% of all geothermal plants are single-flash power plants, which account for about 43% of the total installed geothermal worldwide capacity (DiPippo, 2012). The potential environmental impacts from a single flash system, during normal operation, are mainly caused when geothermal steam emits non condensable gases, such as hydrogen sulfide (H2S), carbon dioxide (CO2) and methane (CH4) (DiPippo, 2012). Since single-flash and double-flash power plants have the same potential environmental impacts, this research just focuses on the single flash geothermal power plant.

Geothermal binary plants are the most widely used type of geothermal power plants until August 2011 (DiPippo, 2012). In a binary system water or steam from the geothermal reservoir never interacts with the turbine units and in that way differ from flash steam systems. Recently 235 geothermal units of this type of power plant are in operation in 15 countries, covering 40% of all the geothermal units in operation around the world (DiPippo, 2012). Also, several binary power plants added flash steam plants to produce more power. Binary power plants are popular in recent years as they emit only few greenhouse gases (Frick et al., 2010). The only environmental impact of this type of plant is during the heat rejection phase since the geo-fluid is pumped from the reservoir, through heat exchangers and rejected completely to the reservoir (DiPippo, 2012). What's more, the cycle working fluid is entirely within pipes, heat exchangers, and the turbine. The only potential pollution from binary plants is thermal pollution (DiPippo, 2012). Thus, during the operation of a binary power plant, there are very few environmental impacts. However, the construction of binary plants needs large amounts of raw materials and energy (Frick et al., 2010).

Dry-steam geothermal plants have very low potential environmental impacts. The non-condensable gases in the steam are isolated in the condenser and the hydrogen sulfide can be removed by vacuum pumps or steam-jet ejectors.

All in all, geothermal energy production does less damage to the environment than conventional fossil fule 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 the 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).

1.2. Life cycle assessment

Life cycle assessment (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). LCA is been considered as an effective tool to achieve a holistic approach on evaluating the environmental impacts of products (Karlsdottir et al., 2010). 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 roads associated with the power plant and the operation of the power plant itself (Karlsdottir et al., 2010; Frick et al., 2010; Lacirignola & Blanc, 2013).

1.3. Problem statement

The utilization of geothermal energy mainly focuses on two categories: power generation and direct use (Bayer et al., 2013). This study will only consider geothermal energy (GTE) used for electricity generation. The majority of the research carried out on LCA for GTE systems focuses on the LCA of large-scale geothermal power plants. Large-scale geothermal power plants are usually built in developed areas with a well distributed electricity grid. In many rural areas however local communities are not connected to such a grid and therefore still rely on fossil fuels or have no access to electricity at all. Small-scale geothermal power plants can be a solution. They can be built in both developed and undeveloped areas (off-grid areas).

IF technology company under the GEOCAP project has developed a small, modular geothermal power plant that can fit in a 40 foot shipping container. After instalment this small-scale binary system produces around 500 kW of clean, reliable and cheap electricity, without requiring fuel or emitting any harmful greenhouse gasses. However, the potential of small scales geothermal plants, especially their environmental performance still needs to be explored more (personal communication, Niek Willemsen, 25 August, 2016).

The focus and also innovation in this research is to carry out a LCA for a small-scale GTE system, MiniGeo and compare its environmental impacts with those of a large-scale GTE production system.

1.4. Main aim and objectives

In this research the LCA of a large-scale flash system will be compared with a small-scale binary system for the construction and operation phase.

In order to reach this aim the following objectives were defined in this study:

1) To identify and describe different GTE electricity production systems
2) To design and develop a life cycle assessment (LCA) framework for a GTE system
3a) To design and implement a life cycle inventory (LCI) analysis for different GTE systems
3b To explore and assess the potential life cycle environmental impacts (LCIA) and factors related to the construction and operation activities
4) To compare a large-scale flash with a small-scale binary GTE system based on the life cycle based environmental impacts.

For each objective specific research questions are formulated, as is presented in table 1. The methodology and techniques needed to answer those questions, as well as data requirement and expected output to reach each objective are included in this table as well.

1.5. Thesis outline

Chapter 2 describes the literature reviews of the technical aspects of geothermal energy electricity production systems as well as LCA for geothermal energy systems.

Chapter 3 presents the LCA framework of this research for geothermal energy systems

Chapter 4 explains the life cycle inventory (LCI) analysis for different GTE systems.

In chapter 5 the environmental impacts of a large-scale flash system are presented, for the construction, operation, disposal and for all the GTE phases together.

In chapter 6 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.

Chapter 7 includes the discussion, conclusions and recommendations

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

Table 1 Research framework

	Research objectives	Research questions	Methodology/ Techniques	Data	Expected output
1	To identify and describe different GTE electricity production systems	a) What are the different GTE techniques for electricity production? b) What are the geo-technical characteristics of a large-scale GTE plant (like Wayang Windu)? c) What are the geo-technical characteristics of a small- scale GTE plant (MINIGEO)?	Expert knowledge & Literature review	Books and articles on GTE systems & techniques	Main technical characteristics of large-scale & small-scale GTE systems
2	To design and develop a life cycle assessment framework for a GTE system	a) What is the system boundary? b) What is the functional unit? c) What is the general LCA framework for GTE systems? d) What LCA software can be applied for GTE systems?	Literature review; LCA software; Expert knowledge	Parameters distinguishing GTE scenarios	LCA framework for a generic GTE system; LCA software used
3	A) To design & implement a life cycle inventory (LCI) analysis of GTE systems	a) Which GTE processes can be included in LCI? b) Which materials are needed for the different GTE processes? c) Which parameters are needed for LCI processes (for a large-scale and small-scale system)?	Literature review; LCA method (LCI)	Articles of LCA on GTE systems; LCA software;	System boundary & system unit; General Life cycle inventory framework; List of parameters
	B) To explore and assess the potential life cycle environmental impacts and factors related to the construction and operation activities	a) What are the potential environmental impacts and indicators in the construction, operation and disposal phase (for a large-scale and small-scale system)? b) What are the references to compare the impacts?	LCA method (LCIA); literature review; expert knowledge	Indicator data for each impact; LCA software;	Impacts, indicators and specific data for each indicator; References
4	To compare a large-scale flash with a small-scale binary GTE system based on the life cycle environmental impacts.	a) What is the difference between a large-scale flash & small-scale binary GTE system? b) Which system is performing more sustainable and effective?	LCA method (LCIA comparison); Literature review & Expert knowledge	LCA software;	Comparison of a large- scale flash and small-scale binary GTE system

2. LITERATURE REVIEW

The literature review will focus on the technical aspects of geothermal energy technology (2.1) as well as life cycle assessment (LCA) framework for geothermal energy systems (2.2).

2.1. Technical aspects of geothermal energy technology

Geothermal resources and different reservoirs are described in section 2.1.1. Section 2.1.2 explains the geothermal conversion systems. Section 2.1.3 discusses the difference between large and small scale geothermal plants.

2.1.1. Geothermal resources and reservoirs

A geothermal resource is an abnormally high geothermal gradient but there may also be geothermal resources in hot dry rock.(Reference) Thermal energy stored in rock and fluid within the rock inside the earth's crust. If cooling 1 km^3 of rock down by 10 degree, 5000GWh thermal energy would be released. Due to various geological processes, some regions (such as volcanic areas) have high temperatures and flow rates of geothermal resources at very shallow depths (Hirschberg S.W. & Burgherr, P., 2015).There are four main kinds of geothermal resources: hydrothermal, geo-pressured, hot dry rock, and magma. Currently, hydrothermal is the only widely used geothermal resource. The other three resources are still in the infant stages of development [a] ([a] http://lsa.colorado.edu/essence/texts/geothermal.html).
Hydrothermal resources have the common ingredients of water (hydro) and heat (thermal). Hydrothermal resources are the only used geothermal resources currently (DiPippo, 2012). Hydrothermal resources are used for different energy purposes depending on their temperature and depth. When the temperature of a hydrothermal resource is around 100-150 °C (Walraven et al., 2013). It is called low hydrothermal temperature. Low temperature geothermal resources can be directly used in spas or to heat buildings. Heat from geothermal resources is used to dry ceramic, lumber, vegetables, and other products. When the temperature of a hydrothermal resource is above 150 °C, the resource can be used to generate electricity.
The efficiency of heat transfer within rocks is very slow. In order to increase that transfer efficiency, water is used as a medium for extracting and transporting heat. Through injection geothermal wells, cool water can reach the hot rock, then makes contact with the rock (heat exchanger) and finally the hot water is pumped back to the surface. This is how a geothermal reservoir works (Hirschberg S.W. & Burgherr, P., 2015).
A geothermal reservoir is a subsurface region where the rocks contain hot water and/or steam that can be withdrawn using wells. It is a continuous state of convective flow, which carries heat from deep underground to exploitable depths. The essential elements of a geothermal reservoir are heat (high temperature), working fluid (water and/or steam) and permeable flow rates as shown in Figure 1. Rainwater and snowmelt feed underground thermal aquifers. When hot water or steam is trapped in cracks and pores under a layer of impermeable rock, it forms a geothermal reservoir (Blodgett, 2014).

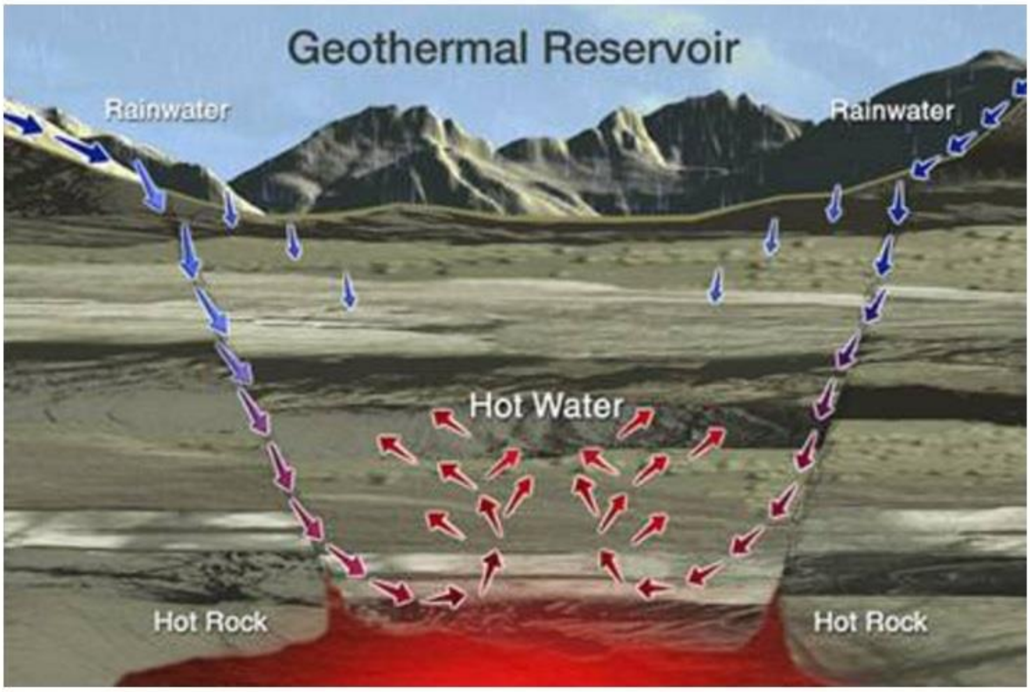


Figure 1 Geothermal reservoir (Source: Blodgett, 2014)

2.1.2. Geothermal conversion systems and power plants

As described in chapter 1, geothermal power plants are classified into three commercial types of conventional geothermal power plant systems: flash, binary and dry steam (Blodgett, 2014). The depth, temperature and geological characterization of geothermal resources are not exactly the same. In order to exploit geothermal resources wisely, various geothermal energy electricity production systems are applied. Figure 2 shows the different geothermal systems used for geothermal resources at different depths and temperatures.

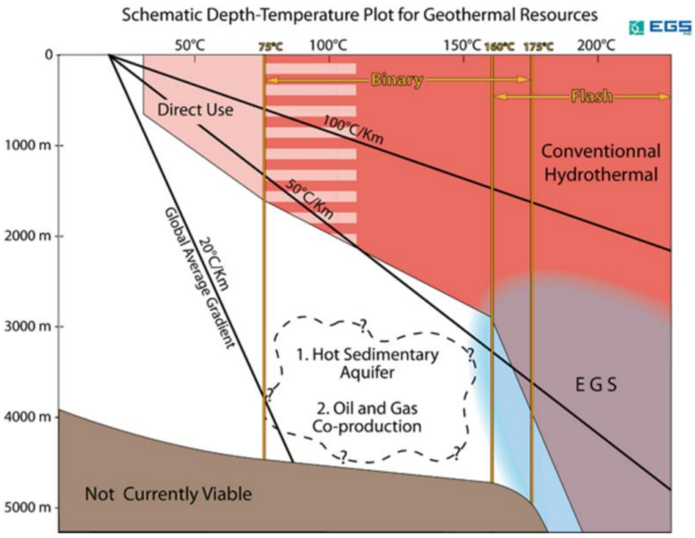


Figure 2 Schematic Depth-Temperature Plot for Geothermal Resources

(Source: https://geothermal.org/what.html; EGS: Enhanced geothermal system)

Flash systems can be used for moderate and high temperature liquid-dominated resources. The binary systems can be utilized for the lower temperature liquid-dominated resources. Dry steam systems can be used for dry-steam resources. In the next section, the different geothermal power plants combined with their conversion systems are described.

a) Flash power plant system

In a geothermal flash power plant, high pressure separates steam from water in a steam separator as the water rises and as pressure drops (Matuszewska ., 2011). The steam is delivered to the turbine then powers a generator. The liquid is reinjected into the reservoir. Figure 3(a) and 3(b) shows the system diagram of a flash conversion system and flash system power plant, respectively. A Single flash system power plant has one turbine and a double flash system power plant has two turbines.

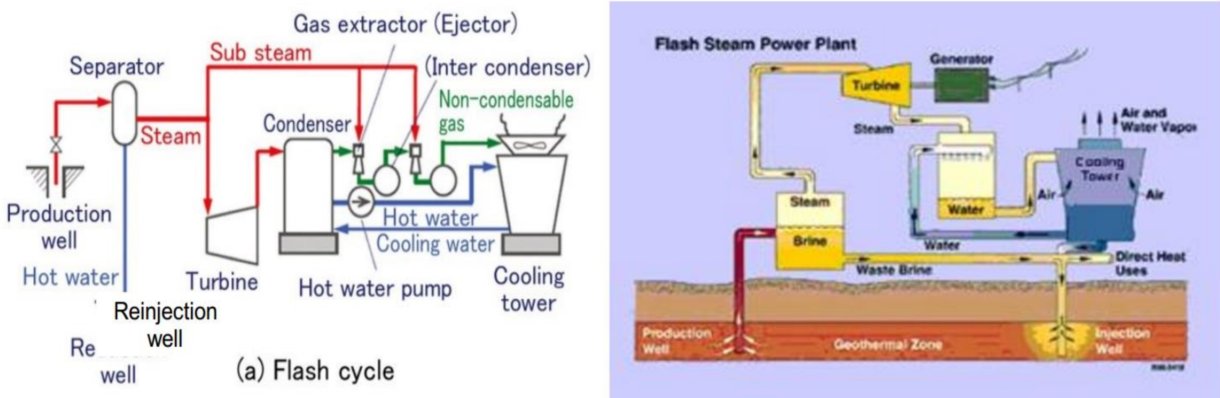


Figure 3 System diagram of typical flash system and flash system power plant

3(a) Flash conversion system (Fukuda et al., 2015) 3(b) Flash power plant (Blodgett, 2014)

b) Binary power plant system

A binary system utilizes an Organic Rankine Cycle (ORC), in which geothermal water is used to heat a second liquid that boils at a lower temperature than water, such as isobutene or pentafluoropropane (Matuszewska ., 2011). This is called a working fluid. A heat exchanger separates the water from the working fluid while transferring the heat energy. When the working fluid vaporizes, the force of the expanding vapor, like steam, turns the turbines that power the generators. The geothermal water is then reinjected in a closed loop, separating it from groundwater sources and lowering emission rate further. Figure 4(a) shows the system diagram of binary conversion system and figure 4(b) of an air cooled binary power plant.

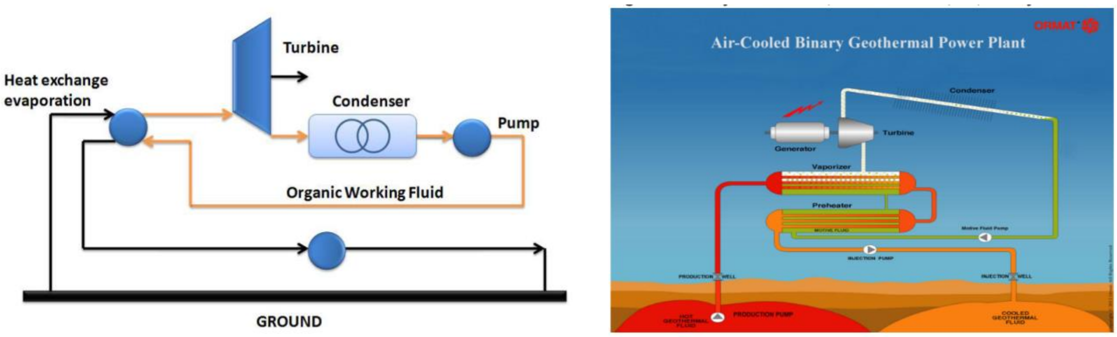


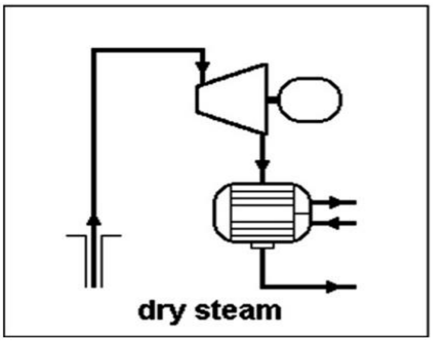
Figure 4 System diagram of typical binary system and binary system power plant

4(a) Binary conversion system (Matuszewska., 2011) 4(b) Binary power plant (Blodgett, 2014)

c) Dry steam power plant with dry steam system

Geothermal dry-steam power plants were the earliest commercial power plants, which were located in Tuscany, Italy. Because the geo-fluid only consists of steam, it was easy to install a mechanical device to make use of the available energy (DiPippo, 2012). Dry-steam plants are simpler and more economic than flash-steam ones since there is no geothermal brine. Until August, 2011, there were 71 units of this type of plants in operation, which accounts of 12% of all geothermal plants and 27% of the total geothermal capacity around the world (DiPippo, 2012). The two major dry steam power plants in the world are: Larderello and The Geyser, in Northern California, U.S. (DiPippo, 2012).

In a geothermal dry steam power plant, steam alone is produced directly from the geothermal reservoir and is used to run the turbines that power the generator. Because there is no water, the steam separator used in a flash plant is not necessary. Figure 5(a) and 5(b) shows the system diagram of dry steam system and dry steam power plant, respectively.



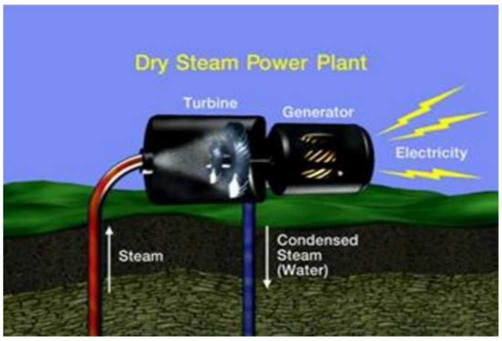


Figure 5 System diagram of dry steam system and dry steam power plant

5(a) Dry steam (DiPippo, 2012) 5(b) Dry steam power plant (Blodgett, 2014)

This research will only focus on flash and binary power plants because they are currently most often used by GTE development.

The key differences between the different geothermal energy conversion systems are shown in table 2, in terms of reservoir temperature, utilization efficiency, plant cost and complexity and current usage.

