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SCREENING ENVIRONMENTAL ASPECTS OF GEOTHERMAL ELECTRICITY PRODUCTION THROUGH THE APPLICATION OF A LIFE CYCLE ASSESSMENT (LCA) APPROACH – CASE STUDY: NESJAVELLIR POWER PLANT IN ICELAND

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ABSTRACT

Production of clean energy at low cost and minimal emissions with sufficient capacity to meet the growing population is a challenge foreseen for the energy sector. Over-exploitation of fossil fuels impairs the environmental systems, consequently affecting public health. Renewable energies are promising alternative sources for future energy supply due to fewer emissions to the environment. This study aims at screening the environmental aspects of geothermal power production using the Life Cycle Assessment (LCA) approach. It intends to understand and identify weak points in the life cycle of geothermal energy development and utilization as well as learning about the existing mitigation measures. Understanding the impacts which emanate from each stage of the life cycle of a geothermal production system is key in decision making especially when selecting the best available technologies (BATs) to mitigate the impacts with the least impacts on the environment. Nesjavellir geothermal power plant in Iceland was chosen as a case study to understand the contextual environmental impact of geothermal life cycle development. Iceland is one of the leading countries in geothermal energy utilization. Therefore, referencing a geothermal power plant in Iceland as a case study can set the stage for decision-makers in public and or private sectors, whose countries are on the verge of planning to develop and utilize geothermal resources, such as Tanzania, on the environmental aspects that need thorough environmental monitoring.

1. INTRODUCTION

For many years, energy from conventional fuels has been the driving force for socio-economic development. Energy in the form of electricity is widely used to meet the demands of different sectors such as industry, transport, services, and households. The share of electricity produced in the world from non-renewable sources is 73.8% (fossil fuels and nuclear) compared to renewable energy sources which make up 26.2% of the primary energy supply (REN21, 2019). Intensive use of fossil fuels such as coal, oil and natural gas has resulted in environmental implications such as the depletion of natural resources, emissions and pollutions, deforestation and soil degradation (World Energy Council, 2004). All of these implicate the environment and public health which ultimately conflicts the dimensions of sustainable development: the economy, society and the environment.

From an environmental perspective, the environmental systems are exposed at large by human actions from local transcending to global, which threatens the ecological balance. The majority of people depend on intrinsic values of the environmental systems for meeting the most basic modern services for social and economic advancement. It is evident that current energy habits, which are the biggest contributor to massive destruction of the environment, need to change in order to harmonize economic development with respect to the human needs (society) while respecting the environment. In doing so, spurring to alternative energy sources is paramount as opposed to conventional fuels as is prompt sustainable transition to the most basic modern services (IAC, 2007). To date, renewable energies such as geothermal energy are contested amongst the alternative energy sources contemplated in future primary energy supply, due to effects it prevails to the dimensions of sustainable development during utilization.

Determining the sustainability of energy systems, whether based on conventional fuels or renewable sources, effective analytical methodologies are of significance when evaluating the environmental impacts of energy systems to the surrounding environment prior to development. The Life Cycle Assessment (LCA) approach is one of the environmental analytical methodologies that pursues to evaluate the overall environmental performances of certain systems/processes in a comparative manner by analysing each stage of the entire product system from raw materials extraction over transport, production, and use to the disposal stage. The results of the analysis direct decision-makers in early stages of projects in public or private organizations to select the system/process with the least environmental impacts. In addition, the tool can assist in uncovering weak points within the system and suggest the best available technologies (BATs) to mitigate such weak points.

This study aims to survey the environmental life cycle performance of geothermal power production. It seeks to understand and identify weak points in the life cycle of geothermal energy development. Similarly, it intends to highlight effective mitigation measures currently in use that have reduced environmental impacts emanating from geothermal power plants. The results of this study intend to set a stage for decision-makers in public and or private sectors whose countries are on the verge of planning to develop and utilize geothermal resource, such as Tanzania. It also targets advisory and regulatory agencies whose focus is to provide advice to matters pertaining to environmental conservation and management. Understanding the impacts will pave the way for utilization of the geothermal resource in the country with as low environmental impacts as possible.

Nesjavellir geothermal power plant located in the southwest of Iceland is studied as a reference to understand the contextual life cycle environmental impacts of geothermal energy development. Iceland is chosen because it is one of the leading countries in the world to date that uses geothermal energy as a primary energy supply source for heat and electricity generation (Ragnarsson, 2015).

2. GEOTHERMAL ENERGY PRODUCTION AND ENVIRONMENTAL ASPECTS

2.1 Overview of geothermal energy development and utilization

Climate change and other associated impacts due to over-exploitation of fossil fuels, resource depletion, and energy shortage are the most pressing challenges the world is experiencing (Bromley, 2005). Emerging international initiatives such as Sustainable Energy for All (SEFA, 2019) and the UN's Sustainable Development Goals (UN SDGs, 2019) are at the forefront in providing alternatives sources of energy for future primary energy supply in a sustainable manner. Renewable energies are promising sources for future energy supply due to fewer emissions of greenhouse gases (GHGs) into the atmosphere and other related environmental and health impacts.

According to REN21 (2018), growth in renewable energy sources intensified in 2017 due to several factors such as concerns about energy security, the environment and human health, growing demand for energy in emerging and developing economies, the need for access to electricity and clean cooking energies, policy initiatives, ambitious international targets and increasing access to finance. Amongst the renewable energy sources that have currently grown in the energy sector as well as being contemplated for the future primary energy supply is geothermal energy.

Geothermal energy is a renewable energy source obtaining its thermal energy from the sub-surface of the Earth where it is produced in the mantle and crust through the decay of radioactive isotopes of potassium (K), uranium (U), and thorium (Th), as well as from primordial heat retained since the formation of the earth. Figure 1 illustrates geothermal energy processes in the subsurface of the earth. High temperature magma heats nearby rock and water which seeps down through fissures into the permeable rock. The heated water or steam rises to the surface to form surface manifestations such as hot springs, geysers, fumaroles, mud pools, boiling grounds, and deposits of sinter of sulphur and other minerals. In some cases, the heat can be trapped underground by impermeable rock layers forming geothermal reservoirs (Mortensen and Hardarson, 2019).

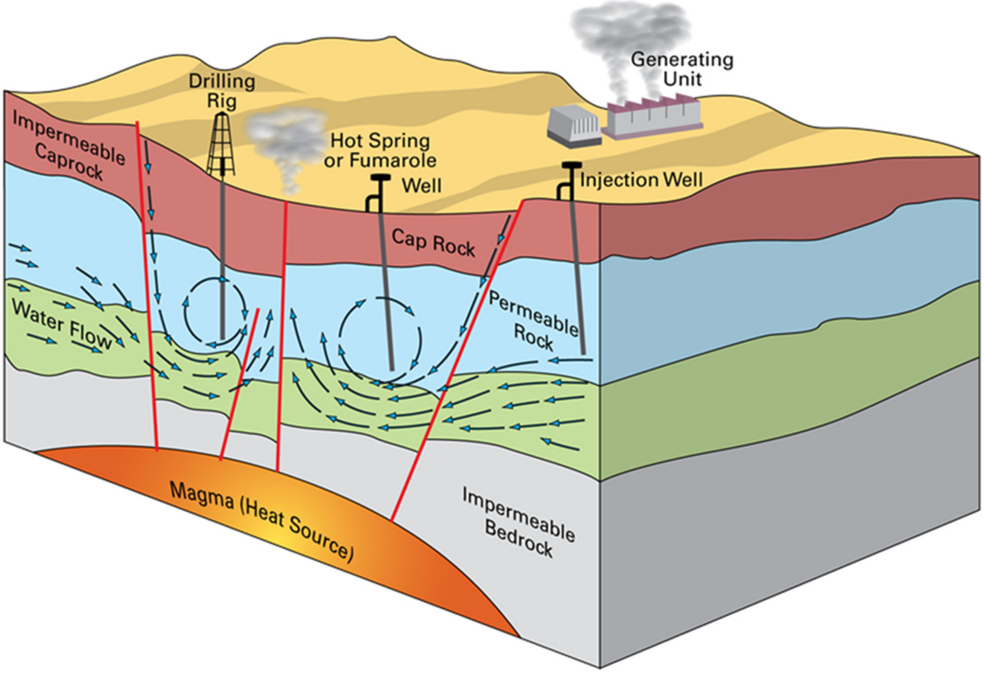

FIGURE 1: Geothermal energy processes in the subsurface (British Geological Survey, 2019)

The heat is brought closer to the surface of the earth through volcanic activity along the edges of the tectonic plates. It is exploited by drilling, converted into a useful form of energy depending on the characteristics of the geothermal fluid and reservoirs temperature. Geothermal resource properties are extremely connected to geo-mineralogical occurrences and highly dependent on site-specific factors that allow the formation, storage, and conservation of the reservoir (Parisi and Basosi, 2019).

There are two types of geothermal reservoirs depending on the temperature (and enthalpy) of the geothermal fluid system. These are high-temperature and low-temperature geothermal reservoirs. In a high-temperature geothermal resource the temperature of the geothermal fluid is above 200°C at 1000 m depth below the surface and the energy in the geothermal fluid of this reservoir type can be harnessed to generate electricity. In the low-temperature geothermal resource the geothermal reservoir temperature is below 150°C at 1000 m depth and the energy can be used directly, e.g. for heating (Ragnarsson, 2015).

Compared to some other renewable energies, of late geothermal has received a lot of attention due to both political and scientific goals of reducing GHGs emissions. It is debated due to its ability to lower life cycle GHGs emissions compared to fossil fuels and to increase global energy security as it has higher capacities, capable of supplying baseload electricity and heat production.

A geothermal resource is naturally replenished on a human time-scale through inflow of fluid from the surroundings and additionally through re-injection of the tapped geothermal fluids back into the reservoir. Therefore, this energy source is neither impacted by global depletion of resources nor by the fluctuation of fossil fuel prices (Frick et al., 2010; IRENA, 2017a; IRENA, 2019). Further, it is weather independent in contrast to wind and solar energy sources. Owing to these qualities, geothermal energy can be a sustainable and renewable energy source if constant environmental monitoring is engaged to minimize over-exploitation of the reservoir, e.g. by re-injection of excess geothermal fluid withdrawn from the reservoir.

The utilization of geothermal resources worldwide has augmented rapidly during the last three decades. According to IRENA (2019), by the end of 2016 25 countries across the world had geothermal power plants operating representing a total installed capacity of 13 gigawatts electric (GWe) with annual electricity generation reaching 80.9 terawatt-hours (TWh), amounting to 0.3% of global electricity production. In 2017, a total of 82 countries were reported to have geothermal direct use (for e.g. heating) with a total installed thermal capacity of 70 gigawatts thermal (GWth).

According to Lund and Boyd (2015) the annual thermal energy used directly from geothermal sources amounts to 588,000 terajoules (TJ). This amount comprises about 55.3% for ground-source heat pumps, 20.3% for bathing and swimming, 15% for space heating, 4.5% for greenhouses and open ground heating, 2% for aquaculture pond and raceway heating, 1.8% for industrial process heating, 0.4% for snow melting and cooling, 0.4% for agricultural drying and 0.3% for other uses.

Of the 25 countries generating geothermal power, the United States America (USA), the Philippines, Indonesia, Mexico, Italy, New Zealand, Iceland, and Japan produce more than 90% of the geothermal energy. This reflects the locations of geothermal power plants in geologically young and active volcanic areas with high geothermal gradient. In these areas, geothermal reservoirs are often at shallow depths and can be accessed in less than 2 km (Lund and Boyd, 2015).

