Life Cycle Assessment of the Geothermal Power Plant in the Patuha Geothermal Field, Indonesia

Gloria Gladis Sondakh

Thesis of 60 ECTS credits
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Abstract

Every country is aiming to increase the utilization of renewable and low-carbon energy, in order to reduce the emissions of greenhouse gases (GHG). Geothermal energy is one of many renewable energy sources that emits significantly less GHG than fossil-based energy sources. A 55 MWe geothermal power plant in Indonesia, owned by PT Geo Dipa Energi (GeoDipa), has implemented a number of strategies to achieve environmentally friendly production. As part of the strategy, a Life Cycle Assessment (LCA) is required to assess the potential negative impacts on the environment of the geothermal drilling, construction, and operation of the Patuha geothermal power plant. The LCA method for this research relies on the general framework outlined in ISO 14040:2006 and ISO 14044:2006 for environmental management. Following the impact analysis considered by ReCiPe2016 impact methodology, 19 impacts were discovered for the drilling and construction stages, and 10 impacts for the operation stage. The significant consumption of steel and concrete for the casing, pipelines, turbines, and generator are the major contributors to the impacts for the drilling and construction stages. Furthermore, the operation stage contributed significantly to climate change, fine particulate matter formation, and terrestrial acidification. The results reveal that the GHG (in CO_2 equivalents) emissions at the Patuha geothermal power plant account for 43,3 g CO_2 eq/kWh which is lower than the global average for geothermal power generation (122 g CO_2/kWh) and about 10 times less than fossil fuel-based electricity production. Overall, it can be concluded that environmental impacts of the power plant are considerable, however, significantly lower than similar fossil fuel-based power plants.

Lífsferilsmat Jarðvarmavirkjunar á Patuha Jarðhitasvæðinu, Indónesíu

Gloria Gladis Sondakh

March 2022

Útdráttur

Öll lönd stefna að því að auka hlutfall á endurnýjanlegum orkugjöfum til að draga úr losun gróðurhúsalofttegunda. Jarðvarmi er einn endurnýjanlegra orkugjafa sem losar töluvert minna af GHL, samanborið við aðra orkugjafa líkt og jarðefnaeldsneyti. Pathuha jarðvarmavirkjunin í Indónesíu (55 MWe), í eigu PT Geo Dipa Energi (GeoDipa), hefur innleitt ýmsar áætlanir sem stuðla að umhverfisvænni framleiðslu. Hluti af áætluninni er lífsferilsmat til að meta þá þætti sem kunna að hafa neikvæð áhrif á umhverfið vegna jarðborana, byggingar- eða rekstrarstig jarðvarmavirkjunarinnar. LCA aðferðin fyrir þessa rannsókn byggir á stöðlum sem lýst er í ISO 14040:2006 og ISO 14044:2006 fyrir umhverfisstjórnun. Eftir LCA greininguna var notast við ReCiPe2016 aðferðafræðina til að greina áhrifaþætti og 19 áhrifaþættir fundust fyrir borunar- og byggingarstigin sem og 10 áhrifaþættir fyrir rekstrarstigið. Helstu þættir sem hafa áhrif á borunar- og byggingarstigið eru mikil notkun á stáli og steypu, leiðslum, túrbínum og rafölum. Ennfremur stuðlaði rekstrarstigið verulega að loftslagsbreytingum vegna myndunar fíns svifryks og súrnun jarðvegs. Niðurstöðurnar sýna að losun gróðurhúsalofttegunda (í CO_2 ígildum) frá Patuha jarðvarmavirkjuninni er 43,3 g CO_2 eq/kWh sem er töluvert lægra en heimsmeðaltal fyrir orkuframleiðslu jarðvarmavirkja (122 g CO_2/kWh) og um 10 sinnum minna en raforkuframleiðsla með jarðefnaeldsneyti. Á heildina litið má álykta að umhverfisáhrif virkjunarinnar séu umtalsverð en þó töluvert minni en umhverfisáhrif sambærilegra virkjana sem framleiða orku með jarðefnaeldsneyti.

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Master of Science

I dedicate this thesis to GRO-GTP (Geothermal Training Programme) in Iceland and PT Geo Dipa Energi (Persero) in Indonesia.

Acknowledgements

"For I know the plans I have for you," declares the Lord,"plans to prosper you and not to harm you, plans to give you hope and a future".

Jeremiah 29:11 (NIV)

I would like to convey my appreciation to the GRO-GTP and PT Geo Dipa Energi (Persero) who have provided me the opportunity to pursue a Master's degree in Iceland. This report would not have been possible without the assistance of my supervisors (Einar Jón Asbjörnsson, Marta Rós Karlsdóttir, and David Christian Finger) and Kristján Valur Vilbergsson who generously shared knowledge that helped me to learn about the GaBi software. I would like to express my gratitude to my Mom (Deitje Ronny Gerung), Dad (Albert Brami Sondakh), Brothers (Ronald Peterson Sondakh and Allan Dave Sondakh) for their endless prayers and support, as well as my Indonesian colleagues who assisted me throughout the data collection process. I would especially like to express my gratefulness to God for providing me with everything I could possibly need in my life.

Preface

This dissertation is original work by the author, Gloria Gladis Sondakh. Portions of the introductory text are used with permission from Sondakh et al (2022) of which I am an author.

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List of Abbreviations

Ar	Argon
As	Arsenic
CH_4	Methane
FRP	Fibre Reinforced Plastic
CO_2	Carbon dioxide
GaBi	Ganzheitliche Bilanzierung
GHG	Greenhouse Gas
GWP	Global Warming Potential
H_2	Hydrogen
H_2S	Hydrogen sulfide
Hg	Mercury
kg	Kilogram
kWh	Kilo-Watt hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^3	Cubic meter
MWh	Mega-Watt hour
N_2	Nitrogen
NH_3	Ammonia

Chapter 1

Introduction

Life Cycle Assessment of Geothermal Power Plant in Patuha Geothermal Field, Indonesia, is a research conducted to determine the environmental impacts of the drilling, construction, and operation stages of the power plant. This research was prepared in accordance with ISO 14040:2006 (Environmental management – Life cycle assessment – Principles and framework) and ISO 14044:2006 (Environmental management – Life cycle assessment – Requirements and guidelines) standards.

1.1 Hypotheses

The research questions to be answered in this LCA study are as follows:

1. What environmental impacts are caused during the life cycle of the Patuha geothermal power plant, accounting for the drilling stage, construction stage, and operation stage?
2. What unit processes have the highest contribution to the environmental impacts (hotspot) at the Patuha geothermal power plant?
3. How are the results of the research compared to other geothermal LCA results?
4. What are the alternative improvements that can be implemented to lessen the environmental impact at the Patuha geothermal power plant?

The research hypotheses are as follows:

1. The drilling stage is the main factor that can impact the environment, which means that the drilling stage has a higher impact than the construction and operation stages.
2. The construction stage is the main factor that can impact the environment, which means that the construction stage has a higher impact than the drilling and operation stages.
3. The operation stage is the main factor that can impact the environment, which means that the operation stage has a higher impact than the drilling and construction stages.

1.2 Background

Environmental issues originating from greenhouse gas (GHG) emissions are becoming a global concern. In excess amounts, GHGs will undoubtedly have a negative impact on the environment and humans. In the twenty-first century, lowering greenhouse gas emissions into the environment has proven to be one of the most challenging concerns to address (Masson-Delmotte et al., 2018). For the first time in hundreds of years, the last five years have been the warmest on record. It is believed that daily human activities, such as burning fossil fuels for power plants, cars, industry, and airplanes, are wholly responsible for this rapid warming. In burning fossil fuels, greenhouse gases such as CO_2 are released into the atmosphere, contributing to the greenhouse effect and temperature rise. Currently, all countries worldwide are working towards the use of clean energy that emits very low levels of greenhouse gases. Geothermal energy is a greener energy source that is also regarded to be an environmentally friendly energy source. Most geothermal power plants emit only a small amount of GHGs, with a global average of 122 g CO_2/kWh (Fridriksson et al., 2016). There are only a few cases where geothermal power plants release substantial levels of GHGS, such as the Chiusdino power station in Italy, which emits 477 g CO_2/kWh (Basosi et al., 2020). There is yet another geothermal power station in Turkey, located in Gediz Graben, which emits 1800 g CO_2/kWh. The geological situation in Turkey, where the geothermal reservoir is located within a metamorphic basement consisting primarily of carbonate rock, is responsible for the high amounts of emissions that have been recorded (Aksoy et al., 2015).

The classification of geothermal systems is generally categorized based on reservoir temperature. There are various classifications that range from low-temperature to high-temperature at 1 km depth below the surface (Mohammadzadeh Bina et al., 2018). According to Muffler and Cataldi (1978), reservoirs with a temperature of 90°C, 90°C–150°C, and >150°C are classified as low-temperature, intermediate-temperature, and high-temperature respectively. Hochstein (1990) defined <125°C as low temperature, 125°C–225°C as intermediate temperature, and >225°C as high temperature. This classification reflects the utilization possibilities of geothermal energy. There are two types of geothermal utilization, both indirect use and direct use. Indirect use is the use of heat energy from intermediate and high-temperature reservoirs, converting it to other forms of energy, such as electricity production. Direct use is the use of low-temperature geothermal energy from its source without being converted into other energy, which is usually used for non-electric purposes, such as greenhouse heating, space heating or cooling, sauna or steam bathing, agricultural and fishery drying, and other similar applications (Gehringer & Loksha, 2012). As a result of indirect use, geothermal gases such as CO_2, H_2S, H_2, N_2, CH_4, NH_3, and Ar are often released into the environment. Among the most significant GHG associated with geothermal systems, CO_2 is the most abundant gas. There are numerous environmental impacts linked with the use of geothermal energy (Fridriksson et al., 2016).

In areas of the world where geothermal resources are abundant, geothermal energy has been widely utilized since 1913 (Fridleifsson, 2001). Indonesia is one of the countries investing in the development of geothermal power. According to estimates, Indonesia has a total geothermal potential of 29 gigawatts (GW) (Darma et al., 2021). A large amount of power has been generated from these resources in recent years, with a total capacity of 2289 MW achieved by 2020. Because of its total installed capacity, Indonesia is ranked as the world's second-largest geothermal energy producer behind the United States (Huttrer, 2021).

The government has committed to increasing new and renewable energy share in the energy mix to 23% by 2025. Given that Indonesia is a country with substantial geothermal reserves, PT Geo Dipa Energi (Persero) ("GeoDipa"), as a state-owned enterprise (SOE) in the geothermal sector, is committed to assisting the government in meeting the target set by the government. Following the Indonesia Geothermal Energy Development Road Map, GeoDipa aims to maximize the geothermal energy potential in order to promote national productivity in the long term while also increasing national economic growth (GeoDipa, 2020).

The primary activities of this corporation include all aspects of geothermal energy generation, from exploration and exploitation to power generation development. One of the geothermal fields developed by GeoDipa is known as the Patuha Geothermal Field. GeoDipa successfully constructed a 55 MW geothermal power plant unit in the Patuha Geothermal Field in 2014. All of the geothermal steam produced by this field is used as an energy source to generate power, which is then distributed to the surrounding areas of Java, Madura, and Bali. This field is located around Mount Patuha in West Java, approximately 40 kilometres south of Bandung, Indonesia (Figure 1.1) (GeoDipa, 2020).

GeoDipa considers environmental protection to be one of the most essential responsibilities involved with doing business. It will not only be beneficial to the community and the environment, but it will also provide value to the long-term operations. The practice of environmental responsibility is accomplished through the prevention and reduction of activities that have the potential to pollute or destroy the natural environment (GeoDipa, 2020).

Since the power plant commenced operations, a number of initiatives have been implemented to mitigate the negative impact on the environment. An overview of the environmental impacts generated by geothermal operations can be obtained using the Life Cycle Assessment (LCA) technique, which is one of the analytical methodologies available. For a variety of products, notably in the manufacturing business, LCA is a commonly used method. However, there is fewer information on geothermal LCAs due to the rarity of geothermal LCA research. As a result, this research was carried out in order to provide knowledge and insight to geothermal energy developers regarding the environmental impacts of geothermal power plants.

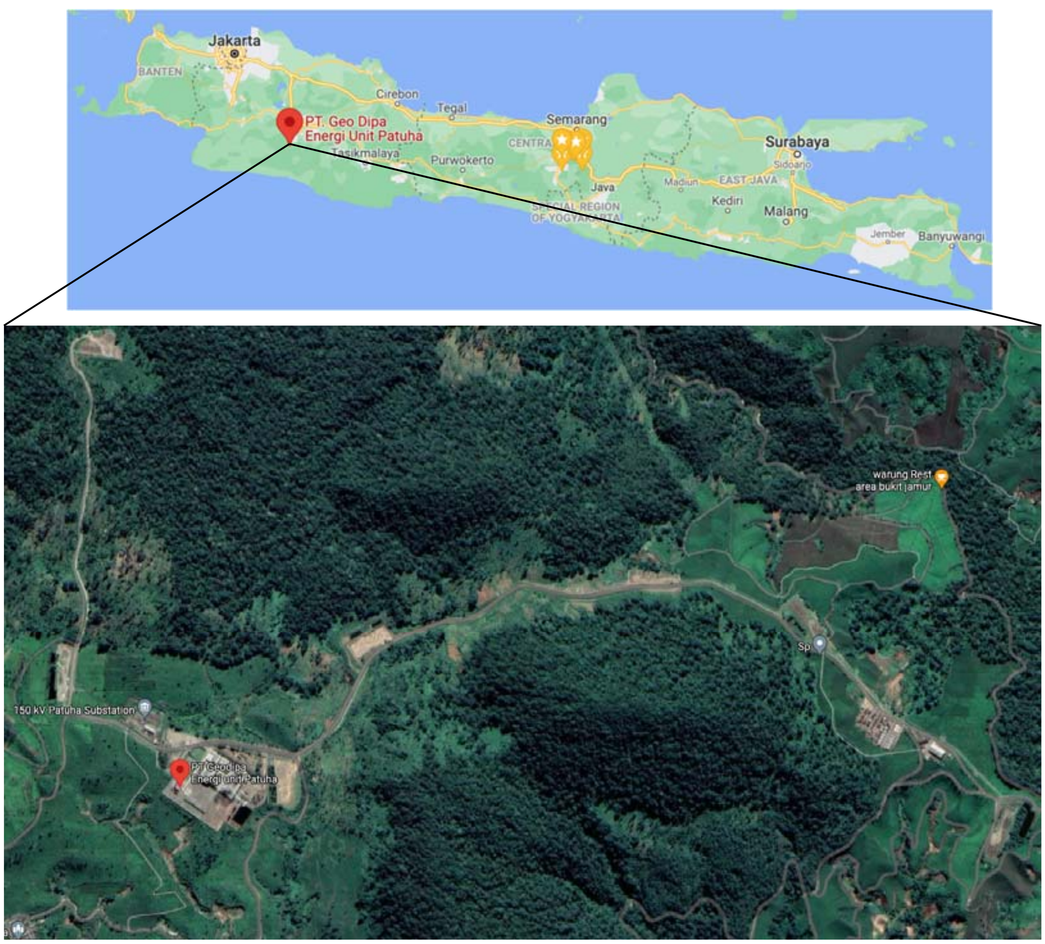

Figure 1.1 - Location of the Patuha Geothermal Field

1.3 Overview

1.3.1 Geothermal development stages

Geothermal projects require the completion of several stages, each of which takes a long time and is a difficult task. Each stage is defined by a collection of deliverables or inputs and a set of exit criteria and outputs. Decisions will be made based on the data collected at each stage (Sondakh, 2018). The test-drilling stage is often seen as high-risk due to the challenges in estimating resource capacity and the costs associated with its development. The risk is reduced after test-drilling, but the cost will increase at the construction stage, where the costs reach up to 60% of the total project cost (Gehringer & Loksha, 2012). Figure 1.2 shows the stages in geothermal development, together with the project cost and risk profile.

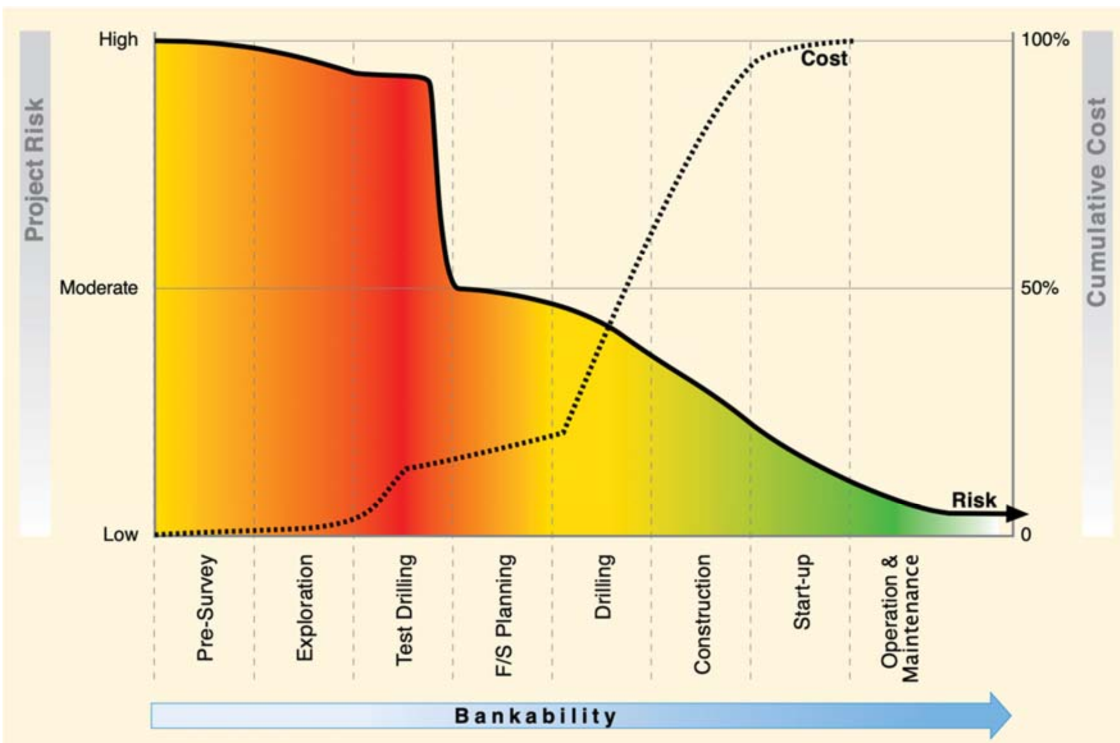

Figure 1.2 - Project cost and risk profile at geothermal development stages (ESMAP, 2012)

PRELIMINARY SURVEY

The Preliminary Survey aims to determine regional or national geothermal potential. This survey requires a literature review for geological, hydrological, or hot spring/thermal data, drilling data, anecdotal information from local communities, and, where accessible, remote sensing data from satellites (Gehringer & Loksha, 2012).

EXPLORATION

The exploration stage involves surface studies in the form of geochemical, geological, and geophysical exploration to prove the existence of geothermal resources. This stage is carried out when the project has met the legal requirements. The chemical elements in the manifestation will be analyzed in a geochemical survey to determine the source of water or steam, including the reservoir temperature and hydrological system. This study is being carried out to assess the upflow and outflow of two phases of geothermal resources: the gaseous phase (vapor fluid) and the fluid phase (water, and a mixture of steam and water). A geological survey entails thorough geological mapping, which includes rock type, geological structure, manifestation data, alteration mapping, and other details. Geophysical exploration maps changes in rock physical qualities caused by geothermal activity processes. Resistivity, gravity, and magnetic techniques are common to measure it (Gehringer & Loksha, 2012).

TEST DRILLING

At this stage, drilling is carried out for 3 to 5 full-size wells (diameter over 8 inches/20 cm) or slim holes (6 inches/15 cm diameter) with a drilling program designed to confirm the existence, exact location, and potential reservoir. If the first well fails to produce steam, downhole data is compared to the preliminary geological, geochemical, and geophysical studies to determine the next target drill site. The drilling for the second exploratory well will be carried out only when the first well is successful, and the drilling location should not be too far apart from the initial well. After the drilling is finished, well logging and discharge tests are performed. The results of the well surveys and tests may verify the resource, and when combined with the findings of previous investigations, a more defined conceptual model can be developed (Gehringer & Loksha, 2012).

PROJECT REVIEW AND PLANNING

In this stage, the developer evaluates all existing data, including new data from the exploratory phases. The test drilling results will allow the project developer to complete the feasibility study, which will include all financial calculations, conceptual engineering for all components to be developed, and a drilling program. The project developer identifies the most cost-effective project size and the necessary investments during this stage. The feasibility study expenditures covered all costs from the preliminary survey through the test-drilling stage, as well as a contingency for all financial, legal, and environmental agreements, permits, desk-top, and engineering work required to move the project into the construction stage (Gehringer & Loksha, 2012).

DRILLING

Drilling is the stage in which production and reinjection wells are drilled in order to complete the field development strategy according to the power capacity goal. One or more drilling rigs are required depending on the drilling program and the well drilling pad. The length of time for drilling a geothermal well is determined by several factors, including the depth of the well, geology (rock), and the capability of the drilling rig. According to a well-accepted rule of thumb, every successful production well produces 5 MW of electrical power in the power plant. Simultaneously with the drilling, the project partially starts constructing the pipelines connecting the wells to the plant (Gehringer & Loksha, 2012).

CONSTRUCTION

Installing a steam gathering system or SAGS, separator, turbine, generator, condenser, and cooling tower are all part of the construction stage. SAGS is a steam pipe system that runs from the wellhead to the power plant and back for reinjected fluids. On a turnkey basis, the cost for a 50 MW power plant ranges from US$ 1 to 2 million per MW installed. This cost estimate excludes transmission lines and substations, which vary greatly depending on installation (Gehringer & Loksha, 2012).

START-UP AND COMMISSIONING

This stage is the final stage before the power plant begins normal operation. It can take several months to fine-tune the efficiency of the power plant and all other equipment, including the pressures from the wells, etc. This stage typically entails resolving numerous technical and contractual difficulties with the plant supplier. The costs for this stage are included in the construction stage investments (Gehringer & Loksha, 2012).

OPERATION AND MAINTENANCE

There are two types of operation and maintenance: steam field O&M and power plant O&M. Steam field O&M covers wells, pipelines, infrastructure, etc, with actions such as cleaning existing wells, drilling new wells (make-up wells) from time to time to recoup lost capacity, and maintaining other field equipment. O&M power plants cover turbines, generators, cooling systems, and substations, among other things (Gehringer & Loksha, 2012).

1.3.2 Patuha Geothermal Field

The Patuha Geothermal system is a vapor-dominated reservoir with temperatures ranging between 215-230°C (Ashat et al., 2019). The surface manifestations include fumaroles, which can be found in Cibuni crater, Putih crater, and Ciwidey crater at elevations ranging from 1800 to 2250 masl, and thermal springs, which can be found at lower elevations ranging from 1600 to 1850 masl in the southern, western, and northwest regions of the Patuha Field (Layman & Soemarinda, 2003). The total amount of geothermal energy that can be generated in the surrounding area is expected to be 400 MW.

Patuha Geothermal Field operates 10 production wells and 3 reinjection wells in order to maintain steam supply to Patuha Unit 1 power plant. All of the production wells at Patuha tap into a relatively shallow reservoir. The majority of the production and injection wells are located in the eastern part of the field. Well PPL-01, PPL-02, PPL-02A, PPL-03, PPL-03A, PPL-03B, PPL-04, PPL-05, PPL-06 and PPL-07 are wells that produce fluids with a vapor fraction of nearly 100 % which are recently operating to support the production and maintain steam supply to the power plant. Figure 1.3 shows the location of the wells, steam gathering system, and power plant at the Patuha Geothermal Field.

Geothermal production facilities depend on the type of fluid flowing from the well. The fluid at the well head at the Patuha Geothermal Field is in the form of a steam phase where the steam produced is dry steam, and the amount of brine is very small so that the steam can flow directly to the turbine. This is different from two-phase fluids (vapor phase and liquid phase), which require a fluid separation process through a separator to separate the vapor phase from the liquid phase (PWC, 2013).

At the Patuha Geothermal Field operation, the dry steam is transported from the wells through the steam pipeline at the gathering system on the surface. Branch pipelines from all wellpads are interconnected with the main pipeline that is constructed in front of each pad along the existing access road. The steam pipelines are made from carbon steel, where the thickness is designed to allow the steam pressure and flow rate and prevent corrosion and erosion by fluid. The pipeline is covered with insulation material to avoid temperature drops (PWC, 2013).

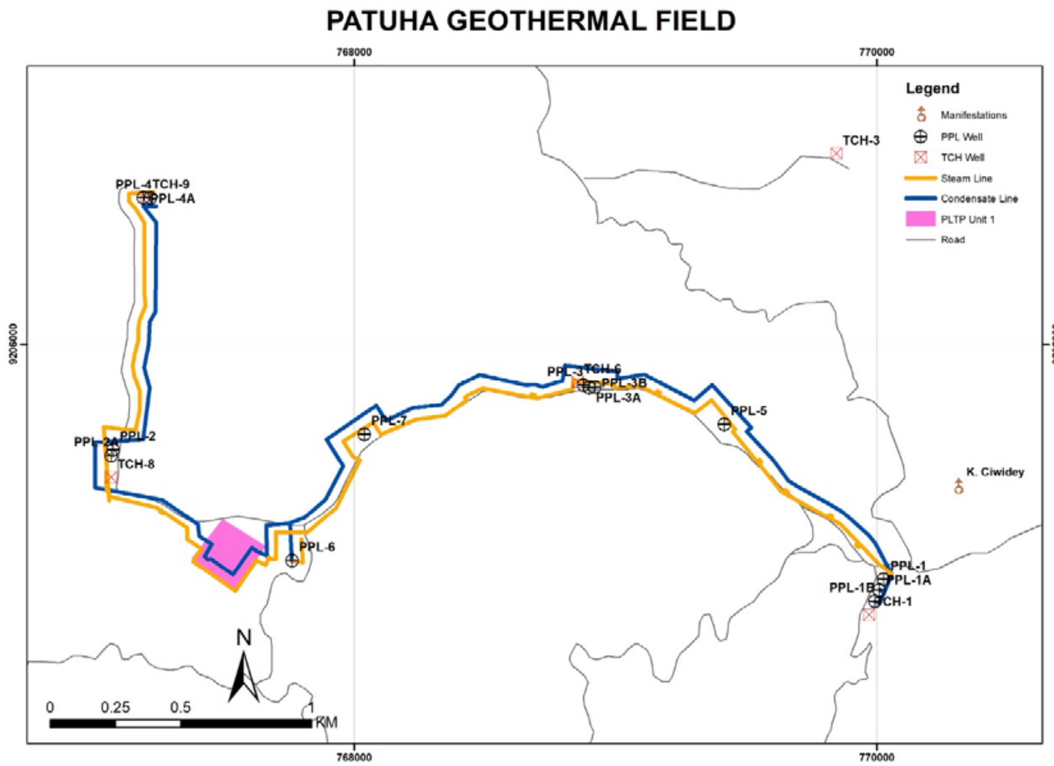

Figure 1.3 - Location of the power plant and gathering system of the Patuha Geothermal Field

From the gathering system, the steam flows through a demister where the moisture residue and particles are removed. The steam then flows to the turbine and rotates the turbine which is coupled with the generator. The exhaust steam from the turbine is flowed to be condensed in the condenser and extracted by the condensate pump then sent to the cooling tower. Non-condensable Steam or Non-condensable Gas (NCG) is cooled in the condenser to reduce the accompanying steam and is extracted by a two-stage ejector system to the cooling tower fan stack, then exhausted to the atmosphere. Some of the results from the condensation collected in the brine pond are pumped using a brine pump, then flowed directly into the well injection so that the brine is injected back into the subsurface (PWC, 2013). The process flow diagram is shown in Figure 1.4.

The following is an explanation of the surface facilities used for geothermal production at the Patuha Geothermal Field (PwC, 2013):

PRODUCTION WELL

Wells are drilled for the sole purpose of allowing the production of geothermal energy, in the form of hot liquid or steam, or a two-phase mixture, from a specific target or a geothermal reservoir. Valves are installed in the production wells, placed in a concrete cellar. These valves help regulate the flow of fluid out of the production wells to the surface.

STEAM ABOVE GROUND SYSTEM (SAGS)

The SAGS consists of the pipelines and equipment that will be utilized to transport the steam that will be converted into electricity. The pipeline is installed from each well pad to the geothermal power plant. Since the geothermal fluid in Patuha is in the steam phase, the flow pipe in the field is more simple, consisting only of a flow pipe that extends from the well to the turbine.