Table 2 Comparison of basic geothermal energy conversion systems (Source: DiPippo, 2012)

Type of plant	Reservoir temperatures, °C	Utilization efficiency, %	Plant cost and complexity	Current usage
Single-flash	200–260	30–35	moderate	widespread
Double-flash	240–320	35–45	moderate → high	widespread
Dry-steam	180–300+	50–65	low → moderate	special sites
Basic binary	125–165	25–45	moderate → high	widespread

2.1.3. The difference between large and small scale geothermal system plants

The geo-technical differences between large-scale and small-scale GTE systems are the size of the plant (Kw electricity) and the depth of wells. In general, small scale power plants produce between 300 kW and 1 MW electricity production (Kutscher, 2001). (Soediono, 1989) defines the small-scale geothermal power plant as small when the capacity electricity is 5 MW or below 5MW. Therefore, this research defines the geothermal large-scale geothermal power plant as large when the installed capacity is above 5MW.

Large-scale geothermal systems are usually built in more developed areas (on-grid). However, small scale geothermal system can be built in both developed and undeveloped areas (personal communication, Niek Willemsen, 25 August, 2016).
MiniGeo is a small scale binary system and is designed to provide electricity in off-grid remote communities. The benefit of a binary system is no gas is emitted from geothermal fluid and the power plant building area is small enough to use shipping containers. http://www.iftechnology.nl/off-grid-electricity-production-with-minigeo

2.2. Life cycle assessment (LCA) methodological framework for GTE systems

Chapter 2.2 explains the general life cycle assessment method according to ISO, starting with a general description of a LCA framework (2.2.1), followed by an explanation of the different components of this LCA framework (sections 2.2.2 – 2.2.4). In chapter 2.3 examples are given of LCA studies carried out for GTE systems.

2.2.1. General description of a LCA framework and software

Life Cycle Assessment is a process to evaluate the environmental impacts of a product, process or activity throughout its life cycle by identifying and quantifying energy and raw materials used and disposals released to the environment. LCA is considered as a decision support tool for both policy makers and industry in evaluating the life cycle impacts of a process or product. The International Organization for Standardization (ISO) prepared a general LCA framework, as shown in Figure 6.

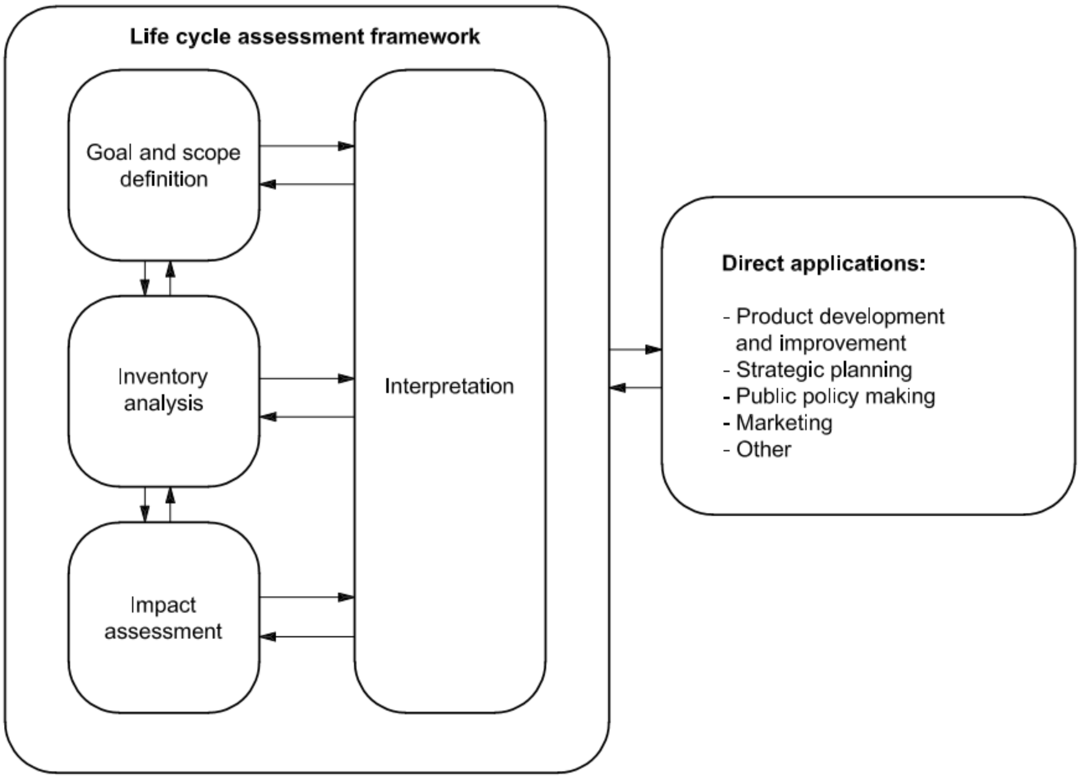


Figure 6 LCA framework

(Source: ISO 14040, 2006**)**

The requirements of ISO 14044 must be considered when performing a LCA. A typical LCA project plan includes the following main steps (ISO 14040, 2006):
1. Goal definition and scope: Identify a product, process or technology; define the context, system boundaries and level of detail.
2. Inventory analysis (LCI): Identify and quantify the inputs (materials and energy) and output (environmental releases).
3. Impact assessment (LCIA): Assess and quantify the potential environmental impacts (on both human health and ecology).
4. Data interpretation: Summarize and discuss the results from the LCI and LCIA to recommend or select a better product/process/technology

LCA software

Part of this research was spent on the exploration of various LCA software packages, such as Gabi and SimaPro, which are both widely used in LCA studies.
SimaPro is a commercial LCA software (https://www.pre-sustainability.com/simapro). The benefit res of SimaPro is we can add our own process data into the LCI calculations (Technosphere). Also, default data from the integrated database can be used and then (partly) replaced by its own data.

Gabi is a free LCA software for education (http://www.gabi-software.com/international/software/). Gabi has a very user friendly interface. We can add data to every process in the project considered and the relation between flow and processes can be determine precisely in the LCI.

As SimaPro has a more integrated database and more importantly, it has an Indonesian deep well drilling, pipeline construction and deep well closure dataset specifically for Indonesia, SimaPro was selected to conduct a LCA for GTE systems in this research.

2.2.2. Goal and scope definition

The main goal and purpose of the LCA are part of the goal definition. Typical scope items to address are functional unit and system boundary.

Function, functional unit and reference flows

A system may have a number of possible functions and the one(s) selected for a study depend(s) on the goal and scope of the LCA.
The functional unit defines the quantification of the identified functions (performance characteristics) of the product. The primary purpose of a functional unit is to provide a reference (common unit) to be able to compare two or more products,
It is also important to determine the reference flow, as part of the functional unit. A reference flow is "the measure of product components and materials needed to fulfill the function, as defined in the functional unit" (ISO 14040, 2006).

System boundaries

LCA is conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. Ideally, the production system should be modelled in such a manner that inputs and outputs at its boundary are elementary flows. However, resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study (ISO 14040, 2006).
When setting the system boundary, several life cycle stages, unit processes and flows should be taken into consideration.

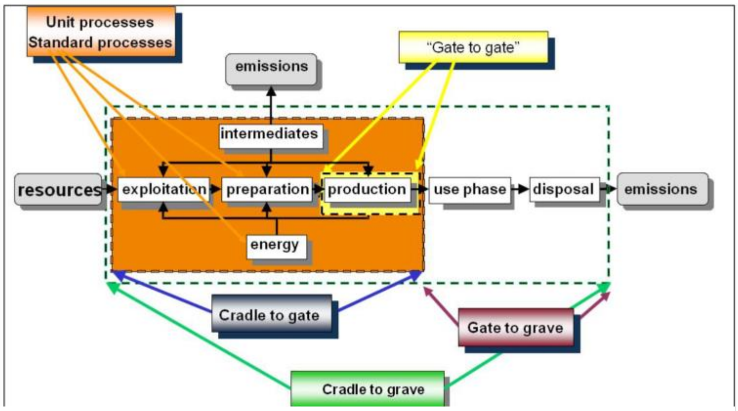


Figure 7 System boundaries of a LCA

(Source: PE International, no date. Gabi tutorial from http://www.gabi-software.com/international/support/gabi-4-learning-center/paper-clip-tutorial/)

Figure 7 shows the four different system boundaries that can be used in LCA studies (ISO 14040, 2006): cradle to gate, gate to grave, gate to gate and cradle to grave. Specifically, cradle to gate is the construction phase of a system/product. Gate to grave represents the operation and disposal phase. The relations within the production part are called gate to gate. The whole life cycle process including construction, operation and disposal phases together is cradle to grave. This study will consider a cradle to grave approach for the LCA of a large-scale flash system and a cradle to gate analysis for a small-scale binary system (Mini-Geo).

Data quality requirements

Data quality requirements specify in general terms the characteristics of the data needed for the study. Descriptions of data quality are important to understand the reliability of the study results and properly interpret the outcome of the study. A large part of this research was spent on literature reviews of LCA studies for GTE and data requirements.

2.2.3. Life cycle inventory analysis (LCI)

Data collection and calculation procedures to quantify relevant inputs and outputs of a product system are the main elements involved in a LCI.

Figure 8 shows the process of setting up a LCI. The process of conducting a LCI is iterative. As data is collected and more is learned about the system, data requirements or limitations may be redefined or a change in the data collection procedures may be required.

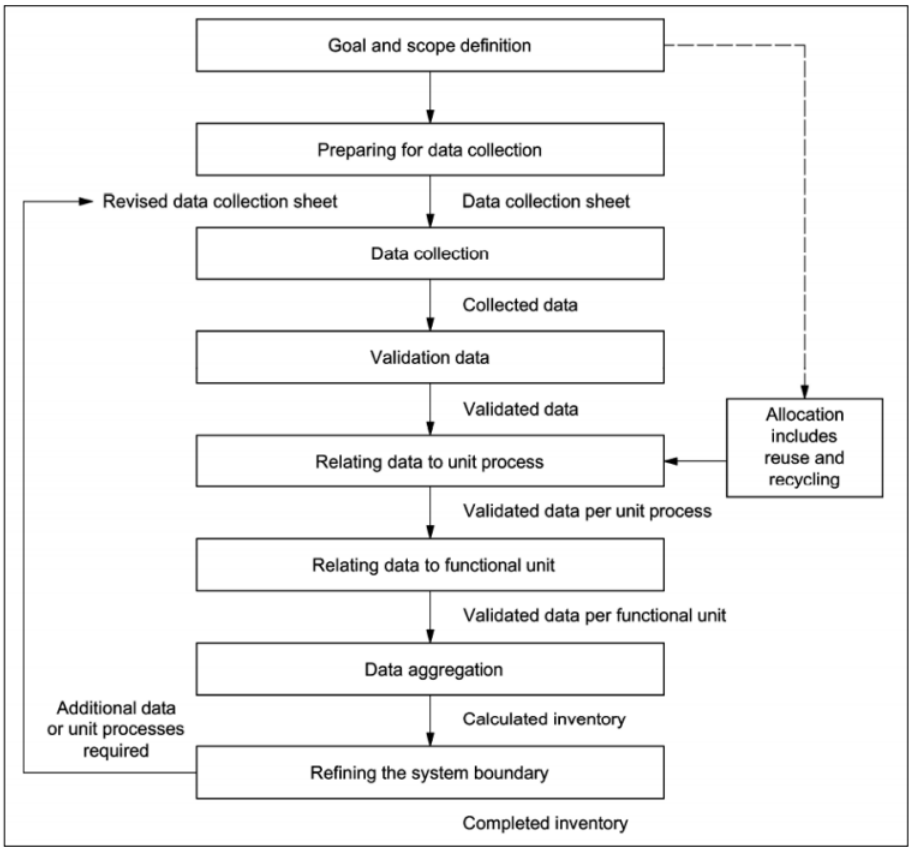


Figure 8 Data collection and calculation process

(Source: Gabi tutorial from http://www.gabi-software.com/international/support/gabi-4-learning-center/paper-clip-tutorial/)

The diagram (Figure 9) below illustrates the main lifecycle stages to be considered in LCA.

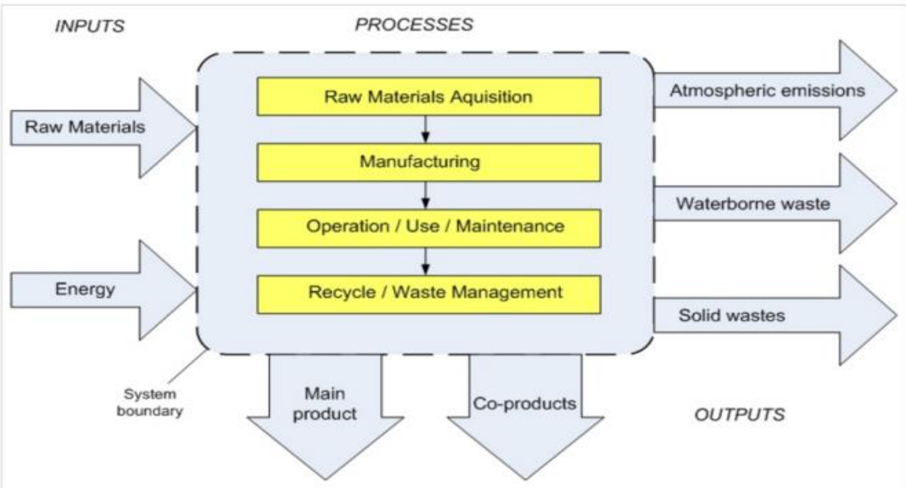


Figure 9 Main flows and stages considered in life cycle assessment
(Source: https://www.e-education.psu.edu/eme812/node/701)

The first step is the raw material acquisition. Second step is the manufacturing and construction. The third one is operation, use or maintenance. The last step is the decommissioning stage (recycling or waste disposal). Each of these stages has inputs of material and energy and outputs, for example atmopspheric emissions, waterborne wastes and/or solid wastes (adapted from https://www.e-education.psu.edu/eme812/node/701).

2.2.4. Life Cycle Impact assessment

The Life Cycle Impact Assessment (LCIA) identifies and evaluates the amount and significance of the potential environmental impacts arising from the LCI. Firstly, the inputs and outputs are classified to impact categories and their potential impacts are quantified based on characterization factors. Figure 10 shows an example of the conversion from emissions to impact potentials via classification and characterization.

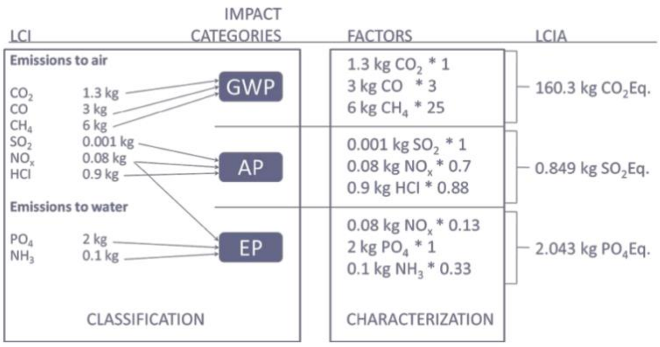


Figure 10 Example of impact categories and related factors

(Source: Gabi tutorial from http://www.gabi-software.com/international/support/gabi-4-learning-center/paper-clip-tutorial/)

In LCA, the amount of used resource used and emissions by a product/process are compiled in the Life Cycle Inventory (LCI). LCIA is performed to assess the environmental impacts, such as climate change, human health, etc. Generally, climate change, acidification, eutrophication, human toxicity, eco-toxicity, photochemical ozone formation, aquatic toxicity (marine and fresh water) are included in LCIA as impact categories. Each impact category needs specific impact indicators. Therefore, due to the different emissions and resources consumed, different products/systems can be compared based on the impact categories.

LCIA methods

Many LCIA methods exist, such as CML-IA, Impact 2002+, ReCiPe Endpoint/ Midpoint, Ecoindicator 99, Ecological Scarcity Method and TRACI. In table xx three currently widely used LCIA methods in LCA are compared. In this research, CML-IA is selected, as this invloves eleven problem oriented environmental impact categories, which are relevant for the LCA of GTE.
Table 3 adapted from (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) shows the different impact categories and related indicators selected for this research (personal communication with Niek, IF technology). The detailed impact modeling information is in Appendix 1.

Normalization

In the LCIA the impact of the different LCA stages are quantified. But how bad or good are those impacts? Therefore the impacts have to be compared with some reference values.

Normalization is a process to compare the quantified impact category values to a reference value available in a region, country or worldwide for a time period, such as one year. The references can be, for example, the overall emission of CO2-equivalent in Indonesia for a year and also can be the CO2-equivalent of one person in China within a year.

Table 3 Overview of three currently used environmental impact assessment methods for LCA

LCIA method	CML-IA baseline	Recipe	Impact 2002 +
	http://cml.leiden.edu/software/data-cmlia.html		http://www.epfl.ch/impact
Impact Categories			
Climate change	kg CO2-eq./kg emitted to air GWP100	CO2-eq / kg emitted	kg CO2eq.
Ozone layer depletion	kg ethylene -11-eq./kg emitted to air	CFC-11-eq. emitted	kg CFC-11 eq. into air
Human toxicity	kg 1,4-DCB-eq. emitted to air/kg emitted to air water, soil	1,4-DCB to air/kg emission for toxic impacts	in air, soil, agricultural soil and water) kg chloroethylene into air eq. into air (cancer & non cancer) kg PM2.5eq. into air
Acidification	kg SO2-eq./kg emitted to air	kg SO2-eq. /kg, time horizon 500 years	kg SO2 eq. into air
Terrestrial eutrophication	kg $PO4^{3--}$ eq./kg emitted to soil.	None	kg SO2 eq. into air
Aquatic eutrophication	kg $PO4^{3--}$ eq./kg emitted to water.	kg N-eq/kg emission for marine eutrophication ; kg P-eq/kg emission for freshwater eutrophication.	kg PO4 3- eq. into water
Eco-toxicity: Fresh water, Marine aquatic terrestrial	kg 1,4-DCB-eq. emitted to fresh water, sea water or soil/kg emitted	1,4-DCB to water or soil/kg emission. Categories are freshwater, marine water and soil ecosystems	kg triethylene glycol eq. into water / soil
Photochemical oxidation	kg ethylene eq./kg emitted to air	kg NMVOC-eq./kg emitted	kg ethylene eq. into air

Abiotic depletion	kg antimony equiv./kg extraction		
Land use	m2.yr/m2.yr	(occupation) m2.yr, (transformation) m2	m2 organic arable crop
Lonising radiation	None	air, 14 river, 14 ocean) kBq U-235 air- eq/kBq	in air, 13 in water) Bqeq carbon-14 into air
Resource consumption	kg antimony eq./kg extracted	mineral extraction Mc values [-/kg],Fossil fuel, upper heating value [MJ/kg]	MJ total for energy

2.2.5. Interpretation

The aim of interpretation, one of the ISO 140440 requirements, is to check if the data and processes implemented in the research are correct. This can be done by carrying out an uncertainty and/or sensitivity analysis.

2.3. LCA studies for GTE systems

(Karlsdóttir et al., 2015) present a life cycle inventory (LCI) of a flash geothermal combined heat and power plant located in Iceland. This LCI describes the material and energy demands in construction and operation phase of a geothermal combined heat and power plant located in Iceland. This LCI describes the material and energy demands in construction and operation phase of a geothermal combined heat and power plant. Gas emissions, waste water and waste heat are also included. This LCI was used for most of the parameters for a large-scale flash power system.
A summary of the literature review of the current life cycle assessment of GTE power plants is given in Appendix 2.

3. LCA FRAMEWORK FOR GTE SYSTEMS

Geothermal energy is generally considered more sustainable and causes less pollution compared to conventional electricity production systems using coal or fossil fuels. But how sustainable is a GTE production system if the whole life cycle – from construction, operation to finally disposal – is considered? And are there differences between GTE systems?

LCA can be used as a method to compare both positive and negative environmental impacts of different energy systems for their entire life cycle. In LCA, the environmental performance of energy systems including both the construction phase of energy systems (including the material and energy used in the construction phase), the electricity production phase (operation phase) and the disposal phase. In addition, LCA can also predict the potential impacts (such as global warming potential, human toxicity etc.) of the different GTE phases.
(Karlsdóttir et al., 2015)describes a LCA for a large-scale flash system in Iceland: the functional unit, system boundary, LCI components, choice of impact categories, method for impact assessment, principles for allocation and data quality requirements. Based on this information and the literature review on LCA for GTE systems, a LCA framework for GTE was compiled, as shown in Figure 11.