2.2 Status of geothermal potentials and development in Tanzania

Tanzania, situated in the eastern part of Africa, is traversed by both eastern and western branches of the East African Rift System (EARS). The western branch of the rift runs along the western side of Lake Victoria and the edge of the East African plateau while the eastern branch runs from the southern extreme of the Kenya segment through the northern Tanzania segment. These segments are dominated by the alkaline and carbonatites volcanism of Oldoinyo Lengai. The occurrence of the carbonatites attribute to the deep source of the lavas occasioned by the thick cratonic crust in the region. Alkaline lavas are predominant in the areas around Kilimanjaro where a micro-rift graben is located near Arusha and further south. The western and eastern branch together with the Malawi rift form a triple junction at the Rungwe volcanic complex as seen in Figure 2 (Mnjokava et al., 2015).

Several reconnaissance studies in geothermal prospect areas have been conducted since 1949. These studies included measurements of surface manifestations, e.g. hot springs, such as temperature, water, and gas flow (IRENA, 2017b). The surface manifestation studies have revealed about 50 geothermal hot springs in different geological settings of the country and the total capacity is estimated to exceed 5,000 MW_{th}. These geothermal hot springs are located in five zones as depicted in Figure 2.

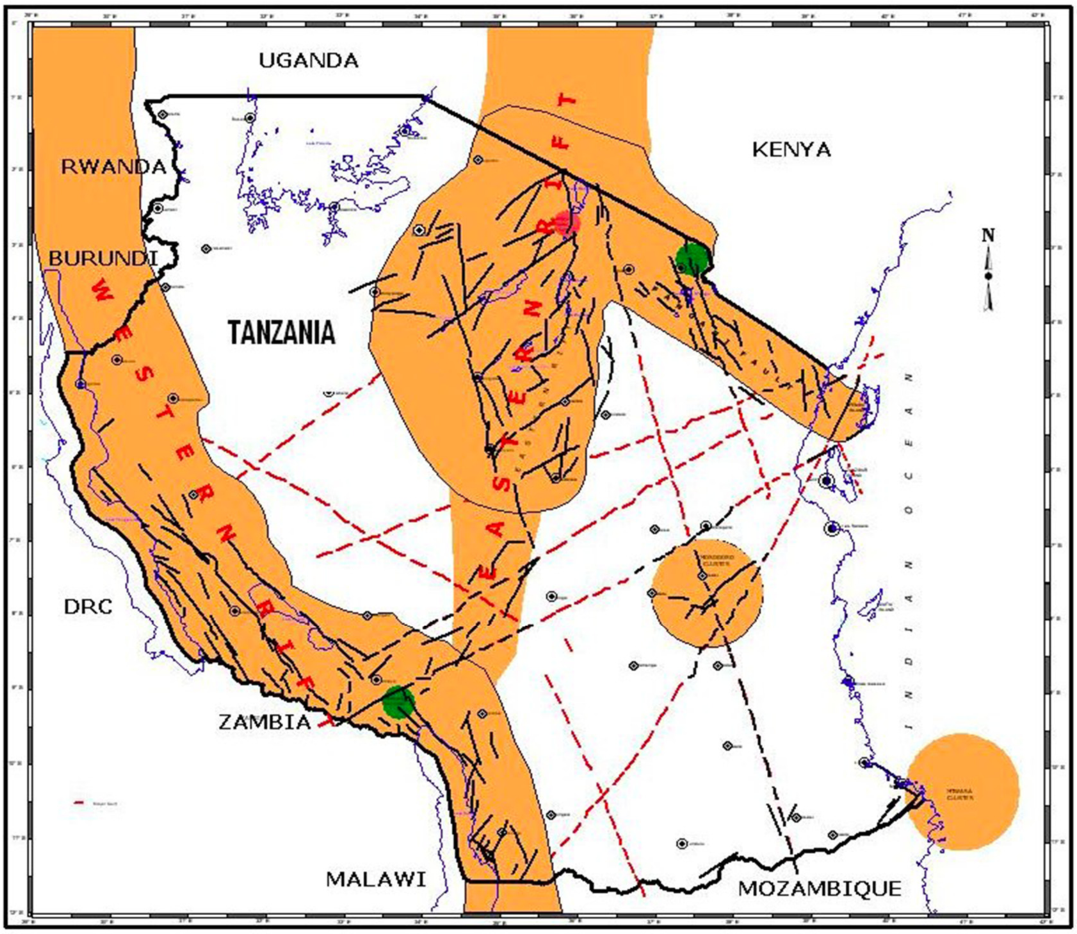

FIGURE 2: East African Rift System in Tanzania (Mnjokava et al., 2015)

i. The Northern Volcanic Province – geothermal systems in this area include Lake Eyasi, Lake Natron and Lake Manyara as well as Mountains Meru and Masware in Kilimanjaro, Arusha and Mara Regions.
ii. The South-Western Volcanic Province – geothermal systems in this area include Ngozi, Songwe, Kasimulu, Kiejo-Mbaka, Mbarali, and Daraja la Mungu in Mbeya region.
iii. The western rift of Lake Tanganyika – geothermal systems in this area include Mtagata, Majimoto-Rukwa, Mapu, Ivuna, and Rock of Hades.
iv. The Eastern Coastal belt – geothermal systems here are associated with rifting and magmatic intrusions (the Rufiji Basin) together with the Luhoi Spring site.
v. Intra-cratonic geothermal systems – includes sites like Mponde, Takwa, Hika, Gonga, Msule, Isanja, Ibadakuli, Balangida, Kondoa, Balangidalalu, Mwanka, Nyanosi and Majimoto-Mara in Singida, and Dodoma regions

The Tanzania Geothermal Development Company as an implementing public entity spearheads the development of geothermal energy in the country. Several exploration studies are currently in progress in different geothermal sites such as Kisaki, Natron, Luhoi and Mbaka–Kiejo. Drilling of exploration and testing wells is being planned for the Ngozi and Songwe geothermal sites located in the South-Western Volcanic Province (Figure 3) in the Mbeya region (Kabaka et al., 2016). It is believed that these two sites are part of the same geothermal system. According to a study by Geotherm (2008), the heat source is located underneath Ngozi volcano with outflows at Songwe.

Detailed exploration studies, and refining of geothermal conceptual models, have been ongoing while drilling targets for exploration wells expected to be drilled in fiscal year 2019/2020 in the Ngozi site

FIGURE 3: Location of geothermal prospects in Tanzania (Mnjokava, 2012)

have been identified (Kajugus et al., 2018). Based on the geothermometric results, the geothermal reservoir of the Ngozi prospect is estimated to have a temperature of 232 ± 13°C based on the observed outflow temperature on the lake bed of 89°C, total dissolved solids (TDS) of 15,800 ± 2,300 mg/kg (Na – Cl composition) and PCO_2 of 15 ± 4 bar. In Songwe, geothermometry of the hot springs suggests the temperature to be 112 ± 16°C (Kabaka et al., 2016).

Drilling of slim holes near the Ngozi caldera and thermal gradient wells in Songwe areas are in the pipelines. There the potential exists to harness the resource for domestic and industrial purposes once exploration drilling and testing have been concluded. Therefore, considering the efforts the country has made by conducting surface studies and now by preparing for the drilling of exploration and testing wells, it is substantial that the potential environmental performance relative to the geothermal life cycle is understood entirely prior to further development. This can be done by learning from the experiences of other countries where environmental management practices, when it comes to geothermal development and management, have been well advanced.

The Government of Tanzania through its implementing agency the National Environment Management Council (NEMC) is an overseer of all environmental management issues in the country. The NEMC assists in rendering technical advice as well as coordinating and regulating development activities for the protection of the environment and sustainable use of natural resources in the country. Environmental Management Act No. 20 of 2004 gives legal mandates to NEMC to safeguard the environment by undertaking environmental enforcement, compliance, and monitoring, review and monitoring environmental impact statements, research and raising awareness among the public.

With such mandates, the NEMC has a key role to play in the review and monitoring of the environment impacts of geothermal energy development in the country as well as in environmental monitoring once a power plant is set-up and operating, to mitigate environmental and health impacts. It is therefore of paramount importance that this study sets a stage to gather the current understanding of the environmental life cycle aspects of a geothermal power plant to assist the NEMC, a technical advisory agency in decision making, on the matters concerning the environment, public and the economy at large in the near future. Through understanding the impacts, the way can be paved for the utilization of geothermal resources in the Tanzania with minimal environmental impacts.

2.3 Possible environmental impacts from geothermal energy utilization

The use of geothermal energy, like any other energy sources, produces impacts on the environment that are very site-specific due to the nature of the geothermal resource, geological age, volcanic activity, and reservoir depth. In most cases, environmental impacts are associated with the type of technology employed for power generation and/or heat production from the geothermal resource. Many studies have delineated impacts to the environment in the form of land use, geological threats, emissions to the atmosphere, emissions to water, emissions to rock mass, water consumption, impact on biodiversity, noise and light emissions and heat as shown in Figure 4. For this study, the impacts are clustered according to their effect on land, air, and water and described by how they relate to different parts of the life cycle of a geothermal power plant.

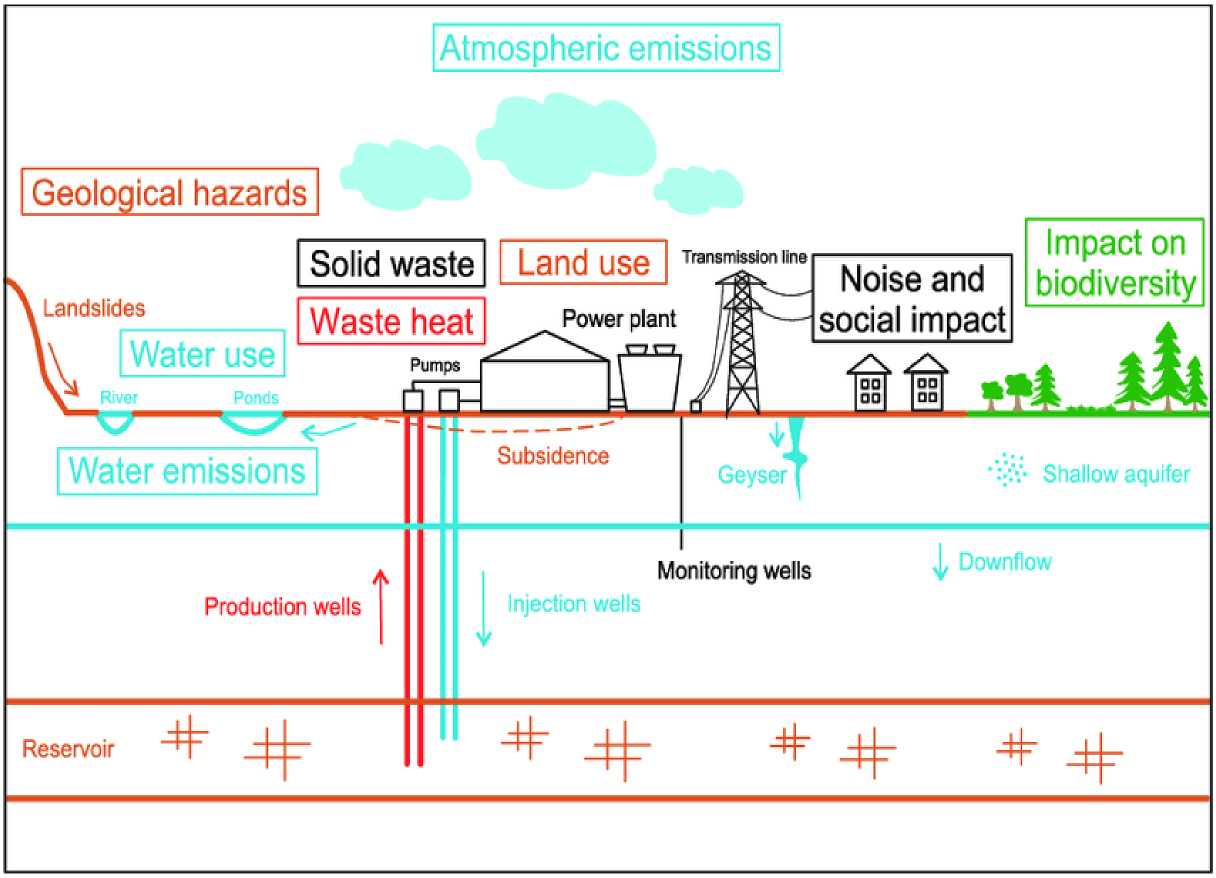

FIGURE 4: Life cycle environmental impacts of geothermal power production (Bayer et al., 2013)

2.3.1 Impact on air

This impact category is associated with the discharge of geothermal gases to the atmosphere during production, which contributes to climate change and air pollution. Naturally in geothermal reservoirs, geothermal fluids comprise non-condensable gases (NCGs) such as carbon dioxide (CO_2) hydrogen sulphide (H_2S) and traces of hydrogen (H_2), nitrogen (N_2), methane (CH_4), ammonia (NH_3), argon (Ar), radon (Rn), volatile metals (boron, arsenic and mercury), minerals, silicates, carbonates, metal sulphides and sulphates. During production, these gases are released into the atmosphere as steam or vapour (Parisi and Basosi, 2019).