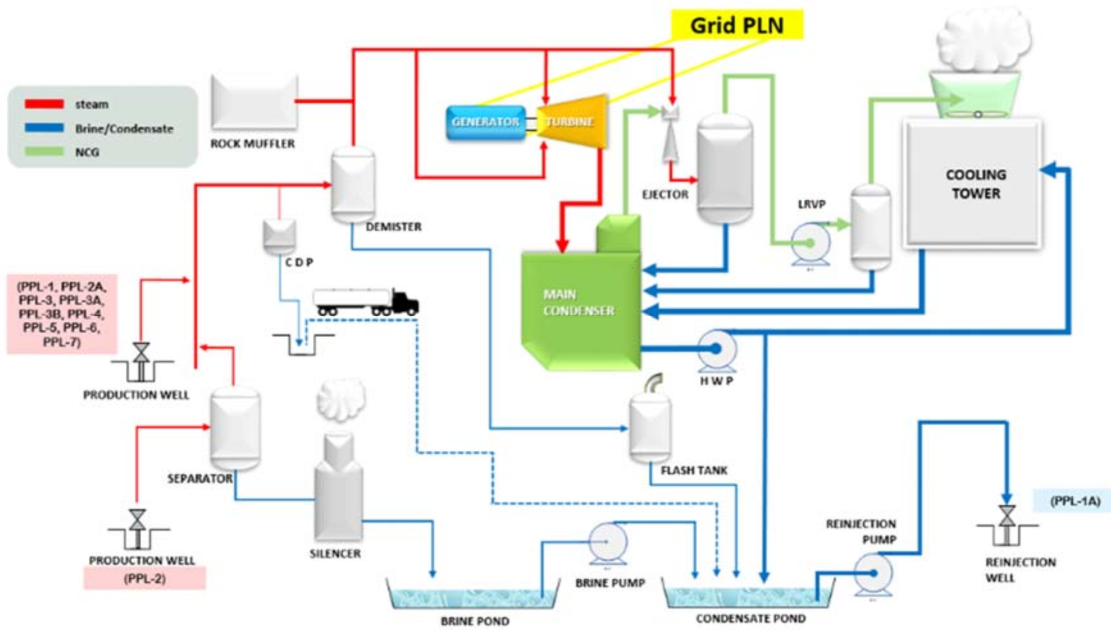

Figure 1.4 - Process flow diagram of the Patuha Geothermal Field

ROCK MUFFLER

Function as a pressure regulator so that the steam pressure entering the turbine is always constant. When there is excess steam, the rock muffler removes the excess steam.

DEMISTER

The steam will be sent into the turbine after passing through a centrifugal filter. The demister is responsible for capturing and removing the water droplets that are present in the steam. The remaining moisture and particles will be eliminated, resulting in only steam entering the turbine during operation.

TURBINE AND GENERATOR

The turbine is the primary equipment used to transform geothermal energy into mechanical energy. In the steam turbine, the energy content of the steam flow is converted into mechanical energy. Through the rotational movement of the turbine, the directly-coupled generator generates electric power, while the exhaust steam flow is discharged into the condenser through an exhaust duct. The condensed exhaust steam from the turbine is removed by hot pumps and transported to cooling towers for cooling. The type of turbine used in the Patuha power plant is a standard single or dual axial-flow impulse/reaction turbine with an inlet pressure of 5 - 10 ata and an outlet pressure of 0,05 – 0,15 ata. The turbine drives at 3000 rpm and drives a direct linked synchronous generator.

CONDENSER

The condenser is responsible for condensing the exhaust steam that comes out of the turbine through direct contact with the cooling water that comes from the cooling tower. The pressure is vacuum air pressure conditions, resulting in a pressure that is lower than atmospheric pressure. The NCG is cooled in a specific condenser section. The type of condenser used in Patuha is direct contact or spray type with an integral gas cooling section.

COOLING TOWER

Function as a coolant and as a final exhaust unit in the form of steam or gas. Water extracted from the condenser is delivered to the top of the cooling tower by hot well pumps, with the goal of lowering its temperature as it passes through. The excess condensed water from the process that occurs in the cooling tower is then stored in a reinjection pond. The NCGs are driven to the cooling tower exhaust and released to the atmosphere. The cooling tower used by Patuha is an induced draft tower with a low clog fill.

GAS REMOVAL SYSTEM

The gas removal system removes NCGs that are contained in the main steam from the main condenser. NCG is removed from the condenser by a hybrid vacuum system. The exhaust steam that is not condensed in the condenser is pulled in using the first stage and second stage ejectors and then pumped to the cooling tower for cooling before being recirculated back to the condenser. The driving steam is drawn from the main steam line when the ejectors are running.

REINJECTION POND AND REINJECTION WELL

The reinjection well is located at the reinjection pond. Brine and condensate from the process at the power plant are reinjected to the reinjection well. The water kept in the pond will be treated with NaOH to neutralise the pH of the water before being reinjected into the reinjection well. Reinjection aims to maintain subsurface steam pressure, recharge water for reservoirs, and reduce ground subsidence. With reinjection, the wastewater produced does not contaminate surface water as it would otherwise.

1.4 Life Cycle Assessment

Life Cycle Assessment (LCA) is a method used to evaluate the environmental loads associated with a product, process, or activity. This assessment includes the extraction and acquisition of raw materials, followed by the production and manufacturing of energy and materials, and ending with waste management (processing or disposal). Calculation of the amount of energy, materials used, as well as emissions and waste released into the environment are carried out to identify environmental impacts on a product. The assessment results are disclosed through a number of environmental indicators used to carefully detect various ecological loads associated with the process or activity. LCA can support decision-making with scientific data and competence so that the results are accurate and useful for environmental improvement (ISO 14040, 2006). Furthermore, LCA can identify hidden impacts of services, processes and products that occur either upstream or downstream of the main process or use phase of a product.

To conduct an analysis of all processes in the life cycle of a product, ISO (International Standards Organization) establishes a general framework in ISO 14040:2006 and ISO 14044:2006 concerning environmental management (Figure 1.5). The general framework consists of several phases that are interlinked.

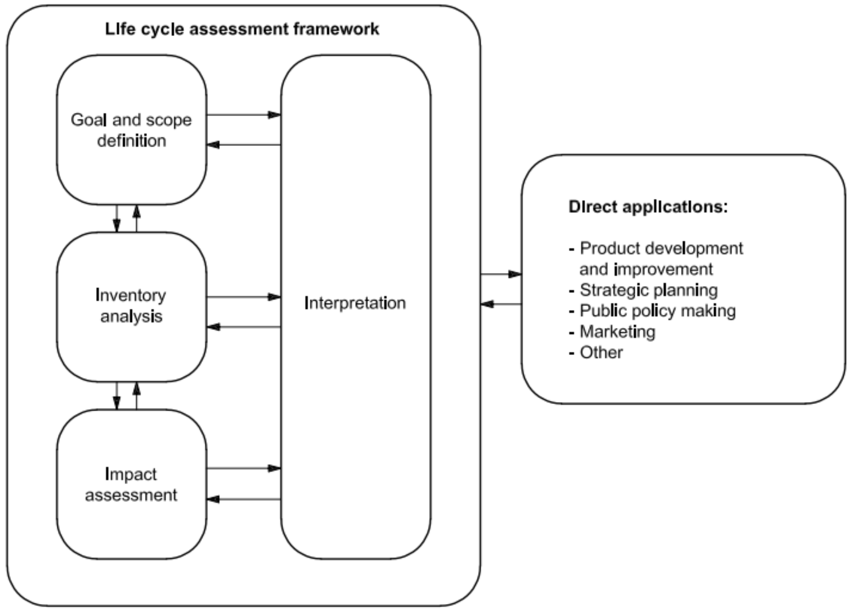

Figure 1.5 - Phases of LCA

1.4.1 Goal and scope

Goal and scope are guidelines that can help with the consistency of LCA research. This phase is the initial phase that provides an overview of the research objectives, system boundaries, data source quality requirements, and specifications of the functional unit of analysis (ISO 14040, 2006).

The goal states the intended application of the study, the reasons for conducting the research, the target audiences to be communicated, and whether the results can be used for comparative assertions that are intended to be publicly disclosed. The scope is the key parameter that describes how the study is done. This includes the product system studied, the function of the product system, the functional unit, the system boundary, allocation procedures, impact categories selected and impact assessment methodology, data requirements, assumptions, limitations, initial data quality requirements, type of critical review, and also the type and format of the report required for the study (ISO 14040, 2006). Three key parameters of the scope are the product system studied, the functional unit, and system boundaries (Matthews et al., 2014). Subchapter 2.2 will cover the key parameters of this research.

PRODUCT SYSTEM

A product system is modelled from the product life cycle in the form of a collection of processes that provide a certain function where the function represents the performance characteristics of the product system (Matthews et al., 2014). The product system is divided into a set of unit processes (Figure 1.6).

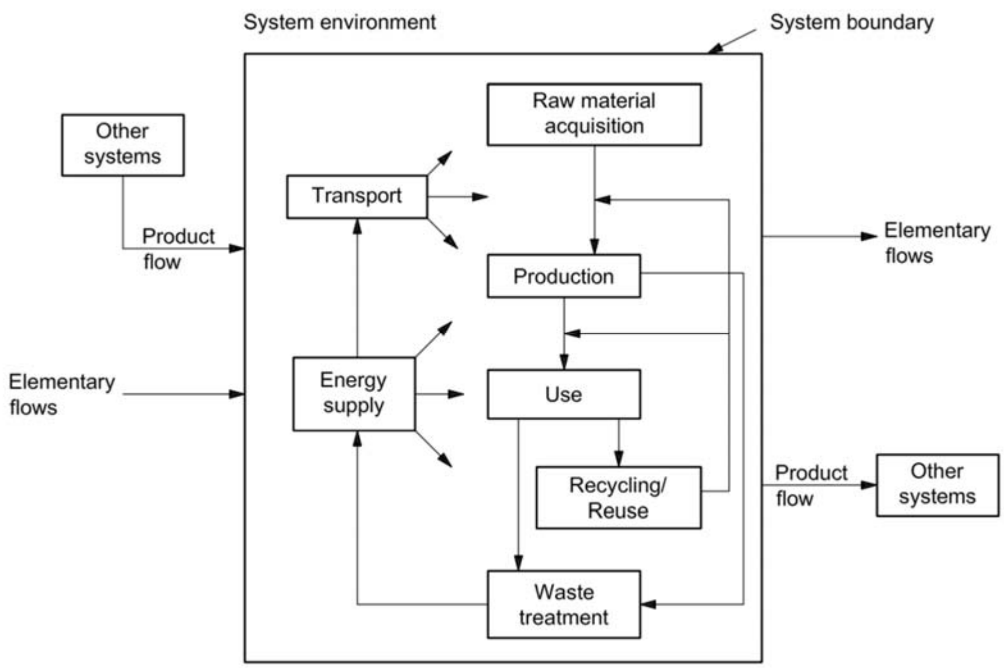

Figure 1.6 - A product system for LCA (ISO 14040, 2006)

A unit process to another unit process is linked by intermediate flows (Figure 1.7). A unit process to other product systems is linked by the product system. A unit process to the environment is linked by elementary flows that include resource utilization and releases to air, water and land associated with the system (ISO 14040, 2006).

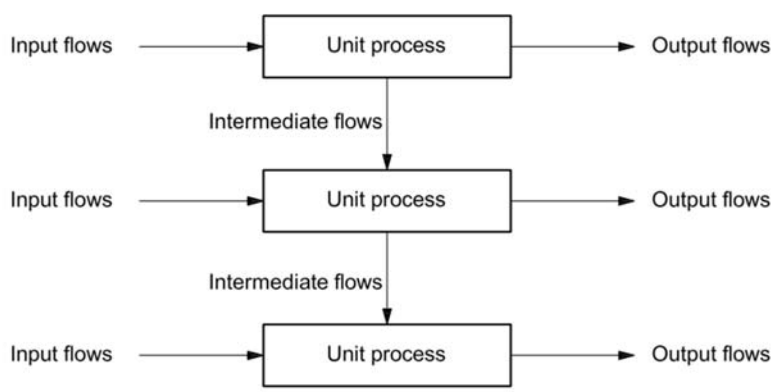

Figure 1.7 - A set of unit processes within a product system (ISO 14040, 2006)

FUNCTIONAL UNIT

The functional unit is a quantitative description of the identified product function. The primary purpose of the functional unit is to provide references related to inputs and outputs. An appropriate functional unit is helpful to ensure the comparison of LCA results. To compare the results of the LCA, it is necessary to ensure that the comparison of results of the LCA is carried out on the same basis (ISO 14040, 2006). Matthews et al., (2014) created a table that provides examples to make it easier to distinguish between product systems, functions, functional units, and examples of LCI results (Table 1.1).

Table 1.1 Relationship between function, functional unit, and example LCI results (Matthews et al., 2014).

Product System	Function	Functional Unit	Example LCI Results
Power plant	Generating electricity	1 kWh of electricity generated	kg CO_2 per kWh
Christmas tree	Providing holiday joy	1 undecorated tree over 1 holiday season	MJ energy per undecorated tree per holiday season
Hand dryer	Drying hands	1 pair of hands dried in a restroom facility	MJ energy per pair of hands dried in the restroom
Light bulb	Providing light	100 lumens light for 1 hour (100 lumen-hrs)	g Mercury per 100 lumen-hrs

SYSTEM BOUNDARIES

The scope of the LCA can be divided into four types of scope (Figure 1.8) (ISO 14040, 2006; Kupfer et al., 2021):

a. *Cradle to grave*: starts from raw materials (all activities from material acquisition/exploitation) through product operations until the finished products are consumed by a consumer (disposal, recycling, and reuse).
b. *Cradle to gate*: starts from the raw materials through the operation process before being used by the consumer.
c. *Gate to gate*: the shortest life cycle because it only reviews the activities closest to it, starting from the production steps on-site to commissioning steps, before being used by the consumer.
d. *Gate to grave*: starts from the production steps on-site to the finished products are consumed by a consumer (disposal, recycling, and reuse).

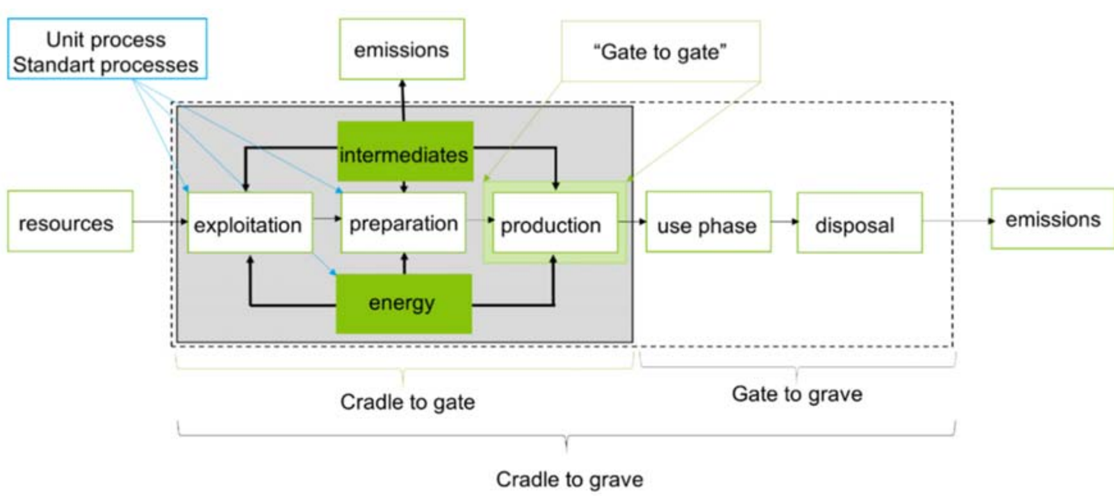

Figure 1.8 Type of LCA scope (Kupfer et al., 2021)

1.4.2 Life Cycle Inventory

Life Cycle Inventory (LCI) is a phase to inventory input data (raw materials and energy) and output data (waste and emissions to air, water, and soil) that occur throughout its life cycle. Figure 1.9 shows the simplified operational steps for inventory analysis based on ISO 14044 (2006). This phase consists of data collection, data calculation, and allocation of flows and releases. In data collection, the inputs and outputs of a unit process are quantified. The data can be in the form of measured, calculated, or estimated data. This should refer to the details of the relevant data collection process, the time of data collection, and further information on quality indicators because it will significantly affect the conclusions of the study (ISO 14044, 2006). In addition, data collection can be either primary or secondary data. Primary data collection is done by directly measuring the inputs and outputs of a process on-site, while secondary data collection comes from life cycle databases, literature sources, and other past work (Matthews et al., 2014).

Data calculation needs several operational steps, such as data validation, relating data to unit process and functional unit, and refining the system boundary. All calculation procedures must be applied consistently and explicitly documented. All assumptions made must also be clearly stated (ISO 14044, 2006).

The allocation phase is a quantitative process for assigning a certain number of inputs and outputs to various process products. Therefore, it must be ensured that the number of inputs and outputs allocated from a processing unit is equal to the inputs and outputs of the processing unit before allocation (ISO 14044, 2006).

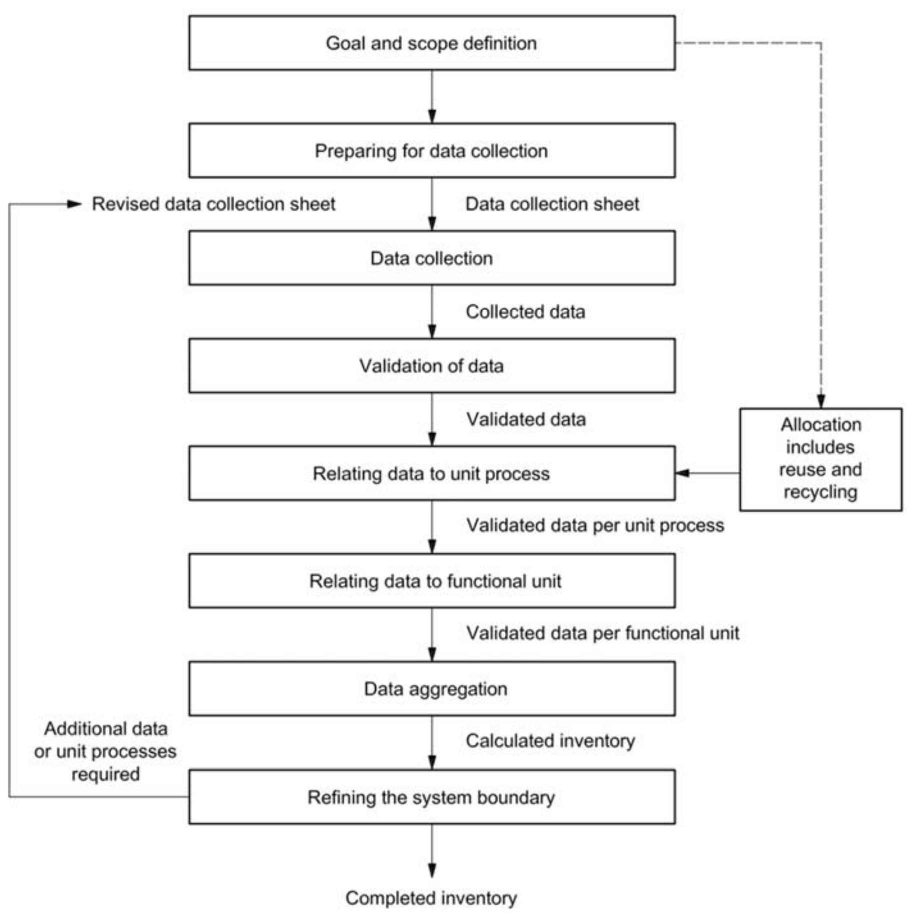

Figure 1.9 - Operational steps for inventory analysis (ISO 14044, 2006)

1.4.3 Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) evaluates potential impacts on the environment using the results of a life cycle inventory. This is the phase of analysis regarding the type and value of each category of impact. All impacts on resource use and the resulting emissions are grouped and quantified using characterization factors that are then weighted according to the level of contribution so that the information can be used to interpret environmental impacts (ISO 14040, 2006).

Based on ISO 14040 (2006), LCIA phases consist of mandatory elements and optional elements (Figure 1.10). Mandatory elements start with the selection of impact categories, category indicators, and characterization models that must be justified and consistent with the goal and scope of the LCA. The impact categories are selected as the focus of the LCA study and shall cover the environmental issues of the analysed product system. Once the relevant category is selected, the LCI results are classified into one or more impact categories. After the classification, the environmental impact needs to be described and quantified by applying characterization factors. Each impact category has its characterization factor (ISO 14044, 2006).

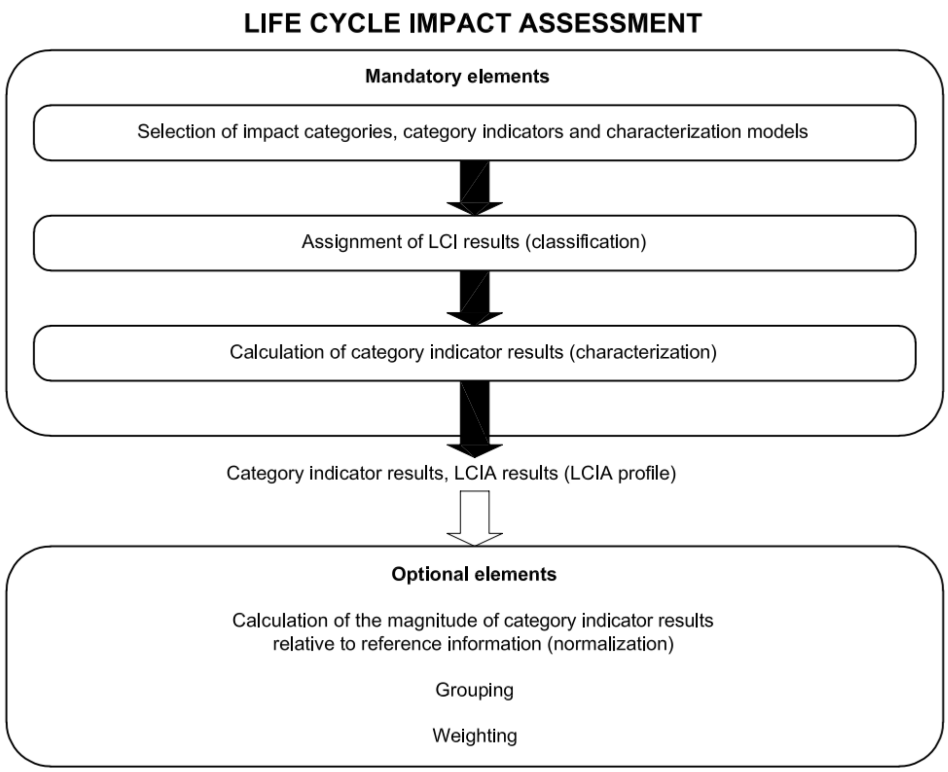

Figure 1.10 - Elements of the LCIA phase

The optional elements include normalization, grouping, and weighting. Normalization is a calculation that involves the magnitude of the category indicator results relative to some reference information in order to understand the relative magnitude for each indicator result of the product system. Grouping involves sorting the impact categories on a nominal basis and/or the ranking of the impact categories in each hierarchy. In grouping, the impact categories are assigned into one or more sets. Weighting involves steps that are value-choices-based, not scientifically based. Weighting includes two possible procedures: converting the indicator results/normalized results with selected weighting factors and/or aggregating the converted indicator results/normalized results across impact categories. This is the process of comparing different impact indicator results according to their significance (ISO 14044, 2006).

There are two main approaches to classify and characterize environmental impacts: the midpoint approach and the endpoint approach. These approaches give different detail levels. The midpoint approach is a problem-oriented approach that provides a more specific cause-effect chain of the environmental and physicochemical changes in the environment before the endpoint is reached. The endpoint approach or damage approach provides environmental impact at the end of the cause-effect chain and provides indicators at the level of Areas of Protection (Bare et al., 2000).

According to GaBi (Ganzheitliche Bilanzierung) software, there are complete assessment methodologies, such as CML 2001, ReCiPe 2016, TRACI 2.1, UBP 2013, EDIP 2003 (Hauschild 2003), Ecoindicator 99, Environmental Footprint 2.0, and Environmental Footprint 3.0 Impact 2002+, and ILCD/PEF (Kupfer et al., 2021). These methodologies have different midpoint impact categories and endpoint areas of protection. For example, the impact categories of ReCiPe 2016 methodology consist of 18 midpoint impact categories and 3 endpoint areas of protection (Figure 1.11) (Huijbregts et al., 2017), while the European Commission's ILCD guidelines consist of 14 midpoint impact categories and 3 endpoint areas of protection (M. Hauschild, 2014).

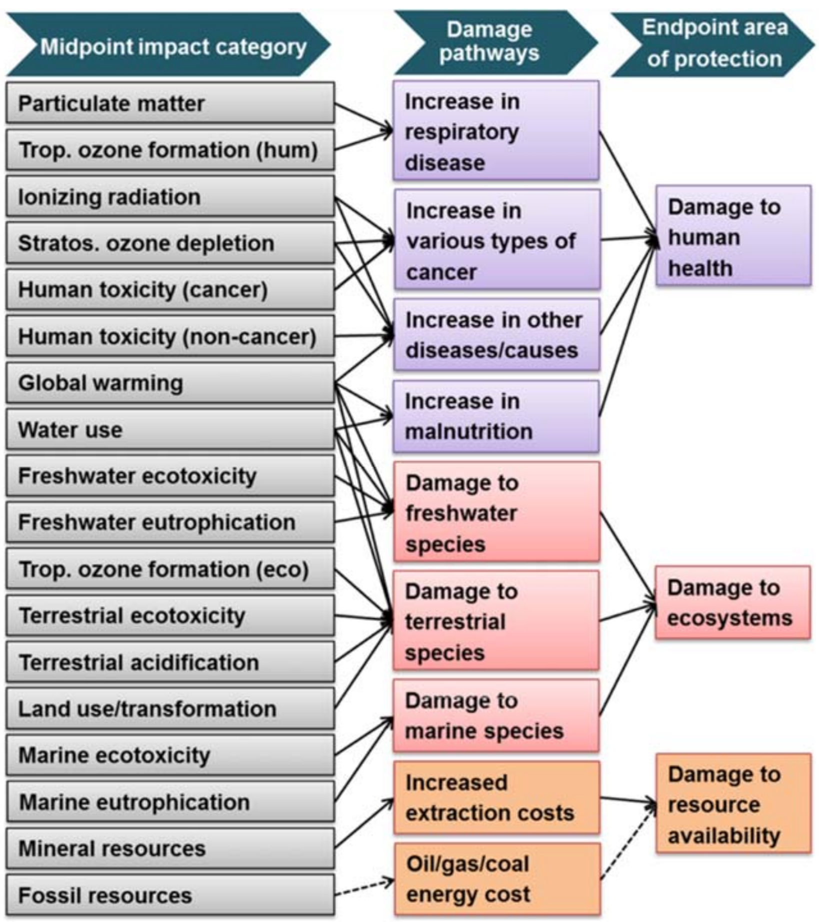

Figure 1.11 - Impact categories of ReCiPe 2016 methodology

Each category of impacts in ReCiPe 2016 describes impacts that affect the environment and area of protection. This method provides characterization factors that represent global scale. ReCiPe 2016 is the broadest set of midpoint impact categories. An overview of the midpoint categories and related impact indicators is described below.

CLIMATE CHANGE

Climate change is the long-term shift in average weather patterns globally or regionally. The impact of global warming on the climate is known as climate change. Global warming is the phenomenon of the increase in the average surface temperature of the earth caused by greenhouse gas emissions in the atmosphere, such as carbon dioxide, nitrous oxide, methane, and other gases. The greenhouse gases allow sunlight to reach the earth's surface while preventing part of the heat from escaping, resulting in some heat being stored and the planet being warmer. The greater the concentration of greenhouse gases in the atmosphere, the more heat is trapped (Henderson-Sellers, 2010).

FINE PARTICULATE MATTER FORMATION

The emissions of nitrogen oxides (NO_x), ammonia (NH_3), and sulfur dioxide (SO_2) are forming aerosol fine particulate matter formation (aerosol $PM_{2.5}$) in the air. This will damage human health (Huijbregts et al., 2017).

FOSSIL DEPLETION

Fossil depletion or fossil resource scarcity is quantified in kilograms of oil equivalent. Because oil is a limited resource, only a certain amount is available for extraction. It is assumed that all the conventional oil is depleted, thus causing an increase in costs due to changes in production techniques or geographical location of fossil resources production (Huijbregts et al., 2017).

FRESHWATER CONSUMPTION

Water use leads to a reduction in freshwater availability, followed by three different stages of impacts on water shortage for irrigation, reduction in plant diversity, and changed river discharge. Further, the water shortage will be followed by malnutrition and vulnerability of the population and damage to human health. Reduction in plant diversity and changed river discharge impacts ecosystem quality (both terrestrial and fresh water quality) (Huijbregts et al., 2017).

