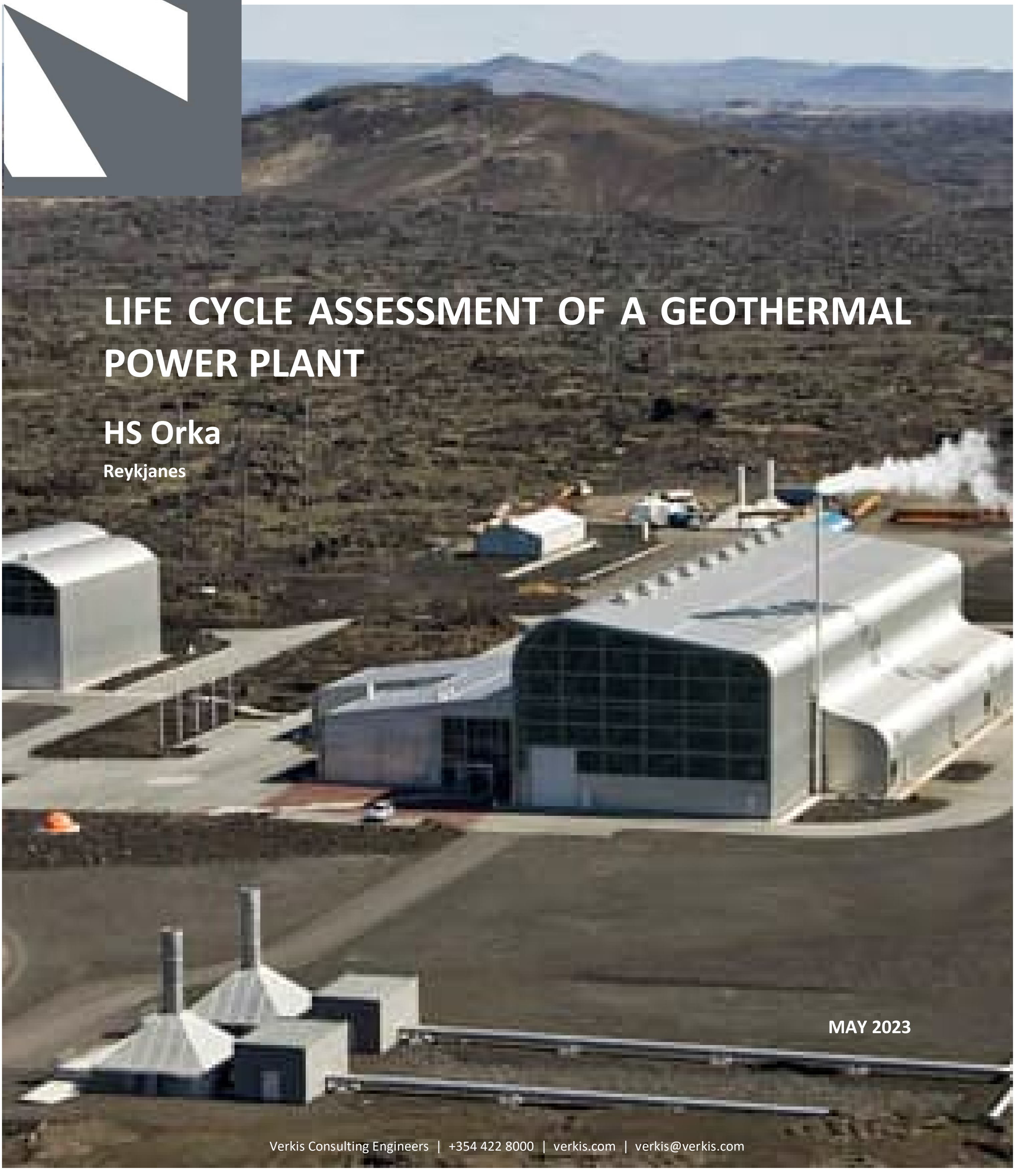
# LIFE CYCLE ASSESSMENT OF A GEOTHERMAL POWER PLANT

## HS Orka

**Reykjanes**



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ABSTRACT:

HS Orka aims to become aligned with the EU taxonomy regulation and therefore a life cycle assessment needs to be performed on their production. The carbon footprint for the Reykjanes power plant was determined to be **17.1 g $CO_2$ eq. per kWh** of energy produced at the power plant over a 30-year lifespan. In the study the scope, system boundary and data collection are described. Results indicate that direct emission of $CO_2$ is the single largest factor for the global warming potential.

| | |
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| KEYWORDS (ENGLISH):<br>Life cycle assessment, geothermal energy, carbon footprint, global warming potential | KEYWORDS (ICELANDIC):<br>Lífferilsgreining, jarðvarmi, kolefnisfótspor, gróðurhúsaáhrif |

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# Independent Limited Assurance Report to HS Orka hf. on the Life Cycle Assessment of a Geothermal Power Plant – HS Orka – Reykjanes

We were engaged by HS Orka hf. (here after HS Orka or the company) to conduct an independent limited assurance on a life cycle assessment for Reykjanesvirkjun and reported in "Life Cycle Assessment of a Geothermal Power Plant – HS Orka – Reykjanes (her after HS Orka's LCA Report) issued by Verkís hf. The scope of our limited assurance was as following:

- If the Life Cycle Emissions reported in the HS Orka's LCA Report" were documented in accordance with the ISO 14067 standard and reported with no material misstatement.

## Limited assurance conclusion

Based on our work performed and evidence obtained, nothing has come to our attention that causes us to believe that above mentioned parts of HS Orka's LCA Report is not, in all material respect, in line with relevant data reviewed.

## Inherent Limitations in Preparing the Sustainability Information

Sustainability and greenhouse gas (GHG) Information is subject to inherent uncertainty because of incomplete scientific and economic knowledge about the likelihood, and effect of possible future physical and transitional climate-related impacts.

## HS Orka management responsibilities

The management at HS Orka is responsible for publishing a LCA regarding the life cycle carbon intensity of the Reykjanes plant that is free from material misstatement. This responsibility includes designing, implementing and maintaining internal control relevant to the preparation of the report that is free from material misstatement, whether due to fraud or error. Further the management of HS Orka is responsible for that their employees and hired contractors that prepare and set up the LCA analysis and report are properly trained and that information systems are up to date.

## Our Responsibilities

Our responsibility is to examine the above-mentioned part of HS Orka LCA Report and to report thereon in the form of an independent limited assurance conclusion based on the evidence obtained. We conducted our engagement in *International Standard on Assurance Engagements (ISAE) 3000 (Revised), Assurance Engagements Other Than Audits or Reviews of Historical Financial Information* issued by the International Auditing and Assurance Standards Board. That standard requires that we plan and perform our procedures to obtain a meaningful level of assurance about whether the above mentioned parts of the LCA report is in all material respect free form material misstatement. The procedures performed in a limited assurance engagement vary in nature and timing from, and are less in extent than for, a reasonable assurance engagement. Consequently, the level of assurance obtained in a limited assurance engagement is substantially lower than the assurance that would have been obtained had a reasonable assurance engagement been performed.

The firm applies International Standard on Quality Management 1, which requires the firm to design, implement and operate a system of quality management including policies or procedures regarding compliance with ethical requirements, professional standards, and applicable legal and regulatory requirements. We have complied with the independence and other ethical requirements of the International Ethics Standards Board for Accountants' *International Code of Ethics for Professional Accountants (including International Independence Standards) (IESBA Code),* which is founded on fundamental principles of integrity, objectivity, professional competence and due care, confidentiality and professional behaviour.

## Procedures

Limited assurance of above-mentioned parts of HS Orka's LCA Report consists of obtaining information, particularly from employees responsible for the information provided in the LCA report, analyse, evaluate and confirm as appropriate. These procedures included i.e.:

- Benchmarked against previous geothermal LCAs and consulted with experts to identify key hotspots in geothermal LCAs
- Interviews with HS Orka data managers and Verkís LCA practitioners
- Critical review of LCA report against ISO 14044 standards
  - The critical review process shall ensure that:
    - the methods used to carry out the LCA are consistent with this International Standard
    - the methods used to carry out the LCA are scientifically and technically valid
    - the data used are appropriate and reasonable in relation to the goal of the study
    - the interpretations reflect the limitations identified and the goal of the study
    - the study report is transparent and consistent.
- Critical review of LCI development and LCA calculations
- Identify material data inputs and request data sample for representative subset
- Inspection of LCA results/calculations

Reykjavík, 14 July 2023

**KPMG ehf.**

Helga Harðardóttir

## *Summary*

Reykjanes geothermal power plant is owned and operated by HS Orka, generating heat and power. The geothermal power plant was commissioned in 2006 and has installed capacity at 100 $MW_e$. A new power plant expansion that will begin generating energy in 2023 is currently under construction. The goal of this study is to summarize the work and result using the life cycle assessment method for energy production at Reykjanes power plant, according to the ISO 14040 and ISO 14044 standards. The life cycle assessment analyzes greenhouse gas emission and the environmental impact per kWh of combined heat and power at the Reykjanes power plant, represented in global warming potential. The system boundaries of the life cycle assessment include the extraction of resources, the production of raw materials, building materials and equipment, transport of raw materials, construction materials, equipment and waste, construction of the power plant as well as operation and maintenance of the power plant over a 30-year lifetime with associated direct emissions from the process, even though the direct emissions have not been directly linked to the geothermal power plants production. It is assumed that the power plant will not be torn down at the end of its lifetime but rather that major electricity production equipment will be renewed, buildings maintained and metals from old equipment recycled. The Reykjanes power plant has a carbon footprint of 17.1 g $CO_2$-eq. per kWh of energy produced. The main source of the carbon footprint, accounting for 15.1 g $CO_2$-eq. per kwh, is the direct release of greenhouse gases from the operating geothermal wells. Where $CO_2$ emissions are the dominant cause and other greenhouse gases, including $CH_4$, were negligible. Other life cycle stages, such as resource and construction and end-of-life, account for 2.0 g $CO_2$-eq. per kwh, with operational energy usage and well and earth works being the largest contributor. A longer lifetime results in lower carbon footprint, therefore it is beneficial to maintain the geothermal power plant.