Content of the gaseous emissions from a geothermal reservoir are site-specific. Although geothermal energy on average produces less CO_2, CH_4, SO_2 and NO_x than conventional fossil fuels, attention is required when monitoring CO_2 and CH_4 due to their contribution to climate change. Besides, according to Kristmannsdóttir and Ármannsson (2003), during power production excessive heat in the form of steam is also emitted which affects cloud formation and local weather conditions.

Subsequently, studies done by the International Geothermal Association (IGA) conclude that CO_2 emissions from geothermal plants range from 4 to 740 g/kWh with a weighted average of 122 g/kWh. This range is lower than that of fossil fuel power plants of natural gas, coal, and oil where CO_2 emissions range from 450 g/kWh to 1,300 g/kWh (Ármannsson, 2003).

Moreover, another important geothermal gas is H_2S which is considered a nuisance to the environment causing air pollution once emitted. At low concentrations the gas smells like rotten eggs. Exposure to H_2S in high concentration is very toxic to humans. Silicates, carbonates, and sulphates in form of deposits may also cause problems for the environment. For instance, silica deposits have contributed to forest damage in the Wairakei geothermal field in New Zealand (Heath, 2002).

2.3.2 Impact on water

This category of impacts covers issues of water consumption and discharge of the effluents. During the life cycle of the geothermal energy production water is needed from the beginning of drilling operations, through construction and during operation phases. The drilling process consumes a lot of water used as a base for drilling mud, carrying away drill cuttings and cooling the drill bit. During the construction phase, water is used as one of the methods to control dust, for mixing concrete and for domestic use by the construction crew while during operation phase, depending on the geothermal technology in use, some geothermal power plants which use the flash steam technology consume a lot of water for cooling. This is quite conflicting especially in areas where availability of water is scarce (Shortall et. al, 2015).

Another impact is caused by wastewater (effluents) discharged into the surrounding environment (surface and or shallow underground waters). Geothermal fluids are generally either more acidic or alkaline than ground water and sometimes have excessive salt concentrations, therefore once released from the power plant, they can cause chemical pollution to surface water. Depending on the geological formation of the reservoirs, most of the geothermal fluids contain chlorides and sulphides, as well as arsenic, boron, and aluminium. Sometimes in high-temperature geothermal fields, high concentration of cadmium, mercury, and lead are found. Disposal of water containing these pollutants in high concentrations may lead to their accumulation in sediments and organisms from where it enters the food chain and can eventually cause health impacts on humans (Kristmannsdóttir and Ármannsson, 2003).

According to the National Water Commission (2012), geothermal technology poses the risk of contaminating groundwater by connecting previously unconnected aquifers through boreholes or connecting contaminated zones and aquifers. Thermal pollution of river water by geothermal plants causes damage to aquatic ecosystems. This is due to the discharged heat which elevates the temperature in the aquatic ecosystems causing a drop in oxygen levels or even migration of aquatic species.

2.3.3 Impact on land

This category of impacts includes activities on the land, which most of the time result in changes in the landscape, the disappearance of natural features, soil pollution, biodiversity loss, induced seismicity, noise, and natural hazards. As known, the geothermal resource is situated within the earth's crust, so advanced technologies are needed to transport the resource to the surface for utilization. Extensive land use is required for the installation of a power plant. Therefore, the construction and operation of a geothermal plant affects the various types of land use in the region from agriculture, forest reserves and settlements to industrial use. In special cases the displacement of people or villages is required to pave the way for such developments.

Surface disturbances occur during drilling and the positioning of drill rigs, which requires excavation and the clearing of trees, bushes or grasses to make way for construction activities and the creation of access roads to and from the well-field. In the case of a power plant which produces hot water for heating, the construction of access roads for the pipelines (over land or buried into the ground) is necessary. The installation of pipelines utilizes a considerable amount of land, which is natural habitat to intrinsic species, plants, animals, microorganisms and other dependent ecosystems. Soils are compacted due to construction activities reducing soil fertility and functioning such as the capacity to retain water, permeability, and aeration that over time may contribute to soil erosion.

Many geothermal fields are situated in areas demarcated as protected areas, which are of touristic or cultural importance, such as national parks or of historic interest such as forest reserves with dispersed population density (Kristmannsdóttir and Ármannsson, 2003). Once the area is earmarked for its geothermal potential, the possibilities of losing its scenery increase depending on the measures propagated to protect and conserve the natural features during construction and operation phases.

Further, the withdrawal of geothermal fluids from the subsurface for production of energy usually affects surface manifestations such as hot springs, fumaroles, geysers, which often disappear or move to another area. In some cases, the probability of natural hazards such as landslides and seismicity, depending on the geological conditions of a particular geothermal field, increase. In New Zealand for instance, more than 100 geysers have disappeared, mainly due to geothermal development, and recovery is hardly possible. Recurrent withdrawal of geothermal fluids without replenishing the reservoir system leads to land subsidence. This is caused by a decline of the reservoir pressure causing pore spaces to collapse. Evidence of land subsidence due to geothermal utilization was observed in the Wairakei geothermal field in New Zealand which experienced subsidence rates of 45 cm/year. In Larderello in Italy subsidence has averaged 25 cm/year and in Svartsengi in Iceland 1 cm/year. Usually, subsidence reflects the depletion of the reservoir (Bayer et al., 2013).

Subsidence can affect the stability of the infrastructure of the geothermal power plant, that is pipelines, well casings, and drains. Moreover, if the plant is situated in the vicinity of a populated area, instability of buildings may be the consequence. In addition, geothermal power plants generate unwanted noise which at times is considered a threat to public health. Noise is emitted in different phases of the geothermal development. During exploration and drilling, a lot of the noise that is generated ranges between 80 dB to 120 dB while during the operation phase noise levels can be 71 dB to 83 dB (Shortall et al., 2015).

3. ICELAND CASE STUDY: NESJAVELLIR GEOTHERMAL POWER PLANT

3.1 Geothermal energy in Iceland

Iceland is a country that is rich in geothermal resources and a leading country in the world in its utilization. The country is situated on the Mid-Atlantic ridge which is the boundary between the North

American and Eurasian tectonic plates. Ragnarsson (2015) describes that these plates are constantly moving apart at a rate of about 2 cm per year. The movement of the tectonic plates together with geological processes, e.g. volcanic and intrusive activity, that occur frequently have led to an abundance of geothermal energy resources.

About 68% of the primary energy used in Iceland is derived from geothermal resources while the remaining 32% come from hydropower and imported fossil fuels to cater the transport sector. Basically, geothermal energy drives the economy of Iceland. It is used for electricity generation and direct use purposes such as space heating, industrial applications, swimming pools, snow melting, greenhouses and fish farming (Ragnarsson, 2015). For heating purposes alone, hot water produced from geothermal power plants meets 96% of the country's heating demand while 27.3% of the electricity demand is met by geothermal energy. In 2018, about 755 MWe installed capacity was available from the geothermal resources and the country still has large unexploited geothermal potential (Karlsdóttir et al., 2020).

3.2 Nesjavellir geothermal power plant

Nesjavellir geothermal power plant is the second largest geothermal power plant among the eight geothermal power plants operating in Iceland. It is located in the Hengill Central Volcano area, a high-temperature zone in southwest Iceland about 27 km from the capital city of Reykjavík (Figure 5). Following an intensive drilling and testing phase in the 1980s, the construction activities finally began in 1987 and the plant was commissioned in 1990 (Mannvit, 2019). The primary purpose of the plant is to produce hot water for space heating in the Reykjavík area and electricity generation. ON Power (Orka náttúrunnar), a subsidiary of the municipally owned utility company Reykjavik Energy (Orkuveita Reykjavíkur), operates the plant along with another large geothermal power plant, Hellisheidi, both located in the Hengill volcanic region (Lund, 2005).

Initially, the plant generated about 560 l/s of 82^0C hot water, which is equivalent to 100 MWth for district heating, using geothermal steam and water to heat cold ground water. At the same time, production of electricity started with the installation of two 30 MWe steam turbines. By that time, 14

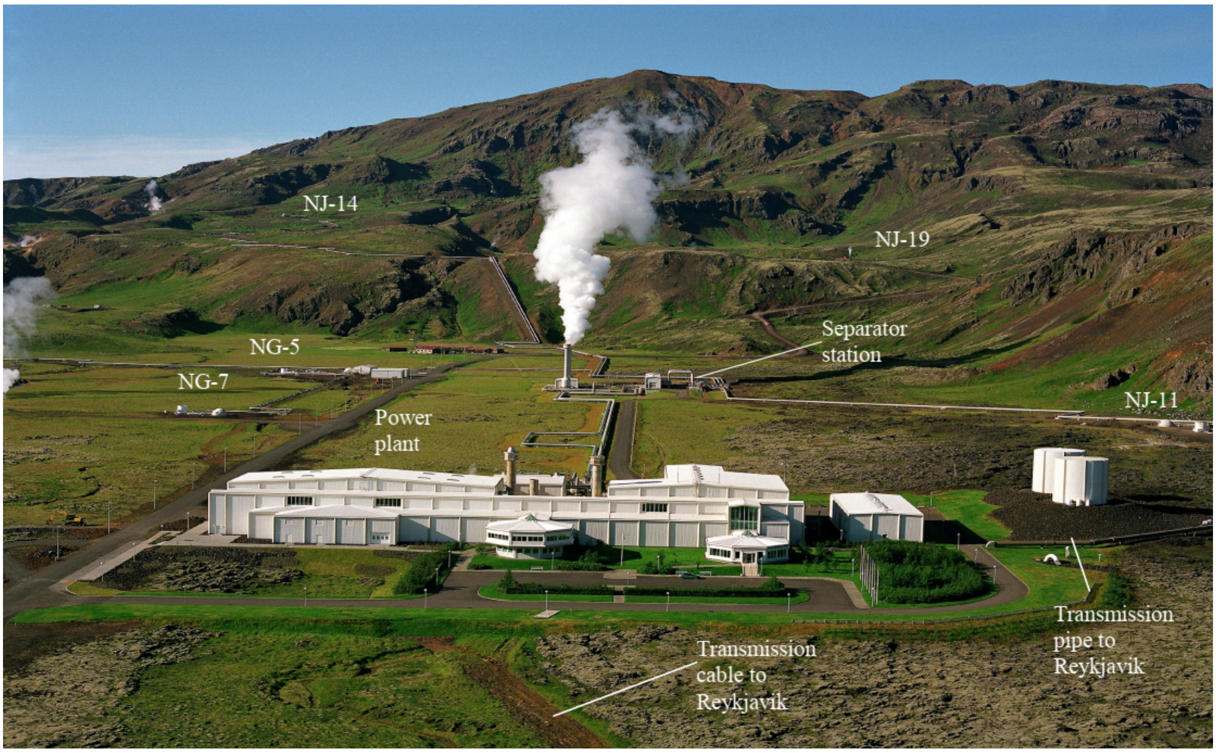

FIGURE 5: Overview of the Nesjavellir combined heat and power plant site (Lund, 2005)

boreholes had been drilled and connected to the power plant for production except for one borehole that did not perform sufficiently (Lund, 2005). The plant underwent some major developments from 1990s to 2005 to increase its capacity by adding two more steam turbines of 30 MWe capacity, adding heat production and by drilling more production wells. Today the plants installed electric capacity corresponds to 120 MWe and the installed thermal capacity is 1,640 l/s of 85^0C hot water, which is equivalent to 300 MWth. The power plant produces from 27 production wells with depths ranging from 1,000 to 2,000 m (Lund, 2005). An overview of the power plant is shown in Figure 5.