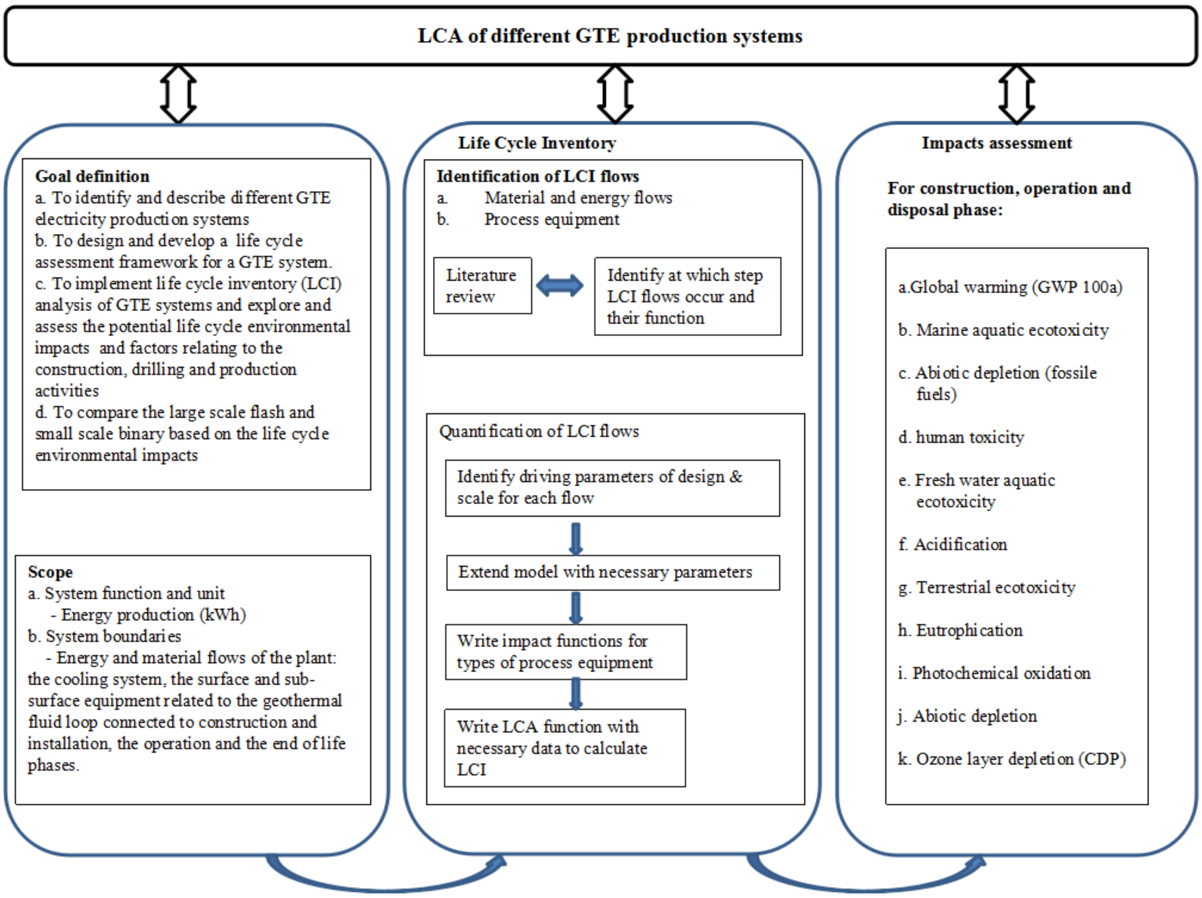


Figure 11 LCA framework for GTE electricity production systems

3.1. GTE functional unit and system boundary

The GTE functional unit used in this research is electricity production (kWh).

As explained in section 2.2.3, 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 3) end of life phase including the decommissioning and recycling or disposal of the components 4) the transportation among above mentioned stages. Figure 12 shows the system boundary for a geothermal energy system in Iceland. 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.

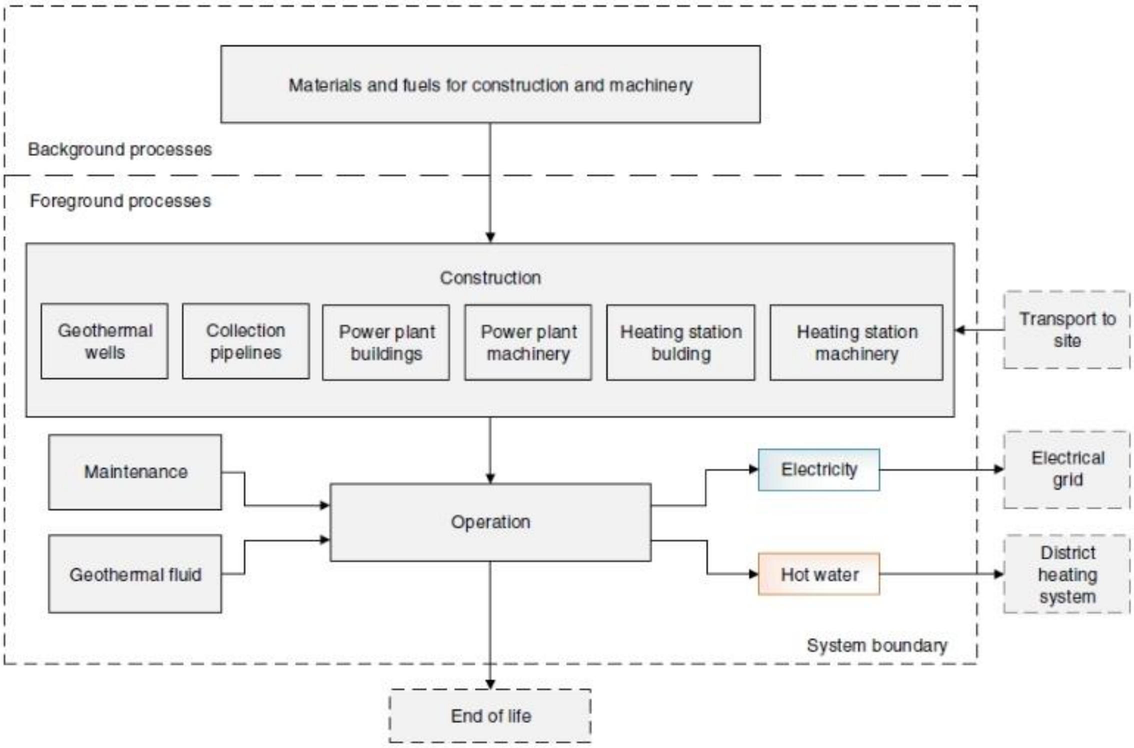


Figure 12 General system boundary for geothermal energy systems

(Source: Karlsdóttir et al., 2015)

3.2. 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. Figure 3.3 gives an overview of the information included in the LCI for the different LCA stages regarded in this study. The total processes in the construction phase are inside the yellow frame. The LCI analysis can be conducted in LCA software, in this case SimaPro was used.

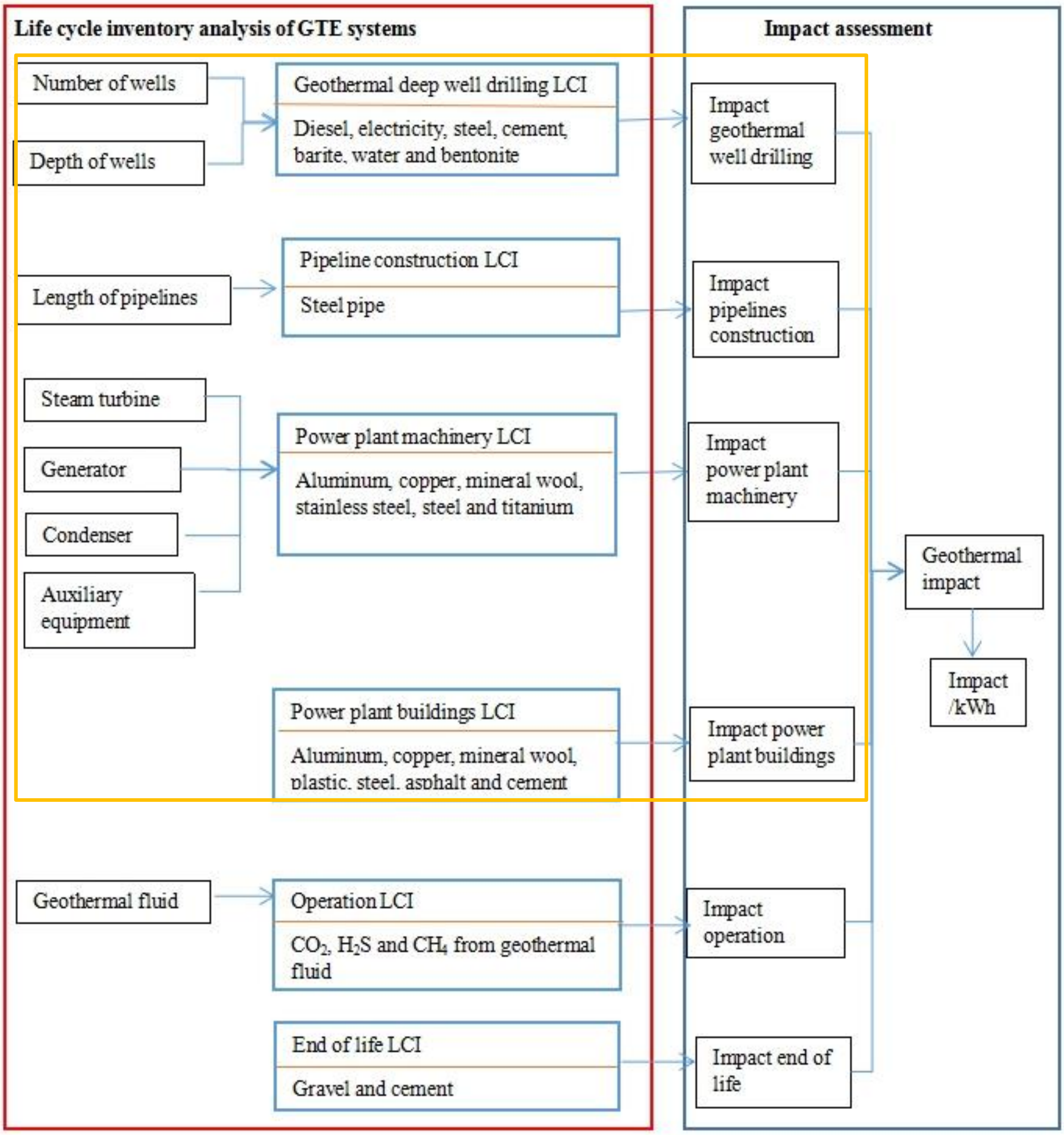


Figure 13 The components and processes in LCI analysis of large-scale flash system

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

Impact assessment is based on the four LCA phases described section 3.1, the system boundary. An overview of possible environmental impact categories as well as specific impacts and emissions for a GTE system is given in Figure 14.

Figure 3.4shows the direct life cycle environmental impacts of a geothermal power production system

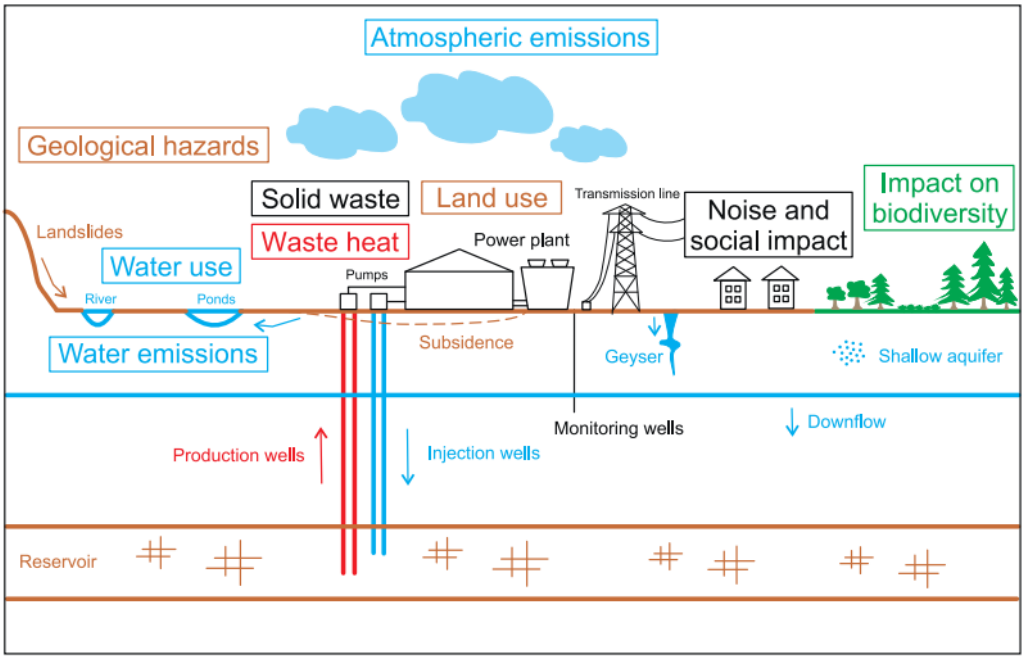


Figure 14 Direct life cycle environmental impacts of a GTE power plant

(Source: Bayer et al., 2013)

When the LCIA is applied to geothermal energy systems, a number of impact metrics need to be identified. Table 4 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.

Table 4 Overview of three currently used environmental impact assessment methods for LCA

LCIA method	CML-IA baseline	Recipe	Impact 2002 +
	http://cml.leiden.edu/software/data-cmlia.html		http://www.epfl.ch/impact
Impact Categories			
Climate change	kg CO2-eq./kg emitted to air GWP100	CO2-eq / kg emitted	kg CO2eq.
Ozone layer depletion	kg ethylene -11-eq./kg emitted to air.	CFC-11-eq. emitted.	kg CFC-11 eq. into air.
Human toxicity	kg 1,4-DCB-eq. emitted to air/kg emitted to air water, soil	1,4-DCB to air/kg emission for toxic impacts	in air, soil, agricultural soil and water) kg chloroethylene into air eq. into air (cancer & non cancer) kg

			PM2.5eq. into air
Acidification	kg SO2-eq./kg emitted to air	kg SO2-eq. /kg, time horizon 500 years	kg SO2 eq. into air
Terrestrial eutrophication	kg PO4^{3--}- eq./kg emitted to soil.	None	kg SO2 eq. into air
Aquatic eutrophication	kg PO4^{3--}- eq./kg emitted to water.	kg N-eq/kg emission for marine eutrophication ; kg P-eq/kg emission for freshwater eutrophication.	kg PO4 3- eq. into water
Eco-toxicity: Fresh water, Marine aquatic and terrestrial	kg 1,4-DCB-eq. emitted to fresh water, sea water or soil/kg emitted	1,4-DCB to water or soil/kg emission. Categories are freshwater, marine water and soil ecosystems	kg triethylene glycol eq. into water / soil
Photochemica l oxidation	kg ethylene eq./kg emitted to air	kg NMVOC-eq./kg emitted	kg ethylene eq. into air
Abiotic depletion	kg antimony equiv./kg extraction		
Land use	m2.yr/m2.yr	(occupation) m2.yr, (transformation) m2	m2 organic arable crop
Lonising radiation	None	air, 14 river, 14 ocean) kBq U-235 air- eq/kBq	in air, 13 in water) Bqeq carbon-14 into air
Resource consumption	kg antimony eq./kg extracted	mineral extraction Mc values [-/kg],Fossil fuel, upper heating value [MJ/kg]	MJ total for energy

3.4. Comparison of GTE systems

In this research, 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 large-scale flash system used in this research is Wayang Windu. Wayang windu is a large-scale single flash system, which is located in Indonesia. 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] ([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. The main reason to compare a large scale with a small scale geothermal plant is because little knowledge exists of the life cycle assessment of small scale geothermal plants. 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.

4. LIFE CYCLE INVENTORY (LCI) ANALYSIS OF DIFFERENT GTE SYSTEMS

Chapter 4.1 explains the LCI used for assessing a large-scale flash system. This is described in more detail for the construction phase (Chapter 4.1.1), the operation phase (Chapter 4.1.2) and the disposal phase (Chapter 4.1.3). In chapter 4.2 the LCI is described for a small-scale binary system, MiniGeo, for the construction phase (4.2.1) and the operation phase (4.2.2)

4.1. LCI for a large-scale flash system

4.1.1. Construction phase

In the construction phase, geothermal deep well drilling, collection pipelines, power plant machinery and power plant buildings are considered in this research. The reason to choose these construction processes is based on the study of (Karlsdóttir et al., 2015). The reason of this study to choose these processes are based on

Table 5 Life cycle inventory data for the large-scale flash system - Wayang Windu

Construction phase			
	Unit	Input/ Output	Amount
Geothermal well drilling (total drilling length: 62402m[d])			
Steel	kg/m $_{well}$	Input	309[a]
Cement	kg/m $_{well}$	Input	213 [a]
Barite	kg/m $_{well}$	Input	20 [a]
Bentonite	kg/m $_{well}$	Input	20 [a]
Water	m^3/m $_{well}$	Input	0.5 [a]
Electricity	kWh/m $_{well}$	Input	3932 [a]
Diesel	MJ/m $_{well}$	Input	111 [a]
Drilling waste	kg/m $_{well}$	Output	466 [a]
Wastewater	m^3/m $_{well}$	Output	0.5 [a]
Pipeline construction Total pipeline length:22km[e]			
Steel pipe	kg/m $_{pipes}$	Input	197[b]
Total steel pipe			4334000
Power plant machinery			
Aluminum	kg/MW	Input	242 [b]
Copper	kg/MW	Input	363 [b]
Mineral wool	kg/MW	Input	246 [b]
Stainless steel	kg/MW	Input	2,343 [b]
Steel	kg/MW	Input	8,616 [b]
Titanium	kg/MW	Input	523 [b]
Power plant buildings			
Aluminum	kg/MW	Input	578 [b]
Copper	kg/MW	Input	152 [b]
Mineral wool	kg/MW	Input	567 [b]
Steel	kg/MW	Input	11943 [b]
Asphalt	kg/MW	Input	31624 [b]
Cement	kg/MW	Input	86 [b]

Operation phase : 110MW			
CO2 from geothermal fluid	Kg/kWh	Output	0.0416[c]
H2S from geothermal fluid	Kg/kWh	Output	0.00102[c]
CH4 from geothermal fluid	Kg/kWh	Output	0.00000326[c]
Disposal phase			
Gravel	kg/m $_{well}$	Input	18.4 [a]
Cement	kg/m $_{well}$	Input	1.75 [a]

[a] Ecoinvent 3.0 database for deep well drilling in Indonesia ; [b] Life cycle inventory data for flash system from (Karlsdóttir et al., 2015)

[c] Gas emission data from (Marchand et al., 2015) ; [d] well drilling length from (Ketenagalistrikan et al., 2014)

[e] Length of pipelines from (Murakami et al., 2000)

In table 5 (upper orange section) an overview is given of all the GTE materials for the different construction processes, as well as their measurement unit and amount. All geothermal deep well drilling data and parameters are based on data from Indonesia and taken from the Ecoinvent 3.0 database in SimaPro 8.0. This database provides unit processess and life cycle inventories in various industrial areas. The data and parameters for pipeline construction, powerplant machinery and powerplant buildings are based on the LCI data for a large-scale flash system in Iceland (Karlsdóttir et al., 2015).

4.1.2. Operation phase

In the operation phase of a large-scale flash system, CO_2, H_2S and CH_4 emit from geothermal fluid (table 4.1, blue section). As the amount of CH_4 is very low, this output is not included in this research. In reality, the maintenance processes during the operation phase, such as making up wells, pipelines collection and scaling of turbine, are also important. However, since very limited maintenance information is available currently, the maintenance phase is not included in this research.

4.1.3. Disposal phase

The main process of disposal phase for this study is the well closure. The material used for the well closure contains gravel and cement. The data for large flash system are collected in Ecoinvent 3.0.

4.2. Small-scale binary system (Mini-Geo)

Since MiniGeo is a new concept and not yet implemented, there are no site specific data available. Therefore, all the LCI data for the construction are provided by the MiniGeo expert in IF technology. In this research the disposal phase is excluded as no MiniGeo power plant is yet constructed.