FRESHWATER ECOTOXICITY

Freshwater ecotoxicity impact refers to the impact of freshwater ecosystems. Exposure to freshwater pollution endangers the environment and human health (ECETOC et al., 2016).

FRESHWATER EUTROPHICATION

Freshwater eutrophication occurs when nutrients are discharged into the soil or freshwater bodies, increasing nutrient levels, such as phosphorus and nitrogen. The concentration of chemical nutrients present in the ecosystem can trigger the overgrowth of algae. This algal bloom can block the sunlight, so the sunlight cannot reach the bottom. Bacteria start to break down the dead plants and algae, then use up oxygen in the water, which becomes anoxic, which results in a loss of species. The impact of emissions on freshwater is determined by phosphorus transfer from soil to freshwater bodies, residence time in freshwater systems, and the fraction of potentially lost (PDF) due to an increase in phosphorus concentration in freshwater (Huijbregts et al., 2017).

HUMAN TOXICITY

Human toxicity illustrates the presence of chemicals that have the potential to contribute to cancer or other adverse human health effects. Human toxicity is the potential harm of a unit of chemicals released into the environment. This impact potential is calculated based on an index that shows the potential for chemicals that can damage the environment. For example, high exposure to arsenic or mercury may cause possible adverse health effects (Shimako et al., 2017).

IONIZING RADIATION

Ionising radiation is radiation that can release radioactive which can cause damage to human health and ecosystems (Frischknecht et al., 2000).

LAND USE

The impact of land use is in the form of long-term land use or changes in the type of land use. Long-term land use is generally in the form of agriculture. Changing the type of land use is in the form of converting nature into urban areas. This land use can cause natural degradation, resulting in reduced habitat availability and diversity of wildlife species (Brentrup et al., 2002).

MARINE ECOTOXICITY

Additional inputs of (essential) metals into the oceans cause impacts in the marine environment, leading to toxic effects. The sea and oceanic compartments are included in the estimates of marine ecotoxicological impacts in the egalitarian and hierarchic scenarios, whereas the individualistic scenario only includes the sea compartment in the calculations for essential metals, such as cobalt, Copper, Manganese, Molybdenum, and Zinc (Huijbregts et al., 2017).

MARINE EUTROPHICATION

Marine eutrophication results from an increase in phosphorus and nitrogen levels in marine ecosystems, which is caused by the runoff and leaching of plant nutrients from the soil and the discharge of those nutrients into riverine or marine systems. Benthic oxygen depletion is one of the environmental impacts of marine eutrophication caused by nutrient enrichment. One of the most severe and widespread causes of marine ecosystem disruption is the emergence of hypoxic waters and, if excessive, anoxia and "dead zones". Eutrophication is usually characterized by excessive plant and algal growth (Huijbregts et al., 2017).

The effects on marine water are based on how dissolved inorganic nitrogen (DIN) is transferred from the soil and freshwater bodies, or directly to marine water, its residence time in marine systems, and how dissolved oxygen (DO) depletion affects the potential disappearance fraction (PDF) (Huijbregts et al., 2017).

METAL DEPLETION

Metal depletion or mineral resource scarcity is based on the extraction of minerals and measured in kilograms of copper equivalent. It is assumed that mineral mines with higher grades have been explored and extracted first, resulting in a decrease in average ore grade worldwide (Huijbregts et al., 2017).

PHOTOCHEMICAL OZONE FORMATION (ECOSYSTEMS AND HUMAN HEALTH)

The formation of the photochemical zone describes the formation of ozone at the ground level of the troposphere. This is caused by the photochemical oxidation of Volatile Organic Compounds (VOC) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunlight. The impact of high concentrations of tropospheric ozone is that it can damage vegetation, the human respiratory tract, and artificial materials through reaction with organic matter (Preiss, 2015).

STRATOSPHERIC OZONE DEPLETION

The ozone layer is in the stratosphere and acts as earth‘s sunscreen, absorbing damaging ultraviolet light. The ozone layer has gotten thinner due to Chlorofluorocarbons (CFCs) from refrigeration, air conditioning and plastic foam manufacturing. This poses a threat to the health of living things. Apart from CFCs, ozone layer depletion is also caused by substances such as Hydrochlorofluorocarbons (HCFCs), halons, methyl bromide and carbon tetrachloride (Singh & Bhargawa, 2019).

TERRESTRIAL ACIDIFICATION

Acidification happens due to the deposition of inorganic chemicals (NO_x, NH_3, and SO_2) from the atmosphere to the ground. Almost all plant species survive in a specific range of acidity. However, a considerable deviation from the optimal threshold for plant life damages plant species and can induce a shift in plant species diversity and occurrence (Burns et al., 2011).

TERRESTRIAL ECOTOXICITY

Terrestrial ecotoxicity impacts terrestrial organisms from toxic substances, such as pesticide emissions into agricultural soil (Borrion et al., 2012).

The midpoint and endpoint of ReCiPe 2016 have three perspectives to similar group types of assumptions and choices on the ReCiPe 2016 method (Table 1.2). These perspectives are based on issues that can avoid future damage, such as time or expectations of proper management or technology development (Huijbregts et al., 2017).

Table 1.2 Perspectives in ReCiPe 2016 methods (Huijbregts et al., 2017)

Perspective	Abbreviation	Explanation
Individualist	I	Short-term (e.g. a 20-year timeframe for global warming, GWP20). Based on impact types that are undisputed and technological optimism concerning human adaptation.
Hierarchist	H	Medium-term (e.g. a 100-year timeframe for global warming, GWP100). Based on most common policy principles regarding the time frame and plausibility of impact mechanism.
Egalitarian	E	Long-term (e.g. a 1000-year timeframe for global warming, GWP1000). Impact types are not yet fully established but consider all impact pathways for which data is available. This is based on a precautionary perspective.

1.4.4 Life Cycle Interpretation

Life Cycle Interpretation is the final phase of LCA providing conclusions, recommendations, and recommendations adapted to the goal and scope of the study (ISO 14040, 2006). The life cycle interpretation includes two primary steps: identification of significant issues and evaluation. From the LCI and LCIA, each product or process that has a significant contribution to environmental impact is identified. The significant issues are obtained from the inventory data (e.g. energy, emissions, discharges, waste), impact categories (e.g. resource use, climate change), and significant contributions from life cycle stages to LCI or LCIA results (e.g. transportation, energy production) (ISO 14044, 2006).

The evaluation aims to establish confidence in the LCA results so that the LCA study can provide a clear and understandable view for interested parties to the LCA results. There are 3 steps taken to strengthen the calculations and facts in the interpretation stage, namely completeness check, sensitivity check, and consistency check (ISO 14044, 2006).

COMPLETENESS CHECK

A completeness check is a verification process to ensure that information and data from the life cycle assessment are available and complete in order to make decisions according to the definition of objectives and scope. If the information and data are incomplete, a data gap will be created, so an approach is needed to determine the value of the data gap (ISO 14044, 2006).

SENSITIVITY CHECK

A sensitivity check is a verification process to assess the reliability of the final results and conclusions. This is done by determining whether they are affected by uncertainties in the data or methods used in the LCA study (ISO 14044, 2006).

CONSISTENCY CHECK

Consistency checks whether assumptions, methods and data have been applied consistently throughout the study and following the definition of the objectives and scope established before conclusions are drawn. The subjects highlighted in the consistency check procedure include region, system boundaries, and elements of impact assessment (ISO 14044, 2006).

1.5 Literature review

1.5.1 Geothermal LCA in Iceland

HELLISHEIDI GEOTHERMAL COMBINED HEAT AND POWER (GCHP)

Hellisheidi GCHP is one of the sources of renewable energy in Iceland. At this power station, high temperature geothermal is utilized in combined heat and power production. Karlsdóttir et al., (2015) presented a Life Cycle Inventory (LCI) for the construction, operation, and maintenance of the GCHP. One of the goals of this study is to provide information for future Life Cycle Assessment studies on geothermal power plants.

LCI presented in this study used site-specific parameters for normalization of inventory data, such as a number of wells and the total meters drilled per site, the length of the collection pipelines, and the installed electrical and thermal capacity (Table 1.3) (Karlsdóttir et al., 2015).

Table 1.3 Site-specific parameters of Hellisheidi GCHP (Karlsdóttir et al., 2015)

Site-specific parameter	Unit	Value for Hellisheiði
Reservoir		
Number of wells drilled	–	64
Total meters drilled	m	137,776
Collection pipelines	m	36,000
Power plant		
Installed capacity—double flash	MW	303.3
Installed capacity—single flash	MW	270
Heating station		
Installed capacity—heat production	MW_{th}	133

The functional units used for this study are defined for the product system as 1 kWh of electricity for electricity generation and 1 MJ or 1 kWh of heat for district heating production. Without considering transmission losses and thermal losses, the lifetime span of the power plant is assumed to be 30-year of operation (Karlsdóttir et al., 2015).

All available primary and secondary data were used for this LCI study. The primary data for the construction stage includes the material and fuels used for geothermal wells, collection pipelines, power plant buildings, power plant machinery, heating station building, and heating station machinery. The use of materials is very dominant in the construction stage. For the construction of geothermal wells, the inventory includes well drilling and casing, also wellhead equipment and structures. The total length of materials and construction work for collection pipelines is 36 km. The single flash power plant includes the construction of a powerhouse, staff facilities, powerhouse piping, and cold water works (Karlsdóttir et al., 2015).

Operation and maintenance data for this LCI is very site-specific due to the unique characteristics of geothermal resources. Mass flows, temperatures, and chemical composition of geothermal fluid differ from one to another geothermal resource. The operational stage is dominated by the use of natural resources, such as groundwater and geothermal fluids. For this LCI, the operation and maintenance data include the use of geothermal fluid for the operation of GCHP, composition and mass flow of geothermal fluid from wells, the need for make-up wells, groundwater needs, the lifetime of the power plant, the power plants capacity factor, auxiliary power demand, and estimated total heat production (Karlsdóttir et al., 2015).

The secondary data is converted with calculation procedures that consist of diesel fuel use during excavation and fill processes and water and cement used in a ready-made concrete mix. The LCI study also included direct emissions of gases, wastewater, and waste heat. Geothermal fluid in Hellisheiði contains a mixture of steam and brine, where the NCGs of the fluid are emitted to air. The input and output data for the electricity generation and heat production are shown in Table 1.4 and Table 1.5 (Karlsdóttir et al., 2015).

The results showed that the construction stage made a dominant contribution to the total use of bulk materials and resources for electricity production. The use of diesel was 96%, water was 99%, and steel was 47% for the geothermal wells. The use of aluminium was 38%, and mineral wool insulation was 84% for the collection pipelines. For the power plant buildings, the use of cement was 46%, asphalt was 98%, and plastic was 99%, while the power plant machinery used 67% of copper and 64% of stainless steel. For heat production, the results showed that the construction stage contributed dominantly to the use of bulk materials, while the use of resources is dominant in the operational stage. The distribution of resources and material used in the construction stage of the Hellisheiði GCHP is shown in Figure 1.12 (Karlsdóttir et al., 2015).

Table 1.4 Input and output data for the 270 MW single flash and 303,3 MW double flash (Karlsdóttir et al., 2015)

Inputs and outputs	Input/output	Unit	Construction		Operation		Maintenance		Total		Accuracy
			SF	DF	SF	DF	SF	DF	SF	DF	
Natural resources											
Geothermal fluid	Input	g/kWh	–	–	1.40E+04	1.25E+04	–	–	1.40,E+04	1.25E+04	*l*
Groundwater	Input	g/kWh	20.3	18.1	4,000	3,561	5.1	4.5	4,025	3,583	*l*
Energy flows and fuels											
Thermal energy, geothermal fluid	Input	kJ/kWh	–	–	2.37E+04	2.11E+04	–	–	2.37E+04	2.11E+04	*m*
Thermal energy, reinjected fluid	Output	kJ/kWh	–	–	4,256	1,596	–	–	4,256	1,596	*m*
Waste heat, from cooling towers	Output	kJ/kWh	–	–	1.35E+04	1.38E+04	–	–	1.35E+04	1.38E+04	*m*
Waste heat, condensate to shallow wells	Output	kJ/kWh	–	–	200	194	–	–	200	194	*m*
Waste heat, to thermal production	Output	kJ/kWh	–	–	2,072	1,844	–	–	2,072	1,844	*m*
Electricity	Input	kJ/kWh	–	–	139	144	–	–	139	144	*l*
Diesel	Input	kJ/kWh	5.4	4.8	–	–	1.3	1.2	6.7	6.0	*h*
Earthwork requirements											
Excavation	Input	m3/kWh	2.3E-05	2.1E-05	–	–	3.4E-06	3.0E-06	2.7E-05	2.5E-05	*m*
Fill	Input	m3/kWh	1.7E-05	1.6E-05	–	–	1.3E-06	1.3E-06	1.8E-05	1.7E-05	*m*
Products consumption											
Portland cement	Input	g/kWh	0.27	0.26	–	–	0.04	0.03	0.30	0.29	*m*
Steel	Input	g/kWh	0.45	0.42	–	–	0.09	0.08	0.54	0.50	*m*
Stainless steel	Input	g/kWh	1.3E-02	1.2E-02	–	–	4.2E-06	3.8E-06	1.3E-02	1.2E-02	*h*
Aluminum	Input	g/kWh	8.5E-03	8.0E-03	–	–	1.2E-03	1.1E-03	9.7E-03	9.1E-03	*m*
Copper	Input	g/kWh	2.3E-03	2.3E-03	–	–	–	–	2.3E-03	2.3E-03	*m*
Mineral wool	Input	g/kWh	2.9E-02	2.6E-02	–	–	6.3E-03	5.6E-03	3.5E-02	3.2E-02	*l*
Asphalt	Input	g/kWh	0.14	0.16	–	–	–	–	0.14	0.16	*l*
Plastic	Input	g/kWh	3.1E-03	3.2E-03	–	–	–	–	3.1E-03	3.2E-03	*l*
Glass fiber reinforced plastic (GRP)	Input	g/kWh	9.3E-03	9.4E-03	–	–	–	–	9.3E-03	9.4E-03	*h*
Transformer oil	Input	g/kWh	2.9E-03	3.0E-03	–	–	–	–	2.9E-03	3.0E-03	*m*
Silica flour	Input	g/kWh	3.0E-02	2.7E-02	–	–	7.5E-03	6.7E-03	3.8E-02	3.4E-02	*h*
Bentonite	Input	g/kWh	6.3E-02	5.6E-02	–	–	1.5E-02	1.4E-02	7.9E-02	7.0E-02	*h*
Lignosulfonate	Input	g/kWh	2.9E-03	2.6E-03	–	–	7.2E-04	6.4E-04	3.6E-03	3.2E-03	*l*
Sodium hypochlorite	Input	g/kWh	–	–	–	–	1.2E-02	1.3E-02	1.2E-02	1.3E-02	*m*
Air emissions											
CO2	Output	g/kWh	–	–	19.6	17.5	–	–	19.6	17.5	*m*
H2S	Output	g/kWh	–	–	5.0	4.5	–	–	5.0	4.5	*m*
H2	Output	g/kWh	–	–	0.21	0.19	–	–	0.21	0.19	*m*
CH4	Output	g/kWh	–	–	0.03	0.03	–	–	0.03	0.03	*m*
Waste flows											
Brine, reinjected	Output	g/kWh	–	–	6,300	5,608	–	–	6,300	5,608	*m*
Steam, evaporated condensate	Output	g/kWh	–	–	1,260	1,122	–	–	1,260	1,122	*m*
Condensate, to shallow wells	Output	g/kWh	–	–	3,360	2,991	–	–	3,360	2,991	*m*
Condensate, reinjected	Output	g/kWh	–	–	3,080	2,742	–	–	3,080	2,742	*m*

Table 1.5 Input and output data for the heat production (Karlsdóttir et al., 2015)

Inputs and outputs	Input/output	Unit	Construction	Operation	Maintenance	Total	Accuracy
Natural resources							
Groundwater	Input	g/MJ	9.8E-03	4.8E+03	–	4.8+03	*l*
Energy and fuels							
Electricity, from geothermal	Input	kJ/MJ	–	15.8	–	15.8	*l*
Waste heat, from geothermal	Input	kJ/MJ	–	1.7E+03		1.7E+03	*m*
Diesel	Input	kJ/MJ	1.2E-02	–	–	1.2E-02	*m*
Earthwork requirements							
Excavation	Input	m3/MJ	1.2E-06	–	–	1.2E-06	*h*
Fill	Input	m3/MJ	8.7E-07	–	–	8.7.E-07	*h*
Products consumption							
Portland cement	Input	g/MJ	1.5E-02	–	–	1.5E-02	*m*
Steel	Input	g/MJ	3.4E-02	–	3.0E-05	3.4E-02	*h*
Stainless steel	Input	g/MJ	1.7E-03	–	1.3E-04	1.8E-03	*m*
Aluminum	Input	g/MJ	4.6E-04	–	1.1E-06	4.7E-04	*l*
Copper	Input	g/MJ	1.1E-04	–	9.2E-07	1.1E-04	*l*
Mineral wool	Input	g/MJ	4.4E-04	–	5.4E-06	4.4E-04	*l*
Asphalt	Input	g/MJ	2.7E-03	–	–	2.7E-03	*l*
Plastic	Input	g/MJ	1.7E-06	–	1.7E-07	1.8E-06	*l*
Waste flows							
Silica	Output	g/MJ	–	–	6.1E-05	6.1E-05	*l*

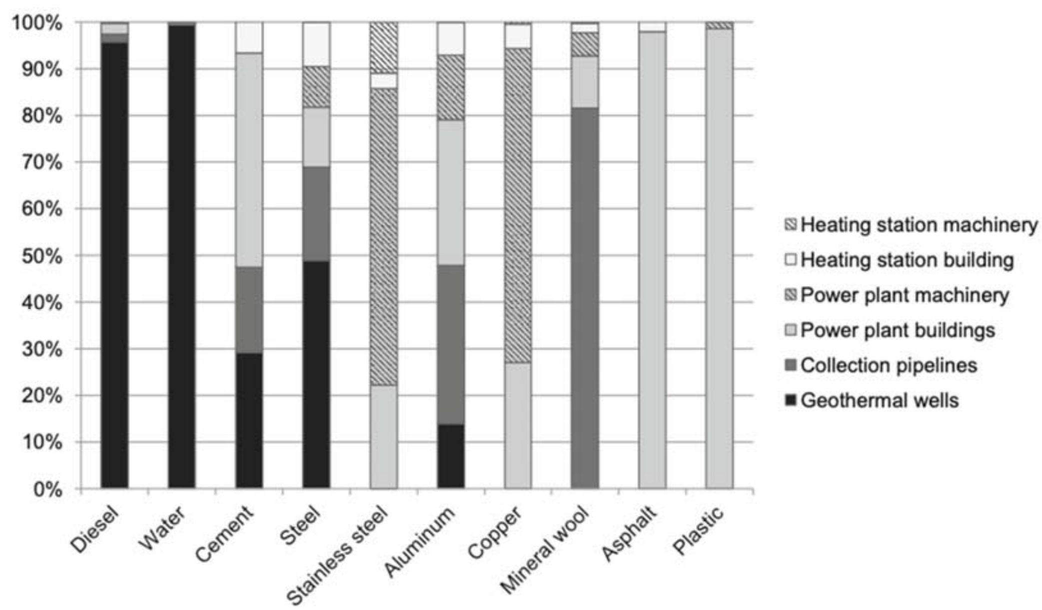

Figure 1.12 - Resource and material use distribution in construction stage of the Hellisheiði GCHP (Karlsdóttir et al., 2020)

To continue the LCI study by Karlsdóttir et al., (2015), an LCA study was conducted for a GCHP in Hellisheiði, Iceland. This power plant has two functions: production of 303 MWe electricity generation and 133-267 MWth hot water production for district heating. The study aims to determine the environmental impacts of Hellisheiði GCHP and investigate the effects of the operational improvement on the plant. The LCA study is considered "cradle-to-gate", which analyzed the environmental impacts at the construction and operation stages, including the construction of the steam collection and reinjection systems, the drilling of make-up wells during maintenance, and the use of geothermal fluid during operations. Functional units for this study are 1 kWh electricity for electricity generation 1 kWh of heat for heat production. Assuming the technical lifetime of power plants, 30 years of operation is chosen for the time horizon for the modelling (Karlsdóttir et al., 2020).

The impact assessment of this study used SimaPro 8 software with input and output data based on the LCI that was done by Karlsdóttir et al., (2015) (called as 2012 LCI) and some improvements that were made in 2017 (called as 2017 LCI). 2017 LCI data includes natural variations in the gas content of the geothermal fluid, implementation of CarbFix and SulFix as innovative mitigation methods of geothermal gas emissions, and replacement of diesel-fueled drilling rigs with electrical drill rigs (Karlsdottir et al., 2020).

For the LCIA, the methods applied are the CML-IA baseline and Cumulative Energy Demand (CED) baseline, where the CML-IA used a problem-oriented approach/midpoint approach and included 10 environmental impact categories. In comparison, the CED calculates the total energy use and includes 5 environmental impact categories (Karlsdottir et al., 2020).

The results show that the operation stage causes CO_2, H_2S, and CH_4 emissions based on CML-IA. CO_2 and CH_4 largely contribute to global warming, and CH_4 also contributes to photochemical oxidation potential. H_2S contributes to human toxicity and acidification. Based on the CED impact categories, it is found that the contribution to renewable, wind, solar, and geothermal CED ($CED_{R, S, W, G}$) is quite dominant (Table 1.6). This is due to the geothermal energy content of the fluid that is used as fuel for electricity and heat production (Karlsdottir et al., 2020).

Table 1.6 The impact assessment results for electricity and heat production from Hellisheiði geothermal combined heat and power (Karlsdóttir et al., 2020)

Impact category	Abbreviation	Unit	1 kW h electricity		1 kW h heat	
CML-IA impact categories			2012 LCI	2017 LCI	2012 LCI	2017 LCI
Abiotic depletion	ADP	g Sb eq	1.8×10^{-5}	1.8×10^{-5}	1.5×10^{-5}	1.5×10^{-5}
Abiotic depletion (fossil fuels)	ADP_{fossil}	kJ	21.6	19.7	18.9	16.9
Global warming	GWP100	g CO_2 eq	15.9	11.4	15.8	11.2
Ozone layer depletion	ODP	g CFC-11 eq	2.0×10^{-7}	1.8×10^{-7}	1.6×10^{-7}	1.4×10^{-7}
Human toxicity	HTP	g 1,4-DB eq	5.8	5.0	5.5	4.8
Fresh water aquatic ecotox.	FAETP	g 1,4-DB eq	1.8	1.8	1.7	1.7
Marine aquatic ecotoxicity	MAETP	g 1,4-DB eq	4557.9	4547.4	3827.0	3816.3
Terrestrial ecotoxicity	TETP	g 1,4-DB eq	2.1×10^{-2}	2.1×10^{-2}	2.1×10^{-2}	2.1×10^{-2}
Photochemical oxidation	POCP	g C_2H_4 eq	9.5×10^{-4}	9.1×10^{-4}	8.1×10^{-4}	7.6×10^{-4}
Acidification	AP	g SO_2 eq	9.7	3.6	9.7	3.5
Eutrophication	EP	g PO_4— eq	5.1×10^{-3}	4.8×10^{-3}	4.5×10^{-3}	4.2×10^{-3}
Cumulative Energy Demand (CED) impact categories			2012 LCI	2017 LCI	2012 LCI	2017 LCI
Non-renewable, fossil	$CED_{NR,fossil}$	kWh	6.4×10^{-3}	5.8×10^{-3}	5.6×10^{-3}	5.0×10^{-3}
Non-renewable, nuclear	$CED_{NR,nuclear}$	kWh	3.9×10^{-4}	3.8×10^{-4}	3.1×10^{-4}	3.1×10^{-4}
Non-renewable, biomass	$CED_{NR,bio}$	kWh	3.7×10^{-6}	3.7×10^{-6}	2.0×10^{-6}	2.0×10^{-6}
Renewable, biomass	$CED_{R,bio}$	kWh	1.1×10^{-4}	1.1×10^{-4}	8.1×10^{-5}	8.0×10^{-5}
Renewable, wind, solar, geothermal	$CED_{R,s,w,g}$	kWh	5.2	5.2	5.2	5.2
Renewable, water	$CED_{R, water}$	kWh	3.1×10^{-4}	3.1×10^{-4}	2.8×10^{-4}	2.8×10^{-4}
Total, non-renewable*	CED_{NR}	kWh	6.8×10^{-3}	6.2×10^{-3}	5.9×10^{-3}	5.3×10^{-3}
Total, renewable*	CED_{R}	kWh	5.2	5.2	5.2	5.2
Total	CED_{total}	kWh	5.2	5.2	5.2	5.2

The construction of collection pipelines and drilling and casing of geothermal wells have the most considerable impact on the environment due to the production or use of diesel fuel and the production of steel required for the drilling and completion of geothermal wells. In the operation stage, geothermal fluid extraction is the leading cause of environmental impacts on GCHP. Comparing electricity and heat production, electricity production has a higher impact on the environment than heat production due to the extensive mechanical equipment required for electricity production (Figure 1.13 and Figure 1.14) (Karlsdottir et al., 2020).

The environmental impacts from 2017 LCI are lower than 2012 LCI. The updated 2017 LCI shows improvements in geothermal gasses emissions. The use of electricity for drilling make-up wells reduces emissions due to the decrease in the use of diesel fuel, which resulted in the reduction of abiotic depletion (fossil fuel), ozone layer depletion, photochemical oxidation, eutrophication, and CED fossil. SulFix method is reducing the H_2S emission, which also has a significant change in human toxicity and acidification potential impacts. CarbFix method is reducing CO_2 emission, so the global warming potential is reducing by 30% (Karlsdottir et al., 2020).

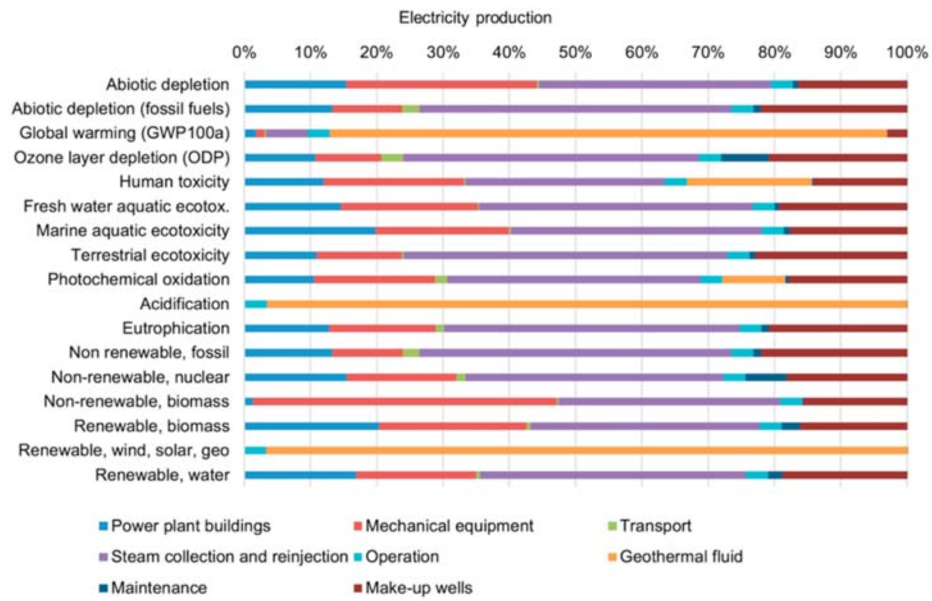

Figure 1.13 - Environmental impacts of the electricity production from Hellisheiði geothermal combined heat and power (Karlsdóttir et al., 2020)

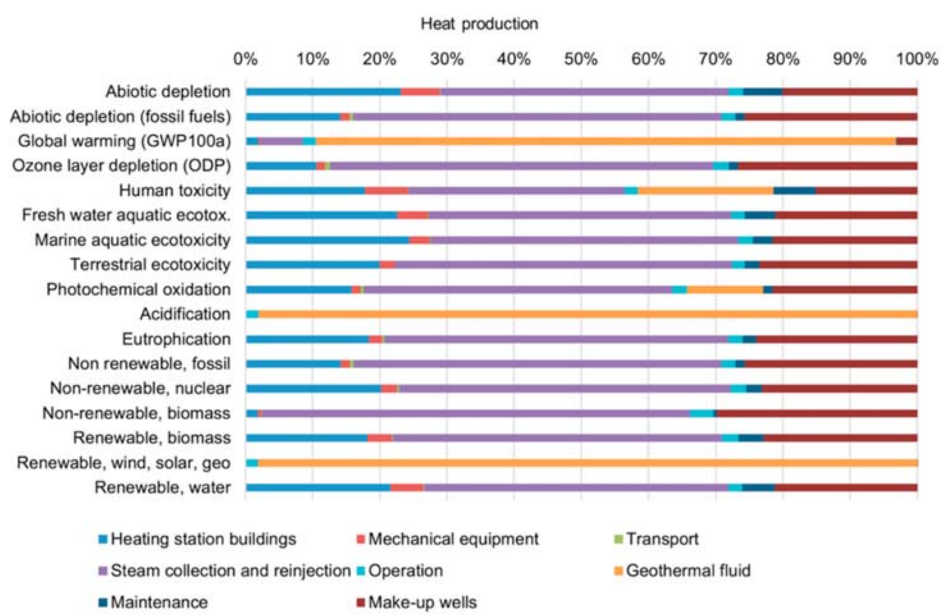

Figure 1.14 - Environmental impacts of the heat production from Hellisheiði geothermal combined heat and power (Karlsdóttir et al., 2020)

THEISTAREYKIR GEOTHERMAL POWER PLANT

Kjeld et al., (2021) completed LCA research for a 90 MW single flash geothermal power plant in Theistareykir, Iceland. Using the LCA approach, this study seeks to determine the environmental impacts of electricity generation at the Theistareykir geothermal power plant. In this study, a functional unit is defined as one kilowatt-hour of electricity generated. According to Product Category Rules, the lifetime of the power plant is defined as 40 years. A sensitivity analysis is performed for a varied lifetime in order to provide a more appropriate comparison. Theistareykir has an annual power output capacity of 738 GWh, which equates to a total generation of 29,5 TWh over its 40-year operational lifetime.