The plant accesses a deep ground water system temporarily to perform re-injection of surplus geothermal water from the plant while the effluent cooling water that is not used for producing hot water for district heating is discharged into a small river close to Lake Thingvallavatn. According to ON Power, the plant operator, it is planned in the near future to develop the re-injection utility for deep re-injection of geothermal fluid and prepare for the experimental re-injection of CO_2 and H_2S gases into the reservoir.

3.2.1 The production cycle of the power plant

The power plant is a combined cycle plant where its production process can be divided into three stages: the collection and processing of steam from boreholes, the collection and heating of cold water and finally electricity production (Figure 6). To begin with, a mixture of steam and geothermal brine at 200°C and 14 bars is collected and transported from the wells to a central separation station. At the separation station, the mixture passes through a steam separator and the two phases are separated, i.e. brine is separated from the steam. Moisture is removed from the steam which is then sent through the steam turbines for co-generation of electricity. Unutilized steam is released through a steam exhaust (Lund, 2005).

In the steam heat exchangers, the steam is cooled from 120°C under pressure into condensate whose heat is transferred to cold freshwater in condensate heat exchangers. During that process, the condensate cools to 20°C. The heat of the separated brine is transferred to cold fresh water by geothermal brine heat

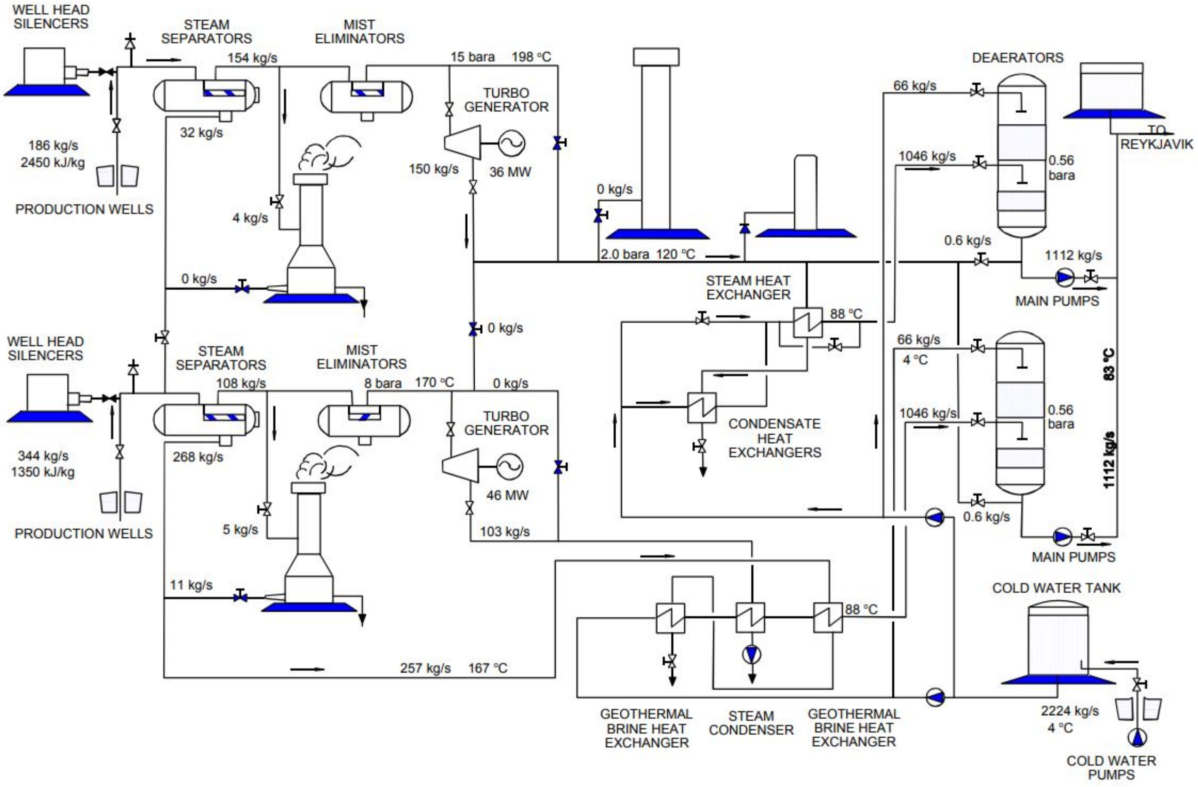

FIGURE 6: A flow diagram of the production cycle at Nesjavellir combined heat and power plant (Lund, 2005)

exchangers. The fresh water is heated to the required temperature and sent through deaerators to remove the bulk of oxygen, since the presence of dissolved oxygen can cause corrosion after being heated. Then water is boiled at low pressure to remove most of the remaining dissolved oxygen and other gases, then it is left to cool to 82 – 85°C. Finally, a small amount of geothermal steam containing acidic gases is injected into the water to remove any remaining oxygen and to lower its pH to prevent corrosion and scaling in the distribution pipelines. The flow chart diagram for the production cycle is shown in Figure 6.

3.2.2 Distribution

The power plant at Nesjavellir is situated at an elevation of 177 m above sea level (Figure 5). The produced hot water is pumped by three 900 kW (1250 hp) pumps through a main pipeline of 900 mm diameter to a 2000 m^3 storage tank in the Hengill area which is located at 406 m elevation. Gravity driven, the hot water flows from the tank through a pipeline of 800 mm diameter to storage tanks in Reynisvatnheidi and Grafarholt on the eastern outskirts of Reykjavik City to be used for heating and hot tap water (Lund, 2005).

4. LIFE CYCLE ASSESSMENT (LCA) APPROACH

4.1 Contextual framework

The Life Cycle Assessment (LCA) approach is a standardized method that allows the evaluation of the environmental impacts of product systems throughout their entire life cycle. It models the interactions of the life cycle stages of a particular product system relative to the environment from extraction of raw materials for manufacturing process, through the production, use of the product, and to its final disposal, therefore encompassing the entire product system (Figure 7). In the disposal stage different waste

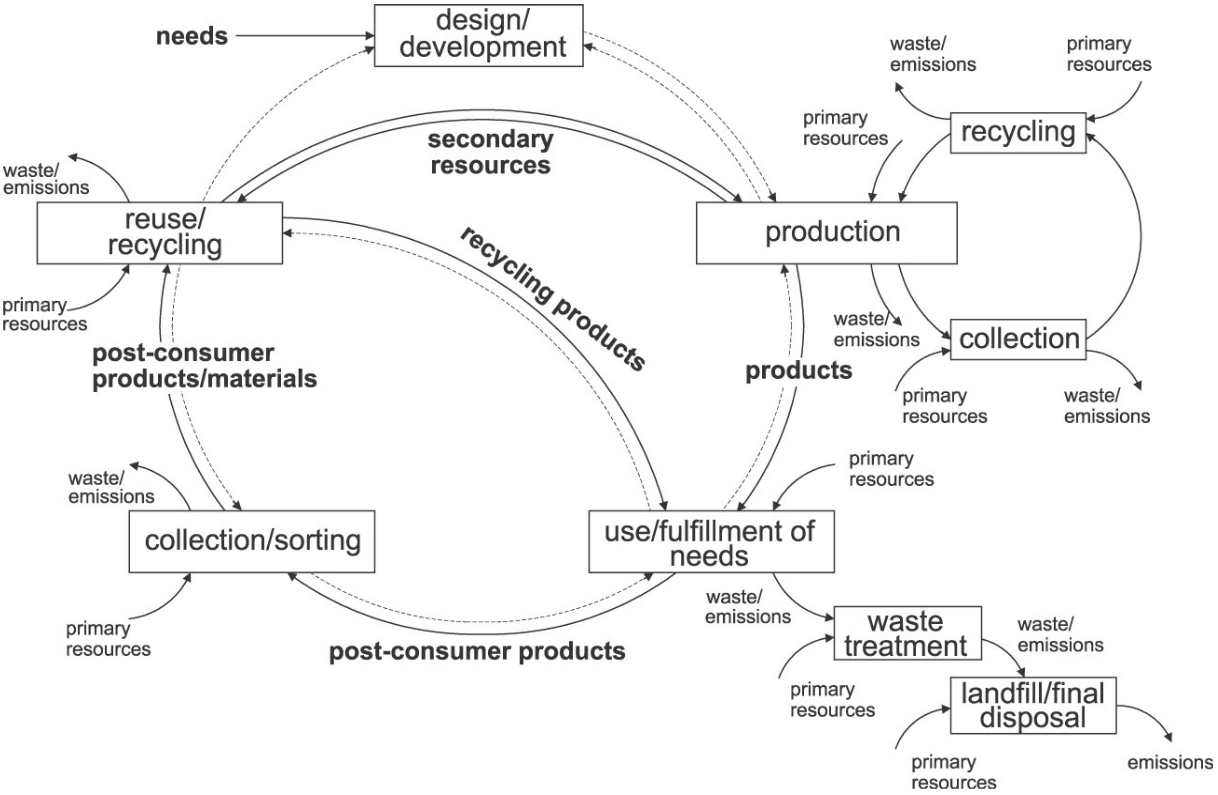

FIGURE 7: Schematic representation of a generic life cycle of a product (the full arrows represent material and energy flows while the dashed arrows represent flows) (Rebitzer et al., 2004)

management systems can be used depending on the decision of the company. Wastes released to the environment can be reused, recycled, recovered as a source of raw materials, incinerated to retrieve energy to feed into the production system or be disposed by landfilling. Throughout the life cycle of a product system energy and raw materials are used as preliminary sources (Figure 8). In other words, a LCA critically enables the identification of the most significant impacts each stage produces and offers observance for improvement to the assessed stages in order to avoid spread of damages from one stage of the cycle to another (Asdrubali et al., 2015).