4.2.1 Construction phase

In order to compare the large-scale flash system with the MiniGeo system, the same processes are taken into account. For the construction phase also geothermal deep well drilling, collection pipelines, power plant machinery and power plant buildings are considered. The parameters and values for each of these processes and related materials are presented in table 6.

4.2.2 Operation phase

There are no emissions from geothermal fluid for a binary system. Therefore this phase is not included in the LCI. However when comparing the large-scale flash with the MiniGeo system (chapter 6), the gasses emitted from geothermal fluid will be set at 0 values for the MiniGeo LCIA.

Table 6 Life cycle inventory data for the small-scale binary system - MiniGeo

Construction phase			
	Unit	Input/ Output	Amount [f]
Geothermal well drilling: Depth of well: 2000m			
Steel	kg/m $_{well}$	Input	44
Cement	kg/m $_{well}$	Input	20
Barite	kg/m $_{well}$	Input	7.5
Bentonite	kg/m $_{well}$	Input	15
Water	m^3/m $_{well}$	Input	5
Electricity	kWh/m $_{well}$	Input	-
Diesel	MJ/m $_{well}$	Input	1077.5
Drilling waste	kg/m $_{well}$	Output	466
Wastewater	m^3/m $_{well}$	Output	5
Pipeline construction Total pipeline length:500m			
Steel pipe	kg/m $_{pipes}$	Input	100
Total steel pipe			50000
Power plant machinery 500kWh electricity production			
Aluminum	kg/MW	Input	2000
Copper	kg/MW	Input	3000
Mineral wool	kg/MW	Input	2000
Stainless steel	kg/MW	Input	17500
Steel	kg/MW	Input	19000
Titanium	kg/MW	Input	4100
Power plant buildings			
Cement	m^3/MW	Input	50
Steel	kg/MW	Input	15000

[f] Niek Willemsen (IF technology)

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

In this chapter, the life cycle impact assessment (LCIA) of a large-scale flash system (Wayang Windu) is described. The impact assessment method and approaches used in this research is explained in chapter 5.1. Chapter 5.2, chapter 5.3 and chapter 5.4 show the LCIA for the construction, operation and disposal phase respectively. The LCIA results for all the LCA stages are summarized in chapter 5.5.

5.1. 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, as was explained in the literature review part in chapter 2). Refer to Appendix 3

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 explained in section 5.2 (figure 15).

Since the impact categories have different measurement units, ***normalization*** is used to make those categories more comparable. The Normalization process available in SimaPro is done by multiplying the value of each impact with the weighting factor (A reference varying for different regions). The weighting factor in SimaPro is the inverse of the normalization value (1/n). As there is no specific normalization method for Indonesia, the internationally accepted World 2000 normalization method is selected for this research.

5.2. LCIA for the construction phase

Table 7 shows the absolute values (column Unit) of each impact category for the different LCA processes separately and for all the processes together (column Total). Deep well drilling shows the highest impact for most impact categories (except human toxicity and abiotic depletion), followed by pipeline construction. Power plant machinery and power plant building has the least environmental impacts in the construction phase. This is also illustrated in Figure 15, in which the percentages per impact category are given for the different GTE processes of the construction phase.

Table 7 The LCIA values of the large-scale flash system for construction phase

Sel	Impact category	Unit	Total	Deep well_drilling_large_flash	Geothermal power plant pipeline construtcion for	Power plant machinery large flash	Power plant building large flash
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	1.97E11	1.83E11	9.9E9	2.45E9	1.45E9
☑	Abiotic depletion (fossil fuels)	MJ	4.02E9	3.56E9	2.74E8	6.06E7	1.25E8
☑	Human toxicity	kg 1,4-DB eq	5.18E8	1.85E8	3.21E8	1.17E7	4.52E5
☑	Global warming (GWP100a)	kg CO2 eq	3.64E8	3.36E8	2.17E7	5.18E6	1.4E6
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	1.27E7	1.19E7	4.16E5	3.91E5	1.32E4
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	1.73E6	1.39E6	3.28E5	6.9E3	4.28E3
☑	Acidification	kg SO2 eq	1.62E6	1.47E6	1.21E5	2.31E4	1.15E4
☑	Eutrophication	kg PO4--- eq	3.45E5	3.25E5	1.52E4	2.87E3	2.28E3
☑	Photochemical oxidation	kg C2H4 eq	8.96E4	7.7E4	8.83E3	3.22E3	580
☑	Abiotic depletion	kg Sb eq	1.49E3	487	637	104	258
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	8.38	5.96	1.55	0.632	0.236

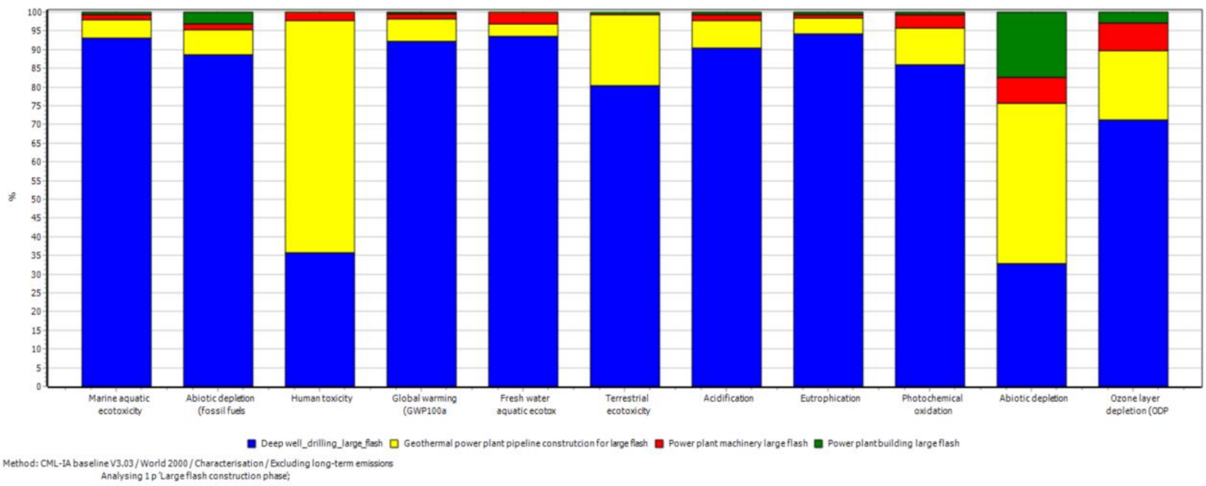


Figure 15 The LCIA for the large-scale flash system - percentages per impact category for the different GTE processes of the construction phase

The above figure shows deep well-drilling has overall the largest impact, followed by pipeline construction.

The impact of deep well drilling is relatively large. All are above 70 % for each impact category except for human toxicity (36%) and abiotic depletion(33%).

For pipeline construction, the impact is relatively large for human toxicity (62%) and abiotic depletion (43%).

For power plant machinery, abiotic depletion (7%) and ozone layer depletion (8%) show some minor impact. The amount of environmental pollutions (0.4% - 3.6%) are overall relatively low compared to those caused by geothermal well drilling and pipeline construction.

The latter is also observed for the impacts of power plant buildings, but in this case only abiotic depletion shows some minor impact.

After normalization:

Table 8 and Figure 16 show the normalized LCIA results for a large-scale flash system. Marine aquatic eco-toxicity shows the highest impact of all the environmental impacts, mainly caused by deep well drilling. For human toxicity, pipeline construction causes more impact than deep well drilling. All the other impact categories show very little impact compared to the World 2000 references.

Table 8 The normalized LCIA values for the large-scale flash system - construction phase

Sel	Impact category	Unit	Total	Deep well_drilling_large_flash	Geothermal power plant pipeline construtcion for	Power plant machinery large flash	Power plant building large flash
☑	Marine aquatic ecotoxicity		0.00102	0.000945	5.11E-5	1.26E-5	7.49E-6
☑	Human toxicity		0.000201	7.16E-5	0.000125	4.52E-6	1.75E-7
☑	Abiotic depletion (fossil fuels)		1.06E-5	9.37E-6	7.2E-7	1.59E-7	3.3E-7
☑	Global warming (GWP100a)		8.71E-6	8.03E-6	5.19E-7	1.24E-7	3.34E-8
☑	Abiotic depletion		7.1E-6	2.33E-6	3.05E-6	4.96E-7	1.23E-6
☑	Acidification		6.8E-6	6.15E-6	5.07E-7	9.68E-8	4.8E-8
☑	Fresh water aquatic ecotox.		5.38E-6	5.04E-6	1.76E-7	1.66E-7	5.57E-9
☑	Photochemical oxidation		2.44E-6	2.09E-6	2.4E-7	8.75E-8	1.58E-8
☑	Eutrophication		2.18E-6	2.05E-6	9.61E-8	1.81E-8	1.44E-8
☑	Terrestrial ecotoxicity		1.59E-6	1.28E-6	3E-7	6.31E-9	3.92E-9
☑	Ozone layer depletion (ODP)		3.69E-8	2.63E-8	6.82E-9	2.79E-9	1.04E-9

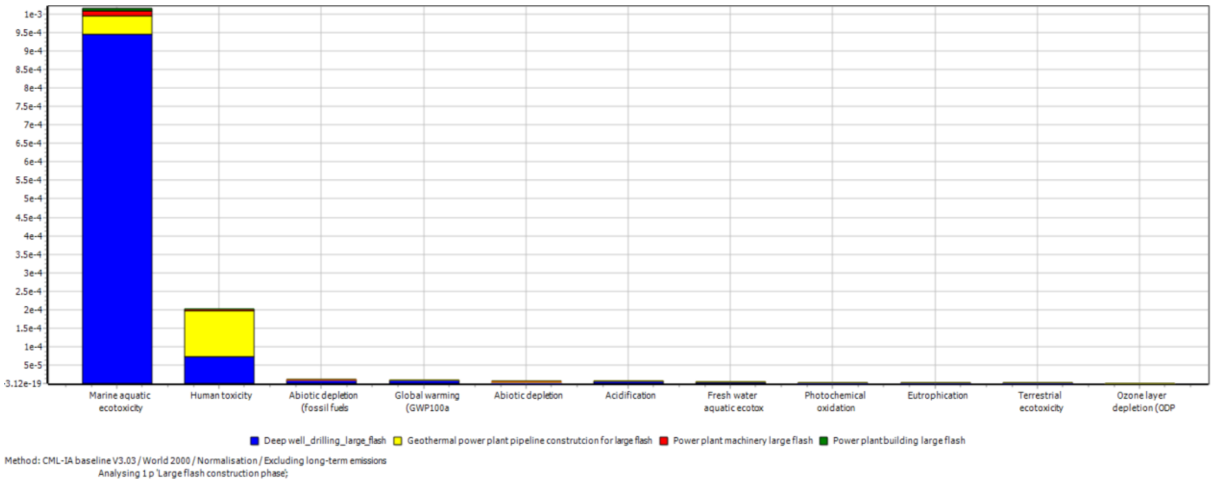


Figure 16 The normalized LCIA values of the large-scale flash system - construction phase

5.3. LCIA for the operation phase of a large-scale flash system

As can be seen from table 9, the only impact of the operation stage comes from gas emissions from geothermal fluid. Global warming shows the highest impact, followed by human toxicity and some minor impact via photochemical oxidation.

Table 9 The LCIA values of the large-scale flash system - operation phase

Sel	Impact category	Unit	Total	Operation phase large flash
☑	Global warming (GWP100a)	kg CO2 eq	5.04E8	5.04E8
☑	Human toxicity	kg 1,4-DB eq	2.72E7	2.72E7
☑	Photochemical oxidation	kg C2H4 eq	237	237
☑	Eutrophication	kg PO4--- eq	x	x
☑	Acidification	kg SO2 eq	x	x
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	x	x
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	x	x
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	x	x
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	x	x
☑	Abiotic depletion (fossil fuels)	MJ	x	x
☑	Abiotic depletion	kg Sb eq	x	x

After normalization:

Table 10 and figure 17 show the normalized LCIA results for the operation phase of a large-scale flash system. Global warming potential and human toxicity are still the most dominant environmental impacts.

Table 10 The normalized LCIA values for the large-scale flash system - operation phase

Sel	Impact category	Unit	Total	Operation phase large flash
☑	Global warming (GWP100a)		1.21E-5	1.21E-5
☑	Human toxicity		1.05E-5	1.05E-5
☑	Photochemical oxidation		6.44E-9	6.44E-9
☑	Eutrophication		x	x
☑	Acidification		x	x
☑	Terrestrial ecotoxicity		x	x
☑	Marine aquatic ecotoxicity		x	x
☑	Fresh water aquatic ecotox.		x	x
☑	Ozone layer depletion (ODP)		x	x
☑	Abiotic depletion (fossil fuels)		x	x
☑	Abiotic depletion		x	x

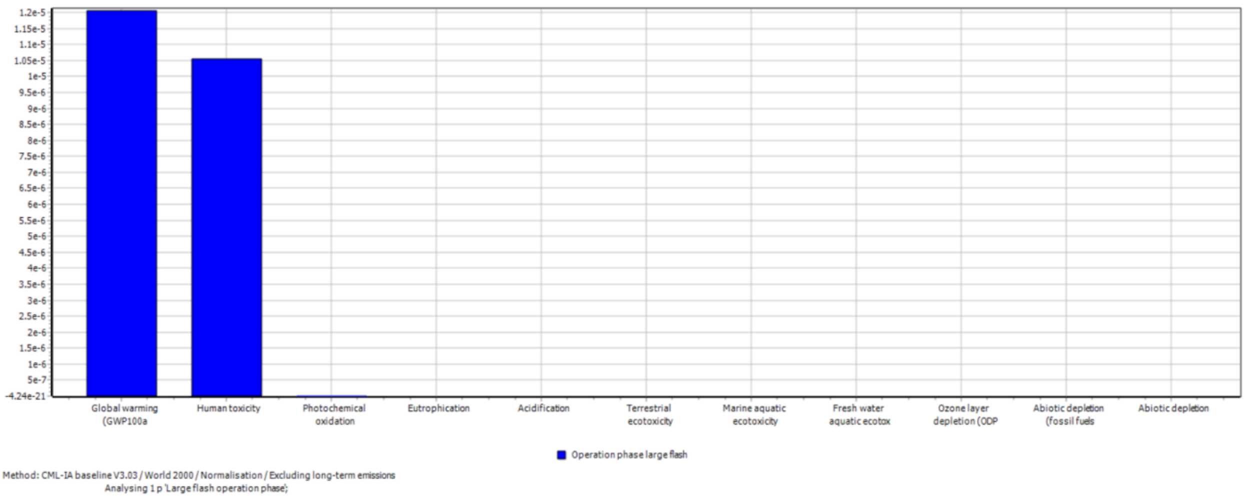


Figure 17 The normalized LCIA values for the large-scale flash system - operation phase

5.4. LCIA for the disposal phase

The main impacts of the disposal phase in a large-scale flash system are caused by the closure of the deep wells. Table 11 shows marine aquatic eco toxicity, abiotic depletion, global warming and human toxicity are the four main environmental impacts for the disposal phase of a large-scale GTE flash system. Fresh water aquatic eco-toxicity and acidification have relatively low impacts, while the other impact categories show very low to hardly any impact.

Table 11 The LCIA values of the large-scale flash system - disposal phase

Sel	Impact category	Unit	Total	Deep well closure for large flash
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	8.94E6	8.94E6
☑	Abiotic depletion (fossil fuels)	MJ	3.2E5	3.2E5
☑	Global warming (GWP100a)	kg CO2 eq	4.64E4	4.64E4
☑	Human toxicity	kg 1,4-DB eq	7.29E3	7.29E3
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	152	152
☑	Acidification	kg SO2 eq	146	146
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	56.7	56.7
☑	Eutrophication	kg PO4--- eq	20.5	20.5
☑	Photochemical oxidation	kg C2H4 eq	6.54	6.54
☑	Abiotic depletion	kg Sb eq	0.0517	0.0517
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	0.00266	0.00266

After Normalization:

Table 12 and figure 18 show the normalized LCIA results for the disposal phase of a large-scale flash system. Marine aquatic eco-toxicity is the main environmental impact of this stage. Human toxicity, global warming, abiotic depletion and acidification show only minor impacts.

Table 12 The normalized LCA values of the large-flash system - disposal phase

Sel	Impact category	Unit	Total	Deep well closure for large flash
☑	Marine aquatic ecotoxicity		4.61E-8	4.61E-8
☑	Human toxicity		2.83E-9	2.83E-9
☑	Global warming (GWP100a)		1.11E-9	1.11E-9
☑	Abiotic depletion (fossil fuels)		8.41E-10	8.41E-10
☑	Acidification		6.12E-10	6.12E-10
☑	Abiotic depletion		2.47E-10	2.47E-10
☑	Photochemical oxidation		1.78E-10	1.78E-10
☑	Eutrophication		1.29E-10	1.29E-10
☑	Fresh water aquatic ecotox.		6.41E-11	6.41E-11
☑	Terrestrial ecotoxicity		5.19E-11	5.19E-11
☑	Ozone layer depletion (ODP)		1.17E-11	1.17E-11

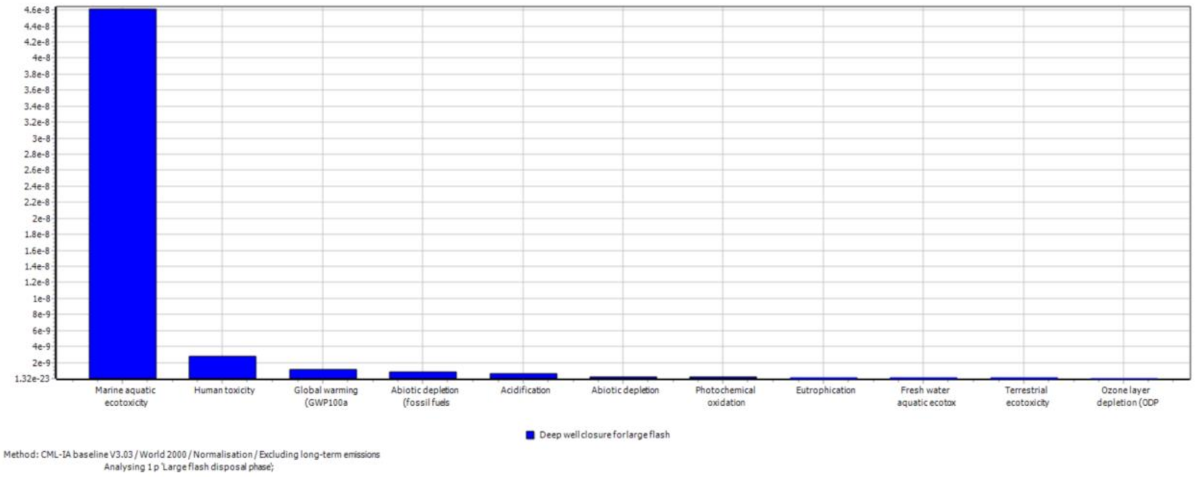


Figure 18 The normalized LCIA values of the large-scale flash system - disposal phase

5.5. Life cycle impact assessment for all GTE stages

Table 13 shows the construction phase has the highest impact for all impact categories compared to the operation and disposal phase. As was explained in section 5.2, deep well drilling causes most of the impacts, followed by pipeline construction, power plant machinery and power plant building.

Table 13 The LCIA values for the different stages of the 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 PO_4^- 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

Sel	Impact category	Unit	Total	Deep well_drilling_large_flas	Geothermal power plant pipeline	Power plant machinery large flash	Power plant building large flash	Geothermal operation phase large flash	Deep well closure for large flash
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	1.97E11	1.83E11	9.9E9	2.45E9	1.45E9	x	8.95E6
☑	Abiotic depletion (fossil fuels)	MJ	4.03E9	3.57E9	2.74E8	6.06E7	1.25E8	x	3.2E5
☑	Human toxicity	kg 1,4-DB eq	5.2E8	1.85E8	3.21E8	1.17E7	4.52E5	2.16E6	7.3E3
☑	Global warming (GWP100a)	kg CO2 eq	4.05E8	3.37E8	2.17E7	5.18E6	1.4E6	4.02E7	4.64E4
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	1.27E7	1.19E7	4.16E5	3.91E5	1.32E4	x	152
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	1.73E6	1.4E6	3.28E5	6.9E3	4.28E3	x	56.8
☑	Acidification	kg SO2 eq	1.62E6	1.47E6	1.21E5	2.31E4	1.15E4	x	146
☑	Eutrophication	kg PO4--- eq	3.46E5	3.25E5	1.52E4	2.87E3	2.28E3	x	20.5
☑	Photochemical oxidation	kg C2H4 eq	8.97E4	7.71E4	8.83E3	3.22E3	580	18.8	6.54
☑	Abiotic depletion	kg Sb eq	1.49E3	487	637	104	258	x	0.0517
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	8.39	5.97	1.55	0.632	0.236	x	0.00266

The percentages per impact category for the four different construction processes and for the operation and disposal stages are shown in Figure 19. 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 the global warming. Table 9 shows global warming, human toxicity and photochemical oxidation are the gas emitted from geothermal fluids. Deep well closure (disposal phase) has an impact on marine aquatic eco-toxicity, abiotic depletion (fossil fuels), global warming and human toxicity (see table 11).