The scope of the LCA is cradle-to-grave, with a system boundary that encompasses the extraction of raw materials, the manufacturing of all components, transportation, the construction of the power station and geothermal wells, operation and maintenance during its designated lifetime, as well as dismantling and disposal or recycling at the end of its designated lifetime. The inventory data for manufacturing and construction comprises materials, fuel use, and waste. For the operation and maintenance, the data includes electricity use and losses, gasoline, diesel oil, biodiesel, waste generation, and gas (CO_2 and H_2S). Aside from that, data on inventory comes from the end-of-life stage and the transmission of electricity. The environmental impact categories used to present results in the LCIA are global warming, ozone depletion, acidification, eutrophication, photochemical ozone creation, depletion of abiotic resources (elements), depletion of abiotic resources (fossil). This is in line with the current requirements for disclosure of information in Environmental Product Declarations 2020 and EN 15804. The software used for the LCIA is GaBi software (Kjeld et al., 2021).

Figure 1.15 shows the results of the LCA of the Theistareykir geothermal power plant. Direct emissions during the operation of the plant throughout its lifetime, as well as the manufacturing of all station components and the consumption of fuel during construction, are the most significant contributors to environmental impacts. The power plant emits 13,8 g CO_2 eq/kWh, and with the electricity transmission, the total emission is 14,7 g CO_2 eq/kWh. The biggest contributor to CO_2 emissions is the direct CO_2 emissions from geothermal fluid during its 40-year lifetime. Drilling activities necessitate the use of large quantities of fuel oil, cement, and steel casing, which also contribute significantly to global warming. The other contributors to global warming are steam supply systems and powerhouse infrastructure, which are primarily responsible for the utilization of large amounts of steel, concrete, and fossil fuels. For the acidification impact, direct H_2S emissions are the most significant source (Kjeld et al., 2021).

The results reveal numerous options for future development projects and operational years, including strategies to reduce CO_2 and H_2S emissions from the geothermal fluid, improve the capacity of the power plant, and/or extend its lifetime through proper maintenance.

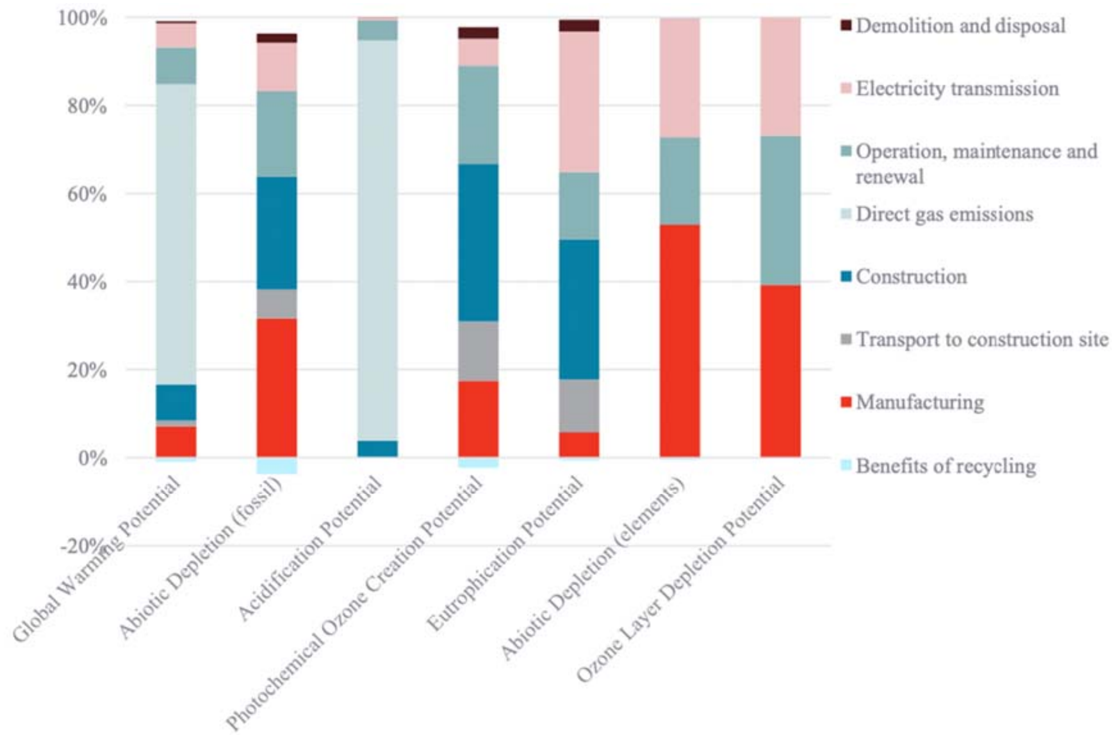

Figure 1.15 - Results for the LCA of the Theistareykir geothermal power plant (Kjeld et al., 2021)

NESJAVELLIR GEOTHERMAL POWER PLANT

Nesjavellir geothermal power plant is the second largest geothermal power plant in Iceland. A total of 120 MWe of electricity and 300 MWth of thermal capacity are now installed. The LCA research was carried out in order to investigate the environmental aspects of geothermal energy production in Nesjavellir. The functional unit of the research is 1 kWh of electricity, with the assumption of a 30-year power plant lifetime. The system boundary comprises the construction and operation stages. The construction stage includes drilling of geothermal wells, installation of pipelines from wells to the power plant, power plant construction and power plant machinery. The operation stage includes use of geothermal fluids and maintenance of the plant. For the data inventory, ON Power (the plant operator) provided primary data that were site specific, while secondary data were adapted from a comprehensive LCI research done for the Hellisheidi geothermal power plant by Karlsdóttir et al. (2015) for the Hellisheidi geothermal power plant. The data was analyzed using the OpenLCA 1.9.0 software (2019) and the Ecoinvent 3.2 cut-off dataset. Table 1.7 summarizes the site-specific parameters for the Nesjavellir geothermal power plant (Mwakangale, 2019).

These results were generated from the ReCiPe 2016 Midpoint (E) and Impact 2002+ impact assessment procedures, as described in Figure 1.16, and were given for six different impact categories to survey the possible consequences of geothermal energy development. Global warming contributes 16,7 g CO_2 eq/kWh, which is greatly influenced by the emission of GHGs such as CO_2 and CH_4 into the atmosphere. Fine particulate matter contributes 0,021g $PM_{2.5}$ eq/kWh, which is negligible in comparison to other impacts. Water consumption accounts for $3,5 \times 10^{-3}$ m^3, with 98% of this amount being from the use of water for cooling the power plant during production. The use of land for the construction stage results in a contribution of $7,09 \times 10^{-5}$ m^2 of a crop area/kWh. The emission of H_2S into the air during the operation stage contributes to 12,9g SO_2 eq/kWh of aquatic acidification. Freshwater ecotoxicity contributes 0,247g 1,4-DCB/kWh due to the material used during the construction stage, especially the construction of the power plant, drilling, and material used for the collection of the pipelines (Mwakangale, 2019).

Table 1.7 Site-specific parameters of Nesjavellir geothermal power plant (Mwakangale, 2019)

Site-specific parameter	Unit	Value for Nesjavellir
Reservoir		
Number of wells drilled	-	27
Total metres drilled	m	43,200
Collection pipelines	m	20,000
Power plant		
Installed capacity – single flash	MW	120

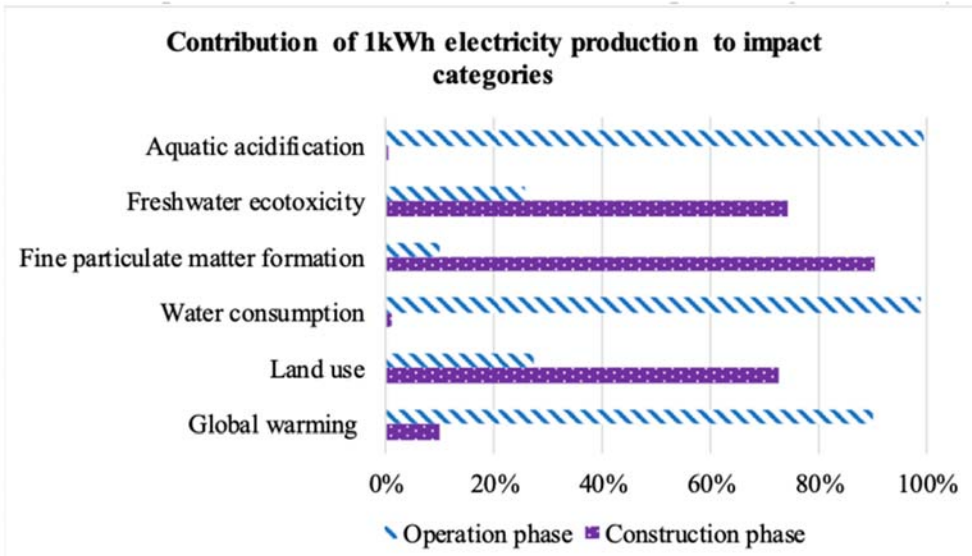

Figure 1.16 - Contribution of operation and construction stages to the environmental impacts (Mwakangale, 2019)

1.5.2 Geothermal LCA in Guadeloupe Island

A Life-Cycle Analysis for a high-temperature geothermal system was performed for Bouillante geothermal power plant, located in Guadeloupe island. The power plants installed are a double flash technology with a capacity of 4,75 MW and a simple flash technology with 11 MW, which are used to provide electricity only. The power plants have unusual configurations, such as using a sea water cooling system and the absence of geothermal fluid reinjection. The objectives of the study are to quantify the environmental impacts of a geothermal plant installed on the islands and compare and identify technological alternatives that potentially reduce its environmental impacts. This LCA study also establishes a general parameterized LCA model for high geothermal systems (230°C to 300°C). In addition, the study includes 5 life cycle stages in the geothermal system, such as drilling of exploration and production wells, construction and installation, operation, and decommissioning (Marchand et al., 2015).

In the study, the Life Cycle Inventory (LCI) was carried out from activities related to the studied system, reports, and interviews with experts. The functional unit is per kWh of electricity production considering 2850 GWh of the 30-year operating period. The inventory for the drilling stage considers the quantities of materials and fuels for four production wells and site preparation, such as road construction. The construction and installation include the manufacturing, installation, land-use for equipment, and maintenance for the 30 years plant lifetime. The operation stage includes the use of water, brine discharge to the ground, seawater and geothermal fluid effluent to the sea, direct emissions to the atmosphere, and drilling of additional production wells. Finally, the decommissioning stage includes recycling, landfill, and cement and gravel for wells closure. Detailed input and output data for this study are shown in Table 1.8 (Marchand et al., 2015).

To assess the environmental impacts of the Bouillante geothermal power plant, there are scenarios used. Exploration and production drilling stages consider the number of production wells that are related to the well potential electric power (energy produced by each well), net power of geothermal power plant, and drilling success rate. Apart from that, the number of reinjection wells that are in ratio 1 for 1 with production wells is also considered. Scenarios for the power plant construction and installation stage and operation stage are scenarios 1, 2a, and 2b. Scenario 1 is a configuration of a geothermal power plant that excludes fluid reinjection in the reservoir but includes a cooling system based on seawater use and seawater pump station construction. Scenarios 2a and 2b are a geothermal power plant configuration that includes fluid reinjection in the reservoir (number reinjection wells) and tower cooling system or aerocondenser cooling system. The end-of-life stage considers 70% steel and 50% copper are recycled, plastic equipment is not recycled (Marchand et al., 2015).

Based on the scenarios for the environmental impact assessment, the results show that scenarios 2a and 2b generate the lowest local environmental impact because scenarios 2a and 2b contribute less than scenario 1 for climate change, acidification, and terrestrial eutrophication, and marine eutrophication categories. On the other hand, scenarios 2a and 2b contribute more than scenario 1 for agricultural and urban occupation and natural transformation categories. Scenario 1 is intermediate between scenario 2a and 2b for all other impact categories. These results are shown in Table 1.9 (Marchand et al., 2015).

The natural land transformation impact is from the drilling stage. The construction and installation stage had the highest impact due to the manufacturing process, which contributed to water consumption, freshwater eutrophication, ecotoxicity, abiotic depletion, cumulative energy demand (renewable and non-renewable), agricultural and urban occupation, and human toxicity. The operation stage is the stage that contributes most to climate change. This stage is the largest source of greenhouse gases (GHG) which generates 90% of total GHG. The CO_2, CH_4, and H_2S emissions from the condensers are contributors to climate change. H_2S emissions contribute to acidification, NH_{4+} emissions contribute to marine and terrestrial eutrophication. Meanwhile, the decommissioning stage does not significantly impact the environment (Marchand et al., 2015).

Table 1.8 Input and output data for Bouillante geothermal power plant (Marchand et al., 2015)

Life Cycle Phase	Element	Quantity	Unit/kWh
Drilling of exploration and production wells	Land use	1.20E-06	m².an
	Road construction	1.41E-06	m²
	Materials for drilling (gravel, concrete, steel mud, cement and sand)	4.98E-03	kg
	Diesel	5.00E-03	MJ
	Road transport	3.16E-04	t.km
	Ship transport	7.77E-03	t.km
	Disposal of mud and mineral waste	2.73E-04	kg
	Total emissions of pollutants to water	8.63E-06	kg
	Land use	1.73E-04	m².an
	Minerals	1.05E-03	kg
Construction and installation	Material for construction and installation (concrete, cement, steel, copper, plastics and electronics components)	6.58E-03	kg
	Road transport	7.38E-04	t.km
	Ship transport	6.46E-03	t.km
	Diesel	1.51E-05	MJ
	Lubricating oil	6.51E-05	kg
Operation	Use of water	6.88E-01	m^3
	Occasional discharges of brine to ground	6.43E-05	kg
	Permanent discharges of Cl^- to the sea	2.94E+01	kg
	Permanent discharges of SO_4^{2-} to the sea	3.95E+00	kg
	Permanent discharges of NH_4^+ to the sea	8.21E-04	kg
	Other permanent discharges to the sea	3.07E+00	kg
	Direct CO_2 emissions to atmosphere	4.16E-02	kg
	Direct H_2S emissions to atmosphere	1.02E-03	kg
	Direct CH_4 emissions to atmosphere	3.26E-06	kg
	Drilling of additional production well	3.86E-10	unit
Decommissioning	Recycling of steel and copper	6.42E-04	kg
	Landfilling of metals	2.77E-04	kg
	Landfilling of minerals	9.19E-03	kg
	Landfilling of plastics	3.14E-06	kg
	Cement for wells closure	2.22E-06	kg
	Gravel for wells closure	2.34E-05	kg

Table 1.9 Impact assessment results for Bouillante geothermal power plant (Marchand et al., 2015)

Impact categories	Units (/kWh)	S1	S2a	S2b
IPCC GWP 100a	kg $CO_{2\ eq}$	4.70E-02	3.85E-02	3.94E-02
Ecological scarcity2006 water consumption	UBP	1.05E-02	8.17E-03	1.24E-02
ReCiPe, freshwater eutrophication	kg P_{eq}	1.68E-06	1.44E-06	2.01E-06
ReCiPe, marine eutrophication	kg N_{eq}	6.42E-04	1.33E-06	1.83E-06
CML2, terrestrial eutrophication	kg $PO4^{--}_{eq}$	2.80E-04	8.04E-06	1.03E-05
ReCiPe, natural land transformation	m²	3.56E-06	4.24E-06	4.70E-06
USEtox, ecotoxicity	CTUe	2.80E-02	2.12E-02	2.70E-02
CML2, abiotic depletion	kg Sb_{eq}	3.71E-05	3.36E-05	3.96E-05
CED Non-renewable	MJ	8.28E-02	7.35E-02	9.27E-02
CED Renewable	MJ	9.19E-04	8.17E-04	1.20E-03
ReCiPe agricultural and urban occupation	m²a	3.74E-04	3.91E-04	5.22E-04
USEtox Human toxicity (cancer)	CTUh	2.23E-13	1.67E-13	3.04E-13
USEtox Human toxicity (no cancer)	CTUh	1.16E-12	1.13E-12	1.43E-12
CML2, acidification	kg SO_2 eq	1.95E-3	1.61E-3	1.61E-3

1.5.3 Geothermal LCA in Italy

Geothermal, wind and solar power plants in Italy were assessed to compare the environmental performances of each operational activity. Chiusdino Geothermal Power Plant was built in 2011 with a capacity of 20 MWe. Pietragalla Wind Farm has been operating since 2011 with a nominal rating of 2 MWe. Serre Persano Difesa Servizi (DS) Photovoltaic Solar Plant was built in the period 2011-2013 with a peak power level of 21 MWe (Basosi et al., 2020).

OpenLCA and Ecoinvent databases were used for analyzing the case studies. The functional unit was 1 kWh of electricity with the expected 30 years lifetime of the power plant. The studies are cradle to grave studies that include the whole life cycle of the system. For the geothermal power plant, the data inventory include construction (production and reinjection wells drilling, well casing and cementing, steam adduction pipeline, condensate pipeline, powerhouse equipment, turbine and alternator, compressors, condensers, intercooler, cooling towers, gas treatment system, building and accessories), operation and maintenance (emissions to air, machinery maintenance, fluid treatment, fluid treatment), and end of life (wells abandonment). For the wind farm, the inventory data include construction (pitches and logistic surfaces, cable-ducts, horizontal axis wind turbine, tower, rotor blades, nacelle, road constructions, substation), operation and maintenance (lubricating oil), and end of life (machinery disassembly). The inventory data for the solar plant include construction (pitches and logistic surfaces, metal carpentry, photovoltaic modules, electrical connections, inverter, delivery cabin), operation and maintenance (diesel for cleaning machine), and end of life (diesel for disassembly). For the LCIA, ILCD 2011 Midpoint+ and ReCiPe Midpoint 2016 methods were performed, and a midpoint approach was applied (Basosi et al., 2020).

The results are shown in Table 1.10 and Table 1.11, where GEO, GEO_AS, GEO_NA referred to geothermal, PV referred to solar photovoltaic, W referred to wind, and NEM referred to the national electricity mix. It showed that the ReCiPe Midpoint 2016 method is preferable to ILCD 2011, representing a more balanced representation of the impacts in different categories. For the geothermal power plant, ReCiPe Midpoint 2016 showed that the power plant contributes significantly to terrestrial acidification, global warming, water consumption, human toxicity non-carcinogenic, marine ecotoxicity, freshwater ecotoxicity, terrestrial ecotoxicity, mineral resource scarcity, and fine particulate matter formation, while ILCD 2011 Midpoint method only showed significant impact on acidification and climate change (Basosi et al., 2020).

Based on the ReCiPe Midpoint 2016 method, the wind power plant contributes significantly to marine ecotoxicity and freshwater ecotoxicity and human carcinogenic toxicity, mineral resource scarcity, and water consumption, while ILCD 2011 Midpoint method only showed little contribution to climate change. The mineral resource scarcity in the wind power plant is caused by the use of lanthanides (rare mineral resources) in the generator. The solar power plant contributes to freshwater eutrophication and land use from both methods. Land use is caused by soil preparation and excavation operations (Basosi et al., 2020).

Table 1.10 ILCD MidPoint 2011+ method results (Basosi et al., 2020)

	GEO	GEO_AS	GEO_NA	W	PV	NEM
Acidification (molc H+ eq)	3,04E-03	1,92E-03	1,14E-02	6,30E-05	1,50E-04	2,34E-03
Climate change (kg CO_2 eq)	4,77E-01	3,01E-01	4,59E-01	1,34E-02	2,66E-02	4,84E-01
Freshwater ecotoxicity (CTUe)	2,09E-03	2,50E-03	8,96E-04	7,41E-04	5,85E-03	5,14E-03
Freshwater eutrophication (kg P eq)	1,18E-05	1,41E-05	2,30E-06	2,88E-06	1,81E-05	9,04E-05
Human toxicity, cancer effects (CTUh)	6,58E-04	4,31E-04	2,38E-03	1,72E-05	6,49E-05	5,09E-04
Human toxicity, non-cancer effects (CTUh)	1,89E-03	2,26E-03	1,21E-03	8,09E-04	1,78E-02	7,62E-03
Ionizing radiation E (interim) (CTUe)	2,80E-02	3,26E-02	1,35E-02	7,33E-03	6,22E-02	1,05E-01
Ionizing radiation HH (kBq U235 eq)	2,31E-03	2,77E-03	2,53E-04	4,28E-04	1,64E-03	2,71E-03
Land use (kg C deficit)	1,74E-04	2,08E-04	4,60E-05	1,76E-04	2,33E-04	9,31E-04
Marine eutrophication (kg N eq)	2,71E-03	3,24E-03	1,19E-03	9,41E-04	7,45E-03	7,05E-03
Mineral, fossil & ren resource depletion (kg Sb eq)	1,13E-06	1,36E-06	1,85E-07	2,27E-07	1,50E-06	7,19E-06
Ozone depletion (kg CFC-11 e)	6,15E-03	7,37E-03	1,68E-03	5,17E-03	6,53E-03	1,47E-01
Particulate matter (kg PM2.5 eq)	1,97E-05	2,36E-05	1,42E-05	3,90E-05	1,79E-05	1,21E-05
Photochemical ozone formation (kg NMVOC eq)	2,41E-08	2,89E-08	4,00E-09	3,36E-09	8,91E-09	3,37E-07
Terrestrial eutrophication (molvc N eq)	9,10E-05	1,09E-04	4,92E-05	3,29E-05	8,03E-05	8,33E-04
Water resource depletion (m^3 water eq)	9,22E-05	1,11E-04	5,00E-05	3,39E-05	8,41E-05	8,48E-04

Table 1.11 ReCiPe 2016 method results (Basosi et al., 2020)

	GEO	GEO_AS	GEO_NA	W	PV	NEM
Terrestrial acidification (kg SO_2 eq)	2,27E-03	1,42E-03	8,58E-03	4,15E-05	9,68E-05	1,58E-03
Global Warming (kg CO_2 eq)	4,77E-01	3,01E-01	4,59E-01	1,34E-02	2,66E-02	4,84E-01
Freshwater ecotoxicity (kg 1,4-DB eq)	2,09E-03	2,50E-03	8,96E-04	7,41E-04	5,85E-03	5,14E-03
Freshwater eutrophication (kg P eq)	1,18E-05	1,41E-05	2,30E-06	2,88E-06	1,81E-05	9,04E-05
Fine particulate matter formation (kg PM2,5 eq)	6,58E-04	4,31E-04	2,38E-03	1,72E-05	6,49E-05	5,09E-04
Human toxicity carcinogenic (kg 1,4-DB eq)	1,89E-03	2,26E-03	1,21E-03	8,09E-04	1,78E-02	7,62E-03
Human toxicity non-carcinogenic (kg 1,4-DB eq)	2,80E-02	3,26E-02	1,35E-02	7,33E-03	6,22E-02	1,05E-01
Ionising radiation (kBq Co-60 eq)	2,31E-03	2,77E-03	2,53E-04	4,28E-04	1,64E-03	2,71E-03
Land use (m^2 yr crop eq)	1,74E-04	2,08E-04	4,60E-05	1,76E-04	2,33E-04	9,31E-04
Marine ecotoxicity (kg 1,4-DB eq)	2,71E-03	3,24E-03	1,19E-03	9,41E-04	7,45E-03	7,05E-03
Marine eutrophication (kg N eq)	1,13E-06	1,36E-06	1,85E-07	2,27E-07	1,50E-06	7,19E-06
Fossil resource scarcity (kg oil eq)	6,15E-03	7,37E-03	1,68E-03	5,17E-03	6,53E-03	1,47E-01
Mineral resource scarcity (kg Cu eq)	1,97E-05	2,36E-05	1,42E-05	3,90E-05	1,79E-05	1,21E-05
Stratospheric Ozone depletion (kg CFC-11 eq)	2,41E-08	2,89E-08	4,00E-09	3,36E-09	8,91E-09	3,37E-07
Ozone formation, Human health (kg NOx eq)	9,10E-05	1,09E-04	4,92E-05	3,29E-05	8,03E-05	8,33E-04
Ozone formation, Terrestrial ecosystems (kg NOx eq)	9,22E-05	1,11E-04	5,00E-05	3,39E-05	8,41E-05	8,48E-04
Terrestrial ecotoxicity (kg 1,4-DB eq)	2,10E-01	1,98E-01	2,67E-01	3,09E-02	1,82E-01	3,18E-01
Water consumption (m^3)	1,60E-01	1,92E-01	3,38E-02	2,18E-02	1,90E-01	3,15E+00

Chapter 2

Methods

2.1 LCA approach

A Life Cycle Assessment is a complex process for the environment. As previously stated, there is a general framework for LCA that includes four stages: definition of goal and scope, inventory analysis, impact analysis, and each stage followed by an interpretation of the results. To generate results for LCA, quantitative data is needed.

The primary technique used in LCA is modelling, which is usually done with the use of dedicated LCA software. In this study, the software used for the analysis is GaBi software, which is compliant with ISO 14040: 2009 and ISO 14044: 2006. Since GaBi software was established in the 1990s, many upgrades and improvements have made this software better and more applicable. The software has enabled companies and LCA practitioners to perform system analysis more efficiently. In 2021, GaBi made several important changes to the databases, which are essential for the LCI process. Using best-practice data and methodologies, the GaBi software database helps to reduce the possibility of errors occurring during the analysis of a product or process. All GaBi software unit processes are designed to be compliant with the laws of physics and thermodynamics, whereby the inputs for mass balance and fuels must correspond to product, waste, and emission outputs (Kupfer et al., 2021).

GaBi is a software that can assist in the development of product sustainability. This software can provide highlights to be able to create a design for the environment with products that can meet environmental regulations. This software can also support the determination of reducing the use of materials, energy, and resources in order to achieve eco-efficiency in the production process. In addition, this software can support the determination of product development that has a smaller environmental footprint (Kupfer et al., 2021).

The database is essential for LCA because it can help to fill in the gaps caused by the limitations in data collection that will be used for assessment. The database includes information on the amount of energy, materials, and emissions used in a certain process or by a specific product. The database used for this study is the Ecoinvent database, which is already integrated with GaBi and included by default in the software. Ecoinvent is a database that provides well-documented data for the LCA in compliance with ISO 14040 and 14044 standards. Datasets help simplify the LCA process and make LCA a reliable tool for environmental assessment. Therefore, LCI datasets are the main emphasis of the database because LCA results are highly dependent on datasets. In the Ecoinvent dataset, uncertainty has been taken into account. Every modification to a unit process dataset will have an impact on the accumulated LCI results. The datasets are interrelated and show the level of direct input and output from one unit of processing goods and services to another (Weidema et al., 2013). Goods and services are described based on the level of the economic regions, both nationally and globally, so that the LCA results are more targeted (Frischknecht et al., 2005). The results of the LCI and LCIA from the Ecoinvent datasets can be used for a comparative assessment to identify goods or services that are more environmentally friendly.

2.2 Goal and scope

The goals of this research are as follows:

1. To assess the potential negative impacts on the environment of the geothermal drilling, construction, and operation of the Patuha geothermal field.
2. To determine the midpoint hotspot that corresponds to the Patuha geothermal power plant.
3. To provide a comparison between the results of geothermal LCA in the world.
4. To provide ideas for alternative improvements that can be implemented to lessen the environmental impact of geothermal energy production in the Patuha geothermal field.