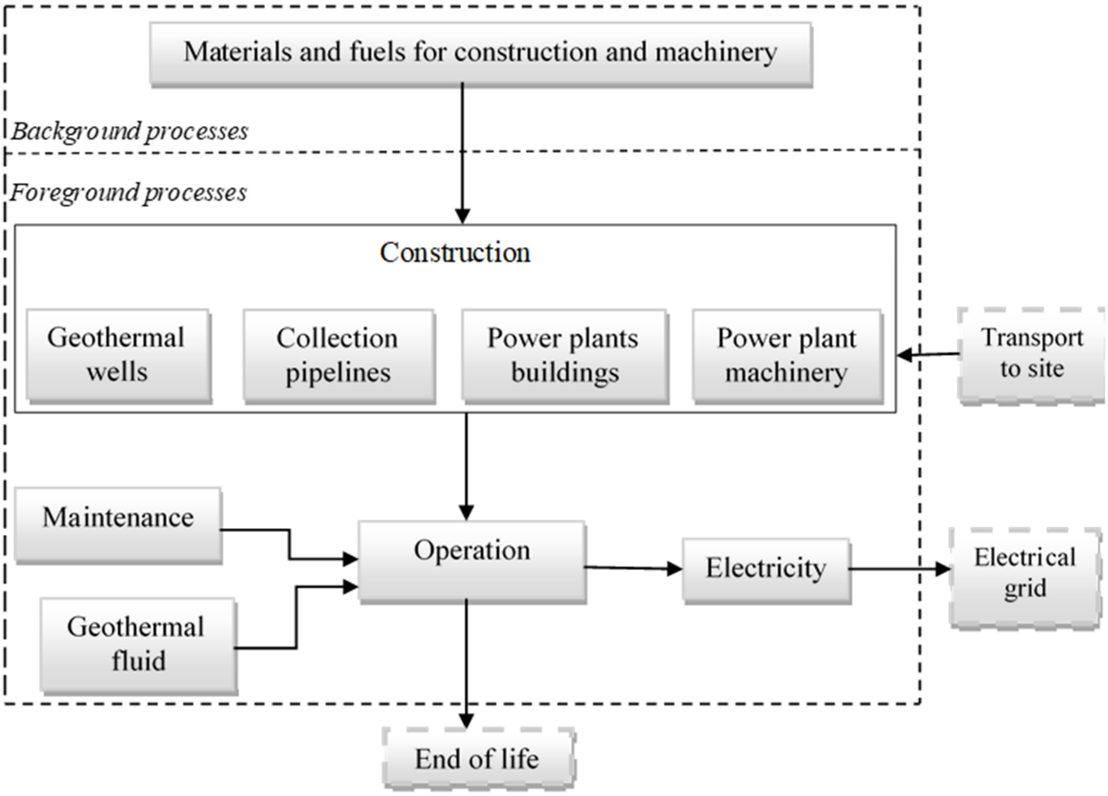

FIGURE 8: System boundaries chosen for the LCA study of Nesjavellir geothermal power plant (Karlsdóttir et al., 2015)

According to the World Energy Council (2004), LCA is a tool for analysing environmental issues through planning of projects and uncovering of weak points, which are "hotspots" in the life of product systems, as well as by comparing for possible alternatives. The results of LCAs can be used to improve the environmental compatibility of systems. To assess the potential environment impacts associated with a product system, a LCA consists of the following steps:

i. Compiling an inventory of relevant energy and material inputs and the associated emissions to the environment;
ii. Evaluating the potential environmental impacts associated with identified inputs and emissions; and
iii. Interpreting the results to facilitate informed decision making.

According to ISO 14040 and its subsequent series, a LCA consists of four stages. These four stages are goal definition and scoping, inventory analysis, impact assessment and interpretation. The goal and scope definition phase specifies the overall aim of the study, the system boundaries, the sources of data and the functional unit that refers to all input and output flows. The inventory analysis details descriptions of all the environmental inputs such as material and energy flows and output emissions from the product system to air, water, and solids. The impact assessment stage involves quantification of the relative magnitude of all the environmental impacts using several indicators. Lastly, the results from the inventory analysis and impact assessment are interpreted to identify critical aspects that require alternative options or optimization of the product system (Asdrubali et al., 2015).

To date, LCA is a prominent tool in the environmental sector that is used for decision making in different scientific fields such as chemical engineering, transportation of products, defining the best available technologies (BATs), energy production and so forth. In the energy production sector, a LCA provides a clear and comprehensive framework to facilitate a comparative analysis of energy systems and their environmental effects to meet sustainability criteria and to assist decision-makers to choose the best energy system for a specific purpose (Geller and Meneses, 2016).

4.2 The need for LCA in geothermal energy production

Geothermal energy is considered a clean energy source in comparison with fossil fuels. However, utilization of the resource can cause negative impacts on the environment. Therefore, it is necessary to assess the environmental performance of the production systems during their entire life cycle of geothermal energy production in order to reach the sustainability goals of the energy sector. LCA can aid in identifying hidden impacts in the up-stream and down-stream life cycle phases of energy production, as well as potential trade-offs in environmental impacts between different energy production technologies.

For geothermal energy development, the LCA approach is perceived as an appropriate tool to determine the potential impacts on the environment when it comes to development and utilization of the resource. In fact, the tool is essential for comparative analysis of different energy conversion technologies to enable technology choices with positive impacts on the environment. Impacts emanating from geothermal projects can be quantified and compared to fossil fuels or any other renewable energy source in terms of energy production systems, processes and emissions, hence, enable decision-makers to select the best system with minimal impacts on the environment.

4.3 Materials and method

The methodology used in this study follows the requirements of the International Organization for Standardization (ISO 14040 and its subsequent series) framework for LCA. It is used to survey the environmental life cycle aspects of electricity generation in the Nesjavellir geothermal power plant in Iceland. Due to time restriction, the component of heat production is not included. OpenLCA 1.9.0 software (2019) and the Ecoinvent 3.2 cut-off dataset were used to analyze material and data.

The materials and data gathered for this study are divided into two categories, that is primary and secondary data. Primary data are information specific to the power plant, obtained directly from the power plant owner ON Power Company (2019), whereas secondary data were obtained from an inventory study done for the Hellisheidi geothermal power plant (Karlsdóttir et al., 2015).

This comprehensive life cycle inventory (LCI) study for Hellisheidi geothermal power plant, published by Karlsdóttir er al. (2015), provides a basis for LCA practitioners to use as reference values for the production of electricity and heat from high-temperature geothermal resources using flash technology. The study further recommends that when the LCI dataset is referenced in a study, inclusive data need to be adjusted to correspond to the specific conditions, that is technology used, parameters and characterization of the geothermal reservoir of the power plant that is being studied.

For this case study, the primary data was adjusted to Nesjavellir geothermal power plant’s specific conditions whereas secondary data was taken from the LCI study for Hellisheidi geothermal power plant and dataset Ecoinvent 3.2 cut-off.

Hellisheidi and Nesjavellir (case study area) are both geothermal combined heat and power (CHP) plants located in the Hengill central volcano area and have high-temperature geothermal reservoirs. Both power plants are operated by ON Power, a subsidiary of Reykjavik Energy which is a public utility company responsible for distribution and sale of both hot water and electricity in Iceland. Hellisheidi geothermal power plant uses double-flash technology whereas Nesjavellir geothermal power plant uses single flash.

4.3.1 The goal and scope definition

This is the first stage of the LCA approach. The product system is described in terms of system boundaries and functional unit. The functional unit is an important basis that enables products or services to be compared and analysed (Rebitzer et al., 2004). For this study, the goal is to survey the environmental life cycle aspects of Nesjavellir geothermal power production by using the LCA approach (Table 1). It seeks to understand and identify weak points in the life cycle of geothermal electricity production. Through the identification of weak points in the cycle, it intends to highlight effective mitigation measures in use that have reduced environmental impacts emanating from the geothermal power plant. Therefore, a comparative analysis with other electricity production systems is included in the results sections. The functional unit for this study is 1 kWh of electricity, as supplied to the national grid by the Nesjavellir geothermal power plant.

TABLE 1: Overview of life cycle stages used for this study (Karlsdóttir et al., 2015)

Life cycle stage	Included in inventory	Excluded from inventory
Construction		
Geothermal wells	Fuel and material used during well drilling and casing Earth works and material required for wellhead equipment	Drill rig infrastructure Transport to site Energy for manufacturing equipment and structures
Collection pipelines	Materials use and earthworks for collection pipelines from wells to power station	Transport to site Energy for manufacturing and laying of pipelines
Power plant buildings	Materials and earthworks required for construction of turbine halls for high- and low-pressure stages, cold-water works, and staff facilities, materials for power hall piping system and electrical systems (low-, medium- and high-voltage cables)	Transport to site Energy for manufacturing of pipelines Interior design of buildings (doors, cabinets, etc.) Electrical control room and computers
Power plant machinery	Materials for all main pieces of equipment as well as electrical transformers for low, medium and high voltage	Transport to site Energy for machinery manufacture
Operation		
Operation of power station	Use of geothermal fluid, groundwater, and electricity, emissions to air and soil from geothermal fluid Heat reinjection to air via cooling towers and to ground via reinjection and shallow wells	Transport of staff
Maintenance		
Maintenance of power station	Drilling of additional (make-up) wells Addition of bleach (sodium hypochlorite, 15%) to cooling water circuit	Regular service maintenance of machinery where parts are overhauled and reused during a 30-year lifetime of power plant

System boundaries for this study include stages of construction and operation (Figure 8). In the construction phase, activities such as drilling of geothermal wells, installation of pipelines from wells to the power plant, power plant construction and power plant machinery are included. The operation phase includes use of geothermal fluids and maintenance of the plant. Due to time limitations, some components of the product systems were not considered here, such as transportation of materials and machinery to the site as well as transmission losses during the delivery of energy to the intended consumers. The decommissioning stage is excluded since this phase has minimal impacts on the environment. A lot of the infrastructure used during construction such as metallic structures are 90% likely to be recycled and demolition is not foreseeable in the coming years. Table 1 presents an overview of the comprehensive life cycle stages considered in this study.

The time horizon chosen for this study is 30 years from now. Nesjavellir started its operations in 1990; therefore, it has now been operating for 29 years. Assumptions are made that the power plant will exceed the commonly used 30 years technical lifespan of power plants. This assumption is realistic with appropriate maintenance. Three of the oldest geothermal power plants in Iceland have already surpassed 30 years of operations. These are Bjarnarflag, Krafla and Svartsengi geothermal power plants which commenced their operations in 1969, 1977 and 1976, respectively (Karlsdóttir et al., 2020). Therefore, since the power plant started its operations in 1990, the assumption includes maintenance and renewal of various mechanical parts during the last 29 years of operation.

4.3.2 Life Cycle Inventory (LCI)

This stage involves estimations for the consumption of resources and the quantity of waste flows and emissions caused by a product life cycle. Data collection and modelling of the system is carried out. Every input such as raw material, fuel, water, and energy, and every output from the system such as product, emissions and waste are recorded (Geller and Meneses, 2016). For this inventory, primary data which are site specific were obtained from ON Power, the plant operator, while secondary data were adapted from a comprehensive LCI study done for Hellisheidi geothermal power plant by Karlsdóttir et al. (2015), as already mentioned. OpenLCA 1.9.0 software (2019) and dataset Ecoinvent 3.2 cut-off were used to analyze data. The inputs were quantified with regard to the function unit of 1 kWh. Primary materials and site-specific parameters for Nesjavellir geothermal power plant are presented in Table 2.