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## Abbreviations

| | |
|---|---|
| $CO_2$ | Carbon dioxide |
| $CH_4$ | Methane |
| CML | CML Characterization Factors method; was created by the University of Leiden, Netherlands |
| $CO_2$-eq. | Carbon dioxide equivalent |
| GHGs | Greenhouse gases |
| GPP | Geothermal power plant |
| GWP | Global warming potential |
| $H_2S$ | Hydrogen sulfide |
| IEA | International Energy Agency |
| LCA | Life cycle assessment or life cycle analysis |
| LCIA | Life cycle impact assessment |
| NEA | National Energy Agency |
| $NO_2$ | Nitrogen dioxide |
| REY | Reykjanes power plant |
| REY1/REY2 | Reykjanes power plant, current plant |
| REY4 | Reykjanes power plant, extension |

# 1 Introduction

## 1.1 Background

HS Orka is an Icelandic power company that owns and operates two geothermal power plants (GPP) in the south of Iceland, Svartsengi and Reykjanes power plants, along with one hydropower plant. The company produces and sells renewable electricity along with hot and cold water to neighboring municipalities. HS Orka has been producing renewable energy and heat since 1978. The company has been growing constantly since then and the newest addition is expansion of the Reykjanes power plant (HS Orka, 2022). Geothermal energy is renewable and base load energy source that has in general negligible negative impacts on the environment (IPCC, 2011). However, all energy production has some environmental impacts, such as those caused by drilling, building and site completion. Nevertheless IPCC states that geothermal energy production will potentially play a meaningful role in mitigating climate change and help meet the future global energy demand (IPCC, 2011) (IPCC, 2022).

The aim of this project is to analyze the environmental impact of the combined heat and power production of Reykjanes power plant, a GGP owned and operated by HS Orka. Greenhouse gas emission from the power plant will be evaluated using life cycle assessment (LCA) methodology. According to the European Environment Agency´s website, “Life-cycle assessment (LCA) is a process of evaluating the effects that a product has on the environment over the entire period of its life thereby increasing resource-use efficiency and decreasing liabilities. It can be used to study the environmental impact of either a product or the function the product is designed to perform. LCA is commonly referred to as a "cradle-to-grave" analysis.” (European Environment Agency, 2023).

## 1.2 Reykjanes power plant

Reykjanes power plant (ice. Reykjanesvirkjun) began producing energy in May 2006 and takes its name after the area Reykjanes where it is located as shown in Figure 1.1. The plant produces electricity with two 50 MW turbines with steam from 26 wells. Warm sea water is generated from the production as sea water is used for cooling. This seawater is sold to companies in HS Orka’s resource park nearby. Recently constructed is an expansion of the power plant with addition of a new 30 MW turbine, that part of the plant is called REY4 (REY3 was designed but never built). The power plants REY1 and REY2 were built were built together in 2006. For the REY4, no new wells will be drilled, it is only an optimization of the current wells (HS Orka, 2022).


**Figure 1.1** **Location of the Reykjanes power plant.**

In Reykjanes, drilling began in 1956 when the first well was drilled for research. In the years 1968 to 1969 seven additional wells were drilled and then one more in the year 1983. These first nine wells were drilled by other companies for research or production of heat for a salt production plant and none of them are currently in operation today. New wells have been drilled since the year 1999, the newest one in 2019, total of 32 wells drilled by HS Orka. In operation today are, as mentioned above, 26 wells (HS Orka, 2022).

In Table 1.1 below key figures for Reykjanes power plant are summarized, both for the current production and for future production with extension. The current production is based on figures provided by HS Orka for energy capacity and sold energy. The future production is based on generation capacity of the extension and the future thermal energy sold is estimated based on known contracts between HS Orka and companies establishing production facilities in the vicinity of the power plant.

**Table 1.1** **Key figures for RPP with and without the new extension.**

| Reykjanes power plant | With-out extension (REY1 and REY2) | With extension (REY4) |
|---|---|---|
| **Installed capacity** | 100 $MW_e$ | 130 $MW_e$ |
| **Turbines** | 2 x 50 $MW_e$ | 2 x 50 $MW_e$ + 1 x 30 $MW_e$ |
| **Electricity generation capacity** | 876 GWh per year | 1106 GWh per year<br>(230 GWh extension) |
| **Thermal energy sold** | Average 480 GWh per year | Estimated average<br>1337 GWh per year |

# 2 Life cycle assessment

## 2.1 Goal and scope

The goal of this life cycle assessment is to analyze the environmental impact and greenhouse gas (GHG) emission per kWh of energy production in the Reykjanes power plant. The LCA study follows the methodology of the ISO 14067 Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification which is based on principles, requirements, and guidelines in ISO 14040 and ISO 14044 standards on life cycle assessment. Guidelines from Geoenvi project for the life cycle assessment for geothermal systems (Blanc, et al., 2020) are followed to ensure that the results are comparable to similar analyses. The European standards EN 15978 and EN 15804 on sustainability in the construction industry was also considered. For the environmental impact assessment, the study uses the CML methodology (CML-IA 2012) ( Guinée, et al., 2002), based on values reported by IPCC. The environmental impact category that is analysed in this study is global warming potential of 100 years ($GWP_{100}$). A cut-off criteria of 1% was applied since the material excluded had under 1% impact on the final results.

The aim of the LCA is to analyze and evaluate the carbon footprint of electricity and heat production in HS Orka´s GGP, Reykjanes power plant.  Furthermore, the results will be used to confirm that combined heat and power produced by HS Orka is aligned with The European Union’s Taxonomy Regulation on the establishment of a framework to facilitate sustainable investment. In addition, a sensitivity analysis will be conducted to examine the environmental impact of various assumptions stated in the LCA.

## 2.2 Functional unit, lifetime, and allocation

The functional unit of the study is 1 kWh of energy (electricity and heat) produced at Reykjanes power plant and delivered to electricity transmission substation.

In Reykjanes, seawater is used for cooling, thus generating warm seawater in addition to electricity generated from steam from the wells. That seawater as well as hot water from separators, is sold to nearby companies. The emission will therefore be calculated as grams of $CO_2$-eq. for each kWh produced of electricity and sold heat over 30 years of life. Lifetime of 30 years is assumed for the analysis based on the Geoenvi guidelines (Blanc, et al., 2020). As Reykjanes has been operating since 2006 the lifetime is from June 2006 until June 2036. The new extension, REY4, was added in the year 2023.

For this study physical allocation procedure was used, however no allocation is made between the heat and electricity. This LCA is performed to show that Reykjanes power plant’s production fulfills the European Union’s Taxonomy requirements. Table 2.1 shows the total energy production number the study is based on.

The heat and electricity production can be seen in Table 1.1. For the total electricity production over the lifetime the published data from the year 2006 until 2022 is used (Orkustofnun, 2022). For the years 2023 until 2036 estimated data, based on the generation capacity of REY4, is used (HS Orka, 2022). Information about thermal energy sold are available from HS Orka for the last 4 years. The average number based on those last four years is used for years 2006 until 2026. In the year 2027 a contract between HS Orka and a buyer of thermal energy will come into effect. Therefore, it is known that thermal energy sold will increase in the year 2027. The electrical energy generation and thermal energy sold are then summarized over the total lifetime as seen in Table 2.1. The total energy production is 49.4 TWh.

**Table 2.1 Energy production over the 30-year lifetime.**

| Reykjanes power plant | Total amount over 30 years lifetime |
|---|---|
| **Electricity generation capacity** | 25.9 TWh |
| **Thermal energy sold** | 23.5 TWh |
| **Total energy production** | 49.4 TWh |

## 2.3 System boundary

The system boundary is described with the process flow diagram in Figure 2.1. The system boundaries of the LCA include the extraction of resources, the production of raw materials, building materials and equipment, transport of raw materials, construction materials, equipment and waste, construction of the power plant as well as operation and maintenance of the power plant over a 30-year lifetime with associated direct emissions from the process. It is assumed that the power plant will not be torn down at the end of its lifetime but rather that major electricity production equipment will be renewed, buildings maintained and that the metals from old equipment are sent for recycling.