2.2.1 Functional unit

The functional unit for this study is impacts per 1 kWh electricity (Eq.1). All data collected at the inventory stage will be linked to the functional unit to provide a reference to which input and output data are normalized.

$$Functional\ Unit = \frac{Impact}{Total\ kWh\ for\ 30\ years}$$

Eq. 1

The functional unit is calculated by taking into account the capacity factor, where the capacity factor formula is Eq.2.

$$\boldsymbol{Capacity\ Factor = \frac{Actual\ energy\ generated\ (MWh)}{Capacity\ (MW) \times Time\ period\ (h)}}$$

Eq. 2

LCA studies frequently make the assumption that power plants have a 30-year operating lifetime, and so the time horizon chosen for this research is 30 years of operation. For the data inventory, mass is expressed as a kilogram (kg), volume is expressed as a cubic meter (m^3), and power output is expressed in Mega-Watt hour (MWh) or kilo-Watt hour (kWh).

2.2.2 System boundaries

The LCA of the Patuha geothermal power plant will model the drilling, construction, and production stages, while maintenance and decommissioning stages are not included (Figure 2.1). The drilling stage includes materials and fuel used for the well drilling, such as mud drilling, casing, and cementing. The construction stage focuses on the materials used for the surface facilities, such as the wellheads, pipelines, demister, turbine and generator, condenser, cooling tower, and reinjection pond. The operation stage includes geothermal fluid and electricity.

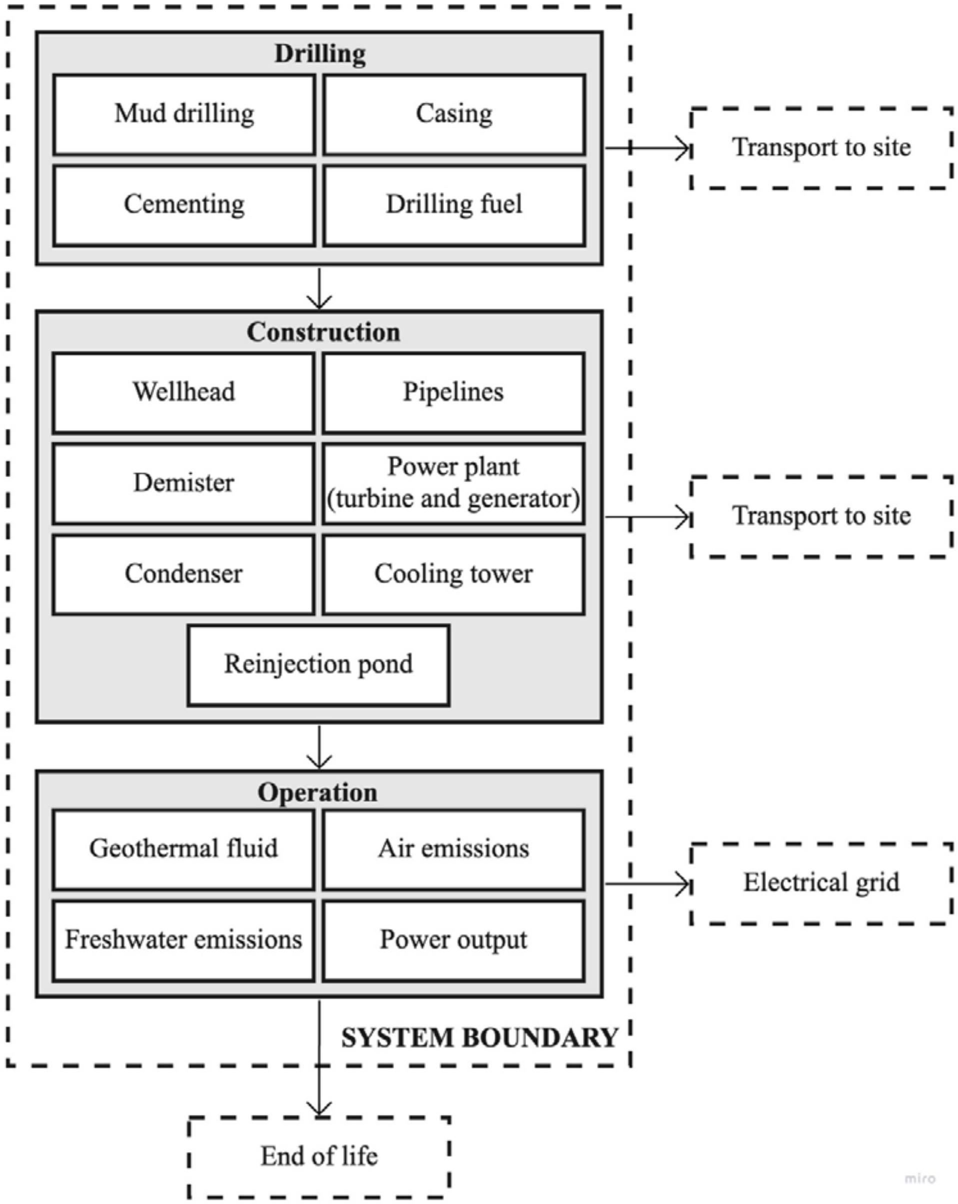

Figure 2.1 - System boundaries for the LCA of Patuha

2.2.3 Data quality

Descriptions of data quality have to be determined at the beginning of the LCA study because it affects the reliability of the results. A good-quality LCA result is obtained by taking into account the data acquisition, time-reference, geographical and technological coverage, precision, and completeness. Table 2.1 provides an overview of the data quality of this research.

Table 2.1 Data quality of the LCA of the Patuha Geothermal Field

Aspect	Explanation
Time-related coverage	The data was obtained in 2021 from PT Geo Dipa Energi, which consists of data from the drilling and construction stage in 1997 until the operation stage in 2021. The lifetime span in this study follows the operation period of a geothermal power plant, which is 30 years.
Geographical coverage	The data is limited to the Patuha Geothermal Field in Pengalengan, West Java, Indonesia.
Technology coverage	The information is relevant for standard geothermal well, wellhead, steam pipelines, demister, single flash geothermal power plant technology, cooling tower, and condenser for geothermal.
Precision	The inventory data is precise to the representation of geothermal power plants. The data source from the company includes documents and reports from 1997 to 2021.
Completeness	The primary data is 90%, and the secondary data is 10%.
Representativeness	The data set reflects the time-related, geographical, and technology coverage.
Consistency	The methodology is consistent with the recommendation of ISO 14040:2006 and ISO 14044:2006.
Reproducibility	The overall results are case-specific. However, the data from inventory might be applied to other case geothermal studies.
Sources of the data	90% is primary data, and 10% is literature data. The primary data is measured, calculated, and estimated from the drilling, construction and operation documents and company reports of the Patuha Geothermal Field.
Uncertainty of the information	The uncertainty is discussed in the Discussion Chapter.

2.3 Life Cycle Inventory

Inventory data includes all process data from the units that are being analysed. The drilling, construction, and operation stages are all taken into consideration in this research. The data inventory is conducted based on input data in the form of raw materials and energy, and output data in the form of waste and emissions. Table 2.2 provides the list of inventory data for the input data that was included and excluded from the research.

Table 2.2 Inventory data included and excluded in the study

Life cycle stage	Included in inventory	Excluded from inventory
Drilling		
Mud drilling	Material use during mud drilling (bentonite, potassium hydroxide, potassium chloride).	Other mud material, loss circulation/prevention material, drill rig infrastructure. Transport to site.

Life cycle stage	Included in inventory	Excluded from inventory
Cementing	Material use during well cementing (portland cement, potassium chloride, water).	Drill rig infrastructure. Transport to site.
Casing	Material use during well casing (steel). Energy for manufacturing of steel pipe.	Drill rig infrastructure.
Drilling fuel	Diesel use during drilling operation for 13 wells.	-
Construction		
Wellhead	Material use for wellhead (steel) and wellhead foundation (concrete and steel).	Energy for manufacturing equipment and structures. Transport to site.
Steam collection	Material use for pipelines (steel pipe), insulation (rock wool and aluminium cladding), foundation (concrete). Energy for manufacturing of steel pipe.	Separator from well PPL-02. Aluminium or stainless steel for the foundation support. Transport to site.
Demister	Material use for demister (steel) and foundation (concrete).	Energy for manufacturing demister. Transport to site.
Power plant (turbine and generator)	Material use for turbine, generator, and hot well pumps (steel), and building (concrete and steel).	Energy for machinery manufacture. Interior design of building. Electrical control room and computers. Transport to site.
Condenser	Material use for condenser (steel).	Energy for manufacturing condenser. Transport to site.
Cooling tower	Material use for condenser (steel and plastic) and foundation (concrete and steel).	Energy for manufacturing cooling tower. Transport to site.
Reinjection pond	Material use for reinjection pond (steel, concrete, plastic).	Transport to site.
Operation		
Geothermal fluid	Brine from ground and reinjected, steam from ground, and reinjected condensate.	-
Air emissions	CO_2, H_2S, and NH_3.	Ar, N_2, CH_4.
Freshwater emissions	NH_3, As, Hg.	-
Power output	Electricity for 30 years of operation.	-

Other minor materials, such as bolts, screws, wood were not included in the inventory because those were considered not to be significant. Transportation and mobilization should be included in the LCA, but there were limitations in data collection because the process during construction was carried out by the previous company.

According to Karlsdottir (2015), LCA required minimum data collection in the form of site-specific parameters. This is the minimal step that must be taken to obtain LCA results when primary data are not available. Therefore, the following are site-specific parameters for the Patuha Geothermal Field with a single flash power plant (Table 2.3).

Table 2.3 Site-specific parameters of Patuha Geothermal Power Plant

Site-specific parameter	Unit	Value for Patuha
Reservoir		
Number of wells drilled	-	13
Total meters drilled	m	22590
Collection pipelines	m	7886
Power plant		
Installed capacity – single flash	MW	55

This LCI phase requires special attention because the quality, accuracy, and representation of the data greatly affect the final interpretation results. According to Karlsdóttir (2015), the accuracy of the inventory is determined by the following data accuracy categories :

- High accuracy (h): The data presented is detailed data from reliable data documentation sources. The estimated data accuracy is 5% more or less than the actual data.
- Moderate accuracy (m): The data presented has a moderate accuracy which requires data extrapolation due to minor data gaps. The estimated data accuracy is 10% more or less than the actual data.
- Low accuracy (l): The data presented has the lowest accuracy, requiring considerable data estimations and/or calculations due to significant data gaps. The estimated data accuracy is 20%-30% more or less than the actual data.

2.3.1 Drilling stage

In Patuha, there are 10 production wells and 3 reinjection wells drilled to accommodate steam requirements and maximize production from a power plant with a capacity of 55 MW. Technically, production wells are drilled directionally at the intersection with a permeable structure at the subsurface to reach the target depth. The depth of the well and the design of each well is adapted to subsurface conditions. This is done to maximize the quality and quantity of production wells and maximize the potential for a higher production capacity.

In accordance with the system boundaries that have been determined, the input data for materials and energy used during drilling of each well includes the depth of the well and the amount and type of drilling mud, casing, and cement used in all wells. The quantities of the materials for this stage depend on the drilling operation steps. For example, when total loss circulation or partial loss circulation occurs in drilling, the drilling operation requires more materials than usual. However, the drilling mud data for this research does not account for the loss of circulation due to limitations in data collection.

MUD DRILLING

Drilling operation requires drilling fluids in the form of liquid or gas and liquid-based fluid, which is also referred to as drilling mud. Drilling mud is used to overcome the formation pressure and as hole cleaning material to keep the well stable. In addition, mud lubricates and cools down the bit with the drilling assembly. It also became a medium for the logging and measurement while drilling tools to send and receive data from and to the surface acquisition modules (Finger and Blankenship, 2012). In this research, the drilling mud is assumed for 13 wells with a depth of 2000 m each. This was done due to limitations in data collection. The total of drilling mud usage is expressed in units of kg where the mud consists of Bentonite, Potassium hydroxide, and Potassium chloride (Table 2.4). Other fluids are not accounted for since the environmental impact is not significant.

Table 2.4 Material use for the mud drilling

Material	Unit	Amount	Dataset	Accuracy
Bentonite	kg	299.000	bentonite [allocatable product]	1
Potassium hydroxide	kg	97.825	potassium hydroxide [34231: Chemical elements n.e.c.; inorganic acids except phosphoric, nitric and sulphonitric; inorganic oxygen compoun[…]]	1
Potassium chloride	kg	533.000	potassium chloride [allocatable product]	1
Portland cement	kg	2.826.794	cement, Portland [allocatable product]	1

WELL CASING

Every well drill requires casing. The casing is a steel pipe in the wellbore, which prevents the hole from formation problems. The casing protects an aquifer, isolates troublesome formations, fluid pressure control, and defines the production zone. Well casings are arranged in several intervals at a certain depth which depends on the physical requirements of the well. The casing design must be able to withstand loads, such as burst pressure, collapse pressure, axial tension, and buckling. Well casing is characterized by diameter, weight, and grade. As drilling goes deeper, the diameter of the hole and casing decreases. The grade or strengths used depends on the well construction (Finger and Blankenship, 2012). The total material used for the casing is shown in Table 2.5. Mass of casing material was converted from ppf (pounds per foot) to kg (kilogram).

Table 2.5 Material use for casing

Material	Unit	Amount	Dataset	Accuracy
Steel	kg	3.108.088	steel, low-alloyed [allocatable product]	h
Steel pipe manufacture	kg	3.108.088	drawing of pipe, steel [4128: Tubes, pipes and hollow profiles, of steel]	h

CEMENTING OF CASING

The casing must be cemented to hold the casing in place and to prevent casing expansion. The cement is pumped down inside the casing. The volume of cement pumped for each well was determined by calculating the total volume of the well and the volumes of the casing and interior and accounting for excess cement for each casing interval (Finger and Blankenship, 2012). The details of cement pumped into each production well in the Patuha Geothermal Field are shown in Table 2.6. Well cementing was converted from bbl (barrel) to kg (kilogram).

Table 2.6 Material use for cementing

Material	Unit	Amount	Dataset	Accuracy
Portland cement	kg	2.826.794	cement, Portland [allocatable product]	h
Potassium chloride	kg	624.343	potassium chloride [allocatable product]	h
Water	kg	641.434	water, harvested from rainwater [18000: Natural water]	h

DRILLING FUEL

This unit process considers the environmental emissions that are directly emitted by the combustion of diesel fuel during the well construction process. According to Karlsdottir (2015), the diesel required for drilling is 53,1 kg/m_{well}. Therefore, the amount of diesel utilized for well drilling in the Patuha Geothermal Field was calculated based on this number and the total depth of all wells in the field (Table 2.7).

Table 2.7 Drilling fuel

Material	Unit	Amount	Dataset	Accuracy
Diesel	kg	92.271	diesel [allocatable product]	m

2.3.2 Construction stage

The inputs to the construction stage cover all materials used to construct wellheads, steam collection, demister, turbine and generator, condenser, cooling tower, and reinjection pond. The materials include steel, concrete, aluminium cladding, rock wool, plastic (high-density polyethylene), and fibre reinforced plastic (FRP).

WELLHEADS

The primary purpose of the wellhead is to provide the pressure seals for the casing and maintain the normal operation of geothermal well production. Wellhead consists of several valves for regulating fluid flow. One of the most important valves is the master valve which is helpful for shutting off the well. The inventory for wellheads materials is the steel for the master valve, wing valve, crown valve and the foundation of the wellheads (Table 2.8).

Table 2.8 Material use for wellheads

Material	Unit	Amount	Dataset	Accuracy
Steel	kg	31.970	steel, low-alloyed [allocatable product]	h
Concrete	m^3	29	concrete, normal [allocatable product]	h

Material	Unit	Amount	Dataset	Accuracy
Steel (foundation)	kg	6008	reinforcing steel [allocatable product]	h

PIPELINES

The pipelines at Patuha analysed in the study were pipelines from each well to main pipelines extending from the well to before demister. The total length of the pipelines is 7885.96 m with various pipeline diameters (8", 10", 14", 16", 20", 22", 36", and 42"). Due to the limitation in the Ecoinvent database, rock wool for the pipeline's insulation is converted from several diameters to 16" or DN (Diameter Nominal) 400. The pipeline is equipped with insulators to avoid overheating. On the outside, the material used to insulate the pipe is also protected with other materials to protect the insulation from mechanical damage. The pipeline insulations are rockwool and aluminium cladding. The foundation of pipelines is included (Table 2.9).

Table 2.9 Material use for pipelines

Material	Unit	Amount	Dataset	Accuracy
Steel	kg	1.214.035	steel, low-alloyed [allocatable product]	h
Steel pipe manufacture	kg	1.214.035	drawing of pipe, steel [4128: Tubes, pipes and hollow profiles, of steel]	h
Rockwool	kg	21.029	insulation spiral-seam duct, rockwool, DN 400, 30 mm [allocatable product]	h
Aluminium cladding	kg	41.337	sheet rolling, aluminium [allocatable product]	h
Concrete	m^3	1635	concrete, normal [allocatable product]	l

DEMISTER

To provide a good quality of steam for the turbine, a demister is required to support the operation. In Patuha Unit 1 operation, there is one demister that removes all condensed liquid and dust particles in steam. Steel for the demister and concrete for the foundation of the demister are included in the inventory of this LCA (Table 2.10).

Table 2.10 Material use for demister

Material	Unit	Amount	Dataset	Accuracy
Steel	kg	30.000	steel, low-alloyed [allocatable product]	l
Concrete	m^3	38	concrete, normal [allocatable product]	m

TURBINE AND GENERATOR

Steel is the primary material used in the construction of the turbine and generator, with copper and aluminum also being used in a few components. The inventory for the turbine and generator also includes the building, which can be seen in Table 2.11.

Table 2.11 Material use for turbine and generator

Material	Unit	Amount	Dataset	Accuracy
Steel	kg	294.087	steel, low-alloyed [allocatable product]	m
Copper	kg	7580	copper, cathode [allocatable product]	m
Aluminium	kg	1516	aluminium, cast alloy [allocatable product]	m
Concrete	m^3	3942	concrete, normal [allocatable product]	m
Steel (foundation)	kg	1.603.346	reinforcing steel [allocatable product]	m

CONDENSER

The condenser in the Patuha Geothermal Field is made of steel. The total steel used for the condenser is shown in Table 2.12. The foundation of the condenser is included in the power plant buildings.

Table 2.12 Material use for condenser

Material	Unit	Amount	Dataset	Accuracy
Steel	kg	133.000	steel, low-alloyed [allocatable product]	l

COOLING TOWER

The main materials used for the cooling tower are steel and plastic. Plastic at the cooling tower works mechanically to lower hot water temperature. The foundation of the cooling tower is made of concrete and steel. The quantity of materials is shown in Table 2.13.

Table 2.13 Material use for cooling tower

Material	Unit	Amount	Dataset	Accuracy
Steel	kg	65.870	steel, low-alloyed [allocatable product]	m
FRP	kg	43.913	glass fibre reinforced plastic, polyester resin, hand lay-up [allocatable product]	m
Concrete	m^3	4207	concrete, normal [allocatable product]	m
Steel (foundation)	kg	35.100	reinforcing steel [allocatable product]	m

REINJECTION POND

In Patuha Geothermal Field, one reinjection pond is used for the operation. The reinjection pond is made of concrete, FRP, and plastic, supported by steel (Table 2.14).

Table 2.14 Material use for reinjection pond

Material	Unit	Amount	Dataset	Accuracy
Plastic	kg	3000	polyethylene, high density, granulate [allocatable product]	m
FRP	kg	450	glass fibre reinforced plastic, polyester resin, hand lay-up [allocatable product]	m
Concrete	m^3	14	concrete, normal [allocatable product]	m
Steel (foundation)	kg	7770	reinforcing steel [allocatable product]	m

2.3.3 Operation stage

The operation stage is forecasted for 30 years of plant operation (8760 hours per year) without considering the maintenance (overhaul) and natural declining well flow. The inventory included geothermal fluid, emissions, and power output (Table 2.15). In most cases, the operation of a power plant requires the use of water from a different source for the cooling tower operation. In the case of Patuha, water is not required because the condensed steam that is pumped from the condenser to the cooling tower is used as make-up water, and the remaining condensed steam is disposed of into a reinjection pond. After passing through the cooling tower, the makeup water returns to the condenser. It continues to circulate in a closed loop to provide makeup water for the cooling tower system.

Table 2.15 Inventory data for the Patuha Geothermal Power Plant operation

Data	Unit	Amount	Dataset	Accuracy
Geothermal fluid, from ground				
Brine	kg	3.818.099.355	Brine [Inorganic intermediate products]	h
Steam	kg	97.665.369.000	Steam (hp) [steam]	h
Emissions to air				
CO_2	kg	557.700.000	Carbon dioxide [Inorganic emissions to air]	h
H_2S	kg	26.910.000	Hydrogen sulfide [ecoinvent long-term to air]	h
NH_3	kg	600.000	Ammonia [Inorganic emissions to air]	h
Emissions to fresh water				
NH_3	kg	300	Ammonia [Inorganic emissions to fresh water]	h
As	kg	30	Arsenic [Heavy metals to fresh water]	h
Hg	kg	3	Mercury [Heavy metals to fresh water]	h
Geothermal fluid, reinjected				
Brine	kg	1.145.429.807	Brine [Inorganic intermediate products]	h

Data	Unit	Amount	Dataset	Accuracy
Condensate	kg	24.281.065.950	Condensate, recycling [Waste for recovery]	h
Power output				
Electricity	MWh	14.454.000	Electricity ID [Electric power]	h

2.4 Life Cycle Impact Assessment (LCIA)

ReCiPe 2016 method was selected for the LCIA. Results for this research were analysed using the midpoint approach with the hierarchist (H) perspective. The considerations of using this method for the research are as follows:

- Recent LCA publications used this method.
- ReCiPe 2016 is up-to-date with the current scientific knowledge since it was updated in 2016.
- ReCiPe 2016 has higher accuracy in quantifying impacts.
- The range of impact categories is wide, including 18 impact categories that show a single environmental problem and a better understanding of the environmental impact.
- Refers to the impact category that has been determined by the Indonesian Ministry of Environment and Forestry and the agreement of the Indonesian Geothermal Association

On the basis of GaBi software and the conversion calculations used in this study, Table 2.16 illustrates the impact categories and indicators that were determined.

Table 2.16 - Impact categories and indicators used for the research

Impact Categories	Indicators
Climate change, default, excl biogenic carbon	g CO_2 eq/kWh
Climate change, incl biogenic carbon	g CO_2 eq/kWh
Fine Particulate Matter Formation	g $PM_{2,5}$ eq/kWh
Fossil depletion	g oil eq/kWh
Freshwater Consumption	m^3/kWh
Freshwater ecotoxicity	g 1,4 DB eq/kWh
Freshwater Eutrophication	g P eq/kWh
Human toxicity, cancer	g 1,4-DB eq/kWh
Human toxicity, non-cancer	g 1,4-DB eq/kWh
Ionizing Radiation	kBq Co-60 eq. to air/kWh
Land use	Annual crop eq.·y/kWh
Marine ecotoxicity	g 1,4-DB eq/kWh
Marine Eutrophication	g N eq/kWh
Metal depletion	g Cu eq/kWh
Photochemical Ozone Formation, Ecosystems	g NOx eq/kWh
Photochemical Ozone Formation, Human Health	g NOx eq/kWh
Stratospheric Ozone Depletion	g CFC-11 eq/kWh
Terrestrial Acidification	g SO_2 eq/kWh
Terrestrial ecotoxicity	g 1,4-DB eq/kWh

Chapter 3

Results

This chapter will address all the environmental impacts resulting from the impact assessment by using the GaBi software and the ReCiPe 2016 method. In order to provide the results, the GaBi program calculates all inventory data, which includes drilling, construction, and production stages of the geothermal system in the Patuha Geothermal Field. Material input, fuel consumption, emission, and the manufacturing process are all included in the inventory data. The result of the calculation in GaBi software was then converted to each impact per kWh based on the assumption that the capacity factor of the power plant in Patuha is 92% and the plant has a lifetime of 30 years.

3.1 Life Cycle Impact Assessment Results

According to the results, the drilling and construction stages were responsible for all of the environmental impacts considered by the ReCiPe 2016 method, such as climate change, fine particulate matter formation, fossil depletion, freshwater consumption, freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionizing radiation, land use, marine ecotoxicity, marine eutrophication, metal depletion, photochemical ozone formation, stratospheric ozone depletion, terrestrial acidification, and terrestrial ecotoxicity. Operation stage contributes to nine impact categories, such as climate change (excl biogenic carbon), climate change (incl biogenic carbon), fine particulate matter formation, freshwater ecotoxicity, human toxicity (cancer), human toxicity (non-cancer), marine ecotoxicity, marine eutrophication, and terrestrial acidification. Table 3.1 shows the life cycle impact assessment results of the Patuha Geothermal power plant.

Table 3.1 Impact results of Patuha Geothermal Power Plant

Impact category	Unit	Impact per stage			Total impact
		Drilling	Construction	Operation	
Climate change, default, excl biogenic carbon	g CO_2 eq/kWh	0,65	0,71	41,94	43,30
Climate change, incl biogenic carbon	g CO_2 eq/kWh	0,65	0,72	41,94	43,31
Fine particulate	g $PM_{2,5}$ eq/kWh	9,79E-04	1,14E-03	0,01	0,01

Impact category	Unit	Impact per stage			Total impact
		Drilling	Construction	Operation	
matter formation					
Fossil depletion	g oil eq/kWh	0,17	0,20	-	0,37
Freshwater consumption	m^3/kWh	9,49E-06	8,96E-06	-	1,84E-05
Freshwater ecotoxicity	g 1,4 DB eq/kWh	0,03	0,05	1,52E-04	0,08
Freshwater eutrophication	g P eq/kWh	2,53E-04	2,94E-04	-	5,47E-04
Human toxicity, cancer	g 1,4-DB eq/kWh	1,60	1,30	8,09E-04	2,90
Human toxicity, non-cancer	g 1,4-DB eq/kWh	0,65	0,94	0,21	1,80
Ionizing radiation	kBq Co-60 eq. to air/kWh	2,60E-05	2,63E-05	-	5,23E-05
Land use	Annual crop eq.·y/kWh	1,74E-05	2,29E-05	-	4,03E-05
Marine ecotoxicity	g 1,4-DB eq/kWh	0,05	0,06	2,06E-04	0,11
Marine eutrophication	g N eq/kWh	4,96E-05	4,38E-05	5,41E-06	9,88E-05
Metal depletion	g Cu eq/kWh	0,01	0,02	-	0,03
Photochemical ozone formation, ecosystems	g NO_x eq/kWh	1,62E-03	2,02E-03	-	3,64E-03
Photochemical ozone formation, human health	g NO_x eq/kWh	1,56E-03	1,93E-03	-	3,48E-03
Stratospheric Ozone Depletion	g CFC-11 eq/kWh	1,74E-07	2,16E-07	-	3,90E-07
Terrestrial Acidification	g SO_2 eq/kWh	1,76E-03	2,18E-03	1,16	1,17
Terrestrial ecotoxicity	g 1,4-DB eq/kWh	1,91	2,45	6,1E-21	4,37

3.1.1 Climate change

Most of the climate change impacts occurred during the operation stage. Climate change (excluding biogenic carbon) and climate change (including biogenic carbon) each contribute the same amount, 41,94 g CO_2 eq/kWh. Climate change (excluding biogenic carbon) accounted for 96,9% of the total contribution, while climate change (including biogenic carbon) contributes for 96,8% of the total contribution. The drilling and construction stages individually contribute 0,65 g CO2 eq/kWh and 0,71 g CO_2 eq/kWh, accounting for 1,5% and 1,6% of climate change (excluding biogenic carbon). For climate change (including biogenic carbon), the drilling stage contributes 0,65 g CO_2 eq/kWh (1,5%), and the construction stage contributes 0,72 g CO_2 eq/kWh (1,7%).

3.1.2 Fine particulate matter formation

In terms of fine particulate matter formation, the operational stage made the most significant contribution, 0,01 g $PM_{2,5}$ eq/kWh, responsible for 83,6% of the total contribution to fine particulate matter formation. On the other hand, the contribution of the construction stage was substantially lower, at 8,8%, with a total of 1,14E-03 g $PM_{2,5}$ eq/kWh, while the contribution of the drilling stage was the lowest with a total of 9,79E-04 g $PM_{2,5}$ eq/kWh, accounting for 7,6% of the total contribution.

3.1.3 Fossil depletion

The impact of fossil depletion is primarily generated during the construction stage, accounting for 53,1%, with a total of 0,20 g oil eq/kWh of the total contribution. The remaining 46,9% of the total contribution is due to the drilling stage, which contributes 0,17 g oil equivalent/kWh. The operational stage has no contribution to fossil fuel depletion.