TABLE 2: Site-specific parameters used for normalization of the inventory data for the construction and operation of Nesjavellir geothermal power plant (Karlsdóttir et al., 2015)

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

A. Construction phase

Drilling of geothermal wells

The construction phase consumes a lot of materials, energy and equipment for the infrastructure of the power plant. Concrete, steel, diesel, excavation of the area, water and cement are raw materials used for drilling geothermal wells, casing and wellhead construction. Concrete and steel support the well opening. For each well, wellhead equipment consists of a well silencer and an aluminium well housing containing the main wellhead valve as well as piping and smaller valves. According to Karlsdóttir et al. (2015), drilling rigs are powered by diesel fuel in Iceland and a large amount of water is used in the drilling process. The consumption of diesel varies between geothermal sites depending on the drill rig and geological conditions. Material used during drilling and casing account for less than 0.5% of the total mass of material (excluding water and diesel) and is not included in the inventory. In addition, not all data were available in the Ecoinvent dataset. Material used per well such as lignosulfonite is not included in the dataset, therefore it was excluded in the calculations of the construction phase of this study, yet it has a minimal effect on the results. Materials used for constructing a well and wellhead are presented in Table 3.

Water consumption during drilling was calculated based on the following:

i. 30 l/s pumping rate;
ii. Water is used during one third of drilling time;
iii. Drilling duration is 12 hrs per day; and
iv. Average drilling time of 45 days per well (Sveinbjörnsson and Thórhallsson, 2014).

TABLE 3: Material, energy and water requirements for drilling of a geothermal well and wellhead equipment, scaled to either the total metres drilled or the number of wells. Amounts calculated for average well design for Hellisheidi power plant are based on 77% wide wells and 13% narrow wells. Take note that the amount of materials was assumed the same for Nesjavellir power plant since the two power plants are operated by the same operating company and located within the same geothermal reservoir (Karlsdóttir et al., 2015)

Geothermal well	Unit	Amount
Depth dependent material use		
Steel[a]	kg/m_{wells}	139
Diesel[a]	kg/m_{wells}	73.7
Average material uses per well		
Portland cement[b]	kg/well	81,3
Bentonite[b]	kg/well	59,6
Silica flour[b]	kg/well	28,9
Lignosulfonite	kg/well	2,79
Perlite[b]	kg/well	1,44
Water (in cement mix)[c]	kg/well	58,7
Water (in drilling)	kg/well	19,400,000
Material and process requirement for wellhead equipment		
Excavation	m^3/well	3,000
Fill	m^3/well	1,000
Concrete	m^3/well	18
Steel	kg/well	14,6
Stainless steel	kg/well	16
Aluminium	kg/well	1,22

[a] Scaled per metre drilled. For drilling of a 1,600m average well in Nesjavellir, 222,000 kg of steel and 118,000 kg of diesel is needed for drilling and casing.
[b] Calculated from a concrete mix of 100 kg Portland cement, 40 kg silica flour (40% by weight of cement, BWOC), 2 kg Wyoming bentonite (2% BWOC), and 2 kg perlite (2% BWOC)
[c] Assuming 80 l of water per 144 kg cement mix

Collection pipelines

Plastics, mineral wool, and aluminium are raw materials for the manufacturing of collection pipelines for geothermal power plants. Due to lack of availability of correct data for the pipeline length, the study assumed the total length to be 20 km. These pipelines are made of steel, insulated with mineral wool and cladded with aluminium sheets. Table 4 presents the inventory data for collection pipelines. The pipes transport geothermal fluid from production wells to the power plant, as well as to reinjection wells. Concrete and steel support the collection pipes. Designs of these collection pipelines are based on the mass flow from the wells and the layout of each geothermal field, therefore material input depends much on the power plant (Karlsdóttir et al., 2015).

TABLE 4: Materials and construction work requirements for collection pipelines at Nesjavellir power plant scaled per metre of pipeline (Karlsdóttir et al., 2015). Amounts for a total of 20 km assumed pipe length

Collection pipelines	Unit	Amount
Excavation[a]	m^3/m_{pipes}	18
Fill[a]	m^3/m_{pipes}	8.3
Concrete[a]	m^3/m_{pipes}	0.3
Steel[b]	kg/m_{pipes}	197
Aluminium[c]	kg/m_{pipes}	6.2
Mineral wool[d]	kg/m_{pipes}	43

[a] For pipe supports
[b] 86% of steel used in pipes, 14% used in supports, black steel with a density of 7,850 kg/m^3
[c] For cladding collection pipes with 1 mm aluminium shell with a density of 2,700 kg/m^3
[d] For insulating collection pipes with 100 mm thick mineral wool with a density of 150 kg/m^3

Power plant buildings and power plant machinery

For the construction of the power plant and plant machinery, plastics, mineral wool, aluminium, concrete, steel as well as excavation of the area are included in the input of the construction phase (Tables 5 and 6). Copper is included for wiring of the power plant and for the main machinery used for electricity production for the single flash. Input data were gathered from OpenLCA 1.9.0 software (2019) and dataset Ecoinvent 3.2 cut-off. The amount of material is categorized based on the activities during the construction phase such as drilling of geothermal wells, construction of collection pipelines from wells to the power plant, construction of the power plant and power plant machinery used in the manufacturing of single flash technology.

TABLE 5: Materials for the main machinery used in the single-flash power plant (SF), scaled per MW of installed capacity (Karlsdóttir et al., 2015)

Machinery	Unit	Amount SF
Steel[a]	kg/MW	8,620
Stainless steel[b]	kg/MW	2,340
Aluminium	kg/MW	242
Copper[a]	kg/MW	363
Titanium	kg/MW	523
Mineral wool	kg/MW	246
Plastic[c]	kg/MW	8
GRP	kg/MW	2,120
Transformer oil[a]	kg/MW	662

[a] Amounts of steel, copper, and transformer oil estimated from total weight and the material composition
[b] 316L grade stainless steel; [c] 100% PE plastic [d] Fiberglass reinforced plastic

B. Operation phase

The operation phase usually requires fewer material resources compared to the construction phase. However, to keep the geothermal power plant operating in its full capacity geothermal fluids, groundwater, and electricity are important inputs together with maintenance of equipment. For geothermal development, this phase is site specific since geothermal reservoirs are in nature unique in terms of available mass flows, temperatures and chemical composition of geothermal fluids. Power plants can have varying operational parameters such as the ratio between the actual power output and the installed potential (capacity factor), groundwater needs and auxiliary power demand. Maintenance of the geothermal power plants is governed by the need for additional wells to sustain the production during the lifetime (Karlsdóttir et al., 2015). Information about the power plant operation, maintenance and the geothermal fluid composition at Nesjavellir is presented in Tables 7, 8, and 9.

TABLE 6: Materials and construction work requirements for the power plant buildings for the single flash (SF) set up at Nesjavellir power plant, scaled per MW of installed capacity (Karlsdóttir et al., 2015)

Power plant buildings	Unit	Amount SF
Excavation[a]	m^3/MW	2.17
Fill[b]	m^3/MW	2.43
Concrete	m^3/MW	86
Steel[c]	kg/MW	11.9
Stainless steel[d]	kg/MW	517
Aluminium[e]	kg/MW	578
Copper[f]	kg/MW	152
Mineral wool	kg/MW	567
Plastic[g]	kg/MW	702
Asphalt[h]	kg/MW	31.6

[a] 7% for construction of roads and preparation of land, 90% for power house, 2% for cold water works, and 1% for staff facilities.

[b] 23% for construction of roads and preparation of land, 76% for power house, 1% for staff facilities.

[c] Mostly, 316L grade stainless steel; [d] For reinforcement of concrete, support beams, and machinery supports

[e] Sheets for wall and roof cladding

[f] In electrical wires, calculated from length, cross-sectional area, and density of 8,790 kg/m^3

[g] 60% polyethylene (PE) plastic and 40% polyvinylchloride (PVC) plastic for piping

[h] Asphalt for roads is estimated by the assumptions of 50 mm thick asphalt with a density of 2,360 kg/m^3.

TABLE 7: The site-specific parameters used for normalization of the inventory data for the operation and maintenance of Nesjavellir geothermal power plant assuming 30 years of lifetime (OR, 2018)

Operational and maintenance data for power plant	Input	Unit	Amount
Power plant parameters			
Capacity factor	-	%	0.87
Life time	-	years	30
Operation (input-raw materials)			
Geothermal fluid[a]	Input	kg/s	530
Groundwater	Input	kg/s	100
Auxiliary power demand factor[b]	Input	%	4
Maintenance			
Making up wells[c]	Input	wells	10
Collection pipelines[d]	Input	m	7,410
Sodium hypochlorite[e] (amount per cooling tower)	Input	kg	100,000
Operational data from past to future (30 year lifetime projections)[f]			
1998-2000	-	MW	60
2001-2004	-	MW	90
2005-2019	-	MW	120
Total production 1998-2019	-	GWh	15.7
Future production 30 years (2020-2050)	-	GWh	27.4
Total past and future production	-	GWh	43.2

[a] Detailed inventory is provided in Table 8. Data is for 2017 from ON Power Company. The total flow of geothermal fluid in 2017 was 16,640,598 tons. The geothermal fluid is a mixture (brine and steam) where brine is 55% and steam 45% of the total geothermal fluid flow from the well.

[b] Based on total produced electricity at Nesjavellir power plant.

[c] Including wellhead equipment, each well make up assumed to be 1,600 m av. depth, detailed inventory presented in Table 3.

[d] Length of collection pipelines for connecting make up wells to power plant is calculated from the average length per well in the construction phase.

[e] Added to cooling circuit for regular cleaning. The amount is used per year.

[f] Time horizon chosen is 30-year lifetime from now. Nesjavellir started operating in 1990; therefore, to date it has been in operation for 29 years. System boundaries include construction and operation phases, therefore past and future data are calculated.

According to the primary data from ON Power Company (2019), additional production wells have been drilled every 2 to 5 years, for this study we assume that a new well is drilled every 3 years. The following assumptions are made for the parameters in the maintenance activity:

i. Production lifetime for this LCA study is considered 30 years;
ii. Every three years, a new well is constructed. Therefore, in 30-year lifetime 10 make-up wells are expected to be constructed;
iii. In the construction phase, the total length of collection pipelines is 20 km;
iv. The power plant is connected to a total of 27 production wells, therefore the average length of collection pipeline used per well is 741 m; and
v. New total length of collection pipelines for 10 make-up production wells within 30-year lifetime is 7,410 m.

Justifications of the specific parameters are presented in Table 7. The amount of sodium hypochlorite per cooling tower is taken from Karlsdóttir et al. (2015) inventory study for Hellisheidi geothermal power plant. The amount remained the same assuming that sodium hypochlorite does not have any impact to the results.

TABLE 8: Total mass flow of the geothermal fluid in 2017 at Nesjavellir geothermal power plant including waste flows and chemical characterization of the geothermal fluid (OR, 2018); 2017 data from ON Power Company (2019). The geothermal fluid is a mixture (brine and steam), where brine is 55% and steam 45% of the total geothermal fluid flow from the well.