Transmission of electricity by high voltage transmission system is out of scope of this assessment and the cut-off is at the electricity transmission substation. Therefore, no transmission losses are considered in this LCA since the electrical grid is outside the system boundary. In power production the product is used in the same year as it is produced. The GHG emissions are therefore emitted during the production phase and used at the same time.

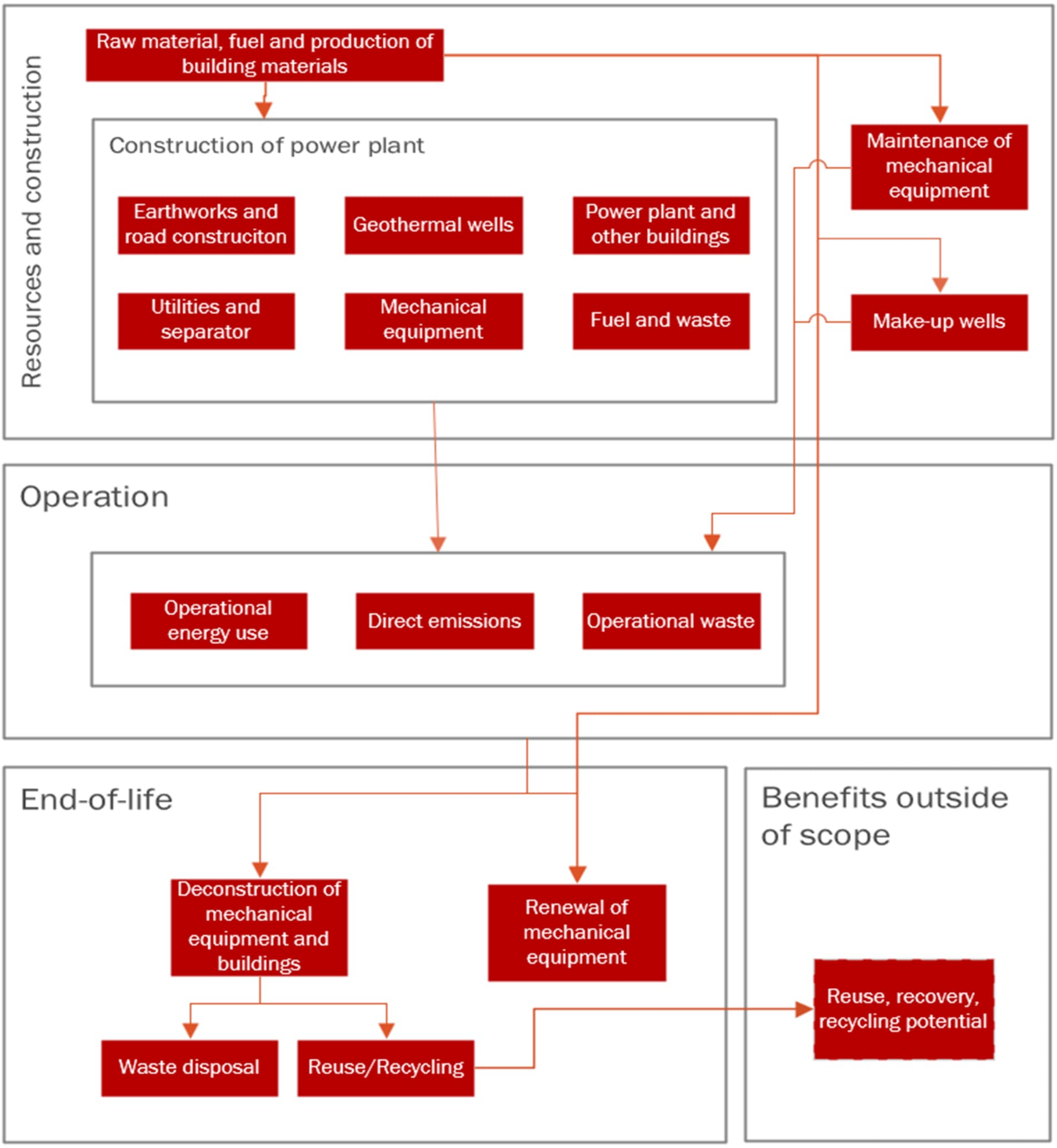


**Figure 2.1** **The main unit processes set up to describe the production of electricity and heat from Reykjanes power plant.**

# 3 Data collection

The software OneClickLCA was used to perform the life cycle assessment. The life cycle inventory was compiled by using primary data from the power plant operator and designers of the power plant, and secondary data from the OneClickLCA database and the Ecoinvent v3.6 database. Data for production of raw materials and building materials was collected from OneClickLCA's database. Direct emissions from geothermal production are based on measurements.

The Reykjanes power plant was built almost 20 years ago. Due to this some of the data needed was unavailable. In those cases, assumptions were made based on available data, input from specialists or recent data. Also, there are some uncertainties regarding the effect of the REY4 expansion on the operation phase. In this chapter the data collection, the quality of the data, high (h), medium (m) or low (l) is stated and limitations are explained, as well as how the data was assumed when limitations occurred.

## 3.1 Production and implementation

Included in the production and implementation phases are:

- Extraction of raw materials and production of building materials for buildings, machinery, and wells
- Transportation of the building materials and machinery to the site
- Fuel consumption during earthworks, road constructions, drilling of wells, constructions of buildings and transport and treatment of construction waste

The product of these phases are the core infrastructures for energy production.

The data for construction of buildings, infrastructure and electrical machinery came from contracts and tender documents. Table 3.1 lists all the tender documents used for data collection. Data for the environmental impact to produce building materials and fuel for Reykjanes power plant is based on European production unless otherwise stated.

**Table 3.1 Contracts for documents used for data collection at Reykjanes power plant.**

| Works | Contract | Explanation |
|---|---|---|
| **Turbine generators** | F0215-1 | Design, manufacturing, and delivery of two 40 or two 50 MW geothermal turbine generator units with auxiliaries. |
| **Turbine condensers and gas removal equipment** | F0215-2 | Design, manufacturing, and delivery of two 40 or two 50 MW geothermal turbine condenser units and/or non-condensable gas removal systems. |
| **Building structures** | F0215-3 | Site layout, road construction, construction of buildings on site. Laying of sewage system and other pipes. All earthwork and construction and operation of the work area during construction. |
| **Machinery and electrical equipment** | F0215-4 | Installation of machinery and electrical equipment, plumping and wiring. Also includes the pre-fabrication of vapor separators and hoods. |
| **Drilling of Geosea wells** | F0215-27 | Drilling and lining of Geosea wells. |
| **Steam turbine** | F0219-401 | Design, manufacturing, and delivery of one 30 MW geothermal steam turbine and auxiliaries. For the expansion of the Power plant. |
| **Building structures** | F0219-407 | Earthwork, construction of new buildings on site also extensions of buildings already on site. Plumping works, ventilation, and electrical works. |
| **Prefabrication of machinery** | F0219-409 | Manufacturing and construction of two MP steam separators and two LP separators and other machinery connected to machinery. |
| **Generator & Interconnection Transformers** | F0219-413 | Design, manufacturing, testing and delivery of one 40 MVA 220-132/16,5 kV unit transformer and one 6,3 MVA, 16,5/11 kV interconnection transformer for the expansion of the Power plant. |
| **Installation of machinery** | F0219-414 | Involves the prefabrication and installation of steel frame floors and the foundations of pipes and equipment. Installation of steam turbines, generators, condensers pumps and other equipment. Installation and connection of all major pipes. |
| **Installation of electrical equipment** | F0219-418 | Involves the construction and installation of substation transformers, distribution cabinets and high voltage cables. Supply and installation of power and control cables. |
| **Drilling of seawater boreholes** | F0219-419 | Drilling, lining and testing of five seawater wells for cooling water. |

### 3.1.1 Building materials

Buildings at Reykjanesvirkjun consist of a powerhouse, substation house and houses for the separators, Figure 3.1 shows the powerhouse under construction. The powerhouse is a steel frame structure on one floor with a footprint approximately 2,300 m² and a height of 20 m. With the expansion of the powerhouse the total footprint is approximately 3,800 m². Substation house is one floor and a steel structure approximately 1,300 m² and a height of 16 m. Table 3.2 shows the amounts of material used in construction of the power plant.

**Figure 3.1 Powerhouse under construction July 2005.**

**Table 3.2 Key figures for material in buildings.**

| Material | Unit | Total amount | Data quality |
|---|---|---|---|
| **Concrete** | Tonnes | 28,645 | *h* |
| **Steel** | Tonnes | 1,946 | *h* |
| **Glass** | Tonnes | 5 | *h* |
| **Rockwool** | Tonnes | 55 | *m* |
| **Aluminum** | Tonnes | 156 | *h* |
| **Rebar** | Tonnes | 1,190 | *h* |
| **High voltage wires (copper)** | Tonnes | 6 | *m* |
| **High voltage wires (aluminum)** | Tonnes | 1 | *m* |
| **Plastic and other material** | Tonnes | 4,937 | *m* |

### 3.1.2 Collection pipelines

The total length of collection pipes at Reykjanesvirkjun is approximately 16 km with different pipe sizes: DN350, DN400, DN450, DN700 and DN1000. The collection pipelines consist of pipes from boreholes, separators, power plant and pipes from sea to the power plant. The collection pipes are made of steel, insulated with mineral wool, and cladded with aluminum sheets. Information was found in the tender documents. Amount for mineral wool and aluminum was estimated using information from (Karlsdottir, et al., 2019). The total amount of materials is summarized in Table 3.3.