3.1.4 Freshwater consumption

Freshwater consumption in Patuha is contributed by two stages: the drilling stage and the construction stage of the project. The drilling stage plays a dominant role in freshwater consumption, accounting for 51,4% and having a total contribution of 9,49E-06 m^3/kWh. In contrast, the construction stage has a contribution of 48,6% and a total of 8,96E-06 m^3/kWh.

3.1.5 Freshwater ecotoxicity

The construction stage is the dominant contributor to freshwater ecotoxicity, followed by the drilling stage, while the operation stage is the lowest significant contributor to freshwater ecotoxicity. It is calculated that the construction stage contributes 0,05 g 1,4 DB eq/kWh (57,8%), the drilling stage contributes 0,03 g 1,4DB eq/kWh (42%), and the operation stage contributes 1,52E-04 g 1,4 DB eq/kWh (0,2%) of the total contribution.

3.1.6 Freshwater eutrophication

Freshwater eutrophication is the environmental impact in Patuha that is caused by the drilling and construction stages. The operation stage does not affect this impact. The total impact of freshwater eutrophication is 5,47E-04 g P eq/kWh consisting of a drilling stage of 46,3% with a total of 2,53E-04 g P eq/kWh and the remaining amount (53,7%) accounting for the construction stage, which is the most contributor with a total of 2,94E-04 g P eq/kWh.

3.1.7 Human toxicity, cancer

Drilling, construction, and operation stages are contributing to human toxicity (cancer). The operation stage has a minor contribution that has a percentage of 0,03% or equal to 8,09E-04 g 1,4-DB eq/kWh. The drilling stage has a higher percentage than other stages in terms of this impact, where the drilling stage has a percentage of 55,11% with a total contribution of 1,60 g 1,4-DB eq/kWh, while the construction stage has a percentage of 44,86% with a total of 1,30 g 1,4-DB eq/kWh.

3.1.8 Human toxicity, non-cancer

Human toxicity (cancer) at the Patuha geothermal power plant is caused by all stages of the project, with the construction stage having the most impact. The contribution from the construction stage is 0,94 g 1,4-DB eq/kWh, which is equal to 52,3% of the total contribution. The second most significant contributing factor is the drilling stage, which provides 0,65 g 1,4-DB eq/kWh or equivalent to 36%. Finally, the lowest contributing factor is the operation stage, which contributes 0,21 g 1,4-DB eq/kWh or corresponds to 11,7% of the total contribution.

3.1.9 Ionizing radiation

The percentage difference between the contribution of the drilling stage and the contribution of the construction stage on ionizing radiation is nearly similar. The drilling stage represents 49,7% of the total contribution, and the construction stage represents 50,3%. Thus, the drilling stage has a total of 2,60E-05 kBq Co-60 eq. to air/kWh and the construction stage has a total of 2,63E-05 kBq Co-60 eq. to air/kWh.

3.1.10 Land use

The total land use impact in Patuha is 4,03E-05 Annual crop eq.·y/kWh. This was driven by the drilling stage, which contributed 1,74E-05 Annual crop eq.y/kWh or 43,2%, and the construction stage, which contributed 2,29E-05 Annual crop eq.y/kWh or 56,8%. Thus, the total contribution of the construction stage is higher than the drilling stage.

3.1.11 Marine ecotoxicity

The drilling, construction, and operation stages are all crucial stages that impact marine ecotoxicity. The construction stage has the highest impact, accounting for a total of

0,06 g of 1,4-DB eq/kWh, or 56,5% of the total contribution. The drilling stage was the second most significant contributor, accounting for 0,05 g 1,4-DB eq/kWh or 43,3% of the total. Finally, the operation stage was the lowest contributor, accounting for 2,06E-04 g 1,4-DB eq/kWh or 0,2% of the total contribution.

3.1.12 Marine eutrophication

The impact of marine eutrophication on the Patuha geothermal power plant can be seen at all stages. The most significant contributor to this impact is the drilling stage, which contributes 4,96E-05 g N eq/kWh, which translates to 50,2% of the total contribution. The construction stage is the next higher stage, with a contribution of 4,38E-05 g N eq/kWh or 44,3% of the total contribution. Finally, the operation stage was the lowest significant contributor, accounting for 5,41E-06 g 1,4-DB eq/kWh or 0,2% of the total contribution.

3.1.13 Metal depletion

The drilling stage and building stage are two factors that impact metal depletion. At this stage, the amount of contribution between the drilling stage and the construction stage is not significantly different. However, the construction stage contributed slightly more than the drilling stage, with the construction stage contributing 0,02 g Cu eq/kWh or equal to 55,5% of the total contribution. In comparison, the drilling stage contributed 0,01 g Cu eq/kWh or equal to 44,5% of the total contribution.

3.1.14 Photochemical ozone formation, ecosystems

The total contribution of the drilling and construction stages to photochemical ozone formation (ecosystems) is 3,64E-03 g NO_x eq/kWh. The drilling stage was responsible for 44,5% of this amount, with a total contribution of 1,62E-03 g NOx eq/kWh. The remaining 55,5% came from the construction stage, which contributed a total of 2,02E-03 g NOx eq/kWh to the overall total contribution.

3.1.15 Photochemical ozone formation, human health

The contribution of the drilling and construction stages impacts photochemical ozone formation (human health) with a total contribution of 3,48E-03 g NO_x eq/kWh. The cumulative contribution of the two stages is similar, with the the drilling stage for 44,7% and construction stage accounting for 55,3%. Drilling stage contributes 1,56E-03 g NO_x eq/kWh and construction stage contributes 1,93E-03 g NO_x eq/kWh.

3.1.16 Stratospheric ozone depletion

The Patuha geothermal power plant produces 3,90E-07 g CFC-11 eq/kWh of stratospheric ozone depletion. The drilling stage contributed 44,5% of the entire contribution (1,74E-07 g CFC-11 eq/kWh), while the construction stage supplied 55,5% of the total contribution (2,16E-07 g CFC-11 eq/kWh).

3.1.17 Terrestrial acidification

The operation has the most significant impact on terrestrial acidification. The operation stage contributed 1,16 g SO_2 eq/kWh, comparable to 99,7% of the total contribution. The remaining portion comprises contributions from the drilling and construction stages, with a combined contribution of 1,76E-03 g SO_2 eq/kWh (0,15%) and 2,18E-03 g SO_2 eq/kWh (0,19%) for each stage.

3.1.18 Terrestrial ecotoxicity

A total of 4,37 g 1,4-DB eq/kWh of terrestrial ecotoxicity was mostly generated from the drilling and construction stages at Patuha. The construction stage made a higher contribution than the drilling stage, with the construction stage accounting for 56,2% of the total contribution and the drilling stage accounting for 43,8%. The total contribution of the construction stage is 2,45 g 1,4-DB eq/kWh, while the total contribution of the drilling stage is 1,91 g 1,4-DB eq/kWh. The operation stage contributed very low,with a total contribution of 6,1E-21.

The overall contribution of the Patuha geothermal power plant to the environmental impacts is depicted in Figure 3.1, which gives a breakdown of the total impacts between the different life cycle stages of the plant. Environmental impact of each process throughout the drilling, construction, and operating stages is depicted in further detail in Figures 3.2, 3.3, and 3.4, respectively.

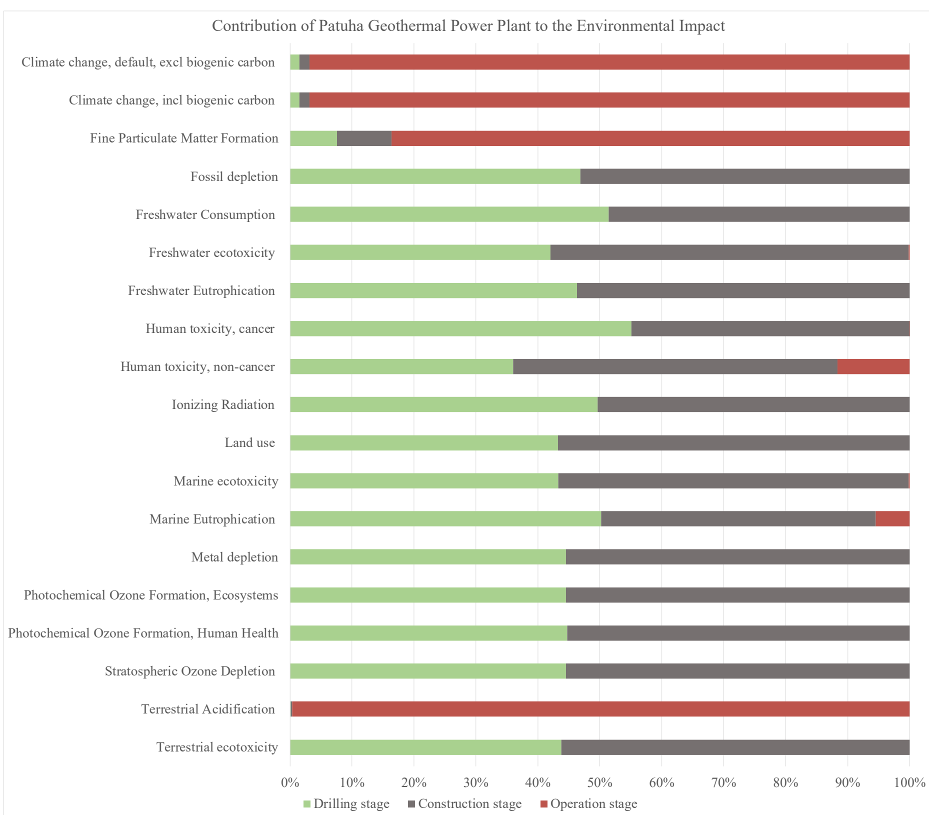

Figure 3.1 - Contribution of the main stages for the production of 1 kWh of electricity at the Patuha Geothermal Power Plant to the environment impact

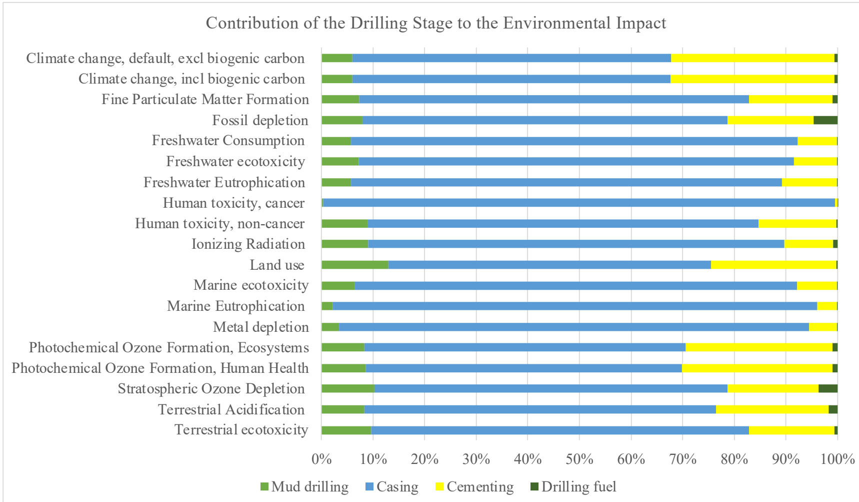

Figure 3.2 - Contribution of the drilling stage to the environmental impact

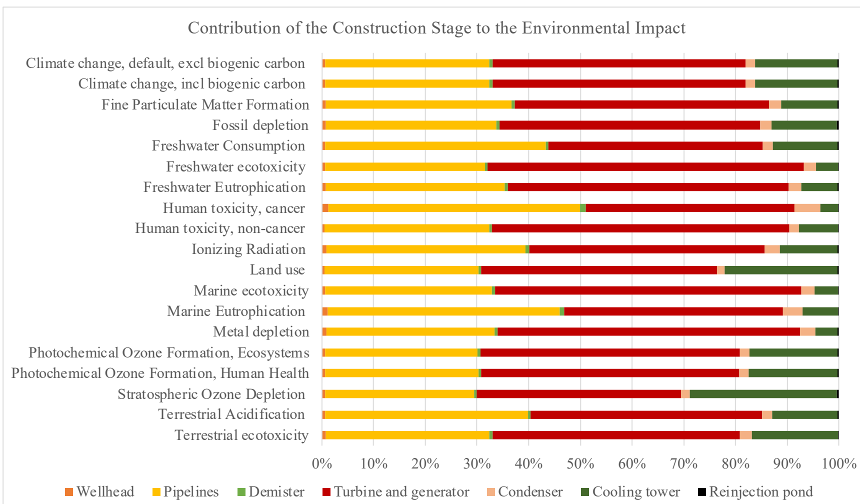

Figure 3.3 - Contribution of the construction stage to the environmental impact

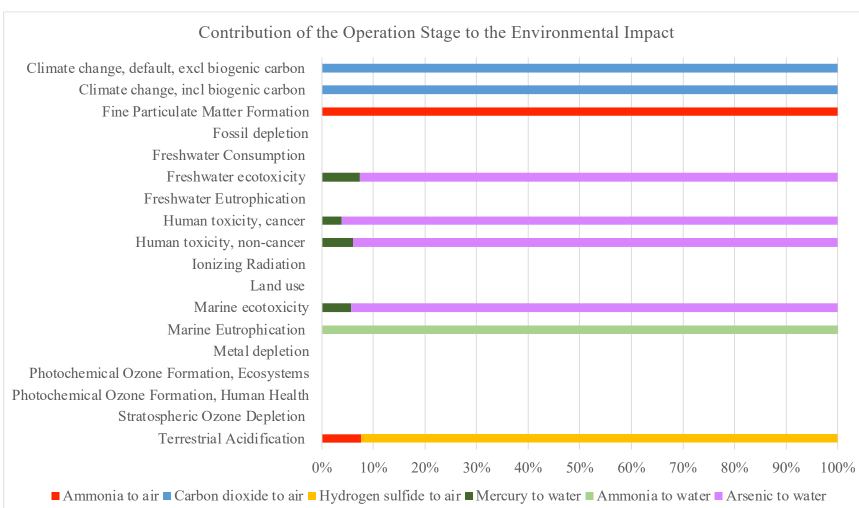

Figure 3.4 - Contribution of the operation stage to the environmental impact

3.2 Midpoint Hotspot

A midpoint hotspot analysis by materials and unit processes is performed for this research. Figure 3.2 depicts the relative contribution of materials for the drilling and construction stages based on the average percentage. Table 3.2 displays the results of the midpoint hotspot analysis by unit processes, which was conducted in accordance with the results of the assessment conducted using the ReCiPe 2016 methodology. The color red denotes the highest percentage, yellow represents a moderate percentage, and the green represents the lowest percentage.

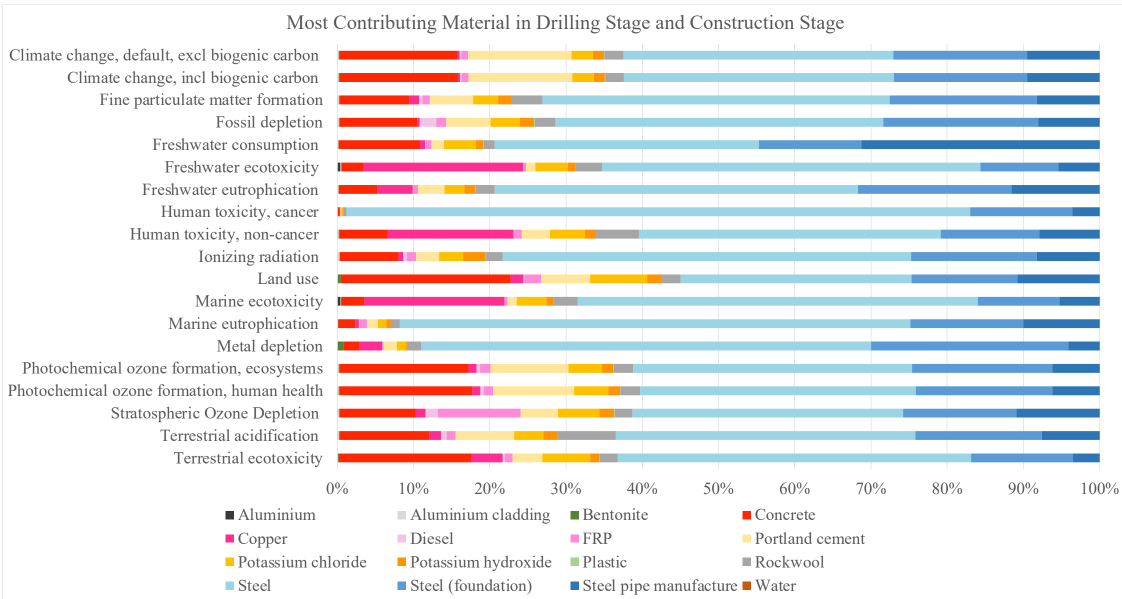

Figure 3.5 - Midpoint hotspot analysis by materials for the drilling stage and construction stage

Table 3.2 Midpoint hotspot analysis by unit process

Midpoint analysis by unit process	Mud drilling	Casing	Cementing	Drilling fuel	Wellhead	Pipelines	Demister	Turbine and	Condenser	Cooling tower	Reinjection pond	Operation
Climate change, default, excl biogenic carbon	0,09%	0,92%	0,47%	0,01%	0,01%	0,52%	0,01%	0,81%	0,03%	0,26%	0,00%	96,86%
Climate change, incl biogenic carbon	0,09%	0,93%	0,48%	0,01%	0,01%	0,53%	0,01%	0,81%	0,03%	0,26%	0,00%	96,85%
Fine Particulate Matter Formation	0,55%	5,72%	1,22%	0,08%	0,06%	3,17%	0,05%	4,33%	0,20%	0,96%	0,02%	83,63%
Fossil depletion	3,74%	33,14%	7,84%	2,16%	0,39%	17,56%	0,30%	26,80%	1,17%	6,67%	0,23%	0,00%
Freshwater Consumption	2,95%	44,52%	3,92%	0,04%	0,31%	20,73%	0,25%	20,14%	0,94%	6,07%	0,12%	0,00%
Freshwater ecotoxicity	3,03%	35,44%	3,53%	0,03%	0,37%	17,84%	0,32%	35,38%	1,35%	2,47%	0,07%	0,19%
Freshwater Eutrophication	2,68%	38,67%	4,92%	0,05%	0,40%	18,58%	0,31%	29,17%	1,30%	3,80%	0,13%	0,00%
Human toxicity, cancer	0,17%	54,70%	0,23%	0,01%	0,59%	21,81%	0,50%	18,12%	2,23%	1,54%	0,06%	0,03%
Human toxicity, non-cancer	3,19%	27,27%	5,45%	0,07%	0,29%	16,67%	0,24%	30,15%	0,95%	3,97%	0,09%	11,67%
Ionizing Radiation	4,47%	40,08%	4,68%	0,43%	0,43%	19,41%	0,36%	22,91%	1,46%	5,64%	0,13%	0,00%
Land use	5,60%	27,06%	10,48%	0,11%	0,31%	16,90%	0,27%	25,90%	0,83%	12,42%	0,13%	0,00%
Marine ecotoxicity	2,80%	37,12%	3,33%	0,05%	0,39%	18,19%	0,33%	33,53%	1,43%	2,59%	0,07%	0,19%
Marine Eutrophication	1,09%	47,14%	1,91%	0,04%	0,47%	19,93%	0,40%	18,72%	1,73%	3,00%	0,09%	5,48%
Metal depletion	1,54%	40,54%	2,41%	0,02%	0,49%	18,01%	0,37%	32,48%	1,61%	2,41%	0,13%	0,00%
Photochemical Ozone Formation, Ecosystems	3,70%	27,75%	12,63%	0,43%	0,36%	16,35%	0,29%	27,90%	1,00%	9,44%	0,16%	0,00%
Photochemical Ozone Formation, Human Health	3,80%	27,47%	13,04%	0,43%	0,35%	16,37%	0,29%	27,61%	0,99%	9,49%	0,15%	0,00%
Stratospheric Ozone Depletion	4,59%	30,46%	7,86%	1,61%	0,32%	16,04%	0,26%	21,92%	0,97%	15,75%	0,22%	0,00%
Terrestrial Acidification	0,01%	0,10%	0,03%	0,00%	0,00%	0,07%	0,00%	0,08%	0,00%	0,02%	0,00%	99,66%
Terrestrial ecotoxicity	4,24%	32,04%	7,29%	0,23%	0,40%	17,80%	0,35%	26,89%	1,26%	9,37%	0,11%	0,00%

3.3 Comparison of results with other studies

It is of interest to conduct a comparative assessment of the available LCA studies in order to gain more information about how the contribution of GWP differs between the geothermal fields. Therefore, several LCA studies of geothermal energy are addressed to compare the contribution and variability associated with emissions from electricity generation with flash technology. As indicated in Table 3.3, each LCA study produces different GWP results.

Table 3.3 Comparison of GWP results of High-Temperature Flash technology

Reference	Year	Location	Lifetime (years)	Capacity (MW)	Total GWP (g CO_2 eq/kWh)
Karlsdottir et al. (2017 LCI)	2020	Iceland	30	303	11,4
Kjeld et al.	2021	Iceland	40	90	13,8
Hondo	2005	Japan	30	55	15
Karlsdottir et al. (2012 LCI)	2020	Iceland	30	303	15,9
Sondakh	**2022**	**Indonesia**	**30**	**55**	**43,3**
Marchand et al.	2015	Guadeloupe	30	16	47
Sullivan et al.	2014	United States	30	50	109
Sullivan et al.	2013	United States	30	10	126,1
Skone et al.	2012	United States	25	50	245,2
Basosi et al.	2020	Italy	30	20	477

This research also looked to Hondo (2005), (Skone et al., 2012), Sullivan & Wang (2013), Sullivan et al., (2014), and Marchand et al., (2015), all of whom reported on operational and construction emissions from a geothermal power plant (Figure 3.6). The quantity of GHG construction stage in Sondakh (2022) shown in this table is the sum of the drilling and construction stages.

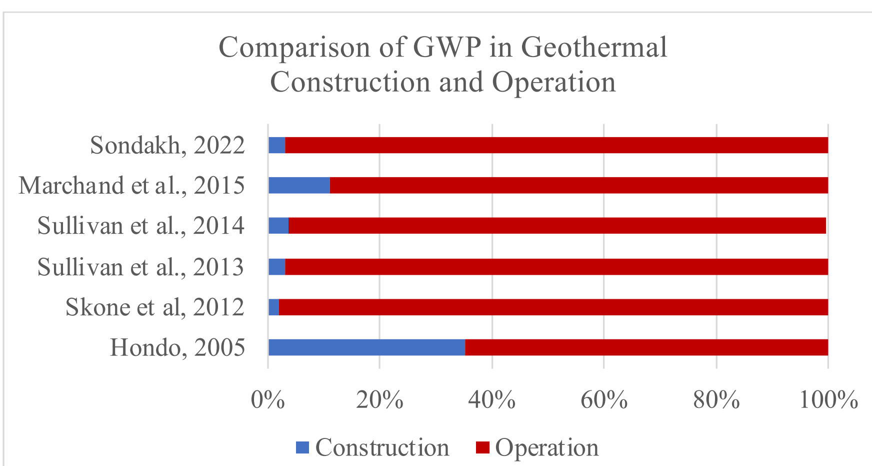

Figure 3.6 - GWP from the construction and operation stage of High Temperature Flash technology

A comparison is made between LCA of GHG from other types of electricity production systems in order to determine the features of non-renewable and renewable energy systems, such as, coal power, natural gas combined-cycle power, nuclear power, concentrated solar power, photovoltaic (PV), wind power (according to UNECE, 2021) and geothermal power (according to a literature review conducted for this study) (Figure 3.7).

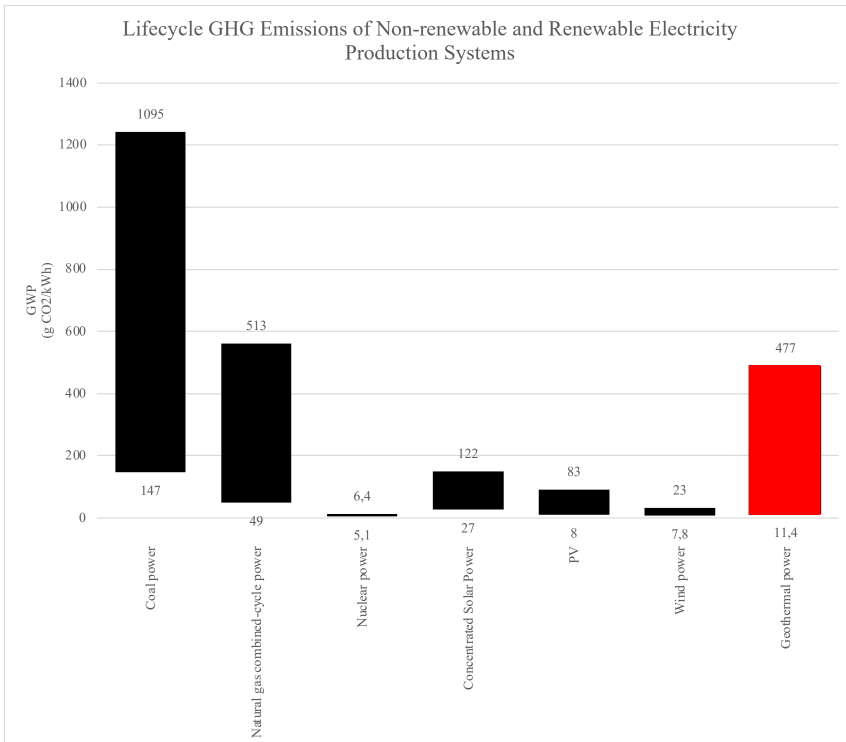

Figure 3.7 - Comparison of Lifecycle GHG Emissions of non-renewable and renewable electricity production systems

Chapter 4

Discussion

This research aims to identify the environmental impacts of the geothermal drilling, construction, and operation processes at the Patuha Geothermal Field. This chapter will briefly discuss the results of the LCIA. According to the findings, the environmental impact assessments have indicated that climate change has the most significant impact on the Patuha geothermal power plant. Environmentalists and world leaders have been discussing the greenhouse effect for the past few decades, and global warming is a problem closely connected to this research. Furthermore, this chapter will compare the LCA results from this research to comparable LCA outcomes from other studies.

This research intends to discover strategies to reduce the environmental impact of geothermal energy production in the Patuha Geothermal Field. Therefore, numerous possible improvements that can be made to the Patuha geothermal power plant will be discussed in this chapter.

4.1 Life Cycle Interpretation

Based on the assessment results conducted using the ReCiPe 2016 method, the causes of each environmental impact will be discussed in this chapter. Each of the three figures in Figure 3.2, 3.3, and 3.4 illustrates a graphic that describes the contribution made by each process in further detail.

4.1.1 Climate change

Climate change (excluding biogenic carbon) and climate change (including biogenic carbon) in this study reveals a relatively high impact of CO_2 emissions compared to other impacts, with each having an amount of 43,3 g CO_2 eq/kWh which illustrates the contribution of GHG emissions from the drilling, construction, and operation stages. Climate change including biogenic carbon refers to CO_2 emitted as a result of the burning or decomposition of organic matter, especially biomass and its derivatives, for example, including carbon dioxide released during the combustion of wood and biogas created during decomposition. Excluding biogenic carbon indicates that the CO_2 absorbed by plants is not included in the calculation (Kupfer, 2021).

The drilling stage generated CO_2 from all the unit processes, such as casing, cementing, mud drilling, and diesel. The casing is the highest contributor to climate change because this process uses a considerable amount of steel, and the energy used for steel production comes from fossil energy resources. Portland cement used for the cementing job is also the cause of climate change due to the high release of CO_2 during cement production.

Other materials, such as potassium chloride, potassium hydroxide, and bentonite contribute minimal climate change for the mud drilling job.

The materials used in the wellhead, pipelines, demister, turbine and generator, condenser, cooling tower, and reinjection pond for the construction stage result in GHG emissions during their production stages. Material inputs that have the highest impact on climate change include steel for machinery, steel for foundations, and concrete. Other materials that impact the GWP results include rock wool, aluminium cladding, copper, aluminium, FRP, and plastic, but these materials have no substantial impact on the climate change results.

In Patuha operation, high operational emissions are caused by the release of NCG in the form of CO_2. The CO_2 is released after the geothermal fluid passes through the turbine, from the cooling tower to the atmosphere. When carbon is in the air, it contributes to climate change, which will become a problem if the GHG is too high. Geothermal fluid comes from a high-temperature geothermal reservoir, and accordingly contains NCG, which flows throughout the cycle of the geothermal power plant, with CO_2 representing the most abundant NCG in the fluid. The majority of the CO_2 in the fluid comes from the source rock of the geothermal system, igneous rock, containing carbonates formed due to chemical reactions between the rocks and the fluids in the system (Fridriksson et al., 2016).