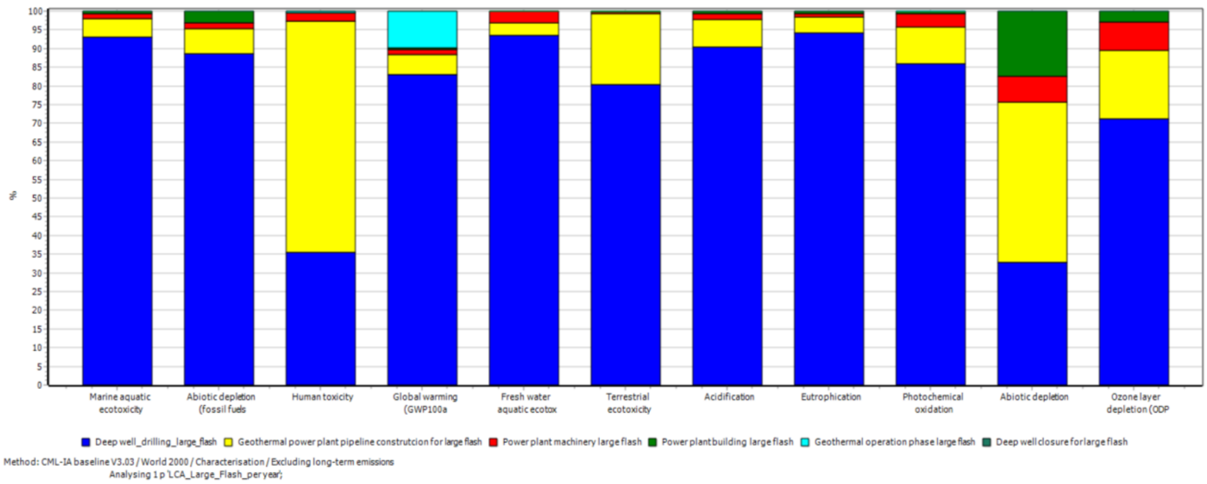


Figure 19 The LCIA for the large-scale flash system - percentage category for the different GTE processes of the construction, operation and disposal phases

After Normalization:

Figure 20 show the normalized LCIA results of all the LCA stages of a large-scale flash system. Marine aquatic eco-toxicity is highly dominant among all the environmental impacts, mainly caused by geothermal deep well drilling. 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.

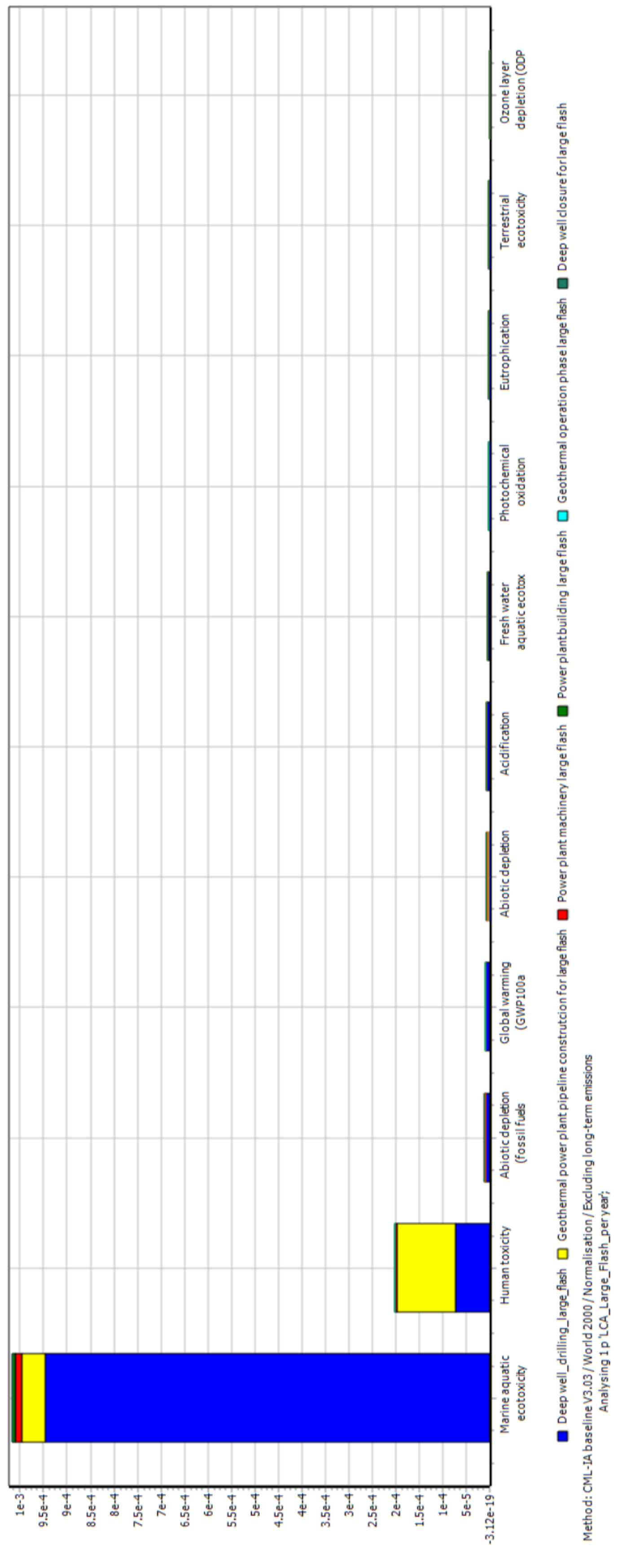


Figure 20 The normalized LCIA values of a large-scale flash system

To summarize chapter 5, it can be said that:

- Geothermal deep well drilling is the most polluted phase during the whole life –cycle of a large-scale flash GTE electricity production system.
- Marine aquatic eco-toxicity is a big environmental concern for the construction phase and specifically deep well drilling contributes most to the impact of 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, bat 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.

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

In this section, the impact of the large-scale flash system, described in chapter 5, will be compared with a small-scale binary system, Mini-Geo. This will be done for the construction phase first (6.1) and then for the four construction processes separately (6.2 – 6.5).

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 chapter 5.3. Also, the disposal phase will not be considered as MiniGeo is not implemented yet and therefore no information is available on this stage for a binary small-scale system.

As was explained in chapter 3, one small-scale binary system like MiniGeo produces 0.5 MWh. To compare this system with a large-scale system like Wayang Windu, producing 110 MWh, 220 small-scale systems are needed to produce the same amount of energy (see Appendix 4).

6.1. Comparison of GTE alternatives – all construction phases together

Table 14 and Figure 21 show both the large-scale flash and small-scale binary system have the highest impact on marine aquatic eco-toxicity, while the large-scale flash system has almost the double amount of the small scale binary one. Both systems indicate nearly the same impact on abiotic depletion, eutrophication and global warming. The small-scale binary system has a bigger environmental impact on human toxicity, photochemical oxidation, abiotic depletion and ozone layer depletion than the large scale flash one. In contrast, the large-scale flash system has, besides the impact on marine aquatic toxicity, more impact on fresh water aquatic eco-toxicity and terrestrial eco-toxicity.

Table 14 The LCIA values of the construction phase of the small-scale binary(MiniGeo) and large-scale flash system(Wayang Windu)

Sel	Impact category	Unit	Large flash construction phase	Small binary construction
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	1.97E11	9.48E10
☑	Abiotic depletion (fossil fuels)	MJ	4.02E9	4.12E9
☑	Human toxicity	kg 1,4-DB eq	5.18E8	1.37E9
☑	Global warming (GWP100a)	kg CO2 eq	3.64E8	3.18E8
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	1.27E7	2.67E6
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	1.73E6	1.17E6
☑	Acidification	kg SO2 eq	1.62E6	2.02E6
☑	Eutrophication	kg PO4--- eq	3.45E5	3.26E5
☑	Photochemical oxidation	kg C2H4 eq	8.96E4	1.54E5
☑	Abiotic depletion	kg Sb eq	1.49E3	4.59E3
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	8.38	32.3

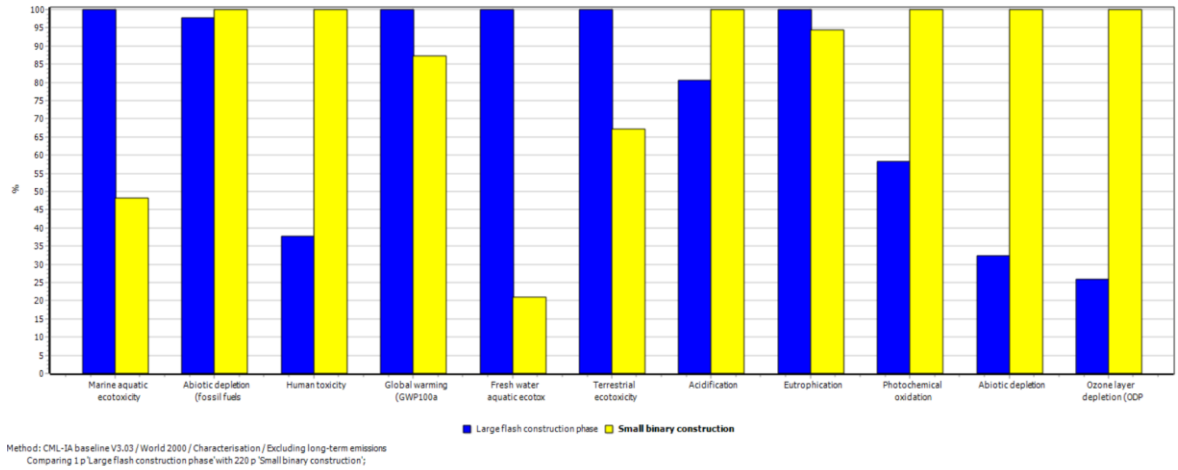


Figure 21 The LCIA for the construction phase of the large-scale flash system and the small-scale binary percentages per impact category

After Normalization:

The normalized values (Table 15 and Figure 22) show marine aquatic eco-toxicity and human toxicity are the two main environmental impacts, whereby a large-scale flash system has more impact on marine aquatic eco-toxicity and a small-scale binary system like MiniGeo more on human toxicity.

Table 15 The normalized LCIA values of the construction phase of the large-scale flash system and the small-scale binary system

Sel	Impact category	Unit	Large flash construction phase	Small binary construction
☑	Marine aquatic ecotoxicity		0.00102	0.000489
☑	Human toxicity		0.000201	0.000532
☑	Abiotic depletion (fossil fuels)		1.06E-5	1.08E-5
☑	Global warming (GWP100a)		8.71E-6	7.61E-6
☑	Abiotic depletion		7.1E-6	2.19E-5
☑	Acidification		6.8E-6	8.45E-6
☑	Fresh water aquatic ecotox.		5.38E-6	1.13E-6
☑	Photochemical oxidation		2.44E-6	4.19E-6
☑	Eutrophication		2.18E-6	2.06E-6
☑	Terrestrial ecotoxicity		1.59E-6	1.07E-6
☑	Ozone layer depletion (ODP)		3.69E-8	1.42E-7

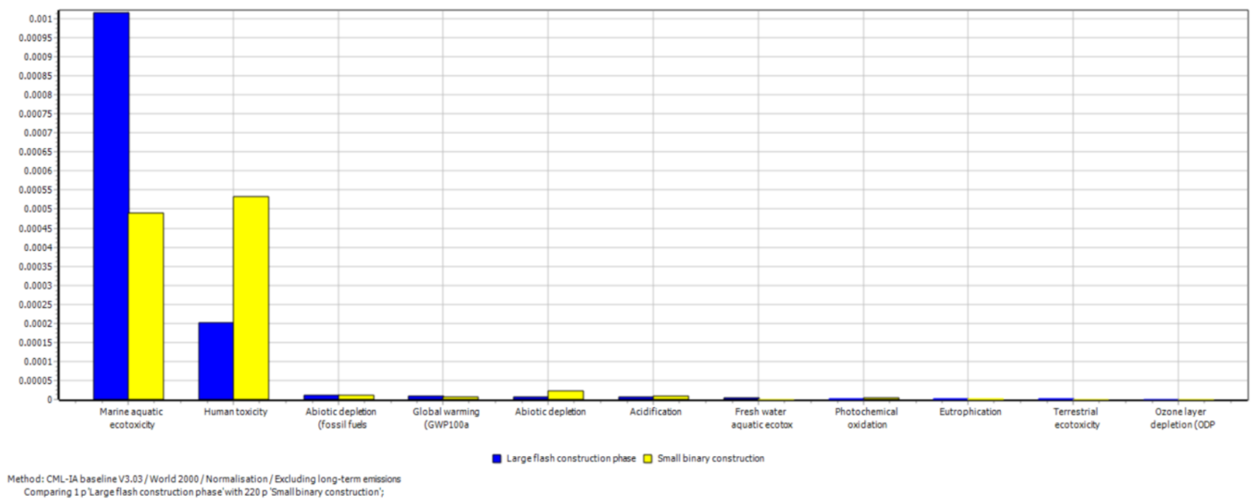


Figure 22 The normalized LCIA values of the large-scale flash system - construction phase

6.2. 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 table 16 and figure 23).

Table 16 The LCIA values of deep well drilling for the large-scale flash system and the small-scale binary system

Sel	Impact category	Unit	Large flash deep well drilling	Small binary deep well drilling
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	1.83E11	4.89E10
☑	Abiotic depletion (fossil fuels)	MJ	3.56E9	2.76E9
☑	Global warming (GWP100a)	kg CO2 eq	3.36E8	2.16E8
☑	Human toxicity	kg 1,4-DB eq	1.85E8	4.54E8
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	1.19E7	1.2E6
☑	Acidification	kg SO2 eq	1.47E6	1.47E6
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	1.39E6	2.66E5
☑	Eutrophication	kg PO4--- eq	3.25E5	2.52E5
☑	Photochemical oxidation	kg C2H4 eq	7.7E4	1.04E5
☑	Abiotic depletion	kg Sb eq	487	1.8E3
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	5.96	23.2

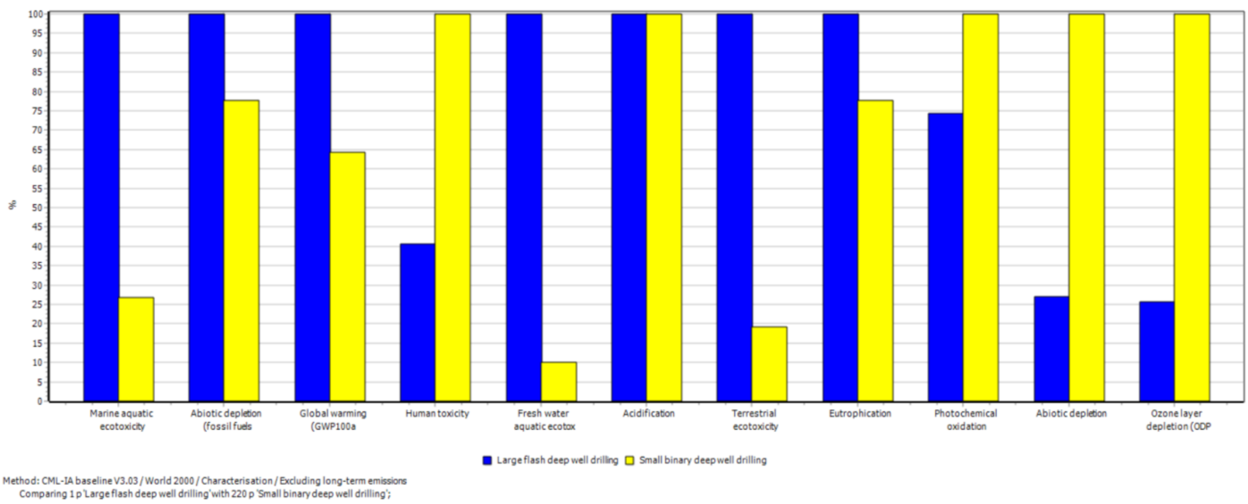


Figure 23 The LCIA of deep well drilling for the large-scale flash system and the small-scale binary system - percentages per impact category

After normalization:

The figures in table 17 and figure 24 show deep well drilling of a large-scale flash system has much more impact on marine aquatic toxicity than a small-scale binary system. In contrast, the impact on human toxicity is higher in a small-scale binary compared to a large-scale flash system, but it should be noted that the impact values are much lower than the ones on marine aquatic toxicity.

Table 17 The normalized LCIA values of deep well drilling for the large-scale flash and the small-scale binary system

Sel	Impact category	Unit	Large flash deep well drilling	Small binary deep well drilling
☑	Marine aquatic ecotoxicity		0.000945	0.000252
☑	Human toxicity		7.16E-5	0.000176
☑	Abiotic depletion (fossil fuels)		9.37E-6	7.27E-6
☑	Global warming (GWP100a)		8.03E-6	5.16E-6
☑	Acidification		6.15E-6	6.14E-6
☑	Fresh water aquatic ecotox.		5.04E-6	5.09E-7
☑	Abiotic depletion		2.33E-6	8.6E-6
☑	Photochemical oxidation		2.09E-6	2.82E-6
☑	Eutrophication		2.05E-6	1.6E-6
☑	Terrestrial ecotoxicity		1.28E-6	2.44E-7
☑	Ozone layer depletion (ODP)		2.63E-8	1.02E-7

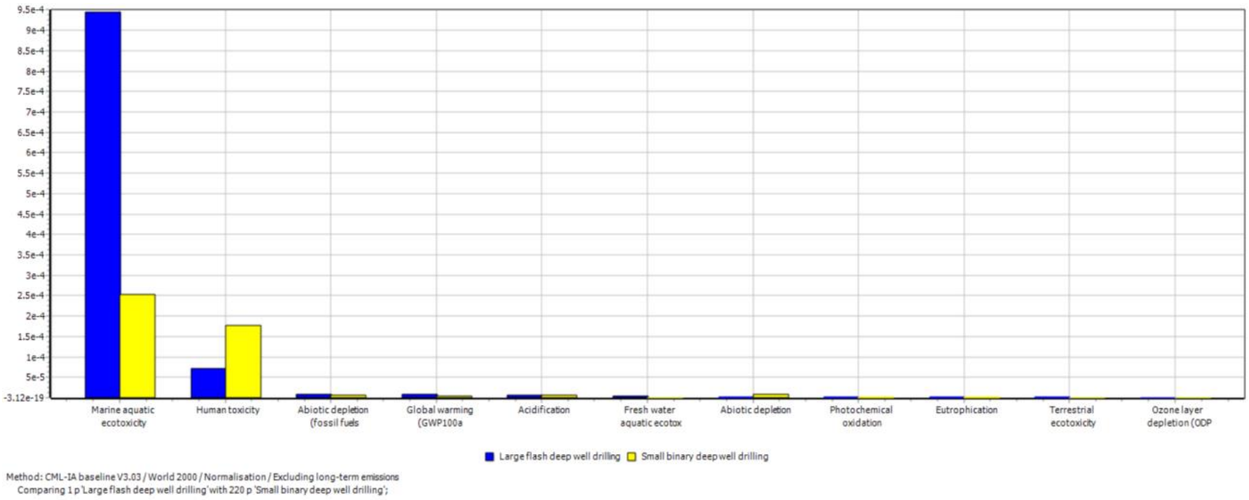


Figure 24 The LCIA of deep well drilling for the large-scale flash system and the small-binary system

6.3. Pipeline construction

As shown in Table 18 and Figure 25, a small-scale binary system has always much more impact on all the impact categories than a large-scale flash system.