**Table 3.3 Key figures for materials in collection pipelines.**

| Material | Unit | Total amount | Data quality |
|---|---|---|---|
| **Steel** | Tonnes | 1,098 | *h* |
| **Aluminum** [a] | Tonnes | 38 | *l* |
| **Mineral wool** [a] | Tonnes | 32 | *l* |

*a* (Karlsdottir, et al., 2019)

### 3.1.3 Machinery

The largest machinery in the current plant consists of:

- Two 50 MW Turbines (Fuji Electric)
- Two 50 MW Condensers (Balcke Dürr)
- Two 50 MW Generators (Fuji Electric)
- Two Bat10 transformers 230-132/16.5kV 80MVA (Tamini)
- One AHT10 transformer 33/11kV 10MVA (Tamini)

With the expansion of the plant additional machinery was added:

- One 30 MW Turbine (Fuji Electric)
- One 30 MW Condenser (Balcke Dürr)
- One 30 MW Generator (Fuji Electric)
- One transformer 220-132/16.5 kV 40 MVA (Tamini)
- One transformer 16.5/11 kV 6.3 MVA (Tamini)

The machinery is made mostly from steel, stainless steel, and copper. It was transported to Iceland by sea-transport from Germany, Japan, Netherlands, and Italy. Figure 3.2 shows the installation and lifting of a turbine. Information about machinery was found in the tender documents and case/work specifications. The total amount of materials is summarized in Table 3.4.

**Table 3.4** **Key figures for machinery materials in Reykjanes power plant.**

| Material | REY1 and REY2 [tonnes] | With new extension [tonnes] | Total amount [tonnes] | Data quality |
|---|---|---|---|---|
| **Stainless steel** | 186 | 86 | 272 | *h* |
| **Steel** | 551 | 474 | 1,025 | *h* |
| **Copper** | 52 | 21 | 73 | *m* |
| **Aluminum** [a] | 24 | 7 | 31 | *l* |

[a]*Amounts for aluminium was estimated using* (Karlsdóttir, et al., 2015)

**Figure 3.2** **Machinery turbine lifting and installation August 2005.**

### 3.1.4 Transportation

For transportation of materials the most common route from each country to Iceland was assumed. It was assumed that all containers, raw material, and machinery were unloaded in Sundahöfn, Reykjavík and trucked to Reykjanes.

Information about the origin of raw materials was found in the tender documents and where information was missing the most common origin for the raw material was assumed. Table 3.5 and Table 3.6 show origin of material and transport distances.

**Table 3.5** **Origin of material and transport distances from manufacturer to Reykjanes.**

| Material | Origin | Transport on land, international and domestic [km] | Transport on sea [km] |
|---|---|---|---|
| **Cement** | Denmark | 170 | 2,500 |
| **Concrete** | Iceland | 55 | - |
| **Rockwool** | Iceland | 330 | - |
| **Steel pipes and structural steel** | Germany | 170 | 3,000 |
| **Steel lining boreholes** | Japan/China | 570 | 21,000 |
| **Rebar** | Estonia | 70 | 3,385 |
| **Timber** | Estonia | 70 | 3,385 |

**Table 3.6** **Origin of machinery and transport distances from manufacturer to Reykjanes.**

| Material | Origin | Transport on land, international and domestic [km] | Transport on sea [km] |
|---|---|---|---|
| **Transformers** | Tamini, Italy | 1055 | 5,200 |
| **Turbines/ Generators** | Fuji Electric, Japan | 206 | 21,000 |
| **Condensers** | Balcke-Dürr, Germany | 350 | 3,000 |

**Figure 3.3 Machinery turbine transported on site in August 2005.**

### 3.1.5 Earthworks

Earthworks involves excavation for the buildings on-site, cold-water tank, transformer stations and filling to and under these structures as well as excavation and filling for ditches where cables and sea cooling pipes are laid.

No data exists on oil consumption during the construction phase. Therefore, it was based on secondary data. The project plan was used to find out the hours used for machinery work (a total of 890 days) and compared to average oil consumption of the main machinery used for this type of structure. Those values came from a recent study for Landsvirkjun on zero emission construction sites, estimates for daily fuel use during construction of a 50-100 MW power plant, 150 km from the capital area, were published, based on a similar project and fuel consumption and engine load factors of equipment. (Mannvit, 2021). The total oil consumption is estimated based on those plans, and the estimated oil use for earthwork is 6.16 million liters.

### 3.1.6 Wells

The quality of the data for the wells is medium as it is based on known data but not detailed information for each well. This applies to both geothermal and geosea wells, including make-up wells.

#### *3.1.6.1 Geothermal wells*

The energy production in Reykjanes is based on geothermal liquid from the wells. The high temperature geothermal liquid consists of steam and hot water. The steam is used to power the turbines that generate electricity.

The total number of wells drilled by HS Orka and included in the scope are 32, and they are listed in Table 3.7. The wells in Reykjanes are up to 3000 m deep. The average well is about 2300 m deep. This is based on information from HS Orka and the National Energy Authority (Orkustofnun, 2022) (HS Orka)

Based on the history of drilling of wells, on average 1 make-up well is drilled every 3 years, so for the rest of the lifetime, until 2036, a total of 5 make-up wells will be needed.

Wells that have already been drilled are included in the production and implementation phase and the make-up wells in the operation phase. Based on HS Orka sustainability policy, they have stated that future wells will be drilled with an electric drill. Figure 3.4 shows drilling in action.

**Table 3.7 Number of wells in the Reykjanes area, the year they are drilled, depth and name of drill used. Þór is the only electrical drill, other drills are powered with diesel oil.**

| Well number | Year drilled | Depth (m) | Name of drill used |
|---|---|---|---|
| **10** | 1999 | 2054 | Jötunn |
| **11** | 2002 | 2248 | Jötunn |
| **12** | 2002 | 2056 | Jötunn |
| **13** | 2003 | 2530 | Geysir |
| **14** | 2004 | 2426 | Jötunn |
| **15** | 2004 | 2507 | Jötunn |
| **16** | 2004 | 2627 | Jötunn |
| **17** | 2005 | 2266 | Jötunn/Geysir |
| **18** | 2005 | 1815 | Geysir |
| **19** | 2005 | 2248 | Geysir |
| **20** | 2005 | 2126 | Geysir |
| **21** | 2005 | 1713 | Geysir |
| **22** | 2006 | 1680 | Geysir |
| **23** | 2006 | 1924 | Jötunn |
| **24** | 2006 | 2114 | Geysir |
| **13b** | 2007 | 2530 | Geysir |
| **14b** | 2007 | 2426 | Jötunn |
| **25** | 2007 | 2180 | Geysir |
| **26** | 2007 | 2200 | Geysir |
| **17b** | 2008 | 3077 | Týr |
| **20b** | 2008 | 3009 | Óðinn |
| **27** | 2008 | 1503 | Óðinn |
| **28** | 2008 | 1200 | Óðinn |
| **29** | 2010 | 2837 | Óðinn |

| Well number | Year drilled | Depth (m) | Name of drill used |
|---|---|---|---|
| **30** | 2011 | 2509 | Óðinn |
| **31** | 2013 | 1223 | Þór (electric drill) |
| **32** | 2013 | 1202 | Þór (electric drill) |
| **33** | 2013 | 2695 | Þór (electric drill) |
| **34** | 2015 | 2695 | Þór (electric drill) |
| **35** | 2017 | 2800 | Þór (electric drill) |
| **36** | 2018 | 2381 | Óðinn |
| **37** | 2019 | 2503 | Þór (electric drill) |

The quantities for material use, energy use and waste from drilling of an average well are summarized in Table 3.8. Material and energy use for the wells was estimated per well instead of per meter to simplify the calculations and since the effect on the results was negligible.

Average diesel oil consumption during drilling is 200,000 L diesel oil per well on average, based on an estimate from a drilling specialist at Icelandic drilling (icel. Jarðboranir) (Sigurjónsson, 2022). This is based on experience from the drilling in Reykjanes. Compared to a recent LCA for Þeistareykir GGP where 183,000 L of oil per well was assumed this estimate is probable. The wells in Reykjanes are wider than the wells in Þeistareykir and therefore the drilling takes longer on average.

An expert in casings for wells estimated the average amount of concrete and steel in well casing (Gunnarsson, 2022).

The estimate is based on the average well in Reykjanes. The figures for waste generated during drilling are from drilling in the newest GGP in Iceland, Þeistareykir (Efla, 2020).