In addition to contributing to climate change, an increase in the concentration of CO_2 will impact the gas extraction system. If it is overloaded, it results in a drop in the condenser vacuum, which results in a significant reduction in the turbine output. Therefore, accurate measurement of NCG content in the geothermal fluid is a vital design parameter to consider for geothermal power plant operation (Fridriksson et al., 2016).

4.1.2 Fine particulate matter formation

Fine particulate matter formation in Patuha is mainly caused by NH_3 present in NCG. The majority of the NH_3 content in the geothermal fluid is discharged into the atmosphere, with only a little portion being injected. Because the released NH_3 could be damaging to the environment, it would be necessary to minimize NH_3 concentrations in order to avoid toxic effects from occurring.

At the drilling stage, most of the impact is derived from the steel utilized in the casing. Other materials that contribute to the fine particulate matter formation include portland cement used in cementing, potassium chloride and potassium hydroxide used in mud drilling, and, to a smaller extent, diesel. Water and bentonite are materials that have minor impact at the drilling stage.

Compared to drilling, the overall impact of the construction stage is slightly higher than the drilling stage. The steel used for turbine and generator foundations makes up most of the total impact, followed by steel used for pipelines, wellheads, turbine and generator cooling towers, condensers, and steel used for cooling tower foundations. Additionally, concrete used in cooling towers and copper used in turbines and generators substantially influences the fine particulate matter formation in the atmosphere. The minor contributor is concrete for the wellhead, demister, and reinjection pond, as well as materials used for reinjection ponds, such as plastic, FRP, steel for the foundation and concrete, and aluminium for the turbine and generator.

4.1.3 Terrestrial acidification

The drilling stage, the construction stage, and the operational stage are the three stages that contribute to terrestrial acidification, with the operation stage having the most impact. The high level of terrestrial acidification observed at the operation stage are produced by the H_2S and NH_3 contained in the NCG, which is released into the atmosphere along with CO_2, resulting in the operation stage having an impact on both climate change and terrestrial acidification. Although H_2S is the most major contributor to terrestrial acidification, according to government guidelines addressing emission quality standards, H_2S levels in the Patuha operation are currently within the quality standard for the operation. Rahayudin et al., (2020) stated that the H_2S values are determined by the reaction of the H_2S gas with the reservoir wall rock. When H_2S gas is released into the atmosphere, it undergoes a variety of chemical reactions depend on the surrounding environment. As a result of its instability, H_2S can be oxidized to sulfur dioxide gas or sulfuric acid (in the case of precipitation) under specific circumstances, and subsequently stored in the ecosystem (Mutia, 2016).

The impact of terrestrial acidification from the construction stage comes mainly from the steel for the casing. Portland cement for cementing also has an impact on this impact category. Additional considerations include the influence of steel pipe manufacture for the casing. Water and potassium chloride, which are used in the cementing job, are two more sources that contribute in insignificant amounts. There is a minor impact on terrestrial acidification from any materials employed in mud drilling mixtures. These ingredients include bentonite, potassium hydroxide, and potassium chloride. Diesel has a minimal impact on this category of environmental impact.

At the construction stage, the steel used in pipelines, turbines, and generators and steel used in the foundation contribute to terrestrial acidification. A considerable contribution to terrestrial acidification is also made through the use of rock wool for pipelines, concrete for cooling towers, and turbines and generators. Other materials, such as aluminium for pipeline insulation, aluminium and copper for turbines and generators, and plastic and FRP for reinjection ponds, have no substantial impact on the environment.

4.1.4 Other impacts

The drilling, construction, and operation stages are responsible for freshwater ecotoxicity, human toxicity (cancer), human toxicity (non-cancer), marine ecotoxicity, and marine eutrophication. At the drilling stage, the use of steel and steel pipe manufacturing for casing are the primary causes of these consequences. Using portland cement and potassium chloride for cementing and potassium chloride and potassium hydroxide for mud drilling are two further factors that contribute to this environmental impact. In addition, other materials, such as water for cementing, bentonite for mud drilling, and diesel, have only a negligible impact on these consequences.

At the construction stage, these impacts are generated mainly by the use of steel, particularly in pipelines and steel (foundation) for turbines and generators. Copper also contributes quite significantly. The use of rock wool for pipes impacts the extent of these problems as well. The usage of concrete, FRP, aluminium cladding, steel pipe manufacturing, plastic and aluminium are also potential sources of the impacts. However, the influence of these materials is not considerable. The overall mercury and arsenic concentrations measured from the reinjection pond are the primary determinants of the aforementioned consequences at the operation stage. However, because the mercury and arsenic concentrations are very low, and are being injected into injection wells in a closed system, it is unlikely that it will interact with nearby groundwater. It is, therefore, possible to omit the negative impacts of mercury and arsenic.

Fossil depletion, freshwater consumption, freshwater eutrophication, ionizing radiation, land use, metal depletion, photochemical ozone formation (ecosystems), photochemical ozone depletion (human health), stratospheric ozone depletion, and terrestrial ecotoxicity are caused by the drilling and construction stages of the project. It should be noted that the operation stage has no contribution to these impacts. Overall, a substantial amount of steel is utilized at these two stages, resulting in a high number of impacts. In addition, the use of Portland cement and potassium chloride in cementing and the use of potassium hydroxide and potassium chloride in mud drilling all contribute to each impact. Water for cementing, bentonite for mud drilling, and drilling fuel are the components that contribute the least to the total contribution of all other materials combined. The use of steel and concrete at the construction stage, in general, has the highest impacts on the environmental impacts, followed by the use of rock wool in the construction stage. Materials such as FRP, aluminium cladding, and plastics have minor impact.

4.2 Midpoint hotspot analysis

A particularly successful strategy for identifying the most significant sources of environmental problems is to conduct in-depth analyses of hotspots within the Patuha geothermal power plant. A hotspot is a point at which a system process has the most significant impact. The corporation may be able to take preventive action based on the identified hotspots to minimize or avoid severe environmental problems associated with the Patuha geothermal power plant.

As a result of the findings, it can be concluded that the operation stage of the Patuha geothermal power plant is a hotspot, with emissions from the cooling tower being the main factor. Cooling towers release a wide range of GHGs, including CO_2, H_2S, and NH_3, which significantly impact the categories of climate change, fine particulate matter formation, and terrestrial acidification. As shown in Table 3.2, the moderate percentage represents the casing, pipelines, and turbine and generator, all of which used a substantial quantity of steel in the drilling and construction stages. Compared to the unit processes listed above, other processes such as the mud drilling, cementing, drilling fuel, wellhead, demister, condenser, cooling tower, and reinjection pond did not significantly contribute to the overall impact results.

Based on the midpoint hotspot analysis by materials, first, steel is the highest contributor contributing to all environmental impacts, contributing most to human toxicity (cancer), metal depletion, and marine eutrophication. Secondly, the steel utilized for the foundation makes a significant contribution, specifically reinforcing steel, responsible for metal depletion, freshwater eutrophication, and fossil depletion. Concrete follows as a material that significantly impacts land use, photochemical ozone formation (human health), and photochemical ozone formation (ecosystems).

This LCA research demonstrates in detail the contribution of materials for the drilling stage, construction stage, and contribution of output from the operation stage, which have a considerable impact on GWP. Appendix D1 shows the GWP contribution of each material in each unit process for the drilling and construction stage. The materials that have the most significant contribution are steel (35,41%), steel for foundation (17,59%), and concrete (15,49%). Steel is the most significant contribution to GWP due to its use in the casing, steam collection, turbine, and generator, while wellheads, condensers, cooling towers, and reinjection ponds utilize only small amounts.

Hu et al., (2014) stated that the high GWP of steel is a result of the blast furnace process in steel manufacturing operations. Since CO_2 emissions from steel manufacturing are a major contributor to GWP, reducing energy consumption is a top priority for environmental protection. A large reduction in CO_2 emissions of steel production can be achieved by using an Electric Arc Furnaces (Hosny et al., 2016). The high GWP of concrete is due to the release of CO_2 from the limestone calcination process to produce cement clinker and the burning of fossil fuels used to reach the required temperature (1400-1500°C) in the kiln (Marinković, 2013). The environmental impact of the concrete industry can be minimised through resource productivity, which can be achieved by conserving resources and energy throughout the concrete-making process, as well as by improving the durability of concrete products (Mehta, 2001).

Appendix D2 illustrates a comparison between the output in the form of emissions to air and emissions to freshwater during the operation stage. It also illustrates the influence of the operation stage output on GWP in greater detail. As previously mentioned, the operation stage is the most significant contributor to climate change among all unit processes, accounting for more than half of the total amount of climate change generated by this unit process. Based on the data on the most contributing output to GWP presented in Appendix D2, it can be concluded that CO_2 emissions into the atmosphere are the primary cause of climate change, which ultimately results in global warming.

4.3 Comparison of results with other studies

The GWP, which represents total GHG emissions, is the most often reported environmental impact category in LCA studies. GHG has risen to the top of the research priority list as a result of the adverse effects of CO_2 emissions climate change. Based on a survey involving emissions from power plants that represent more than 50% of the geothermal capacity installed worldwide in 2001, the global average estimate for operational GHG emissions from geothermal power production was calculated to be 122 g CO_2/kWh (Fridriksson et al., 2016).

The GWP at the Patuha geothermal power plant is found to be lower than the global average for geothermal power. The Hellisheiði geothermal power plant has the lowest impact among all the geothermal power plants listed on the table. In contrast, the Bouillante geothermal power plant is ten times lower than the Chiusdino geothermal power plant. The results are significantly different because of the differences in the quality of the inventory data and the method used for the impact assessment, as well as differences in the characteristics of the geothermal field (temperature, rock properties, and geothermal fluid), types of geothermal utilization, the number of wells, construction, technology, power generation capacity, and capacity factor. Given that geothermal energy development is heavily dependent on local conditions, it is possible that in situ geologic characteristics of a geothermal field will influence the outcomes of the LCA. For example, the emission can be approximated at 790 g CO_2/kWh for power plants located in carbonate rocks, while in volcanic rocks, the emission is 128 g CO_2/kWh (Fridriksson et al., 2016). In addition, due to significant variations in the quality of geothermal fluid between geothermal formations, the amount of CO_2 in the geothermal fluid is highly variable from one geothermal formation to another (Skone et al., 2012).

Carbon footprints in different countries are also contributing to variations in LCA results. Thus it is crucial to understand the factors used in each country, particularly for this study in Indonesia. In addition, it would be necessary to ensure a consistent set of system parameters in order to make a fair comparison of emissions reported from LCA studies (Eberle et al., 2017; Karlsdottir, 2020).

A comparison between studies on emissions from construction and operation emissions in flash power generation technology is shown in Figure 3.6. Overall, the operation stage has higher GWP than the construction stage. Another comparison is between LCA of GHG from other types of electricity production systems as shown in Figure 3.7. According to UNECE (2021), on a global average, the highest contributor among other electricity generation systems is coal power. Without Carbon Capture Storage (CCS), a low of 753 g of CO2 eq/kWh and a maximum of 1095 g of CO_2 eq/kWh are recorded for coal power. If the CCS is installed, these emissions can be reduced to 149–470 g CO_2 eq/kWh. The life cycle emissions of a natural gas combined cycle plant are 403–513 g CO_2 eq/kWh and can be reduced to 92–221 g CO_2 eq/kWh with CCS. As a result of the high energy density of nuclear fuel and the absence of combustion during the electricity generating process, nuclear power emits very low levels of CO_2 (5.1–6.4 g CO_2 eq/kWh), with the majority of the emissions occurring during the extraction, conversion, enrichment of uranium, and fuel fabrication processes.

Figure 3.7 shows that renewable energy emits fewer emissions than non-renewable energy. Hydropower has the potential to produce very low GHG emissions, which may be somewhat countered by the sedimentation of organic materials in reservoirs, which releases (biogenic) GHG. The lowest GHG emissions from hydropower is 6 g CO_2 eq/kWh and the highest is 147 g CO_2 eq/kWh. Assumedly, transportation for dam construction elements could occur over thousands of miles, resulting in a significant proportion of hydropower emission from transport and infrastructure. Concentrated Solar Power (CSP) emits between 27 and 122 g CO_2 eq/kWh due to local conditions, while PV emits between 8 and 83 g CO_2 eq/kWh. Onshore wind turbines emit between 7,8 and 16 g CO_2 eq/kWh of greenhouse gases, while offshore turbines emit between 12 and 23 g CO_2 eq/kWh of greenhouse gases. In comparison to other renewable energy technologies, solar PV and wind have low emissions, with the majority of GHG originating from infrastructure (UNECE, 2021).

Geothermal power (high-temperature flash technology) has the most variability of GHG emissions among other renewable energy sources, ranging from 11,4 to 477 g CO2 eq/kWh, with the majority of geothermal GHG emissions occurring during operation stage (Table 3.3).

4.4 Alternative improvements

4.4.1 CO_2 reduction

Using CO_2 capture technology to reduce emissions from the power plant is an important step forward in the fight against global warming. This method prevents CO_2 from being emitted into the atmosphere, hence limiting the impact of climate change on the environment. A project called CarbFix was initiated in Iceland in 2007. The CarbFix project created methods and technologies to store CO_2 and CO_2-H_2S gas combinations in basalts permanently. It is possible to achieve significant benefits by injecting CO_2 into young basaltic formations. These benefits include a high storage potential as well permanent storage because the injected CO_2 reacts with metals present in the basalts, resulting in the formation of highly stable carbonate minerals (Sigfússon et al., 2018).

The Hellisheidi area has served as the site for implementing this project. After being captured at the power plant, the gases are dissolved in condensate before being injected into a well. The depth of the well is approximately 700 m. The gases react with the basaltic bedrock in the well, resulting in the formation of stable minerals that can be stored in safe and secure storage (Sigfússon et al., 2018).

Each year since the start of the project, the amount of gases injected has been steadily growing. For example, CarbFix2 project had more than 50% injected carbon in the first phase of injection in June to July 2016, then the percentage of injection increased to more than 60% in the second phase in July to December 2017 (Clark et al., 2020). According to Karlsdottir et al., (2020), carbon capture and storage (CCS) by reinjection of CO_2 using the CarbFix process developed at Hellisheidi has resulted in a reduction in the GWP from 15,9 g CO_2eq/kWh to 11,4 g CO_2eq/kWh for electricity. The Hellisheidi plant is expected to have a near-zero carbon footprint by 2025 by increasing the CO_2 capture to 95% of the CO_2 concentration of the fluid with the Carbfix technology (Carbfix, 2021).

4.4.2 H_2S and Hg reduction

Scientists developed the SulFix method for capturing H_2S in the ground. The gas injection was carried out at the SulFix 1 pilot injection location using comparable procedures and technology to those used at the Carbfix pilot injection site. Unlike Carbfix, the gas mixture in SulFix was dissolved on the surface before the injection rather than thoroughly dissolved as in Carbfix. 3350 tons of H_2S had been injected by the end of 2015 (Gunnlaugsson, 2016).

The AMIS® emissions treatment system is another option for lowering H_2S and Hg levels. The NCG can be routed to the AMIS® system for H_2S and Hg reduction instead of being released into the atmosphere. The three fundamental steps of the AMIS® process are removal of mercury by chemical absorption, selective catalytic oxidation of hydrogen sulphide to SO_2, and SO_2 scrubbing by geothermal water (Baldacci et al., 2005). Due to its extremely high abatement efficiencies (more than 99% for both pollutants), the AMIS® method is capable of achieving total power plant emission reductions in the 95-99% Hg and 75-85% for H_2S. The overall reduction is calculated in relation to power plant emissions that are not controlled and are not handled by the AMIS® system. This is an environmentally friendly method because it typically does not necessitate the use of chemicals and does not generate sulphur-based by-products that need to be disposed of or recycled after being processed (Baldacci et al., 2005).

The AMIS® emissions treatment system is installed at the Chiusdino 1 geothermal power station in Italy. With a measured effectiveness of 99,8%, this system eliminates H_2S, and it removes mercury with a measured efficiency of 82,2% (Basosi et al., 2020).

4.5 Contribution to SDG

GeoDipa is committed to environmental sustainability, and as part of that commitment, GeoDipa strives to guarantee that every activity has the maximum possible positive impact on the environment. GeoDipa is mandated to monitor the environmental impact of its operations in accordance with Indonesian environmental regulations. As a consequence, the corporation has committed to undertake regular environmental management and monitoring in the area of the Patuha Geothermal Field on a three-monthly basis. In order to reduce the environmental impact of its operations, GeoDipa has taken a number of steps to reduce the impact of its operations on the environment and has implemented environmental conservation measures, such as water management and monitoring, air management and monitoring, waste treatment, noise management, H_2S monitoring in well and plant area, landslide management, biodiversity management, and environmental complaints mechanism.

The actions for the environment are crucial in achieving the United Nations Sustainable Development Goals. The results of this LCA should assist geothermal companies in solving environmental concerns and making contributions to various Sustainable Development Goals, as described in Table 4.3 (UNDP, 2015).

Table 4.1 Contribution to SDGs (UNDP, 2015)

Goal no.	Sustainable Development Goals
Goal 6	Ensure availability and sustainable management of water and sanitation for all
Goal 7	Ensure access to affordable, reliable, sustainable and modern energy for all
Goal 9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
Goal 11	Make cities and human settlements inclusive, safe, resilient and sustainable
Goal 12	Ensure sustainable consumption and production patterns
Goal 13	Take urgent action to combat climate change and its impacts

4.6 Uncertainty

According to (Hauschild et al., 2018), uncertainty is the probability or confidence for a certain event to occur. In order to improve the reliability and credibility of LCA results, it is vital to address uncertainty. There are many techniques applied to treat uncertainty in LCA, however there is no unified approach to communicate this information in LCA studies. It is essential to be clear about the uncertainty in the various stages of LCA and the impact it has on the final outcomes (Igos et al., 2019).

According to (Hauschild et al., 2018), there are several uncertainty classifications, such as variability, parameter uncertainty, model uncertainty, uncertainty due to choices, relevance uncertainty, epistemological uncertainty, and mistakes. Uncertainty relates to accuracy and precision, therefore, the LCI subchapter of this research explains parameter uncertainty as a result of a lack of data or information. The LCI displays the accuracy of each inventory data to distinguish between inventory with reliable data documentation sources, inventory that requires data extrapolation due to minor data gaps, and inventory that requires considerable data estimations and/or calculations due to significant data gaps.

Uncertainty due to choices arises in the model. The selection of impact assessment methods could affect the LCA results because each impact category at each impact assessment method has different unit and characterization factors. For example, the unit differences of acidification, eutrophication, ecotoxicity, and human toxicity impacts in CML2001, EDIP 2003, ReCiPe 2016, and TRACI 2.1 methods are shown in Table 4.2.

GWP is measured in the same unit, with a different characterisation factor across most impact methods (Hauschild et al., 2018). In contrast to other methodologies, the ReCiPe 2016 method defines GWP as Climate Change. The uncertainty of GWP can be seen in Table 4.3. As a result of the uncertainty, the results for the construction stage range from

0,6967 g CO_2 eq/kWh to 0,7153 g CO_2 eq/kWh, and for the drilling stage range from 0,6335 g CO_2 eq/kWh to 0,6505 g CO_2 eq/kWh for. The TRACI 2.1 method produced the lowest GWP, whereas the ReCiPe 2016 method produced the highest GWP. The findings for the operating stage are consistent across all impact approaches since the GaBi program will produce impact results that are equal to the input data, particularly CO_2.

Table 4.2 Unit differences of impact methods

Impact Categories	CML2001	EDIP 2003	ReCiPe 2016	TRACI 2.1
Acidification	kg SO_2 eq. (Acidification Potential)	m^2 UES (Acidification Potential)	kg SO_2 eq. (Terrestrial Acidification)	kg SO_2 eq. (Acidification)
Eutrophication	kg Phospate eq. (Eutrophication Potential)	kg NO_3 eq. (Aquatic Eutrophication) m2 UES (Terrestrial Eutrophication)	kg P eq. (Freshwater Eutrophication) kg N eq. (Marine Eutrophication)	kg N eq. (Eutrophication)
Ecotoxicity	kg DCB eq. (Freshwater Aquatic Ecotoxicity Potential And Marine Aquatic Ecotoxicity Potential)	-	kg 1,4-DB eq. (Freshwater Ecotoxicity and Terrestrial Ecotoxicity)	CTUe (Ecotoxicity)
Human Toxicity	kg DCB eq. (Human Toxicity Potential)	-	kg 1,4-DB eq. (Cancer and non-cancer)	CTUh (Cancer and non-cancer)

Table 4.3 GWP of the Patuha plant calculated with different impact methods

Methodology	Construction ($g\ CO_2$ eq/kWh)	Drilling ($g\ CO_2$ eq/kWh)	Operation ($g\ CO_2$ eq/kWh)
CML2001 - Aug. 2016, Global Warming Potential (GWP 100 years)	0,7024	0,6402	41,9396
CML2001 - Aug, 2016, Global Warming Potential (GWP 100 years), excl biogenic carbon	0,7007	0,6368	41,9396
EDIP 2003, Global warming	0,7086	0,6447	41,9396
ReCiPe 2016 v1.1 Midpoint (H) - Climate change, default, excl biogenic carbon	0,7136	0,6471	41,9396
ReCiPe 2016 v1.1 Midpoint (H) - Climate change, incl biogenic carbon	0,7153	0,6505	41,9396
TRACI 2.1, Global Warming Air, excl. biogenic carbon	0,6967	0,6335	41,9396
TRACI 2.1, Global Warming Air, incl. biogenic carbon	0,6984	0,6369	41,9396

The sensitivity of a model is the degree to which a change in an input parameter or a choice affects the model result (Hauschild et al., 2018). In this research, sensitivity analysis is performed on a key parameter of power plant production, which is capacity factor. Arvesen & Hertwich (2011) and Hondo (2005) conducted the sensitivity analysis based on capacity factor, which is one of important source of uncertainty. The capacity factor used in this research is 92% and the capacity factor that is addressed in the sensitivity analysis is 100%. This number is chosen to investigate the effects of capacity factor on the LCIA. As shown in Table 4.4, the capacity factor has an influence on the impact categories. The lower the capacity factor, the greater the impact.

Table 4.4 Effects of capacity factor on LCIA

Geothermal Development Stages	Drilling		Construction		Operation	
Capacity Factor	**100%**	**92%**	**100%**	**92%**	**100%**	**92%**
Climate change, default, excl biogenic carbon [g CO2 eq/kWh]	0,60	0,65	0,66	0,71	38,58	41,94
Climate change, incl biogenic carbon [g CO2 eq/kWh]	0,60	0,65	0,66	0,72	38,58	41,94
Fine particulate matter formation [g PM2.5 eq/kWh]	9,E-04	1,E-03	1,E-03	1,E-03	0,01	0,01
Fossil depletion [g oil eq/kWh]	0,16	0,17	0,18	0,20	-	-
Freshwater consumption [m3/kWh]	9,E-06	9,E-06	8,E-06	9,E-06	-	-
Freshwater ecotoxicity [g 1,4 DB eq/kWh]	0,03	0,03	0,04	0,05	0,00	0,00
Freshwater eutrophication [g P eq/kWh]	2,E-04	3,E-04	3,E-04	3,E-04	-	-
Human toxicity, cancer [g 1,4-DB eq/kWh]	1,47	1,60	1,20	1,30	0,00	0,00
Human toxicity, non-cancer [g 1,4-DB eq/kWh]	0,60	0,65	0,87	0,94	0,19	0,21
Ionizing radiation [kBq Co-60 eq. to air/kWh]	2,E-05	3,E-05	2,E-05	3,E-05	-	-
Land use [Annual crop eq.·y/kWh]	2,E-05	2,E-05	2,E-05	2,E-05	-	-
Marine ecotoxicity [g 1,4-DB eq/kWh]	0,04	0,05	0,06	0,06	2,E-04	2,E-04
Marine eutrophication [g N eq/kWh]	5,E-05	5,E-05	4,E-05	4,E-05	5,E-06	5,E-06
Metal depletion [g Cu eq/kWh]	0,01	0,01	0,02	0,02	-	-
Photochemical ozone formation, ecosystems [g NOx eq/kWh]	1,E-03	2,E-03	2,E-03	2,E-03	-	-
Photochemical ozone formation, human health [g NOx eq/kWh]	1,E-03	2,E-03	2,E-03	2,E-03	-	-
Stratospheric ozone depletion [g CFC-11 eq/kWh]	2,E-07	2,E-07	2,E-07	2,E-07	-	-
Terrestrial acidification [g SO2 eq/kWh]	2,E-03	2,E-03	2,E-03	2,E-03	0,08	0,09
Terrestrial ecotoxicity [g 1,4-DB eq/kWh]	1,76	1,91	2,26	2,45	-	-

The influence of the amount of steel and CO2 on the LCI is the next parameter that is used to determine sensitivity. Figure 4.1 provides an illustration of climate change (excluding biogenic carbon). It can be concluded therefore that the quantity on the LCI has an effect on the results of the LCIA, with the higher the quantity on the LCI resulting in a higher impact value.

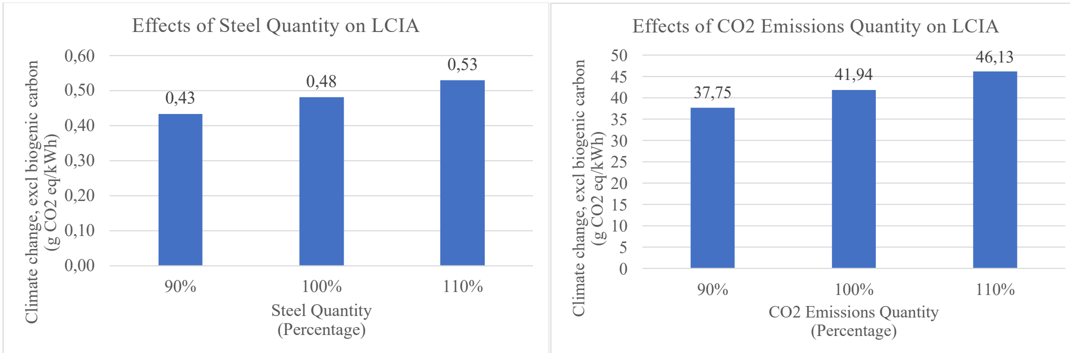

Figure 4.1 - Effects of LCI quantity on LCIA

Chapter 5

Conclusion

In addition to being a clean and renewable energy source, geothermal energy is also environmentally friendly. Nevertheless, some GHGs emitted by geothermal power facilities have an adverse impact on the surrounding environment. CO_2, the most abundant GHG, is responsible for most of these emissions, contributing to climate change. The drilling, construction, and operation stages of the Patuha geothermal power plant are responsible for 43,3 g CO_2 eq/kWh. Among the contributing stages, the most significant is the operation stage, which accounts for 41,94 g CO_2 eq/kWh and is caused by the release of NCG in the form of CO_2 during operation. When CO_2 levels in the atmosphere rise above a certain threshold, climate change can become an issue. The majority of CO_2 in the fluid comes from the source rock of the geothermal system. The remaining significant contributor to climate change is the usage of materials, such as steel for machinery and steel for foundations, as well as the production of concrete.

Fine particulate matter formation in the Patuha geothermal power plant is mostly caused by NH_3 contained in NCG, while terrestrial acidification is caused by H_2S. The NCGs are released into the atmosphere through the cooling tower during the operation stage. The drilling and construction stages contribute less than the operation stage. At the drilling stage, most of the impact is derived from the steel used in the casing, while the most of the impact from the construction stage is derived from the steel used for turbine and generator foundations, followed by steel used for pipelines, wellheads, turbine and generator cooling towers, condensers, and steel used for cooling tower foundations.

Freshwater ecotoxicity, human toxicity (cancer), human toxicity (non-cancer), marine ecotoxicity, and marine eutrophication are all caused by the drilling, construction, and operation stages. The usage of steel and steel pipe manufacture for casing during the drilling stage are the principal sources of these impacts. The key determinants of the aforementioned impacts during the operation stage are the total mercury and arsenic concentrations recorded from the reinjection pond. Because the mercury and arsenic are injected into injection wells in a closed system, they are unlikely to interact with groundwater. As a result, the detrimental effects of mercury and arsenic can be avoided.

The drilling and construction stages of the project are responsible for fossil depletion, freshwater consumption, freshwater eutrophication, ionizing radiation, land use, metal depletion, photochemical ozone formation (ecosystems), photochemical ozone depletion (human health), stratospheric ozone depletion, and terrestrial ecotoxicity. These two stages use a significant amount of steel, resulting in a high number of impacts.