Table 18 The LCIA values of pipeline construction of the large-scale flash and the small-scale binary system

Sel	Impact category	Unit	Large flash pipleline construction	Small binary pipeline construction
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	9.9E9	2.51E10
☑	Human toxicity	kg 1,4-DB eq	3.21E8	8.16E8
☑	Abiotic depletion (fossil fuels)	MJ	2.74E8	6.95E8
☑	Global warming (GWP100a)	kg CO2 eq	2.17E7	5.51E7
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	4.16E5	1.05E6
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	3.28E5	8.32E5
☑	Acidification	kg SO2 eq	1.21E5	3.07E5
☑	Eutrophication	kg PO4--- eq	1.52E4	3.86E4
☑	Photochemical oxidation	kg C2H4 eq	8.83E3	2.24E4
☑	Abiotic depletion	kg Sb eq	637	1.62E3
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	1.55	3.92

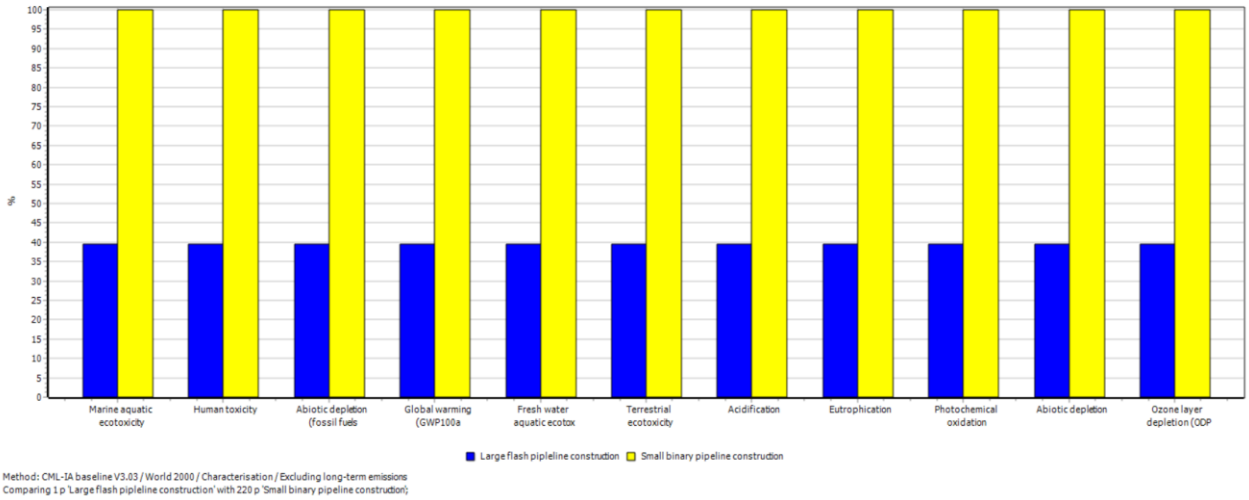


Figure 25 The LCIA values of pipeline construction for the large-scale flash and the small-scale binary system - percentages per impact category

After normalization:

The normalized values show pipeline construction for a small-scale binary system like MiniGeo has relatively much more impact on human toxicity than a large-scale flash system. The impact on marine aquatic eco-toxicity is also higher for a small-scale binary system, but the overall impact values are lower for both systems.

Table 19 The normalized LCIA values of pipeline construction for the large-scale flash and the small-scale binary system

Sel	Impact category	Unit	Large flash pipleline construction	Small binary pipeline construction
☑	Human toxicity		0.000125	0.000317
☑	Marine aquatic ecotoxicity		5.11E-5	0.00013
☑	Abiotic depletion		3.05E-6	7.73E-6
☑	Abiotic depletion (fossil fuels)		7.2E-7	1.83E-6
☑	Global warming (GWP100a)		5.19E-7	1.32E-6
☑	Acidification		5.07E-7	1.29E-6
☑	Terrestrial ecotoxicity		3E-7	7.61E-7
☑	Photochemical oxidation		2.4E-7	6.1E-7
☑	Fresh water aquatic ecotox.		1.76E-7	4.46E-7
☑	Eutrophication		9.61E-8	2.44E-7
☑	Ozone layer depletion (ODP)		6.82E-9	1.73E-8

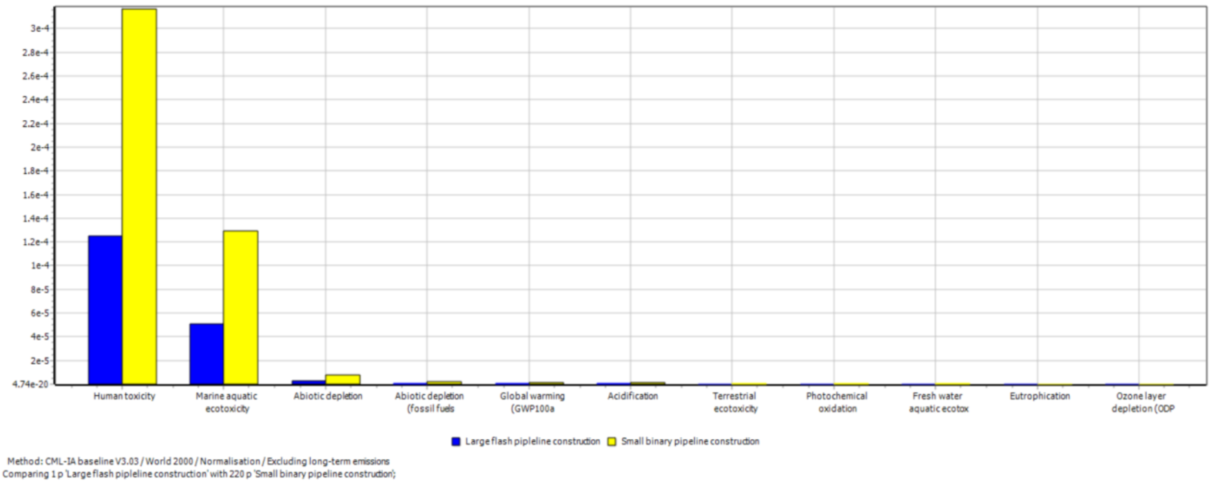


Figure 26 The normalized LCIA values of pipeline construction for the large-scale flash and the small-scale binary system

6.4. Power plant machinery

A small scale binary system needs more material for their machineries to produce the same amount of electricity than a large-scale flash system. A small-scale binary system has therefore relatively much more impact than a large-scale flash system, as can be seen in table 20 and figure 27. Only the impact on fresh water aquatic eco-toxicity is slightly higher for a small-scale binary system compared with a large-scale flash system.

Table 20 The LCIA values of power plant machinery for the large-scale flash and the small-scale binary system

Sel	Impact category	Unit	Large flash power plant machinery	Small binary power plant machinery
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	2.45E9	2.08E10
☑	Abiotic depletion (fossil fuels)	MJ	6.06E7	5.38E8
☑	Human toxicity	kg 1,4-DB eq	1.17E7	1.02E8
☑	Global warming (GWP100a)	kg CO2 eq	5.18E6	4.75E7
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	3.91E5	4.1E5
☑	Acidification	kg SO2 eq	2.31E4	2.43E5
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	6.9E3	6.63E4
☑	Photochemical oxidation	kg C2H4 eq	3.22E3	2.79E4
☑	Eutrophication	kg PO4--- eq	2.87E3	3.47E4
☑	Abiotic depletion	kg Sb eq	104	881
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	0.632	5.21

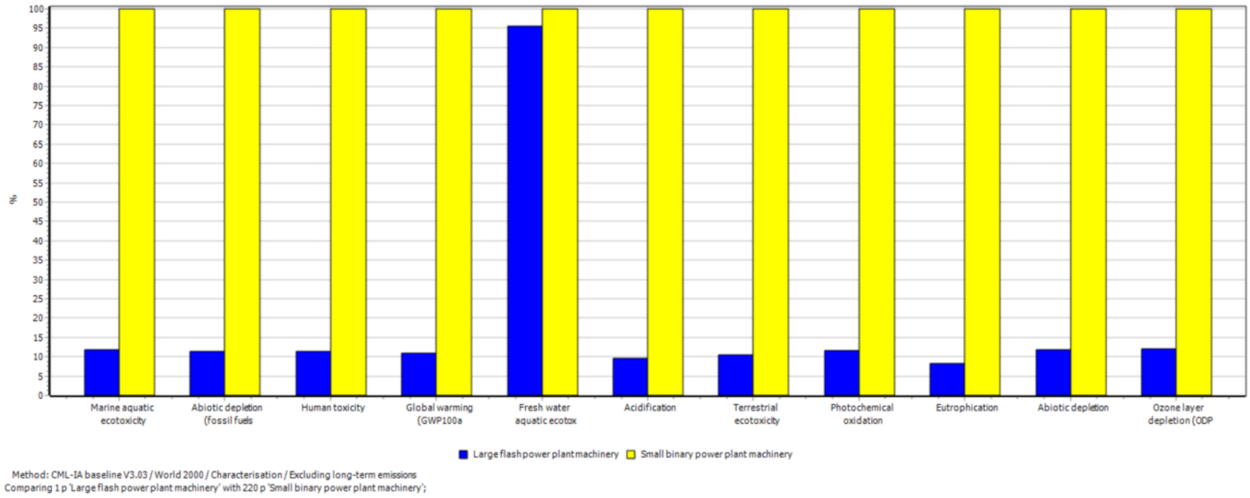


Figure 27 The LCIA values of power plant machinery for the large-scale flash and the small-scale binary system - percentages per impact category

After normalization:

The normalized values in table 21 and figure 28 show the impact of power plant machinery on marine aquatic eco-toxicity is very much higher for a small-scale binary system like MiniGeo than for a large-scale flash system, higher on human toxicity and slightly higher on abiotic depletion. The other impacts are negligible for both systems.

Table 21 The normalized LCIA values of power plant machinery for the large-scale flash and the small-scale binary

Sel	Impact category	Unit	Large flash power plant machinery	Small binary power plant machinery
☑	Marine aquatic ecotoxicity		1.26E-5	0.000107
☑	Human toxicity		4.52E-6	3.95E-5
☑	Abiotic depletion		4.96E-7	4.21E-6
☑	Fresh water aquatic ecotox.		1.66E-7	1.73E-7
☑	Abiotic depletion (fossil fuels)		1.59E-7	1.41E-6
☑	Global warming (GWP100a)		1.24E-7	1.14E-6
☑	Acidification		9.68E-8	1.02E-6
☑	Photochemical oxidation		8.75E-8	7.58E-7
☑	Eutrophication		1.81E-8	2.2E-7
☑	Terrestrial ecotoxicity		6.31E-9	6.06E-8
☑	Ozone layer depletion (ODP)		2.79E-9	2.3E-8

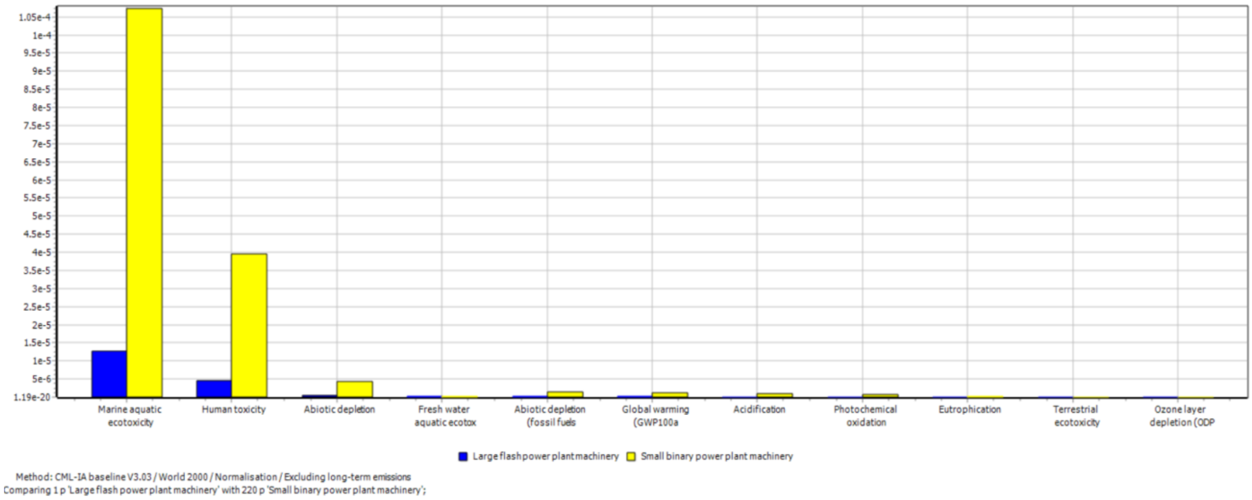


Figure 28 The normalized LCIA values power plant machinery for the large-scale flash and small-scale binary system

6.5. Power plant building

Mini-Geo (a small-scale binary system) is using a container for the power plant building, whereas a large-scale flash power plant needs more materials and energy to build a large building. Table 22 and Figure 29 show a large-scale flash system has much more environmental impacts from power plant buildings than MiniGeo, except for abiotic depletion.

Table 22 The LCIA values of power plant building for the large-scale flash and the small-scale binary system

Sel	Impact category	Unit	Power plant building_large_flash	Power plant building_small binary
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	1.45E9	1.23E7
☑	Abiotic depletion (fossil fuels)	MJ	1.25E8	1.2E8
☑	Global warming (GWP100a)	kg CO2 eq	1.4E6	5.01E3
☑	Human toxicity	kg 1,4-DB eq	4.52E5	1.91E3
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	1.32E4	1.11E3
☑	Acidification	kg SO2 eq	1.15E4	15.7
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	4.28E3	1.6E3
☑	Eutrophication	kg PO4--- eq	2.28E3	133
☑	Photochemical oxidation	kg C2H4 eq	580	21.2
☑	Abiotic depletion	kg Sb eq	258	292
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	0.236	0.00013

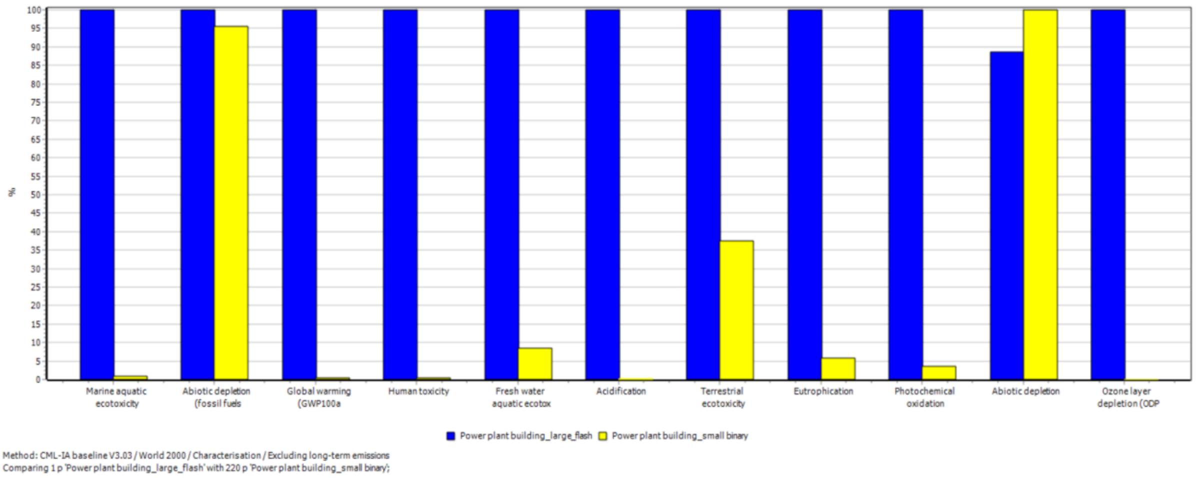


Figure 29 The LCIA values of power plant building for the large-scale flash and the small-scale binary system - percentages per impact category

After Normalization:

The normalized values in table 23 and figure 30 show the impact of a power plant building on marine aquatic eco-toxicity of a large-scale flash system is very high compared to a small-scale binary system like MiniGeo. The impact on abiotic depletion and abiotic depletion (fossil fuels) is rather similar for both systems and relatively low. The other impacts are negligible.

Table 23 The normalized LCIA values of power plant building for the large-scale flash and the small-scale binary system

Sel	Impact category	Unit	Power plant building_large_flash	Power plant building_small binary
☑	Marine aquatic ecotoxicity		7.49E-6	6.34E-8
☑	Abiotic depletion		1.23E-6	1.39E-6
☑	Abiotic depletion (fossil fuels)		3.3E-7	3.15E-7
☑	Human toxicity		1.75E-7	7.4E-10
☑	Acidification		4.8E-8	6.57E-11
☑	Global warming (GWP100a)		3.34E-8	1.2E-10
☑	Photochemical oxidation		1.58E-8	5.77E-10
☑	Eutrophication		1.44E-8	8.4E-10
☑	Fresh water aquatic ecotox.		5.57E-9	4.69E-10
☑	Terrestrial ecotoxicity		3.92E-9	1.46E-9
☑	Ozone layer depletion (ODP)		1.04E-9	5.72E-13

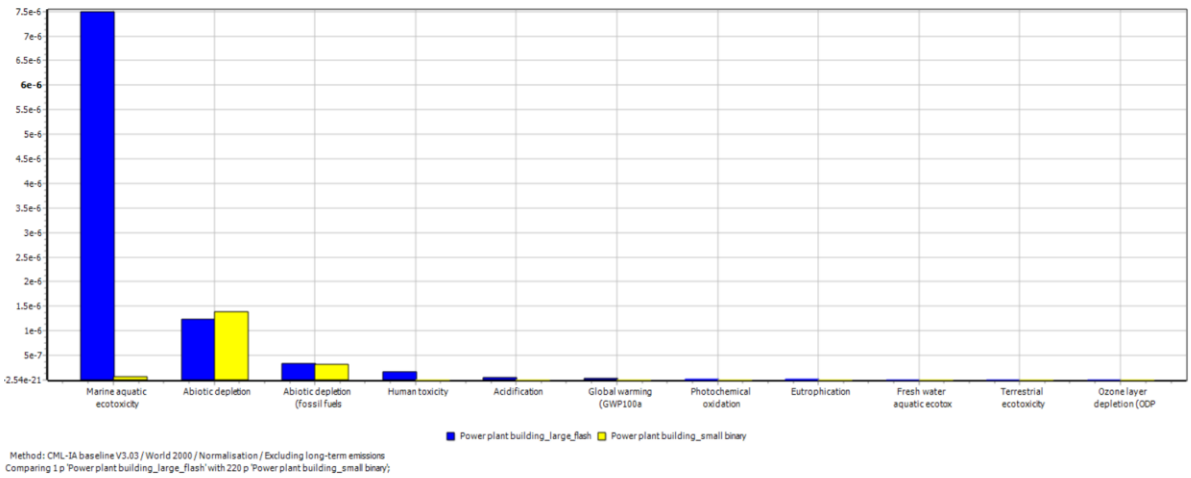


Figure 30 The normalized LCIA values of power plant building for the large-scale flash and the small-scale binary system

To summarize chapter 6, it can be said:
In the construction phase, a large-scale flash system has more environmental impact on marine aquatic eco-toxicity and fresh water aquatic eco-toxicity than a small-scale binary system. That is because of the geothermal well drilling process. A small-scale binary system can cause more acidification, photochemical oxidation, abiotic depletion and ozone layer depletion problems because more materials are used while downscaling the power plant machineries of a small-scale binary system. Abiotic depletion and eutrophication impacts are nearly equivalent for both systems.

In the operation phase, this research assumed for a GTE system, the most environmental concern comes from the gas emitted from geothermal fluids. Since no gas will emit from a binary system in the operation phase, this research considers the operation phase in the LCA for a small-binary system to be more sustainable than a large-scale flash one, which has large impacts on global warming and human toxicity (table 10 and figure 17).

Therefore, a small-scale binary system can be more sustainable when considering the deep well drilling process. In contrast, a large-scale flash system can have better environmental performance when thinking about the process of power plant machinery production and pipeline construction. However, a small-scale binary system is more sustainable in the power plant building construction and for the operation phase.

7. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

In this chapter first the accuracy assessment of a large-scale flash system is discussed, to test how accurate the parameters used in this research are (Chapter 7.1). Chapter 7.2 examines the influence of the LCIA method, used in this study, on the LCA results. Chapter 7.3 compares the LCA results with those found in literature. Chapter 7.4 reflects on the site specific issues and parameters that may influence the LCA. Chapter 7.5 summarizes the conclusions of this research and in chapter 7.6 recommendations and suggestions for future research are given.

7.1. Accuracy assessment

In chapter 5 the results of the LCA for a large-scale flash system were presented. The LCA was based on the parameters defined in the LCI, as shown in table 5 in chapter 4. But how accurate are those values and therefore the results of the LCA?
(Karlsdóttir et al., 2015) developed a life cycle inventory database for a large-sale flash system at a specific location in Iceland. For each parameter, also an accuracy range was given, expressed in % of uncertainty. As no accuracy data were available for Indonesia, the Iceland accuracy % was taken to do an uncertainty analysis for the data used in this research. Those accuracy percentages were adapted in consultation with the geothermal expert, Niek Willemsen, see table 24, fifth column. The values under Amount are the ones used in this research in chapter 5 and 6. The last column shows the uncertainty analysis values using the lowest accuracy range (e.g. 309 – 10%, for steel and the second last column the values based on the highest accuracy range (e.g. 309 + 10% for steel). For both the lowest and highest uncertainty, a LCA was carried out.

Table 24 Life cycle inventory of the large-scale flash with the accuracy range

Construction phase						
	Unit	Input/ Output	Large scale flash		Large scale flash with highest accuracy	Large scale flash with lowest accuracy
Geothermal well drilling	Total drilling length:62402m		Amount	Accuracy p	Amount	Amount
Steel	kg/m well	Input	309	+/-10%	339.9	278.1
Cement	kg/m well	Input	213	+/-10%	234.3	191.7
Barite	kg/m well	Input	20	+/-20%	24	16
Bentonite	kg/m well	Input	20	+/-10%	22	18
Water	m^3/m_{well}	Input	0.5	+/-30%	0.65	0.35
Electricity	kWh/m well	Input	3932		3932	3932
Diesel	MJ/m well	Input	111	+/-10%	122.1	99.9
Drilling waste	kg/m well	Output	466		466	466
Waste water	m^3/m_{well}	Output	0.5	+/-30%	0.65	0.35

Pipelines construction	Total pipeline length:22km					
Steel pipe	kg/m pipes	Input	197	+/-30%	256.1	137.9
Total steel pipe			4334000	+/-30%	5634200	3033800
Power plant machinery	110MW installed capacity					
Aluminum	kg/MW	Input	242[i]	+/-30%	314.6	169.4
Copper	kg/MW	Input	363[i]	+/-20%	435.6	290.4
Mineral wool	kg/MW	Input	246[i]	+/-20%	295.2	196.8
Stainless steel	kg/MW	Input	2,343[i]	+/-10%	2577.3	2108.7
Steel	kg/MW	Input	8,616[i]	+/-10%	9477.6	7754.4
Titanium	kg/MW	Input	523[i]	+/-10%	575.3	470.7
Power plant buildings						
Aluminum	kg/MW	Input	578	+/-20%	693.6	462.4
Copper	kg/MW	Input	152	+/-30%	197.6	106.4
Mineral wool	kg/MW	Input	567	+/-20%	680.4	453.6
Steel	kg/MW	Input	11943	+/-30%	15525.9	8360.1
Asphalt	kg/MW	Input	31624	+/-30%	41111.2	22136.8
Cement	kg/MW	Input	86	+/-20%	103.2	68.8
Operation phase: 110MW						
CO_2 from geothermal fluid	Kg/kWh	Output	0.0416	+/-20%	0.04992	0.03328
H_2S from geothermal fluid	Kg/kWh	Output	0.00102	+/-20%	0.001224	0.000816
CH_4 from geothermal fluid	Kg/kWh	Output	0.00000326	+/-20%	0.000003912	0.000002608
Disposal phase – well closure						
Gravel	kg/m well	Input	18.4[K]		18.4	18.4
Cement	kg/m well	Input	1.75[l]		1.75	1.75

Table 25 and Figure 31 shows the LCA impacts results for the large-scale flash system comparing the research results with the highest uncertainty values (second last column) and with the lowest uncertainty values (last column)

Table 25 The LCA impacts for the large-scale flash system comparing the research results with the highest and lowest uncertainty values

Sel	Impact category	Unit	LCA large scale flash	LCA large scale flash highest accuracy	LCA large scale flash lowest accuracy
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	1.97E11	2.03E11	1.92E11
☑	Abiotic depletion (fossil fuels)	MJ	4.03E9	4.23E9	3.82E9
☑	Human toxicity	kg 1,4-DB eq	5.2E8	6.29E8	4.08E8
☑	Global warming (GWP100a)	kg CO2 eq	4.05E8	4.28E8	3.82E8
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	1.27E7	1.29E7	1.25E7
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	1.73E6	1.83E6	1.64E6
☑	Acidification	kg SO2 eq	1.62E6	1.7E6	1.55E6
☑	Eutrophication	kg PO4--- eq	3.46E5	3.55E5	3.37E5
☑	Photochemical oxidation	kg C2H4 eq	8.97E4	9.69E4	8.26E4
☑	Abiotic depletion	kg Sb eq	1.49E3	1.82E3	1.15E3
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	8.39	9.44	7.33

For most impacts the difference between the three uncertainty classes is not much, except for human toxicity, abiotic depletion and ozone layer depletion. Those three impacts might therefore be either under estimated or over-estimated in this research.

Normalization:

Figure 32 shows the impact values after normalization. The highest impact is for marine aquatic eco-toxicity, followed by human toxicity, but the differences between the uncertainty classes are not very high.

Figure 31 LCA impacts (percentages) for the large-scale flash system with the highest and lowest accuracy values

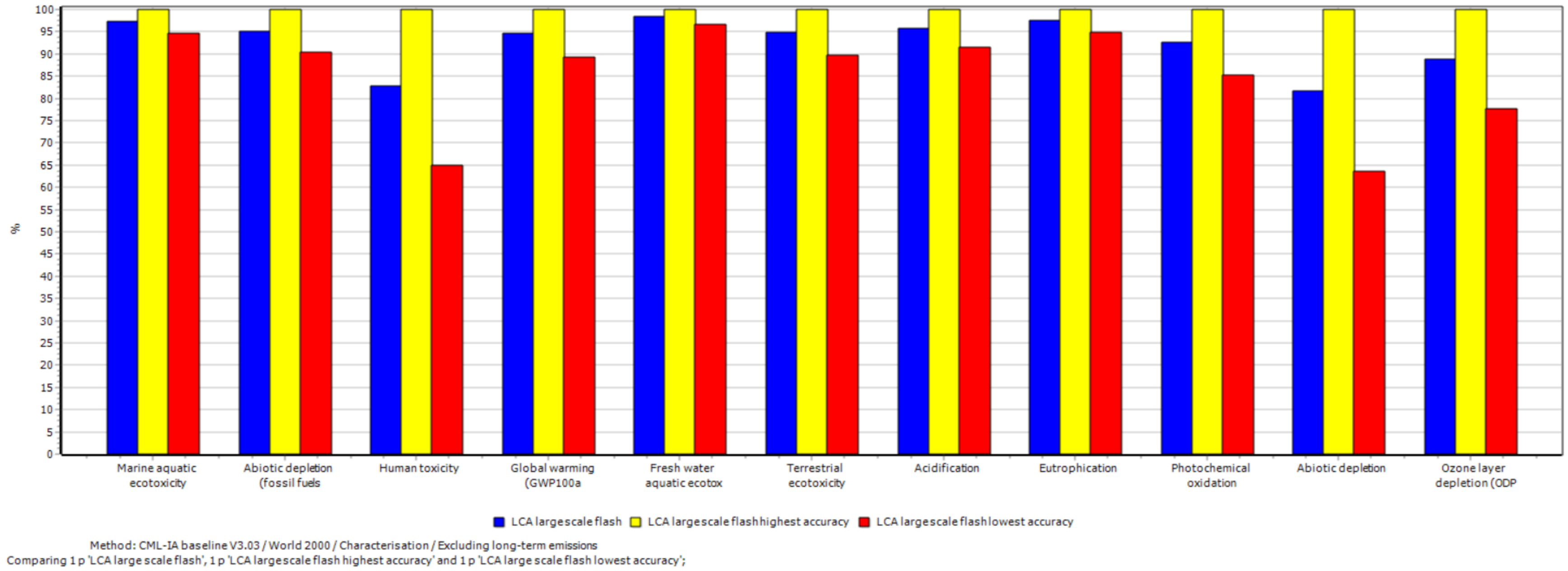
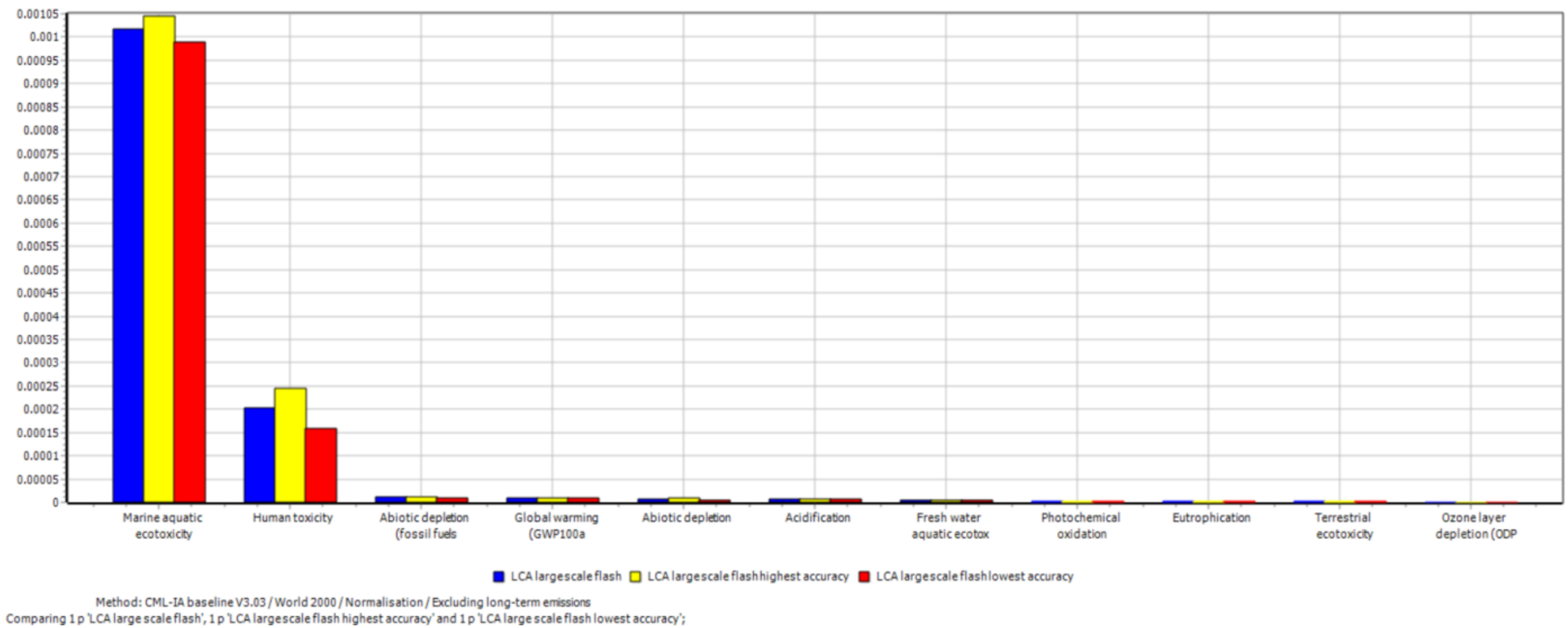


Figure 32 Graphical display of the normalized uncertainty analysis values of the LCA for the large-scale flash system with the highest and lowest uncertainty



7.2. 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 research was the CML-IA baseline method, as mentioned in chapter 3. This method will be compared with the ReCiPe method. As an example the LCA for deep well drilling in the construction phase of a large- scale flash system will be discussed. (Tables 26 a & b and figures 33 a & b) When using the ReCiPe method, climate change appears to be highest impact of deep well drilling, while this was marine aquatic eco-toxicity, when using the CML-IA baseline method.

Table 26 The LCIA values of the large-scale flash system for deep well drilling phase - ReCiPe method (a) and CML –IA baseline method (b)

a) Recipe method:

Sel	Impact category	Unit	Total	Deep well_drilling_larg	Reinforcing steel {GLO}|	Bentonite {GLO}| market	Cement, Portland	Barite {GLO}| market for |	Electricity, medium voltage	Diesel, burned in diesel-electric	Drilling waste {GLO}| market	Wastewater, average {GLO}|
☑	Climate change	kg CO2 eq	3.36E8	x	5.8E7	4.88E4	1.24E7	3.8E5	2.65E8	6.34E5	2.11E5	416
☑	Fossil depletion	kg oil eq	8.03E7	x	1.62E7	1.72E4	1.21E6	9.9E4	6.24E7	2.23E5	1.22E5	94
☑	Metal depletion	kg Fe eq	7.32E7	x	7.1E7	2.13E3	1.53E5	2.49E4	1.97E6	7.64E3	2.12E4	242
☑	Human toxicity	kg 1,4-DB eq	2.38E7	x	1.2E6	3.28E3	4.29E5	2.7E4	6.86E6	1.04E4	1.53E7	114
☑	Particulate matter formation	kg PM10 eq	7.83E6	x	2.41E5	187	1.34E4	1.32E3	7.57E6	4E3	748	1.7
☑	Agricultural land occupation	m2a	5.14E6	x	3.98E6	7.94E3	3.98E5	2.17E4	6.04E5	7.81E4	4.86E4	20.5
☑	Water depletion	m3	3.24E6	3.12E4	1.86E6	405	3.48E4	3.88E4	1.27E6	2.95E3	5.26E3	-1.06E3
☑	Terrestrial acidification	kg SO2 eq	1.35E6	x	2.29E5	394	2.56E4	2.22E3	1.09E6	6.95E3	1.29E3	4.1
☑	Urban land occupation	m2a	1.33E6	x	8.13E5	9.13E3	5.34E4	6.92E3	3.74E5	1.58E3	6.72E4	21
☑	Photochemical oxidant format	kg NMVOC	1.16E6	x	3.11E5	412	2.41E4	1.68E3	8.06E5	1.12E4	1.58E3	2.47
☑	Ionising radiation	kBq U235 eq	8.81E5	x	2.14E5	2.28E3	1.66E5	3.25E4	4.15E5	3.35E4	1.78E4	7.66
☑	Freshwater ecotoxicity	kg 1,4-DB eq	1.99E5	x	2.58E4	36.7	1.54E3	127	1.02E5	269	6.83E4	2.51
☑	Marine ecotoxicity	kg 1,4-DB eq	1.9E5	x	6.66E4	49.3	3.04E3	399	7.62E4	333	4.38E4	2.67
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	7.99E4	x	2.17E3	6.15	277	26.6	3.73E3	15	7.37E4	0.214
☑	Freshwater eutrophication	kg P eq	6.81E4	x	2.95E3	2.54	244	35.1	5.61E4	14.9	8.74E3	1.1
☑	Marine eutrophication	kg N eq	3.64E4	x	5.15E3	13.4	834	60.2	2.99E4	395	50.1	24.4
☑	Natural land transformation	m2	2.38E4	x	6.71E3	3.25E3	785	70.4	1.34E4	234	-593	0.146
☑	Ozone depletion	kg CFC-11 eq	5.98	x	4.06	0.00812	0.367	0.0289	1.34	0.114	0.0571	4.62E-5

b) CML-IA baseline method:

Sel	Impact category	Unit	Total	Deep well_drilling_la	Reinforcing steel {GLO}|	Bentonite {GLO}|	Cement, Portland	Barite {GLO}| market for |	Electricity, medium	Diesel, burned in	Drilling waste {GLO}|	Wastewater, average
☑	Marine aquatic ecotoxicity	kg 1,4-DB eq	1.83E11	x	1.67E10	1.29E7	1.42E9	2.8E8	1.28E11	5.48E7	3.67E10	1.64E5
☑	Abiotic depletion (fossil fuels)	MJ	3.56E9	x	7.18E8	7.61E5	5.37E7	4.38E6	2.77E9	9.85E6	5.37E6	4.19E3
☑	Global warming (GWP100a)	kg CO2 eq	3.36E8	x	5.8E7	4.88E4	1.24E7	3.8E5	2.65E8	6.34E5	2.11E5	416
☑	Human toxicity	kg 1,4-DB eq	1.85E8	x	1.26E8	1.58E4	9.36E5	9.74E4	2.95E7	5.18E4	2.79E7	788
☑	Fresh water aquatic ecotox.	kg 1,4-DB eq	1.19E7	x	4.08E5	200	2.06E4	2.02E3	1.3E6	2.87E3	1.02E7	55.3
☑	Acidification	kg SO2 eq	1.47E6	x	2.51E5	415	2.67E4	2.41E3	1.18E6	6.62E3	1.33E3	3.94
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	1.39E6	x	-7.07E4	63.3	1.46E4	683	5.14E5	314	9.34E5	8.02
☑	Eutrophication	kg PO4--- eq	3.25E5	x	2.61E4	54.2	3.58E3	303	2.67E5	1.4E3	2.69E4	15
☑	Photochemical oxidation	kg C2H4 eq	7.7E4	x	3.82E4	17.3	1.12E3	91.4	3.73E4	221	62.9	0.182
☑	Abiotic depletion	kg Sb eq	487	x	461	0.426	3.08	0.48	21.1	0.0998	0.637	0.00239
☑	Ozone layer depletion (ODP)	kg CFC-11 eq	5.96	x	4.05	0.00809	0.364	0.0288	1.34	0.114	0.0571	4.35E-5

Another crucial part of the LCIA methodology is normalization. Different impact assessment methods use different normalization methods. What's more, it is essential to have a complete normalization inventory. That is because the normalized impact values are equal to the impact values divided by the normalization reference. For example, if the substance contributes dominantly a lot to the environmental impact in the normalization reference values whereas the LCIA method does not include the environmental influence, the normalization values of assessed impact would be underestimated. https://www.pre-sustainability.com/the-normalisation-step-in-lcia

a) b)

Figure 33 The LCIA values (percentages) of the large-flash system for deep well drilling phase a) ReciPe) and b) CML-IA baseline)

7.3. Comparison with results found in literature

In geothermal deep well drilling phase, (Ketenagalistrikan et al., 2014) conducted an environmental impact assessment in the process of deep well drilling specifically for the Wayang Windu power plant. Their findings showed a global warming potential ranging between 1.4 – 3.1 ton CO2 equivalent. In this research 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.

7.4. 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.

7.5. 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 very 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 in this research.

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.

7.6. Recommendations and suggestions for future research

In chapter 2, different GTE power plant and conversion systems are described. Besides the more conventional technologies, alternative technologies can be applied.
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. The classification is presented in Table 7.6 below with a link to related publications. In this research, a large-scale flash system was compared with a small-scale binary one.