**Table 3.8** **Key figures for material use for each well in Reykjanes power plant. The estimated total amount is based on 32 drilled wells with casing.**

| Material | Unit | Average per well | Total amount | Data quality |
|---|---|---|---|---|
| **Concrete** | Tonnes | 870 | 27,831 | *m* |
| **Steel** | Tonnes | 447 | 14,315 | *m* |
| **Diesel oil (26 wells)** | Thousand L | 200 | 5,200 | *h* |
| **Electricity** [a] | MWh | 725 | 4,350 | *h* |
| **Waste** | | | | |
| **Disposable waste** | Tonnes | 2 | 64 | *l* |
| **Timber** | Tonnes | 4 | 128 | *l* |
| **Metals** | Tonnes | 3 | 96 | *l* |
| **Hazardous waste** | Tonnes | 4 | 128 | *l* |

[a] Total of 6 wells drilled with electricity

**Figure 3.4** **Drilling of a well in February 2004 with the drill Jötunn.**

#### *3.1.6.2 Geosea wells*

A geosea well is drilled to collect seawater for the cooling in Reykjanes power plant as opposed to geothermal wells that provide high temperature geothermal liquid and steam. The geosea wells are wider and not as deep as the geothermal wells. In Reykjanes there are 17 geosea wells in total. Twelve wells were drilled in 2004 – 2005 for REY1 and REY2 and then five for REY4 in 2022. Information for raw material amount was taken from tender documents where amounts for 10 geosea wells were provided, amount per well is derived from that. The drilling time and type of casing is a bit different from the geothermal wells. Based on the estimate from Garðar Sigurjónsson at Icelandic drilling (Jarðboranir) that drilling of 2300 m deep geothermal well requires 200,000 L diesel oil on average, its concluded that for shorter geosea wells average oil consumption will be 5200 L for each geosea well. Waste is assumed to be 25% of the waste for drilling a geothermal well. Key figures for the wells are shown in Table 3.9.

**Table 3.9 Key figures for material use in geosea wells.**

| Material | Unit | Average per well | Total amount | Data quality |
|---|---|---|---|---|
| **Concrete** | Tonnes | 12.0 | 204.0 | *m* |
| **Steel** | Tonnes | 8.9 | 151.5 | *m* |
| **Diesel oil (17 wells)** | L | 5,200 | 88,400 | *m* |
| **Waste** | | | | |
| **Disposable waste** | Tonnes | 0.5 | 8.5 | *l* |
| **Timber** | Tonnes | 1.0 | 17.0 | *l* |
| **Metals** | Tonnes | 0.8 | 12.8 | *l* |
| **Hazardous waste** | Tonnes | 1.0 | 17.0 | *l* |

### 3.1.7 Direct emission

Despite geothermal energy generation has much less adverse environmental effects than traditional sources of energy, it does release a variety of gases into the atmosphere (Ármannsson, et al., 2005). For the most part the gases released are carbon dioxide ($CO_2$) and hydrogen sulfide ($H_2S$) but a trace amount of other gases such as methane ($CH_4$), nitrogen ($N_2$), argon (Ar), carbon monoxide (CO), and hydrogen (H) are also released (Gunnarsson, et al., 2013). Carbon dioxide released from exploitation of geothermal energy is not produced during the production process but would eventually be released over time through natural surface venting. Therefore, no additional $CO_2$ is created and released to the atmosphere from the subsurface (IPCC, 2011). The rate at which the gases are released can be influenced by geothermal processing and drilling. However, the influence is unknown since no studies have been performed on this matter with firm results, indicating an increase or decreased on emission. Some research indicates that over a long period the $CO_2$ natural flow will be less than it was before the start of a geothermal energy production in geothermal areas (O'Sullivan, et al., 2021). It should be noted that due to lack of research on release of gases from geothermal areas it cannot be confirmed that the direct emission counted in this study is directly related to the geothermal power plant. Nevertheless, for this study it will be counted as direct emission from the geothermal energy production.

Since the power plant started operating in 2006 emission reported from the year 1998 to 2005 will be counted with production and implementation. In this study, the GHGs $CO_2$ and $CH_4$ will be the only ones considered, as $H_2S$ is not considered a GHG and therefore does not affect the GWP. Methane will be considered due to its potential to absorb significantly more energy than $CO_2$, which could potentially cause larger reflection in the GWP (EPA, 2022).

All emission from the wells after that time is counted with operation. Emission is monitored yearly and reported to the National Energy Authority, see Table 3.10. The methodology has been improved in the past few years but in this study, it was calculated using samples collected at the turbine inlet, for steam quality. These samples are collected 4 times a year on each turbine. The calculation is based on the annual average composition of the gases multiplied by the total amount of steam that has travelled through the turbines. The assumption with this method is however that all the gas goes to the steam phase during separation of steam and brine. For wells during testing, the monitoring is done once manually at the wellhead, and the results extrapolated over the testing period, in relation to the production. There are some variations between years in the emission. This can be explained because emission from a geothermal area is not constant and naturally have some variations. A common trend that can be seen in geothermal areas is the emission is high first after drilling and then gradually lowers and peaks again once new wells are drilled. The data quality for direct emission is high as it is based on measured, published figures.

**Table 3.10 Direct emission during construction phase.**

| Year | $CO_2$ [tonnes] | $H_2S$ [tonnes] [a] | $CH_4$ [tonnes] [b] |
|---|---|---|---|
| **2005** | 1,276 | 19 | 0.1 |
| **2004** | 1,880 | 46 | 0.2 |
| **2003** | 2,856 | 106 | 0.3 |
| **2002** | 1,135 | 40 | 0.1 |
| **2001** | 1,295 | 46 | 0.1 |
| **2000** | 2,042 | 72 | 0.2 |
| **1999** | 1,290 | 42 | 0.1 |
| **1998** | 1,035 | 36 | 0.1 |
| **Total amount** | **12,809** | **407** | **1.4** |

[a] Not a greenhouse gas, does not affect the GWP.

[b] No data for $CH_4$ have been made public on those years. Estimated values are proportional to $CO_2$ emission.

### 3.1.8 Site completion (Road construction)

Site completion involves smoothing out the surfaces around buildings and laying out the surface finishes such as paths with concrete, concrete tiles, gravel. Paved asphalted roads connected to the power plant are 1.9 km long in total. Parking lots are made of asphalt and total area is approximately 15,000 m$^2$. The calculations are based on GPS maps and the finishes from tender documents.

### 3.1.9 Fuel consumption

Fuel consumption for production and implementation time comes mostly from drilling and earthworks. Fuel consumption for drilling is listed in chapter 3.1.6 and for earthworks in chapter 3.1.5.

### 3.1.10 Waste

Figures for waste during construction for buildings was not monitored during construction of REY1 and REY2. During the construction of REY4 figures for waste were monitored by HS Orka through Klappir. Construction waste from REY4 is used to assume total construction waste. Since REY4 is about 30% of installed capacity it is assumed that the waste is also about 30% of waste for REY1 and REY2. The figures are summarized in Table 3.11. The data quality is high for REY4 since that data is very recent, however for REY1 and REY2 the quality is low for the construction waste.

**Table 3.11 Construction waste for production and implementation time.**

| | REY4 [kg] | REY1 and REY2 [kg] | Total amount [kg] |
|---|---|---|---|
| **General waste** | 7,130 | 23,767 | 30,897 |
| **Treated wood** | 56,470 | 188,233 | 244,703 |
| **Metals for recycling** | 12,800 | 42,667 | 55,467 |
| **Hazardous waste** | 833 | 2,777 | 3,610 |
| **Gypsum or rubble** | 9,280 | 30,933 | 40,213 |
| **Inert waste** | 16,100 | 53,667 | 69,767 |

## 3.2 Operation and maintenance

Phases of the operation and maintenance are:

- Energy use during operation
- Waste during operation
- Direct emission from the wells
- Maintenance of buildings and machinery during the lifetime

### 3.2.1 Energy use

Figures for energy use in the years 2019, 2020 and 2021 are provided by HS Orka and published in their sustainability report (HS Orka, 2021). HS Orka uses an external system called Klappir to keep track of their non-renewable energy use. The electricity use is calculated as the difference between produced and sold electricity. The use of non-renewable energy is fuel for cars or machinery. The electricity use was similar in the three years reported and since the figures are high, a small change does not have a significant effect on the results. Again, the average for the three years is used for the lifetime, seen in Table 3.12. The data quality is medium for energy use as it is based on measured values for the last three years, but assumptions are made for the rest. A limitation in the software, OneClickLCA, where specific electricity mix based on International Energy Agency's (IEA) profile for Iceland for 2019 is used, with the GWP of 0.0288 kg $CO_2$-eq. per kWh. The power plant, however, uses its own electricity with a lower carbon footprint as it does not travel via the system.