Mass flow	Unit	Amount SF
Total flow	tons	16,600,000
Thereof steam	tons	7,500,000
Thereof brine	tons	9,139,000
Final waste flows		
To reinjection[a]	m^3	8,400,000
To surface/lake[b]	m^3	7,650,000
Evaporation	m^3	597,000
Chemical characterization of the geothermal fluid (separated brine)		
Arsenic (As)	µg/L	58.3
Barium (Ba)	µg/L	0.25
Cadmium (Cd)	µg/L	<0.002
Cobalt (Co)	µg/L	0.02
Chromium (Cr)	µg/L	0.43
Copper (Cu)	µg/L	2.47
Mercury (Hg)	µg/L	<0.002
Manganese (Mn)	µg/L	1.26
Molybdenum (Mo)	µg/L	2.62
Nickel (Ni)	µg/L	2.44
Phosphorous (P)	µg/L	<1
Lead (Pb)	µg/L	0.01
Titanium (Ti)	µg/L	0.06
Antimony (Sb)	µg/L	0.27
Selenium (Se)	µg/L	7.60
Strontium (Sr)	µg/L	2.11
Vanadium (V)	µg/L	2.46
Zinc (Zn)	µg/L	8.19

[a] Reinjection wells are shallow wells that do not feed the deeper geothermal reservoir.
[b] 46% of the geothermal fluid used in the power plant is released to the surface.

TABLE 9: Unit process for the use of geothermal fluid in Nesjavellir geothermal power plant, scaled to 1 kg of use

Parameters of unit process	**Input/output**	**Unit**	**Amount**
Output to techno sphere			
Geothermal fluid, 1 kg at plant		kg	1
Resources (input from ecosphere)			
Brine, from ground	Input	kg	0.55
Steam, from ground	Input	kg	0.45
Geothermal energy, thermal energy	Input	kJ	1,590
Emissions to air			
CO_2	Output	g	0.87
H_2S	Output	g	0.43
H_2	Output	g	0.02
CH_4	Output	mg	1.86
Emissions to water[a]			
Arsenic (As)	Output	µg	26.8
Barium (Ba)	Output	µg	0.12
Cadmium (Cd)	Output	µg	<0.001
Cobalt (Co)	Output	µg	0.01
Chromium (Cr)	Output	µg	0.2
Copper (Cu)	Output	µg	1.14
Mercury (Hg)	Output	µg	<0.001
Manganese (Mn)	Output	µg	0.58
Molybdenum (Mo)	Output	µg	1.21
Nickel (Ni)	Output	µg	1.12
Phosphorus (P)	Output	µg	<0.46
Lead (Pb)	Output	µg	0.005
Titanium (Ti)	Output	µg	0.03
Antimony (Sb)	Output	µg	0.12
Selenium (Se)	Output	µg	3.5
Strontium (Sr)	Output	µg	0.97
Vanadium (V)	Output	µg	1.13
Zinc (Zn)	Output	µg	3.77

[a] 46% of the waste flow that is released on surface. Calculated from the total presented in Table 8.

4.3.3 Life Cycle Impact Assessment (LCIA) method

In this stage, the inventory results gathered in Section 4.3.2 are transformed into potential environmental impacts based on the characterization and classification models in the OpenLCA and dataset Ecoinvent. Impact assessment method helps to understand and evaluate the potential environmental impacts emanating from a product system, for this case a geothermal power plant. The LCI information gathered in Section 4.3.2 cannot analyse the performance of a geothermal power plant itself, it needs to connect with the LCIA method to extract all information in the LCI and bridge to their potential environmental problems or damages.

According to ISO 14042, the LCI results are categorized into impact categories that are relevant to the scope and goal of the LCA study and each category has an environmental indicator. These categories represent amount of impact potential which are categorized into two:

i. Midpoint categories which signifies environmental problems such as acidification, ozone depletion, climate change, eutrophication and so forth; and
ii. Endpoint categories that indicates environmental damages such as loss of biodiversity, human health impairment and so forth.

Different LCIA methods exist in the OpenLCA software, however, this study selected ReCiPe 2016 Midpoint (E) and Impact 2002+ as LCA impact assessment methods to calculate the potential environmental impacts of 1 kWh of electricity generation. ReCiPe 2016 Midpoint (E) and Impact 2002+ were chosen due to their impact categories for which the study needed to contextualise the potential impacts of geothermal power production for better decision making particularly to countries that are planning to embark into geothermal as source of energy for electricity production.

The ReCiPe Midpoint 2016 method has 18 different environmental indicators but only five impact categories were selected which are water consumption, global warming potential, land use, fine particulate matters and freshwater ecotoxicity. Whereas, Impact 2002+ method has 14 environmental indicators, however, only one impact category is selected which is aquatic acidification. These selected impact categories are of high significance for socio-economic development and requires to be protected since are prone to pollution from industrial activities. Therefore, this study concentrated on only six impact categories due to limited time to understand the impact that the geothermal life cycle imposes on them. The selected impact categories are described below: -

Global warming potential

This category describes a change in global temperature caused by the greenhouse effect due to the release of greenhouse gases (GHGs) by anthropogenic activities. The increase in these emissions is having a conspicuous effect on climate change. The increase in global temperature is expected to cause climatic disturbance, desertification, rising sea levels and spread of disease. Climate change is one of the major environmental effects of economic activity and one of the most difficult to handle because of its broad scale. This category is expressed over the time horizon of different numbers of years with 100 years being the most common (GWP100), it is measured in the reference unit kg CO_2 equivalent (Acero, 2015).

Acidification

This impact category describes potential impacts on soil and freshwater that become more acidic due to deposition of certain pollutants from the air such as acidic gases like ammonia (NH_3), nitrogen oxides (NO_x) and sulphur oxides (SO_x). Acidification potential is expressed using the reference unit kg SO_2 equivalent. The model does not take into account regional differences in terms of which areas are more or less susceptible to acidification. However, this study has modified the impact to include the effects of H_2S emissions. When H_2S is exposed to air, it is converted to SO_2 (Acero et al., 2015).

Eco-toxicity potential

This category provides a method for describing fate, exposure and the effects of toxic substances on the environment. Characterization factors are expressed using the reference unit kg 1,4-dichlorobenzene equivalent (1,4-DCB) and are measured separately for impacts of toxic substances on fresh-water aquatic ecosystems, marine ecosystems, and terrestrial ecosystems. The emission of some substances such as heavy metals can have impacts on the ecosystem (Acero et al., 2015).

Particulate matter

This category estimates the potential effect of fine dust emissions on human health. Particulate matter (PM) is a complex mixture of extremely small particles. Particle pollution can contain a number of components including acids (such as nitrates and sulphates), organic chemicals, metals, and soil or dust particles. A multitude of health problems, especially of the respiratory tract, is linked to particle pollution. This category includes the assessment of primary and secondary particulate matter. Particulate matter is measured in PM2.5 or PM10 equivalents, i.e., particles with a size of 2.5 or 10 µm (Acero et al., 2015). The creation of secondary PM is due to SOx, NOx and NH_3 emissions and CO_2.

Land use

Land use generally refers to the amount and quality of land that is occupied or transformed. It is based on changes in soil organic matter (SOM) due to different categories of land use. SOM is a keystone soil quality indicator and influences properties like buffer capacity, soil structure and fertility. The damage is expressed as "potentially disappeared fraction of species" (PDF) per m^2 or m^2/a (square metre of land per year). To calculate land use effects in LCA studies, these characterization factors need to be multiplied with the land occupation. Biodiversity impacts are not covered in this method (Acero et al., 2015).

Water consumption
This impact category describes the consumption of water and is a measure of the scarcity of a substance. It depends on the amount of resources and the extraction rate. Water consumption is expressed in m^3 (Acero et al., 2015).

4.3.4 Interpretation of the results

The results are presented for six different impact categories selected to survey the potential effects caused by the geothermal energy development, see Table 10 and Figure 9. The results in Table 10 are presented as the total sum for both the construction and production phase for 1 kWh of electricity production, assuming a 30-year lifetime from 2019. Fine particulate matter, freshwater ecotoxicity, global warming, land use, water consumption, and aquatic acidification contribute 0.021g PM2.5 eq, 0.247g 1,4-DCB, 16.7g CO_2 eq, 7.09 x$10^{-5}m^2$ of a crop area, 3.5 x $10^{-3}m^3$, and 12.9g SO_2 eq, respectively.

TABLE 10: Life cycle assessment (LCIA) results calculated from ReCiPe 2016 Midpoint (E) using OpenLCA software

Impact category	Results	Unit
ReCiPe 2016 Midpoint (E)		
	1 kWh of electricity production	
Fine particulate matter formation	0.021	g PM2.5 eq
Freshwater ecotoxicity	0.247	g 1,4-DCB
Global warming	16.7	g CO_2 eq
Land use	7.09E-05	m^2/y crop eq
Water consumption	3.5E-3	m^3
Impact 2002+		
Aquatic acidification	12.9	g SO_2 eq

The results in Figure 9 are scaled as percentage per impact category in order to allow a wide description of values relative to the phases. The values for the different impact categories mostly consist of the

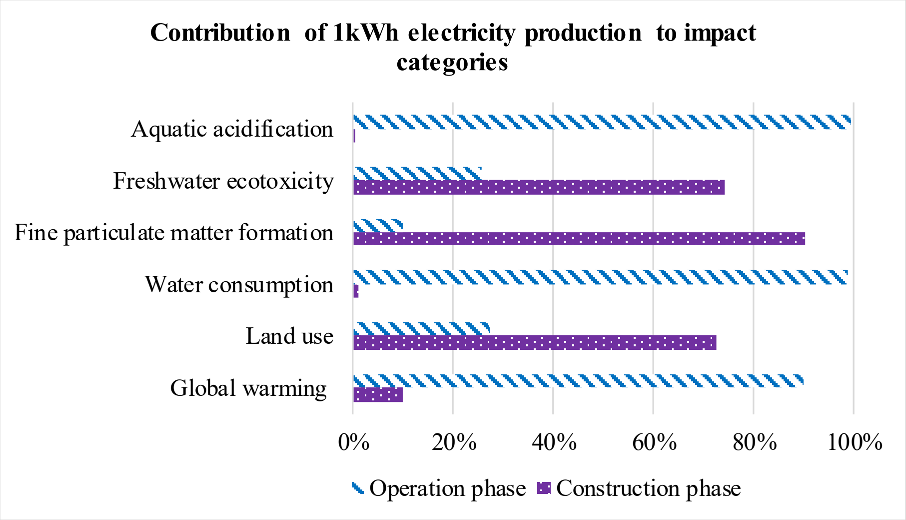

FIGURE 9: Relative contributions of construction and operation phases to the ReCiPe 2016 Midpoint (E) and Impact 2002+ selected impact categories

inputs that were used during construction and operation phases, assuming the time horizon of 30-year lifetime.

According to the results in Figure 9, operation of the geothermal power plant contributes to potential environmental impacts such as global warming, water consumption and aquatic acidification whereas during construction, the affected impact categories are land use, fine particulate matters and freshwater ecotoxicity. Table 11 has exhausted the activities that have direct influence on the potential environmental impacts as calculated by ReCiPe 2016 Midpoint and Impact 2002+ LCIA methodologies.

TABLE 11: Life cycle assessment (LCIA) results calculated from ReCiPe 2016 Midpoint (E) using OpenLCA software presenting relative contribution of activities to selected impact categories

Description	**Results of selected impact categories**					
Activities	**GWP**	**Land use**	**PM2.5**	**Water consumption**	**Freshwater ecotoxicity**	**Aquatic acidification**
Construction phase						
Geothermal wells	4.15%	60.0%	6.32%	0.68%	3.56%	0.03%
Collection pipelines	2.26%	3.88%	4.09%	0.20%	14.5%	0.01%
Power plant building	1.95%	6.04%	64.8%	0.17%	41.0%	0.34%
Power plant machinery	1.56%	2.76%	15.0%	0.16%	15.1%	0.07%
Operation phase						
Geothermal fluid	83.4%	0%	0%	0%	7.00%	99.5%
Ground water	3.83%	2.65%	4.61%	98.4%	9.90%	0.02%
Maintenance						
Make up wells	1.54%	22.2%	2.34%	0.25%	1.32%	0.01%
Collection pipelines	0.72%	1.44%	1.52%	0.07%	5.36%	0%
Sodium hypochlorite	0.59%	0.99%	1.31%	0.08%	2.26%	0%

Impact category for Global Warming Potential (GWP)

Global warming potential is influenced significantly by the emission of greenhouse gases such as CO_2 and CH_4 to the atmosphere. Depending on site-specific conditions such as geological characteristics of the geothermal reservoir, these gases are present to a varying degree in the geothermal fluid. Once the fluid is utilized to operate the power plant these gases are emitted to the atmosphere, contributing to anthropogenic carbon emissions and climate change. In this study, direct emissions originating from the geothermal fluid contributes to 83.4% of the global warming potential. Emitted CO_2 and CH_4 are 13.8g CO_2 eq and 0.14g CO_2 eq, respectively.