Table 27 Overview of publications of GTE system scenarios

Classification of references		Publications
Type of energy produced	Electricity	(Hondo, 2005), (Pehnt, 2006), (Bauer et al., 2008), (Rule et al., 2009), (Fthenakis & Kim, 2010), (Sullivan et al., 2010), (Lacirignola & Blanc, 2013)
	Combined-production of district heat and electricity	(Clark et al., 2009), (Frick et al., 2010), (Karlsdottir et al., 2010), (Matuszewska, 2011) ,(Gerber & Marechal, 2012)
Type of reservoir	Conventional or hydrothermal reservoir	(Hondo, 2005), (Rule et al., 2009), (Karlsdottir et al., 2010), (Sullivan et al., 2010), (Matuszewska, 2011)
	Unconventional reservoir or Hot Dry Rock (HDR) or Enhanced Geothermal System (EGS)	(Pehnt, 2006), (Bauer et al., 2008), (Clark et al., 2009), (Frick et al., 2010), (Sullivan et al., 2010), (Matuszewska, 2011), (Gerber & Marechal, 2012), (Lacirignola & Blanc, 2013)
Type of conversion technology	Flash systems (single or double)	(Hondo, 2005), (Karlsdottir et al., 2010), (Sullivan et al., 2010), (Matuszewska, 2011), (Gerber & Marechal, 2012)
	Organic Rankine Cycle (used a binary fluid)	(Clark et al., 2009), (Rule et al., 2009), (Frick et al., 2010), (Sullivan et al., 2010), (Matuszewska, 2011), (Gerber & Marechal, 2012), (Lacirignola & Blanc, 2013)

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. By lack of transport data, this research could not assess impacts of transportation in this 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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APPENDIX 1 OVERVIEW OF CURRENT ENVIRONMENTAL IMPACT ASSESSMENT METHODS FOR LCA

The sources is from (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010)

LCIA method	CML-IA baseline	Recipe	Impact 2002 +
	http://cml.leiden.edu/software/data-cmlia.html		http://www.epfl.ch/impact
Impact Categories - Midpoint			
Climate change	kg CO2-eq./kg emitted to air GWP100 (J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (Eds.), 2001. IPCC Third Assessment Report: Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, UK.)	CO2-eq / kg emitted GWP100, IPCC Climate Change 2007	kg CO2eq. GWP500, IPCC Climate Change 2001: The scientific basis" report (http://www.grida.no/climate/ipcc_tar/w g1/248.htm
Ozone layer depletion	kg ethylene -11-eq./kg emitted to air ODP steady state (WMO (World Meteorological Organisation), 1992: Scientific assessment of ozone depletion: 1991. Global Ozone Research and Monitoring Project - Report no. 25. Geneva. WMO (World Meteorological Organisation), 1995: Scientific assessment of ozone depletion: 1994. Global Ozone Research and Monitoring Project - Report no. 37. Geneva. WMO (World Meteorological Organisation), 1999: Scientific assessment of ozone depletion: 1998. Global Ozone Research and Monitoring Project - Report no. 44. Geneva.)	CFC-11-eq. emitted GWP100, IPCC Climate Change 2007 (22) CFC-11-eq. emitted / kg WMO (2003), World Meteorological Organization 2003. Scientific Assessment of Ozone Depletion: Global Ozone Research and Monitoring Project - Report No. 47.	kg CFC-11 eq. into air kg CFC-11 eq. into air (*) kg CFC-11eq./kg emitted US EPA Ozone Depletion Potential List, column ODP1 WMO 2002: (http://www.epa.gov/ozone/ods.html). HALON-2311" and "Methyl chloride" midpoint CF derived from Eco-indicator 99 (EI99-2ndv).

Human toxicity	kg 1,4-DCB-eq. emitted to air/kg emitted to air water, soil HTP infinite (Huijbregts, M.A.J., 1999a: Priority assessment of toxic substances in LCA. Development and application of the multi-media fate, exposure and effect model USES-LCA. IVAM environmental research, University of Amsterdam, Amsterdam. Huijbregts, M.A.J., 2000. Priority Assessment of Toxic Substances in the frame of LCA. Time horizon dependency of toxicity potentials calculated with the multi- media fate, exposure and effects model USES-LCA. Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, The Netherlands. (http://www.leidenuniv.nl/interfac/cml/lca2/) Huijbregts, M.A.J., U. Thissen, J.B. Guinée, T. Jager, D. van de Meent, A.M.J. Ragas, A. Wegener Sleeswijk & L. Reijnders, 2000. Priority assessment of toxic substances in life cycle assessment, I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES- LCA. Chemosphere 41: 541-573. Huijbregts, M.A.J., J.B. Guinée & L. Reijnders, 2000. Priority assessment of toxic substances in life cycle assessment, III: Export of potential impact over time and space. Chemosphere (accepted).)	1,4-DCB to air/kg emission for toxic impacts; PM10-eq/kg emission for respiratory impacts USES USES-LCA 2.0 for toxic pollutants (metals and organics). Effect factors are based on the inverse of ED50 extrapolated to humans. The atmospheric European transport model EUTREND for primary and secondary aerosols	in air, soil, agricultural soil and water) kg chloroethylene into air eq. into air (cancer & non cancer) kg PM2.5eq. into air Impact 2002 model for cancer and non- cancer (Pennington et al., 2005; Crettaz et al, 2002 for human dose-response). Ecoindicator 99 for respiratory inorganics. Midpoint is backcalculated from damage

Acidification	kg SO2-eq./kg emitted to air AP (Huijbregts, M., 1999b: Life Cycle Impact Assessment of acidifying and eutrophying air pollutants. Calculation of equivalency factors with RAINS-LCA. Interfaculty Department of Environmental Science, Faculty of Environmental Science, University of Amsterdam, The Netherlands; average Europe total, A&B) (54)	kg SO2-eq. /kg, time horizon 500 years Combination of atmospheric European transport model EUTREND and European soil model SMART 2.0	kg SO2 eq. into air Aquatic acidification From CML 2002, v2.6: "impact assessment juli 2002.xls/characterisation factors. (Data are the same as in CML92). Terrestrial acidification as in Ecoindicator 99 together with terrestrial eutrophication
Terrestrial eutrophication	kg $PO4^{3--}$- eq./kg emitted to soil. Generic EP for each eutrophying emission to air, water and soil, fate not included (Heijungs, R., J. Guinée, G. Huppes, R.M. Lankreijer, H.A. Udo de Haes, A. Wegener Sleeswijk, A.M.M. Ansems, P.G. Eggels, R. van Duin, H.P. de Goede, 1992: Environmental Life Cycle Assessment of products. Guide and Backgrounds. Centre of Environmental Sciences (CML), Leiden University, Leiden.	None	kg SO2 eq. into air Terrestrial eutrophication grouped with terrestrial acidification as in Ecoindicator 99. The damage caused by fertilisers that are deliberately applied on agricultural soil is already included in the land-use damage factors, and should not be considered in the acidification category.
Aquatic eutrophication	kg $PO4^{3--}$- eq./kg emitted to water. Generic EP for each eutrophying emission to air, water and soil, fate not included (Heijungs, R., J. Guinée, G. Huppes, R.M. Lankreijer, H.A. Udo de Haes, A. Wegener Sleeswijk, A.M.M. Ansems, P.G. Eggels, R. van Duin, H.P. de Goede, 1992: Environmental Life Cycle Assessment of products. Guide and Backgrounds. Centre of Environmental Sciences (CML), Leiden University, Leiden.)	kg N-eq/kg emission for marine eutrophication ; kg P-eq/kg emission for freshwater eutrophication. Factors for water and soil emissions are given for N and P total emissions. This can be converted to any N and P species emitted to water or soil, based on molecular weigh Combination of atmospheric European transport model EUTREND and European water model CARMEN	kg PO4 3- eq. into water EPS 2000d IMPACT 2002(+) Aquatic By default, freshwater ecosystems are assumed to be P-limited. Only phosphate emissions considered. Values are from CML 2002, v2.6: "impact assessment juli 2002.xls/characterisation factors". The damage caused by fertilisers that are deliberately applied on agricultural soil is already included in the land-use damage factors, and should not be considered in the aquatic eutrophication category

Eco-toxicity: Fresh water, Marine aquatic terrestrial	kg 1,4-DCB-eq. emitted to fresh water, sea water or soil/kg emitted Three separate impact categories for resp. Fresh Aquatic, Marine Aquatic and Terrestrial Eco-toxicity; FAETP infinite, MAETP infinite and TETP infinite (Huijbregts, 1999 & 2000; see above)	1,4-DCB to water or soil/kg emission. Categories are freshwater, marine water and soil ecosystems USES-LCA 2.0 for toxic pollutants (metals and organics). Effect factors are based on the inverse of the average toxicity derived from EC50 data	kg triethylene glycol eq. into water / soil Impact Impact 2002 model (Pennington et al., 2005). Midpoint is backcalculated from damage
Photochemical oxidation	kg ethylene eq./kg emitted to air POCP (Jenkins, M.E. & G.D. Hayman, 1999: Photochemical ozone creation potentials for oxygenated volatile organic compounds: sensitivity to variations in kinetic and mechanistic parameters. Atmospheric Environment 33: 1775-1293. Derwent, R.G., M.E. Jenkins, S.M. Saunders & M.J. Pilling, 1998. Photochemical ozone creation potentials for organic compounds in Northwest Europe calculated with a master chemical mechanism. Atmospheric Environment, 32. p 2429-2441; high NOx)	kg NMVOC-eq./kg emitted Atmospheric European transport model LOTOS-EUROS for calculation NMVOC and NOx midpoint factors. Further subdivision in individual NMVOCs, based on POCP-values of Derwent and others	kg ethylene eq. into air From Ecoindicator 99
Abiotic depletion	kg antimony equiv./kg extraction		
Land use	m2.yr/m2.yr Land competition, unweighted aggregation of land use (15. Guinée, J.B. (Ed.), M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S.Suh, H.A. Udo de Haes, J.A. de Bruijn, R. van Duin and M.A.J. Huijbregts, 2002. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Series: Eco-efficiency in industry and science. Kluwer Academic Publishers. Dordrecht). (88)	(occupation) m2.yr, (transformation) m2 From CML 2000. With differentiation between urban and agricultural occupation, and transformation of natural areas.	m2 organic arable crop Mainly from Eco-indicator 99, only land occupation considered

Lonising radiation	None	air, 14 river, 14 ocean) kBq U-235 air- eq/kBq Frischknecht et al 2000	in air, 13 in water) Bqeq carbon-14 into air From Ecoindicator 99
Resource consumption	kg antimony eq./kg extracted ADP based on ultimate reserves and yearly extraction rates (15. Guinée, J.B. (Ed.), M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S.Suh, H.A. Udo de Haes, J.A. de Bruijn, R. van Duin and M.A.J. Huijbregts, 2002. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Series: Eco-efficiency in industry and science. Kluwer Academic Publishers. Dordrecht). Primary energy carriers and minerals assessed together. For biotic resources no baseline; reserves and deaccumulation rate as alternatives	mineral extraction Mc values [-/kg], (..) Fossil fuel, upper heating value [MJ/kg]	MJ total for energy, (20) MJ surplus: Additional cumulative non renewable primary energy demand to close life cycle Surplus energy concept from Müller-Wenk, but summing MJ primary and MJ surplus energy for fossil fuels

APPENDIX 2 SUMMARY OF LITERATURE REVIEWS ON CURRENT LCA OF GTE SYSTEMS

Literature	Region	Geothermal plant type	Impact indicator	Impact(per kWh)	Comments
(Karlsdóttir et al., 2015)	ISL	Single & double flash		No data for impacts	Just life cycle inventory analysis
(Marchand et al., 2015)	FR	Single & double flash	a) GWP 100a (IPCC)	0.0385- 0.047kg CO2 eq	
			b) Ecological scarcity 2006 water consump.	0.00817 - 0.0124 UBP	
			c) ReCiPe,freshwater eutrophication	0.00000144 - 0.00000201 kgP eq	
			d) ReCiPe, marine eutrophication	0.00000133 - 0.000642	
			e) CML2, terrestrial eutrophication		
			f) ReCiPe, natural land transformation		
			g) USEtox, eco-toxicity		
			h) CML2, abiotic depletion		
			i) CED Nonrenewable		
			j) CED Renewable		
			k) ReCiPe agricultural and urban occupation		
			l) USEtox Human toxicity (cancer)		
			m) USEtox Human toxicity (no cancer)		
			n) CML2, acidification MJ		
(Frick et al., 2010)	DE	EGS	a) Greenhouse gas emissions	a) Ca. 50−60 g CO2eq	Data for 12 plants case study with capacities varying from 0.46 to 11.1 MW. The base case is a plant with 1.75 MW capacity
			b) Acidification potential	b) Ca. 400 mg SO2eq	
			c) Cumulated energy demand	c) Ca. 600−750 kJ	
			d) Eutrophication	d) Ca. 50−60 mg PO43-	
(Gerber & Marechal, 2012)	CH	EGS	Global warming potential 100a, Eco indicator 99	Functional unit of EGS construction, operation and dismantling	

(Clark et al., 2012)	US	Flash, binary system and EGS	a) Greenhouse gas emissions	Flash: 95g/kWh; Binary:10 g/kWh; EGS: 30g/kWh	a 20-MW EGS plant, a 50-MW EGS plant, a 10-MW binary plant, a 50-MW flash plant, and a 3.6-MW geo-pressured plant that coproduces natural gas.
			b) Water consumption	Flash: 0.01gallon/kWh; Binary: 0.08-0.271 gallon/kWh; EGS: 0.3-0.73 gallon/kWh;	
(Sullivan et al., 2010)	US	EGS, HT	Energy consumption	Ca. 0.2 kWh	
			GHG/kWh output	Ca. 20 g CO_2 eq	
(Lacirignola & Blanc, 2013)	Central Europe	EGS	a) Greenhouse gas emissions	a) Ca. 17−58 g CO_2eq	Data for 10 plants case study with capacities varying from 0.8 to 3 MW.
			b) Acidification potential	b) Ca.300−600 mg SO_2eq	
			c) Cumulated energy demand	c) Ca. 800−900 kJ	
			d) Eutrophication	d) Ca. 40−80 mg PO_4^{3-}	

APPENDIX 3 LIFE CYCLE INVENTORY FOR THE LARGE-SCALE FLASH SYSTEM

Geothermal well drilling of the large-scale flash system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %
Deep well_drilling_large_flash	1.0	m	Length	100 %
(Insert line here)				

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
Water, well, in ground, ID	in water	0.5	m3	Lognormal	1.903		

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
Reinforcing steel {GLO}| market for | Conseq, U	309	kg	Lognormal	1.903		
Bentonite {GLO}| market for | Conseq, U	20	kg	Lognormal	1.903		
Cement, Portland {RoW}| market for | Conseq, U	213	kg	Lognormal	1.903		
Barite {GLO}| market for | Conseq, U	20	kg	Lognormal	1.903		
(Insert line here)						

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
Electricity, medium voltage {ID}| market for | Conseq, U	3932	kWh	Lognormal	1.903		
Diesel, burned in diesel-electric generating set, 10MW {GLO}| market for | Conseq, U	111	MJ	Lognormal	1.903		
(Insert line here)						

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Economic issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
Drilling waste {GLO}| market for | Conseq, U	466	kg	Lognormal	1.906		
Wastewater, average {GLO}| market for | Conseq, U	0.5	m3	Lognormal	1.903		
(Insert line here)						

Pipeline collection of the large-scale flash system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %
Geothermal power plant pipeline construtcion for large flash	1.0	p	Amount	100 %
(Insert line here)				

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Commen
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Commen
Chromium steel pipe {GLO}| market for | Conseq, U	4334000	kg	Undefined				
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Commen
(Insert line here)							

Power plant machinery of the large-scale flash system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %
Power plant machinery large flash	1	MWh	Energy	100 %
(Insert line here)				

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Commen
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Commen
Aluminum ingot, production mix, at plant/US	242	kg	Undefined				
Copper {RER}| production, primary | Conseq, U	363	kg	Undefined				
Rock wool {RoW}| production | Conseq, U	246	kg	Undefined				
Steel, billets, at plant/US	2343	kg	Undefined				
Steel, low-alloyed, hot rolled {GLO}| market for | Conseq, U	8616	kg	Undefined				
Titanium, primary {GLO}| production | Conseq, U	523	kg	Undefined				
(Insert line here)							

Power plant building of the large-scale flash system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Category
Power plant building large flash	1	MWh	Energy	100 %	Electricity b.
(Insert line here)					

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Aluminum ingot, production mix, at plant/US	578	kg	Undefined				
Copper {RER}| production, primary | Conseq, U	152	kg	Undefined				
Rock wool {RoW}| production | Conseq, U	567	kg	Undefined				
Steel, stainless 304, scrap/kg/GLO	11943	kg	Undefined				
Mastic asphalt {GLO}| market for | Conseq, U	31624	kg	Undefined				
Cement, Portland {RoW}| production | Conseq, U	86	kg	Undefined				
(Insert line here)							

Operation phase of the large-scale flash system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation '
Geothermal operation phase large flash	1	p	Amount	100 %
(Insert line here)				

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comn
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comn
(Insert line here)							

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comn
(Insert line here)							

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comn
Carbon dioxide		4576	kg	Undefined				
Hydrogen sulfide		1122	kg	Undefined				
Methane		0.3586	kg	Undefined				

Disposal phase of the large-scale flash system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %
Deep well closure for large flash	1.0	m	Length	100 %
(Insert line here)				

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comme
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Known inputs from technosphere (materials/fuels)

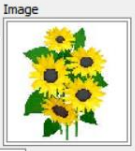
Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comme
Gravel, round {GLO}| market for | Conseq, U	14.7	kg	Undefined				
Cement, alternative constituents 21-35% {RoW}| market for | Conseq, U	0.7833957373	kg	Undefined				
(Insert line here)							

LCA analysis general input of the large-scale flash system:

Input/output | Parameters

Name: LCA large scale flash

Image:



Comment:

Status: None

Assembly	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
	0		Undefined				

Processes	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Deep well_drilling_large_flash	62469	m	Undefined				Construction phase
Geothermal power plant pipeline construtcion for large flash	1	p	Undefined				Construction phase
Power plant machinery large flash	110	MWh	Undefined				Construction phase
Power plant building large flash	110	MWh	Undefined				Construction phase
Geothermal operation phase large flash	8760	p	Undefined				Operation phase
Deep well closure for large flash	62469	m	Undefined				Disposal phase
(Insert line here)							

Waste/Disposal scenario

Comment

Additional life cycles	Number	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)						

APPENDIX 4 LIFE CYCLE INVENTORY FOR THE SMALL-SCALE BINARY SYSTEM

Geothermal well drilling of the small-scale binary system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Category
Drilling well small binary	1.0	m	Length	100 %	Electricity b.

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Water (with river silt)	in ground	5000	kg	Undefined				

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Steel, low-alloyed {GLO}| market for | Conseq, U	44	kg	Undefined				
Bentonite {GLO}| market for | Conseq, U	15	kg	Undefined				
Cement, Portland {RoW}| market for | Conseq, U	20	kg	Undefined				
Barite {GLO}| market for | Conseq, U	7.5	kg	Undefined				

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Diesel, burned in diesel-electric generating set, 10MW {GLO}| market for | Conseq, U	1077.5	MJ	Undefined				

Pipeline collection of the small-scale binary system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Category
Collection construction small binary	1.0	p	Amount	100 %	Electricity b.

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Chromium steel pipe {GLO}| market for | Conseq, U	50000	kg	Undefined				

Power plant machinery of the small-scale binary system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Category
Power plant machinery small binary	1	MWh	Energy	100 %	Electricity b..

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Aluminum ingot, production mix, at plant/US	2000	kg	Undefined				
Copper {RER}| production, primary | Conseq, U	3000	kg	Undefined				
Rock wool {RoW}| production | Conseq, U	17500	kg	Undefined				
Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route, prod. mix, grade 3	19000	kg	Undefined				
Steel, low-alloyed, hot rolled {GLO}| market for | Conseq, U	72000	kg	Undefined				
Titanium, primary {GLO}| production | Conseq, U	4100	kg	Undefined				

Power plant machinery of the small-scale binary system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Category
Power plant machinery small flash	1	MWh	Energy	100 %	Electricity b..
(Insert line here)					

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Aluminum ingot, production mix, at plant/US	242	kg	Undefined				
Copper {RER}| production, primary | Conseq, U	363	kg	Undefined				
Rock wool {RoW}| production | Conseq, U	246	kg	Undefined				
Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route, prod. mix, grade 3	2343	kg	Undefined				
Steel, low-alloyed, hot rolled {GLO}| market for | Conseq, U	8616	kg	Undefined				
Titanium, primary {GLO}| production | Conseq, U	523	kg	Undefined				
(Insert line here)							

Power plant building of the small-scale binary system:

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Category
Power plant building small binary	1	MWh	Energy	100 %	Electricity b.
(Insert line here)					

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
(Insert line here)							

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Steel, stainless 304, scrap/kg/GLO	15000	kg	Undefined				
Cement, Portland {RoW}| production | Conseq, U	50	kg	Undefined				
(Insert line here)							

LCA analysis general input of the small-scale binary system:

Name: Small binary construction

Image

Status: None

Assembly	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
	0		Undefined			

Processes	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max
Drilling well small binary	4000	m	Undefined			
Collection construction small binary	1	p	Undefined			
Power plant machinery small binary	0.5	MWh	Undefined			
Power plant machinery small flash	0.5	MWh	Undefined			