**Table 3.12 Energy use during operation time in Reykjanes power plant.**

| Year | Non-renewable energy [MWh] | Electricity [MWh] |
|---|---|---|
| **Average per year** | 701 | 68,061 |
| **Total over lifetime** | 21,020 | 1,327,190 |

### 3.2.2 Waste

Waste generated during the operation of the power plant has been monitored by HS Orka since 2017. HS Orka uses an external system called Klappir to keep track of their waste disposal. Based on the average of those figures, the data for waste over a lifetime have been calculated. No increase in waste was assumed due to the extension since the increase in the operational activity is unknown. The lifetime total and average waste per year is shown in Table 3.13 The data quality is low for the operational waste.

**Table 3.13 Key figures for operational waste at Reykjanes power plant.**

| | Yearly average based on 2017-2021 [kg] | Total amount [kg] |
|---|---|---|
| **General waste** | 5,840 | 175,200 |
| **Treated wood** | 2,068 | 62,025 |
| **Metals for recycling** | 2,255 | 67,650 |
| **Hazardous waste** | 3,423 | 102,683 |
| **Plastic** | 2,160 | 64,800 |

### 3.2.3 Make-up wells

Make-up wells are drilled and cased as new wells. Therefore, the same figures are used as in chapter Wells , except for diesel oil use as it is assumed that all make-up wells are drilled with an electric drill. The make-up wells are assumed to be five during the lifetime. Figures for make-up wells can be seen in Table 3.14.

**Table 3.14 Amount of material used in make-up wells.**

| Material | Unit | Average per well | Total amount |
|---|---|---|---|
| **Concrete** | Tonnes | 870 | 4,350 |
| **Steel** | Tonnes | 447 | 2,235 |
| **Electricity** | MWh | 725 | 3,625 |
| **Waste** | | | |
| **Disposable waste** | Tonnes | 2 | 10 |
| **Timber** | Tonnes | 4 | 20 |
| **Metals** | Tonnes | 3 | 15 |
| **Hazardous waste** | Tonnes | 4 | 20 |

### 3.2.4 Direct emission

During the construction time yearly emission is reported to the National Energy Agency (NEA). The emission from year 2006 to 2020 has been published on the website of the NEA (Orkustofnun, 2022). The monitoring is done manually at turbine inlets four times a year and the results extrapolated over one year in relation to the production. The average emission per year was calculated based on these years. For the years 2006 to 2020 the emission reported was applied, however for the years 2021 to 2036 the average value was used, represented in Table 3.15. The data quality for direct emission during operation time is medium as it is based on known figures for past years but unknown for the future and geothermal direct emissions tends to vary from year to year. As mentioned before $CO_2$, $CH_4$ and $H_2S$ in geothermal areas are released even though no drilling has taken place, whether partly or completely is unknown.

**Table 3.15 Direct emission during operation.**

| Type of gas | Total amount [tonnes] |
|---|---|
| $CO_2$ | 728,922 |
| $H_2S$ [a] | 25,822 |
| $CH_4$ | 78 |

[a] Not a greenhouse gas, does not affect the GWP.

### 3.2.5 Maintenance

The maintenance values are very unclear but do not have a significant impact on the results. It is therefore assumed to be negligible and excluded from the analysis.

## 3.3 End of life

At the end of the lifetime, it is expected that the power plant will continue operations and not be torn down. This assumption is based on the history of GGPs in Iceland. The oldest GGP in Iceland are close to 60 years of age and are still producing electricity at almost full capacity (Orkustofnun). For example, HS Orka owns and operates the Svartsengi power plant that was commissioned in the year 1974. That is almost 50 years of operation. During that time Svartsengi has been extended and renewed to increase the lifetime of the plant.

For the LCA calculations, the following assumptions are made:

- All machinery for REY1 and REY2 is renewed, figures for new machinery are assumed to be the same as the older ones
    - REY4 will only be 15 years old at end-of-life, so it is assumed that renewal is not needed
- Older machineries are disposed of, and all materials recycled
- It is assumed that the buildings and infrastructure will be maintained so their lifetime is longer than 30 years
- All geothermal wells will stay in operation, and two make-up wells will be added (in addition to the five make-up wells during operation)

Since uncertainty is quite high of what refurbishment of the power plant involves, if there will be additional structures or buildings, thus, no assumptions are made on new buildings or demolition of older ones. Therefore, the quality of this data is low. Table 3.16 shows key figures for the end-of-life.

**Table 3.16** **Total values for the end-of-life.**

| | | | |
|---|---|---|---|
| **New machinery** | | | |
| See Table 3.4 | | | |
| **Make-up wells** | | | |
| | **Material** | **Unit** | **Total amount** |
| **Building material for 2 wells** | Concrete | Tonnes | 1,739 |
| | Steel | Tonnes | 895 |
| **Energy for drilling 2 wells** | Electricity | MWh | 1,450 |

# 4 Results

In this chapter the results of the LCA are displayed, the Life Cycle Impact Assessment (LCIA) for production of 1 kWh of electricity and heat at Reykjanes power plant.

## 4.1 Environmental impact during the life cycle of Reykjanes Power Plant

The results show that the total GWP of the power production is 17.1 g $CO_2$-eq. released per 1 kWh produced over the whole life cycle of the power plant. Figure 4.1 shows how the carbon footprint is distributed between different factors of the power plant's lifecycle over a 30-year lifespan. The major contributing factor to the GWP is direct emissions from the geothermal wells, there the $CO_2$ emissions accounts for majority of the GWP, $CH_4$ has a negligible effect. The determined total carbon footprint for direct emission is 15.1 g $CO_2$-eq. per kWh. As a result, the other factors within the GPP life cycle stages contributes to 2.0 g $CO_2$-eq. per kWh, with energy use being the second biggest contributor, followed by wells and earthworks.

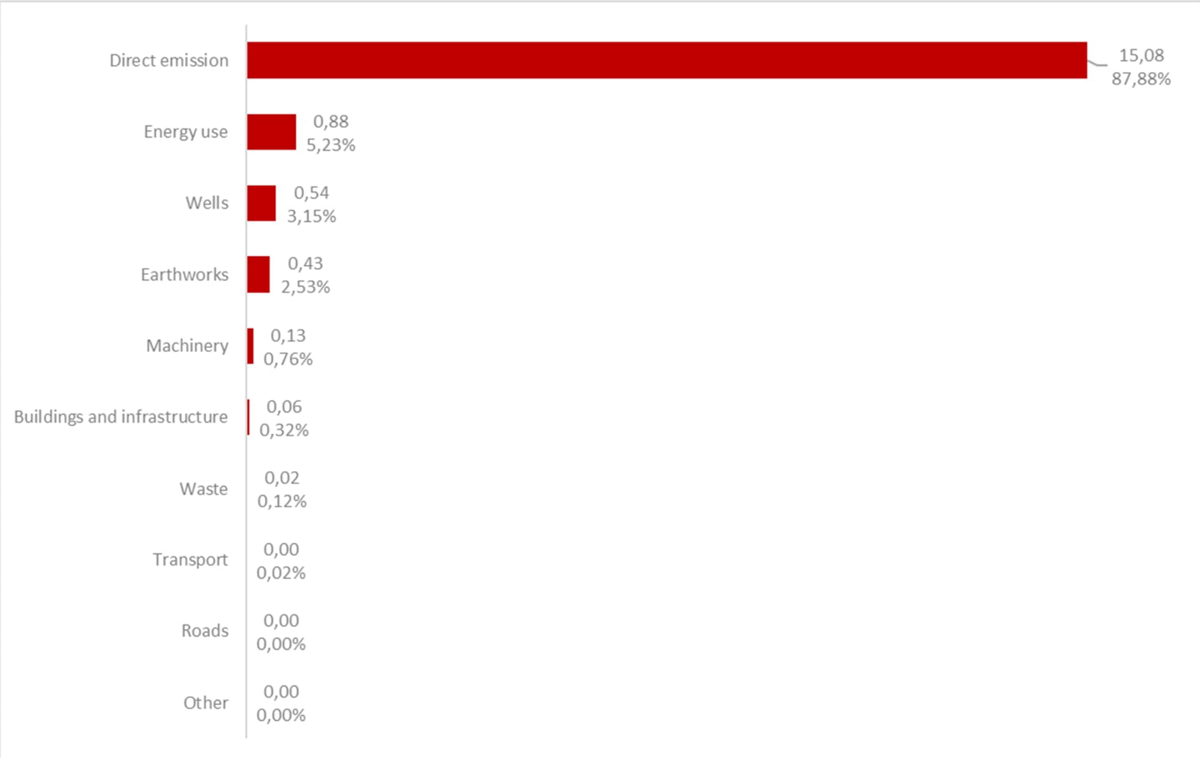


**Figure 4.1 Global Warming Potential total showing both carbon footprint above [g $CO_2$-eq./kWh] and ratio below [%] of each factor in Reykjanes power plant.**

## 4.2 GHG emissions and removals linked to the main life cycle stages

The total GWP for each life cycle stage of Reykjanes power plant is represented in Figure 4.2. The majority of GHG emissions occur during operation life stage, making this stage of the life cycle the most significant GWP contributor, total of 15.9 g CO2-eq./kWh. Construction and resources life stages also has an impact on the GWP. The GWP for the end-of-life stage is the lowest of all life stages. Because of the potential for outside-the-scope reuse, recycling, and recovery, the life stage of external impact is counted as a benefit.