This research involves a midpoint hotspot analysis by unit processes and materials from the drilling, construction, and operation stages. The results of the midpoint hotspot analysis by unit processes indicate that the operation stage of the Patuha geothermal power plant is the main hotspot, with emissions from the cooling tower being the primary contributor. Cooling towers emit a diverse variety of GHGs originated from the geothermal steam, including CO_2, H_2S, and NH_3, which have important consequences for the impact categories of climate change, fine particulate matter formation, and terrestrial acidification. Casing, pipelines, and turbine and generator are identified as other main environmental hotspots by unit processes in the Patuha geothermal power plant. For the midpoint hotspot by materials, it was identified that steel, steel for the foundation (reinforcing steel), and concrete are the main environmental hotspots of the drilling and construction stages in the Patuha geothermal power plant.

When the GWP of the Patuha geothermal power plant is compared to the average GWP of the global geothermal power plants, it is discovered that the GWP of the Patuha geothermal power plant is lower than many other geothermal power plants. The global average is 122 g CO_2 eq/kWh, while Patuha is 43,3 g CO_2 eq/kWh. When compared to other forms of energy, notably non-renewable sources such as coal and natural gas, the usage of renewable energy, particularly geothermal energy, results in lower GHG emissions than these other sources. This is primarily owing to the fact that the vast majority of geothermal energy derives energy from geothermal reservoirs that emit very low amounts of greenhouse gases, as opposed to other energy sources.

The alternative improvements found for the Patuha geothermal power plant are Carbfix, SulFix, and AMIS® emissions treatment systems. Carbfix technology reduces the amount of CO_2 that is released into the atmosphere, hence reducing the negative impact of climate change on the environment. In the fight against global warming, the use of CO_2 capture technology to cut emissions from power plants is a significant step forward in the right direction. The Carbfix project developed methods and technology for permanently storing CO_2 and CO_2-H_2S gas mixtures in basalts, which are now in use worldwide. To deal with H_2S problem, the SulFix technology for trapping H_2S in the ground can be implemented. Other option to consider for lowering H_2S and Hg levels is the AMIS® emissions treatment system is an alternative.

This LCA can be used as an evaluation tool for GeoDipa to analyze environmentally friendly production methods, as well as a source of information for the Indonesian government to assist in the formulation of environmental legislation, particularly in the area of geothermal energy power generation.

Further research is required to develop a more thorough LCI for geothermal power generation, which will allow for more accurate LCA results to be produced. The LCA studies need to look at the exploration phase because of the extensive traveling during the exploration work. As far as material data for the LCI is concerned, it is ideal if the data can be collected directly from the material's supplier in order to improve the accuracy of the data. Furthermore, the impacts of geothermal energy are also not thoroughly established in the LCA study, therefore, a more comprehensive impact analysis for geothermal energy, including seismic event impact, is still needed to be developed.

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Appendix A – Environmental impacts on the drilling stage

Environmental Impacts on the Drilling Stage	Total	Casing		Cementing			Mud Drilling			Drilling fuel
		Steel	Steel pipe manufacture	Water	Portland cement	Potassium chloride	Bentonite	Potassium hydroxide	Potassium chloride	Diesel
Climate change, default, excl biogenic carbon [g CO2 eq/kWh]	**0,6471367**	0,3070468	0,0928180	0,0000114	0,1842817	0,0209206	0,0010531	0,0197328	0,0178598	0,0034125
Climate change, incl biogenic carbon [g CO2 eq/kWh]	**0,6505098**	0,3085036	0,0931600	0,0000114	0,1860748	0,0206729	0,0010705	0,0199415	0,0176484	0,0034265
Fine particulate matter formation [g PM2.5 eq/kWh]	**0,0009794**	0,0006151	0,0001251	0,0000000	0,0001202	0,0000373	0,0000022	0,0000377	0,0000319	0,0000098
Fossil depletion [g oil eq/kWh]	**0,1735129**	0,1014045	0,0212838	0,0000027	0,0213510	0,0076499	0,0003348	0,0069719	0,0065307	0,0079834
Freshwater consumption [m3/kWh]	**0,0000095**	0,0000041	0,0000041	0,0000000	0,0000003	0,0000004	0,0000000	0,0000002	0,0000004	0,0000000
Freshwater ecotoxicity [g 1,4 DB eq/kWh]	**0,0339875**	0,0255159	0,0031422	0,0000002	0,0009853	0,0018675	0,0000434	0,0008131	0,0015943	0,0000255
Freshwater eutrophication [g P eq/kWh]	**0,0002532**	0,0001661	0,0000453	0,0000000	0,0000193	0,0000076	0,0000002	0,0000080	0,0000065	0,0000003
Human toxicity, cancer [g 1,4-DB eq/kWh]	**1,5964078**	1,5093102	0,0752656	0,0000076	0,0032218	0,0035447	0,0001107	0,0017261	0,0030261	0,0001950
Human toxicity, non-cancer [g 1,4-DB eq/kWh]	**0,6470138**	0,4004600	0,0899797	0,0000081	0,0585508	0,0393709	0,0009710	0,0228507	0,0336108	0,0012119
Ionizing radiation [kBq Co-60 eq. to air/kWh]	**0,0000260**	0,0000178	0,0000031	0,0000000	0,0000016	0,0000009	0,0000000	0,0000015	0,0000008	0,0000002
Land use [Annual crop eq.·y/kWh]	**0,0000174**	0,0000078	0,0000031	0,0000000	0,0000026	0,0000016	0,0000001	0,0000007	0,0000014	0,0000000
Marine ecotoxicity [g 1,4-DB eq/kWh]	**0,0478070**	0,0368432	0,0041485	0,0000003	0,0013169	0,0023564	0,0000566	0,0010234	0,0020117	0,0000499
Marine eutrophication [g N eq/kWh]	**0,0000496**	0,0000398	0,0000067	0,0000000	0,0000013	0,0000005	0,0000000	0,0000006	0,0000005	0,0000000
Metal depletion [g Cu eq/kWh]	**0,0147126**	0,0124258	0,0009760	0,0000002	0,0005826	0,0002132	0,0002470	0,0000787	0,0001820	0,0000071
Photochemical ozone formation, ecosystems [g NOx eq/kWh]	**0,0016186**	0,0008472	0,0001618	0,0000000	0,0003733	0,0000860	0,0000070	0,0000541	0,0000734	0,0000157
Photochemical ozone formation, human health [g NOx eq/kWh	**0,0015591**	0,0008025	0,0001548	0,0000000	0,0003700	0,0000845	0,0000068	0,0000534	0,0000721	0,0000148
Stratospheric ozone depletion [g CFC-11 eq/kWh]	**0,0000002**	0,0000001	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000
Terrestrial acidification [g SO2 eq/kWh]	**0,0017609**	0,0009867	0,0002146	0,0000000	0,0003042	0,0000810	0,0000053	0,0000712	0,0000692	0,0000287
Terrestrial ecotoxicity [g 1,4-DB eq/kWh]	**1,9122840**	1,2897657	0,1091648	0,0000395	0,1719416	0,1462004	0,0051595	0,0551219	0,1248109	0,0100796

Appendix B – Environmental impacts on the construction stage

Appendix B1. Environmental impacts on the construction stage

Environmental Impacts on the Construction Stage	**Total**	**Condenser**	**Cooling Tower**				**Demister**		**Pipelines PTH**				
		Steel	**Steel (foundation)**	**Steel**	**Concrete**	**FRP**	**Steel**	**Concrete**	**Rockwool**	**Aluminium cladding**	**Steel**	**Concrete**	**Steel pipe manufacture**
Climate change, default, excl biogenic carbon [g CO2 eq/kWh]	**0,7136425**	0,0131390	0,0050836	0,0065073	0,0898741	0,0118668	0,0029637	0,0008118	0,0335684	0,0020548	0,1199341	0,0349285	0,0362552
Climate change, incl biogenic carbon [g CO2 eq/kWh]	**0,7153487**	0,0132014	0,0050781	0,0065381	0,0905886	0,0115460	0,0029778	0,0008182	0,0332254	0,0020608	0,1205031	0,0352062	0,0363888
Fine particulate matter formation [g PM2.5 eq/kWh]	**0,0011398**	0,0000263	0,0000087	0,0000130	0,0000827	0,0000200	0,0000059	0,0000007	0,0000853	0,0000038	0,0002403	0,0000321	0,0000489
Fossil depletion [g oil eq/kWh]	**0,1966571**	0,0043393	0,0016015	0,0021491	0,0159898	0,0049496	0,0009788	0,0001444	0,0101685	0,0007022	0,0396091	0,0062143	0,0083136
Freshwater consumption [m3/kWh]	**0,0000090**	0,0000002	0,0000001	0,0000001	0,0000008	0,0000001	0,0000000	0,0000000	0,0000003	0,0000000	0,0000016	0,0000003	0,0000016
Freshwater ecotoxicity [g 1,4 DB eq/kWh]	**0,0467334**	0,0010919	0,0001760	0,0005408	0,0009984	0,0002791	0,0002463	0,0000090	0,0027880	0,0000544	0,0099666	0,0003880	0,0012274
Freshwater eutrophication [g P eq/kWh]	**0,0002936**	0,0000071	0,0000023	0,0000035	0,0000117	0,0000032	0,0000016	0,0000001	0,0000137	0,0000008	0,0000649	0,0000045	0,0000177
Human toxicity, cancer [g 1,4-DB eq/kWh]	**1,2993817**	0,0645858	0,0082369	0,0319870	0,0038304	0,0006717	0,0145682	0,0000346	0,0110905	0,0001754	0,5895442	0,0014887	0,0293991
Human toxicity, non-cancer [g 1,4-DB eq/kWh]	**0,9414262**	0,0171363	0,0043789	0,0084870	0,0431601	0,0152960	0,0038653	0,0003898	0,0897642	0,0016651	0,1564217	0,0167737	0,0351465
Ionizing radiation [kBq Co-60 eq. to air/kWh]	**0,0000263**	0,0000008	0,0000002	0,0000004	0,0000017	0,0000007	0,0000002	0,0000000	0,0000012	0,0000001	0,0000070	0,0000007	0,0000012
Land use [Annual crop eq.·y/kWh]	**0,0000229**	0,0000003	0,0000001	0,0000002	0,0000038	0,0000009	0,0000001	0,0000000	0,0000010	0,0000000	0,0000030	0,0000015	0,0000012
Marine ecotoxicity [g 1,4-DB eq/kWh]	**0,0624097**	0,0015766	0,0002522	0,0007808	0,0014412	0,0003809	0,0003556	0,0000130	0,0034440	0,0000668	0,0143911	0,0005601	0,0016204
Marine eutrophication [g N eq/kWh]	**0,0000438**	0,0000017	0,0000003	0,0000008	0,0000009	0,0000009	0,0000004	0,0000000	0,0000011	0,0000001	0,0000156	0,0000003	0,0000026
Metal depletion [g Cu eq/kWh]	**0,0183434**	0,0005317	0,0001816	0,0002633	0,0002991	0,0000531	0,0001199	0,0000027	0,0005936	0,0000074	0,0048536	0,0001162	0,0003812
Photochemical ozone formation, ecosystems [g NOx eq/kWh]	**0,0020175**	0,0000363	0,0000142	0,0000180	0,0002613	0,0000498	0,0000082	0,0000024	0,0000938	0,0000049	0,0003309	0,0001016	0,0000632
Photochemical ozone formation, human health [g NOx eq/kWh	**0,0019254**	0,0000343	0,0000133	0,0000170	0,0002576	0,0000430	0,0000077	0,0000023	0,0000916	0,0000047	0,0003135	0,0001001	0,0000605
Stratospheric ozone depletion [g CFC-11 eq/kWh]	**0,0000002**	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000
Terrestrial acidification [g SO2 eq/kWh]	**0,0021805**	0,0000422	0,0000139	0,0000209	0,0001954	0,0000448	0,0000095	0,0000018	0,0003029	0,0000068	0,0003854	0,0000759	0,0000838
Terrestrial ecotoxicity [g 1,4-DB eq/kWh]	**2,4537030**	0,0551911	0,0124167	0,0273341	0,3250581	0,0444060	0,0124491	0,0029361	0,1031464	0,0013343	0,5037890	0,1263299	0,0426403

Appendix B2. Environmental impacts on the construction stage (continued)

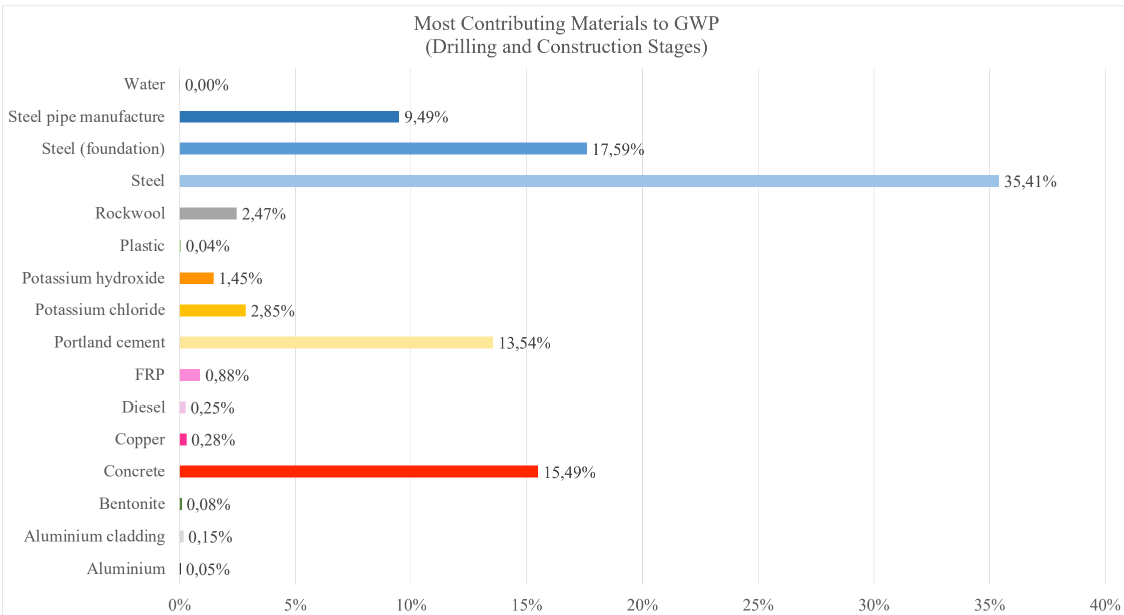
Environmental Impacts on the Construction Stage	Reinjection Pond				Turbine and generator					Wellhead		
	Plastic	Steel (foundation)	Concrete	FRP	Aluminium	Copper	Steel (foundation)	Steel	Concrete	Steel (foundation)	Steel	Concrete
Climate change, default, excl biogenic carbon [g CO2 eq/kWh]	0,0005388	0,0011253	0,0002991	0,0001216	0,0006486	0,0037934	0,2322147	0,0290527	0,0842129	0,0008701	0,0031583	0,0006195
Climate change, incl biogenic carbon [g CO2 eq/kWh]	0,0005392	0,0011241	0,0003015	0,0001183	0,0006461	0,0037849	0,2319622	0,0291906	0,0848824	0,0008692	0,0031733	0,0006245
Fine particulate matter formation [g PM2.5 eq/kWh]	0,0000006	0,0000019	0,0000003	0,0000002	0,0000013	0,0000263	0,0003972	0,0000582	0,0000775	0,0000015	0,0000063	0,0000006
Fossil depletion [g oil eq/kWh]	0,0004028	0,0003545	0,0000532	0,0000507	0,0001824	0,0012928	0,0731556	0,0095949	0,0149826	0,0002741	0,0010431	0,0001102
Freshwater consumption [m3/kWh]	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000001	0,0000024	0,0000004	0,0000008	0,0000000	0,0000000	0,0000000
Freshwater ecotoxicity [g 1,4 DB eq/kWh]	0,0000085	0,0000389	0,0000033	0,0000029	0,0003506	0,0168768	0,0080373	0,0024143	0,0009355	0,0000301	0,0002625	0,0000069
Freshwater eutrophication [g P eq/kWh]	0,0000001	0,0000005	0,0000000	0,0000000	0,0000002	0,0000257	0,0001069	0,0000157	0,0000109	0,0000004	0,0000017	0,0000001
Human toxicity, cancer [g 1,4-DB eq/kWh]	0,0000266	0,0018234	0,0000127	0,0000069	0,0001286	0,0021532	0,3762567	0,1428108	0,0035892	0,0014099	0,0155249	0,0000264
Human toxicity, non-cancer [g 1,4-DB eq/kWh]	0,0002600	0,0009694	0,0001436	0,0001567	0,0010592	0,2628265	0,2000269	0,0378915	0,0404415	0,0007495	0,0041192	0,0002975
Ionizing radiation [kBq Co-60 eq. to air/kWh]	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000003	0,0000084	0,0000017	0,0000016	0,0000000	0,0000002	0,0000000
Land use [Annual crop eq.·y/kWh]	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000007	0,0000054	0,0000007	0,0000036	0,0000000	0,0000001	0,0000000
Marine ecotoxicity [g 1,4-DB eq/kWh]	0,0000108	0,0000558	0,0000048	0,0000039	0,0004195	0,0202419	0,0115215	0,0034861	0,0013504	0,0000432	0,0003790	0,0000099
Marine eutrophication [g N eq/kWh]	0,0000000	0,0000001	0,0000000	0,0000000	0,0000000	0,0000005	0,0000134	0,0000038	0,0000008	0,0000001	0,0000004	0,0000000
Metal depletion [g Cu eq/kWh]	0,0000009	0,0000402	0,0000010	0,0000005	0,0000085	0,0009787	0,0082932	0,0011757	0,0002802	0,0000311	0,0001278	0,0000021
Photochemical ozone formation, ecosystems [g NOx eq/kWh]	0,0000012	0,0000031	0,0000009	0,0000005	0,0000017	0,0000378	0,0006497	0,0000802	0,0002449	0,0000024	0,0000087	0,0000018
Photochemical ozone formation, human health [g NOx eq/kWh	0,0000012	0,0000029	0,0000009	0,0000004	0,0000017	0,0000372	0,0006059	0,0000759	0,0002413	0,0000023	0,0000083	0,0000018
Stratospheric ozone depletion [g CFC-11 eq/kWh]	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000	0,0000001	0,0000000	0,0000000	0,0000000	0,0000000	0,0000000
Terrestrial acidification [g SO2 eq/kWh]	0,0000014	0,0000031	0,0000007	0,0000005	0,0000029	0,0000638	0,0006346	0,0000934	0,0001831	0,0000024	0,0000101	0,0000013
Terrestrial ecotoxicity [g 1,4-DB eq/kWh]	0,0006655	0,0027486	0,0010817	0,0004551	0,0010746	0,1792086	0,5671849	0,1220375	0,3045826	0,0021253	0,0132666	0,0022407

Appendix C – Environmental impacts on the operation stage

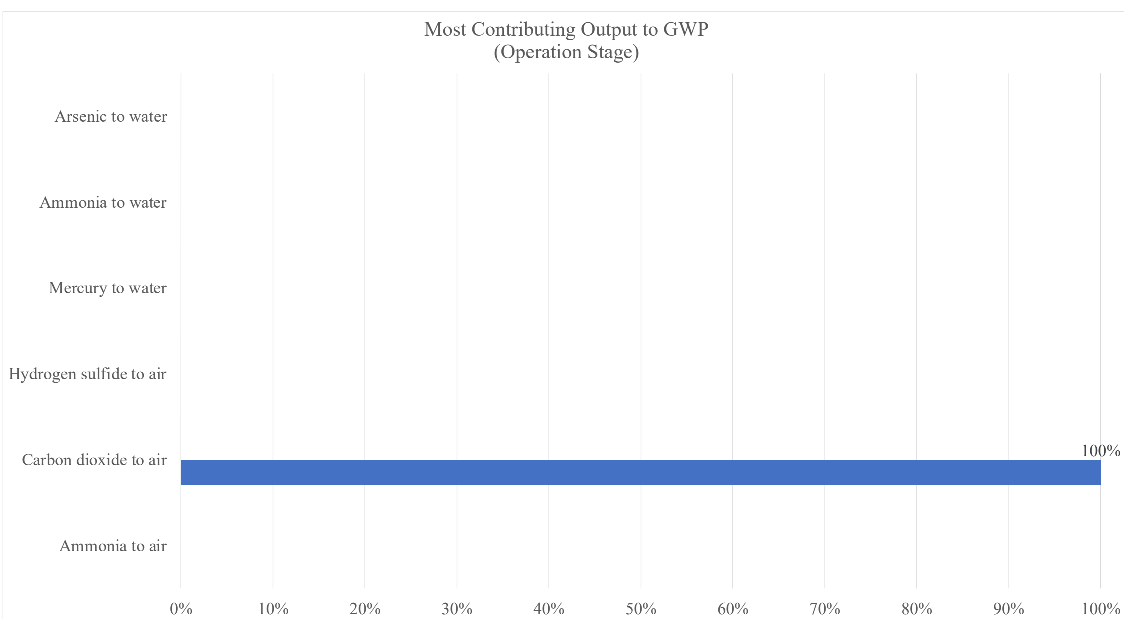
Environmental Impacts on the Operation Stage	Total	Operation					
		Ammonia to air	Carbon dioxide to air	Hydrogen sulfide to air	Mercury to water	Ammonia to water	Arsenic to water
Climate change, default, excl biogenic carbon [g CO2 eq/kWh]	41,9396466	-	41,9396466	-	-	-	-
Climate change, incl biogenic carbon [g CO2 eq/kWh]	41,9396466	-	41,9396466	-	-	-	-
Fine particulate matter formation [g PM2.5 eq/kWh]	0,0108290	0,0108290	-	-	-	-	-
Fossil depletion [g oil eq/kWh]	-	-	-	-	-	-	-
Freshwater consumption [m3/kWh]	-	-	-	-	-	-	-
Freshwater ecotoxicity [g 1,4 DB eq/kWh]	0,0001516	-	-	-	0,0000112	-	0,0001404
Freshwater eutrophication [g P eq/kWh]		-	-	-	-	-	-
Human toxicity, cancer [g 1,4-DB eq/kWh]	0,0008091	-	-	-	0,0000313	-	0,0007779
Human toxicity, non-cancer [g 1,4-DB eq/kWh]	0,2099257	-	-	-	0,0126725	-	0,1972532
Ionizing radiation [kBq Co-60 eq. to air/kWh]	-	-	-	-	-	-	-
Land use [Annual crop eq.·y/kWh]	-	-	-	-	-	-	-
Marine ecotoxicity [g 1,4-DB eq/kWh]	0,0002063	-	-	-	0,0000116	-	0,0001947
Marine eutrophication [g N eq/kWh]	0,0000054	-	-	-	-	0,0000054	0,0000000
Metal depletion [g Cu eq/kWh]	-	-	-	-	-	-	-
Photochemical ozone formation, ecosystems [g NOx eq/kWh]	-	-	-	-	-	-	-
Photochemical ozone formation, human health [g NOx eq/kWh]	-	-	-	-	-	-	-
Stratospheric ozone depletion [g CFC-11 eq/kWh]	-	-	-	-	-	-	-
Terrestrial acidification [g SO2 eq/kWh]	0,0884365	0,0884365	-	-	-	-	-
Terrestrial ecotoxicity [g 1,4-DB eq/kWh]	-	-	-	-	-	-	-

Appendix D – Midpoint hotspot analysis

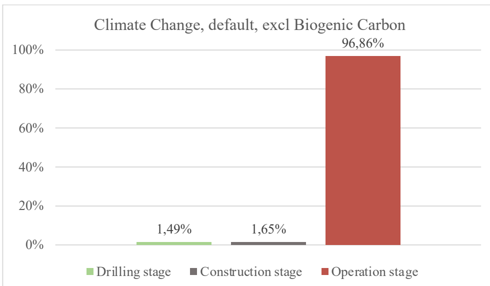
Appendix D1. Contribution of materials used for the drilling and construction stages to GWP

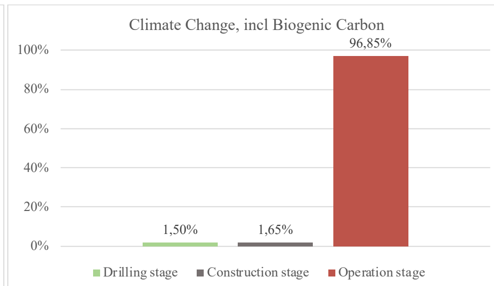


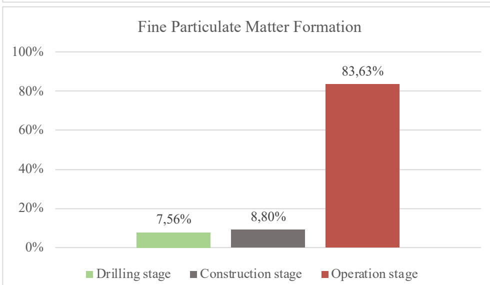
Appendix D2. Contribution of operation stage output to GWP

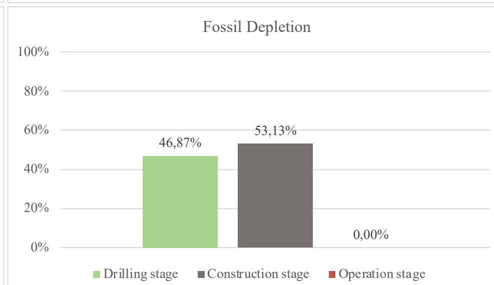


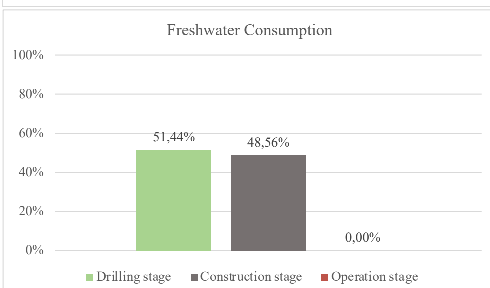
Appendix E – Environmental impacts based on impact categories

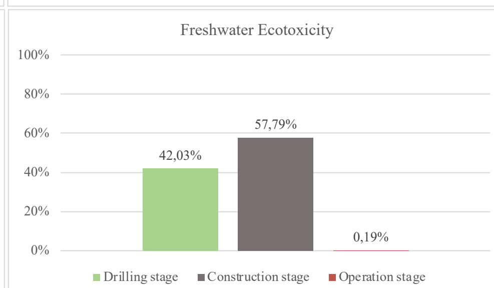


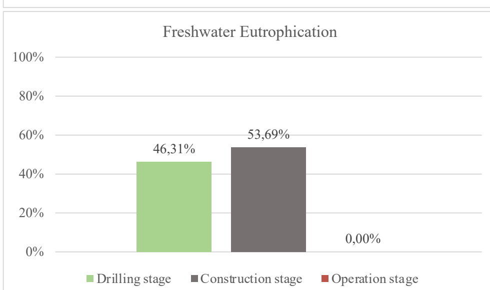


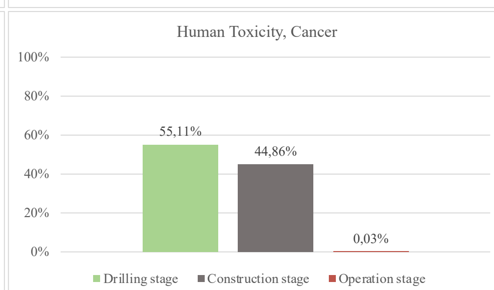


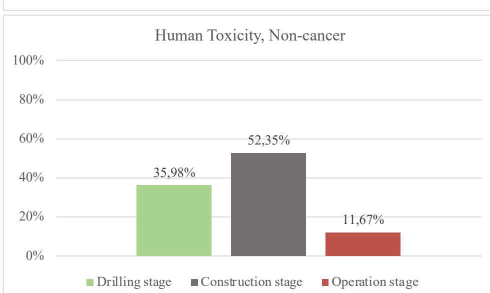


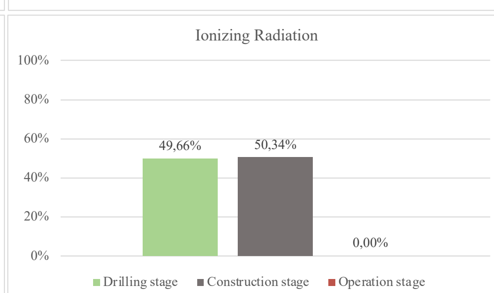













Land Use
100%
80%
60%
40%
20%
0%
43,24%
56,76%
0,00%
Drilling stage
Construction stage
Operation stage
Marine Ecotoxicity
43,29%
56,52%
0,19%
Marine Eutrophication
50,19%
44,33%
5,48%
Metal Depletion
44,51%
55,49%
0,00%
Photochemical Ozone Formation, Ecosystems
44,51%
55,49%
0,00%
Photochemical Ozone Formation, Human Health
44,74%
55,26%
0,00%
Stratospheric Ozone Depletion
44,53%
55,47%
0,00%
Terrestrial Acidification
0,2%
0,2%
99,7%
Terrestrial Ecotoxicity
43,80%
56,20%
0,00%

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