The results are further compared with universal reference values for geothermal power plants that are using flash system technology and other power plants with conventional systems as presented in Table 12 to evaluate the potential contribution to global warming. Results shows that Nesjavellir geothermal power plant's emissions of CO_2 and CH_4 with values of 13.8 g CO_2 eq and 0.14 g CO_2 eq, respectively are well below the average reference values for geothermal power plants using flash technology which are 122 g CO_2 eq and 0.8 g CO_2 eq (Shortall et. al, 2015). Furthermore, in comparison with power plants that are using fossil fuels, geothermal power plants are emitting less GHGs to the environment, making geothermal energy a low emission alternative for future primary energy supply.

TABLE 12: Comparison of impact category GWP results with other energy systems

GHGs emitted	**Nesjavellir geothermal power plant**	**Universal reference values for flash steam geothermal power plants** (Shortall et al., 2015)	**Fossil fuel power plants (natural gas, oil and coal)** (Shortall et al., 2015)
1 kWh of electricity production			
CO_2	13.8 g CO_2 eq	122 g CO_2 eq	450 – 1300 g CO_2 eq
CH_4	0.14 g CO_2 eq	0.8 g CO_2 eq	(CO_2 + CH_4)

The amount of gases released from the geothermal fluid to the environment often depends on the depth of wells and the reservoir and the technology applied, whether it is flash, binary, or combined cycle and if an abatement system is in operation. Geothermal wells which are exceeding 3000 m in depth often yield more non-condensable gases such as CO_2, CH_4, and H_2S, therefore more gases are emitted to the environment through their use (Parisi and Basosi, 2019). However, in the Nesjavellir geothermal field wells are between 1,000 m and 2,200 m deep, therefore, the power plant has considerably less geothermal gases emissions. This is also attributed to geological conditions in the geothermal reservoir.

Abatement systems are used in the geothermal industry as mitigation method to reduce environmental impacts from direct emissions of geothermal gases. As examples, the CarbFix and SulFix methods, capture and store the geothermal gases from the power plant by injecting them into bedrock (Aradóttir et al., 2015). If a power plant has an abatement system, the amount of GHGs and other gases that are emitted is considerably lower than without the system. According to Karlsdóttir et al. (2020), before 2012 Hellisheidi geothermal power plant's GWP was 15.9 g CO_2 eq without the abatement system. After deployment of the CarbFix abatement system in 2014, the GWP was reduced to 11.4 g CO_2 eq.

Furthermore, during the construction phase about 4.15% of the GWP originates from the drilling of the wells. Based on the inventory analysis in Section 4.3.2, diesel is one of the input materials used as an energy source, and when ignites it produces CO_2 which increases potential impact to GWP. Therefore, much of the GWP contribution in this phase originated from diesel. Using electrical powered drills would decrease GWP, but that has not been the case at Nesjavellir up to now.

Impact categories for land use, water consumption and particulate matter

The results for the impact categories of land use, water consumption and particulate matter are compared with the averaged reference values for geothermal power plants for electricity production of 1 kWh in Table 13. The values for Nesjavellir are observed to be lower than the average values. Fine particulate matter emission is negligible.

TABLE 13: Comparison of impact category GWP results with other energy systems

Impact category	**Nesjavellir geothermal power plant**	**Average reference values for geothermal power plants** (Bayer et al., 2013)	**Units**
1 kWh of electricity production			
Land use	7.08×10^{-5} [a]	7×10^{-4}	m^2/y
Water consumption	0.0035	0.038	m^3
Fine Particulate matters	2.06×10^{-5}	N/A	kg PM2.5 eq

[a] Only land use during construction phase is taken into account in the Nesjavellir LCA results. Further analysis should include current land use due to buildings, roads, pipelines etc.

Water consumption during the operation phase accounts for 98% of the total use because a lot of water is required for cooling the power plant during production. Consumption of water for cooling depends on the size of the geothermal power plant and technology in use. For instance, geothermal power plants using binary technology use less water than the ones using flash technology, and Nesjavellir Power Plant uses flash technology for production of electricity. Therefore, in comparison, countries with limited water resources needs to take precautions at early during planning to ensure that freshwater usage for geothermal development and utilization does not conflict with other demands for freshwater.

For the Nesjavellir geothermal power plant, the amount of land calculated from ReCiPe 2016 Midpoint (E) using OpenLCA software is 7.08×10^{-5} m^2 which is lower than the average reference value for geothermal power plants. In general, during the construction phase, land is used for power plant construction, for drilling of geothermal wells and for installation of collection pipelines from geothermal wells to the power plant. Land use needs to be thoroughly considered, especially in countries where geothermal potentials are situated in protected areas, forests, farmlands, and national parks which are restrictive areas for any development.

During construction, particulate matter is emitted in form of fine dust and aerosol fumes from the use of fossil fuels, particularly diesel which is one of the input materials presented in the life cycle inventory analysis in Section 4.3.2. However, based on the results, the amount of PM2.5 is negligible.

Impact categories for aquatic acidification and fresh water ecotoxicity
Impact category for aquatic acidification takes into account the emissions of H_2S to the air, which is measured in SO_2 equivalent. The results show that Nesjavellir geothermal power plant is contributing to aquatic acidification especially during the operation phase. According to the calculations, about 99.5% of the impact is emanating from the geothermal fluid which is emitting 12.9g SO_2 eq of H_2S into the air per kWh. The OpenLCA software and its dataset ecoinvent assumes there is 100% conversion of H_2S to SO_2 for the acidity to be formed. It is important for further research to understand the full conversion of H_2S to SO_2 in Icelandic conditions.

However, emissions of H_2S from geothermal fluids is typical and site specific depending on the characteristics of the bedrock. Icelandic geothermal bedrock is characterized by basaltic rocks which are formed from rapid cooling of lava flows. These rocks tend to contain sulphate and calcite compounds, therefore when exposed, they are likely to emit H_2S and CO_2 (Mortensen and Hardarson, 2019)

LCA results for the impact category of freshwater ecotoxicity in Table 11 indicate that construction phase contributes more compared to the operational phase. This is due to the materials which are used in the construction of the power plant, drilling of the wells and materials for collection pipelines. Therefore, this environmental impact is not evident on-site at Nesjavellir, but rather at the production sites where these materials are being processes. Diesel and drillings fluids contains some organic aromatic compounds which are pollutants when in contact with the environment such as freshwater ecosystems. Therefore, the shallow underground water as well as surface water are most affected.

During the operation phase, lower contribution to freshwater ecotoxicity is observed. It originates from geothermal fluids and ground water utilization and amounts to 7% and 9.9%, respectively. Geothermal fluid or brine contains trace elements such as As, B, Hg, Zn, Pb, Cr, Cd, Ni and others. When brine is concentrated these heavy metals pose a threat to aquatic ecosystems and humans if it finds its way into the food chain. However, Nesjavellir's wastewater contains only small amounts of trace elements. Table 14 presents values of some of the elements observed in the OpenLCA software calculations in grams per 1 kWh of electricity production.

TABLE 14: Life cycle assessment (LCA) results calculated from ReCiPe 2016 Midpoint (E) using OpenLCA software presenting relative contribution of trace elements to freshwater ecotoxicity impact category

Operation phase (geothermal fluid)	**Amount**	**Units**
Chemical composition of final waste flow to lake in 1 kWh of electricity production		
Zinc	0.013	g 1,4-DCB
Copper	0.03	g 1,4-DCB
Selenium	8.51×10^{-4}	g 1,4-DCB
Nickel	8.19×10^{-4}	g 1,4-DCB

5. CONCLUSIONS

The purpose of this study was to preliminarily screen the environmental aspects during the geothermal life cycle for the production of 1 kWh of electricity at the Nesjavellir geothermal power plant. The main emphasis was put on the thorough understanding of weak points in different phases of geothermal power production. Due to time limitations, the study focused on two phases of the geothermal life cycle, that is construction and operation. Assumptions had to be made for some parameters when the original data could not be accessed due to the time restriction.

For future full LCA studies it is important to engross all the stages and activities of geothermal development such as decommissioning, transport and heating systems to calculate the overall potential environmental impact the power plant implies. LCA studies focus on the environmental aspects only disregarding potential social issues. Therefore, social impacts need to be assessed separately. Other potential impacts of geothermal utilizations that are not commonly covered by LCA are; induced seismicity, odour nuisance, noise pollution, land deformation and more.

Based on the LCA results, each phase has its own specific contribution to the potential environmental impacts. For instance, during construction, impact categories that were highly affected are land use, freshwater ecotoxicity, and fine particulate matter production from the use of diesel and other input materials. Land use is important for the installation of a power plant and other auxiliaries. The production of metals, concrete, cement and plastics for the material inputs considered in the life cycle are a large contributor to the environmental effect. Those impacts occur off-site, usually where the materials are being extracted or manufactured.

In the operation phase, emissions of GHGs and other NCGs such as CO_2 and H_2S from the geothermal fluid have an effect on global warming and aquatic acidification potential. However, the results for Nesjavellir are very low when compared to fossil fuel power plants. Hence, making geothermal energy a competitive alternative to fossil fuels for the future primary energy supply is a step forward in the battle against the climate change crisis. Emissions of H_2S and its full conversion to SO_2 affect the acidification potential. It is important to research this conversion under Icelandic conditions to estimate the accuracy of the results and data. In addition, assuming the lifetime of the power plant to be only 30 years also influenced the results.

Geothermal wastewater, or brine, contains heavy metals such as As, B, Hg, Zn, Pb, Cd, Cr and others. The amounts, however, are site-specific. Heavy metals pose health risks to humans as well as to the surrounding ecosystems whether terrestrial or aquatic when concentrations in the geothermal fluid are high. Therefore, periodic monitoring is paramount to ensure that wastewater from geothermal production does not contaminate the environment and affect public health.

A possible mitigation measure is re-injection of excess geothermal fluids and gases from the production process into the reservoir. Such an abatement system is important as it reduces the amount of wastewater and gaseous emissions that come in contact with the environment, such as water bodies, soil and air, hence, making geothermal energy an environmentally friendly and socially accepted source of energy. Re-injection systems also help to maintain pressure and temperature in the reservoir to ensure high long-term production rates.

This study concludes that development of geothermal energy does not cause adverse impacts on the environment in comparison to conventional fuel systems. Countries such as Tanzania that have geothermal potential have to be prepared and learn from the experiences of other countries such as Iceland and the neighbouring country Kenya (conditions and reservoir characteristics in Kenya and Tanzania are very similar) about development scenarios, environmental impacts and their mitigation. The best methods to reduce environmental impacts include an abatement system where geothermal wastewater is re-injected into the reservoir and the diversification of geothermal energy utilization into several uses such as space heating, swimming and spas, and industrial purposes.

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