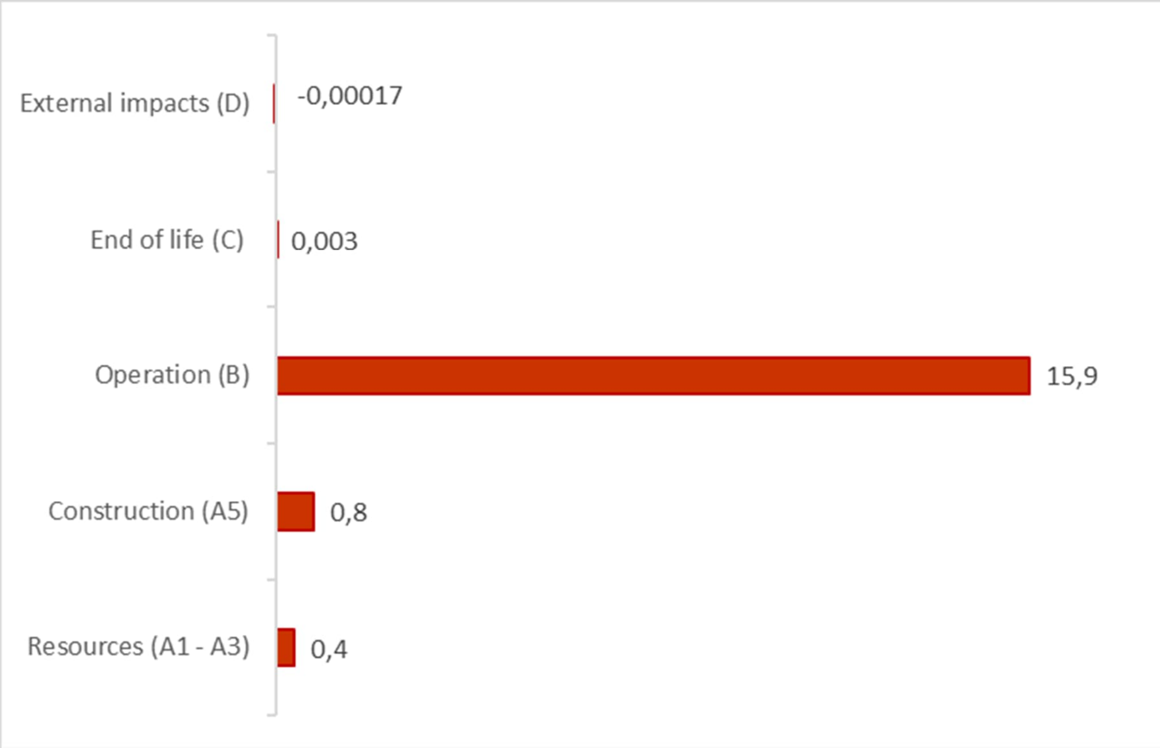


**Figure 4.2 Carbon footprint for each life cycle stage of Reykjanes power plant.**

Figure 4.3 represents the total GWP of processes within each life cycle stage. Within in the end-of-life stage, the waste transport, which contributes 0.003 g $CO_2$-eq./kWh is the largest contributor. This is likely caused by direct emission from fuel usage of transportation. As previously mentioned, the direct emission of $CO_2$ during operation of the power plant, is the largest GWP contributor of the operation life cycle stage, accounting for 14.9 g $CO_2$-eq./kWh. Operational energy use process, releasing 0.90 g $CO_2$-eq. per kWh, is the second largest contributing factor within the operation life stage. Within the resource and construction life stages, the installation into the building has the highest impact on the GWP, with a total GWP of 0.81 g $CO_2$-eq./kWh. Manufacturing of materials is also a significant factor in the life stage, accounting for 0.26 g $CO_2$-eq./kWh.

For GWP transparency, GWP-fossil origin, and GWP-non-fossil origin indicators are important to understand the carbon footprint. Global warming potential fossil is represented in Figure 4.4, displaying the fossil GWP for the processes within each life cycle stage. There the operational energy use is the largest factor; this is due to fossil fuels being part of the national energy mix. Within the resource and construction life stage the process installation into the building has a high impact on GWP fossil, this is because of the fossil fuels used for earthworks and drilling of the wells. Figure 4.5 shows the non-fossil GWP for processes within each life cycle stage, where the uses, and application process dominates. Again, this is a result of $CO_2$ being accounted for as a direct emission from the GPP during operation. The manufacturing process within the resources and contraction stage has a minor impact on the GWP-non-fossil, other processes are negligible.

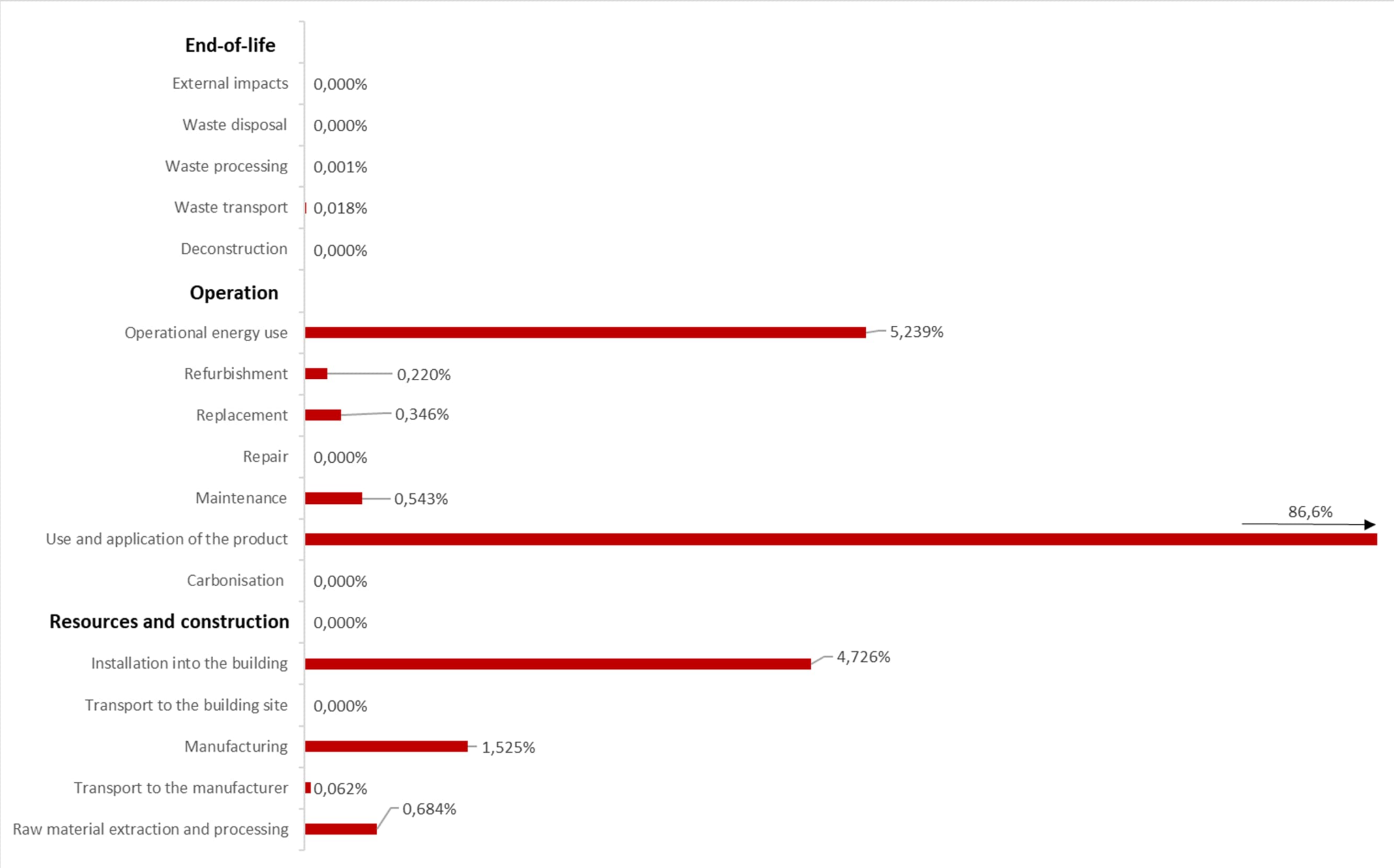


**Figure 4.3 Global warming potential total ratio for each life cycle stage. Note that use and application of the product is much larger than shown in the figure.**

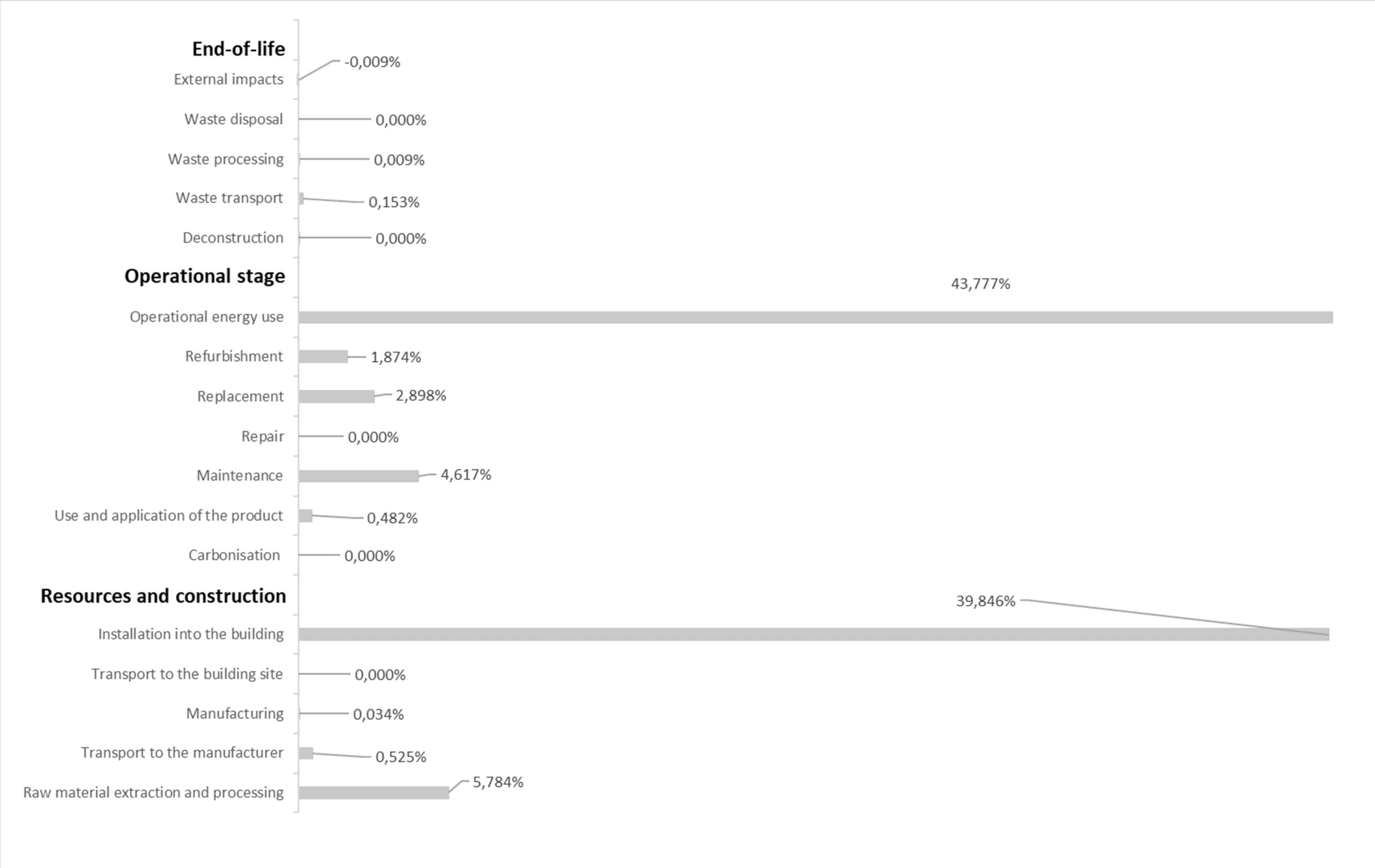


**Figure 4.4 Global warming potential fossil ratio for each life cycle stage.**

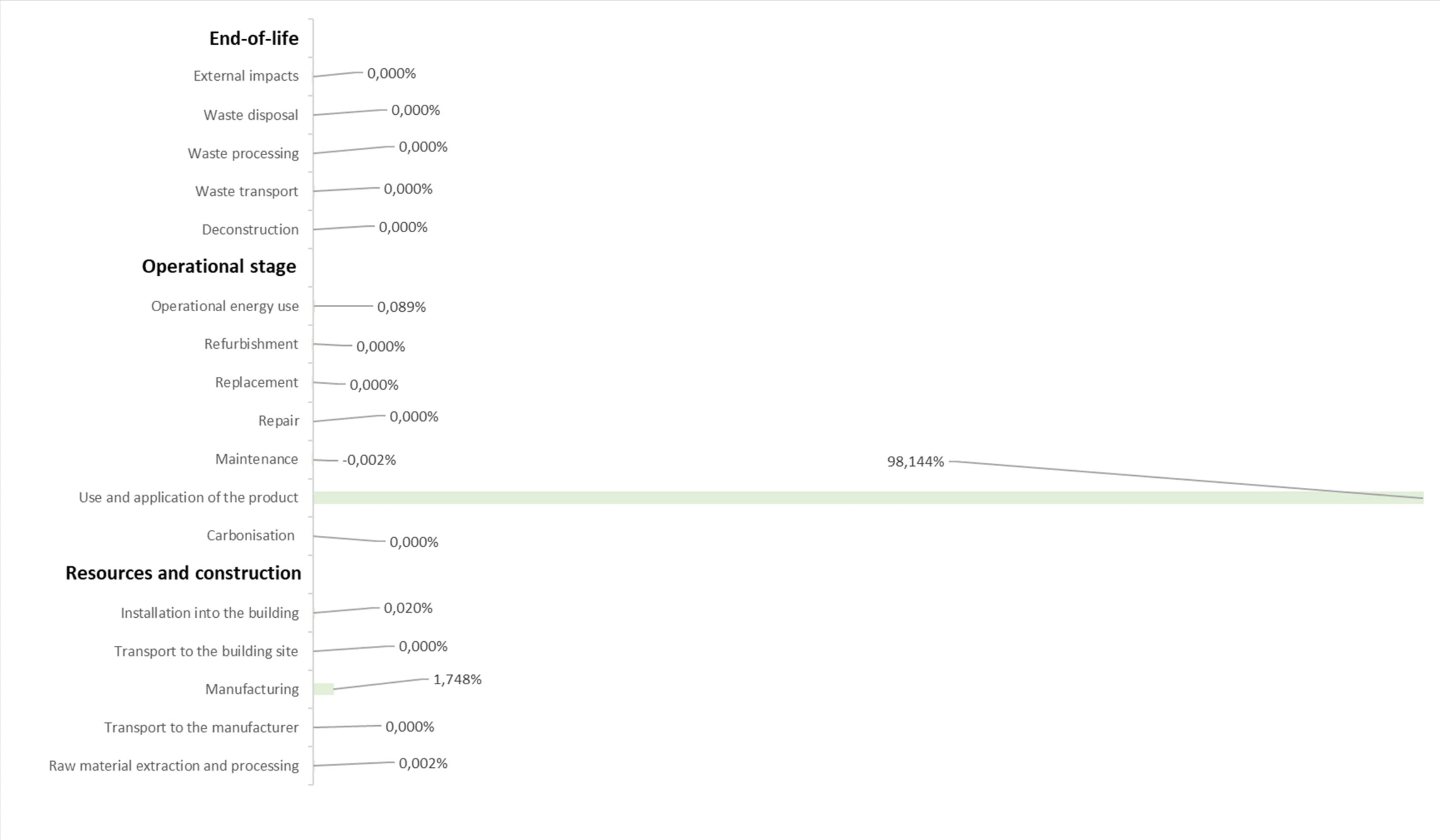


**Figure 4.5 Global warming potential non-fossil ratio for each life cycle stage.**

# 5 Sensitivity analysis

To evaluate the system's sensitivity, various modifications were applied in the sensitivity analysis. Four different sensitivity analyses were performed:

- Direct emission of $CO_2$ and $CH_4$ from operation time of the power plant was decreased and increased up to 50% for the next 15 years.
- The LCA assumes that any future well drilling would involve the use of electrical drills due to HS Orka's sustainability policy. For the following 15 years, it was assumed in the study that 5 new wells would be drilled. Therefore, the impact of diesel oil use, instead of electricity in well drilling operations in the future, was investigated.
- Oil volume was estimated at 200,000 L per well with a 20% uncertainty. For that reason, oil consumption during drilling in this study was both increased and decreased by 20%.
- Lifetime was increased to 40 years, 50 years, and 60 years. In correlation, make-up wells were added (1 for every 3 years), direct emissions ($CO_2$ and $CH_4$) were increased, and the total energy production was increased. Other operational factors were excluded as their effect on the overall carbon footprint is minor.
- The electricity source was modified by using the geothermal power plant’s own electricity. Instead of a specific electricity mix based on IEA for Iceland, according to IEA the electricity mix for Iceland has a low carbon footprint, though it may have an impact on the results.

## 5.1 Direct emission from the power plant

The direct emission of $CO_2$ and $CH_4$ from geothermal areas tend to vary a lot. Since emission for the last 15 years is known, the estimate for future emission was changed to see the effect on the carbon footprint. By modifying the direct emission during operation by 30% the GWP of the power plant per 1 kWh increased and decreased by 2.2 g $CO_2$-eq., see Figure 5.1. When the direct emission was increased to 50% for the next 15 years the GWP increased and decreased by 3.7 g $CO_2$-eq./kWh. As mentioned before the direct emission from GPPs the major contributor to its total carbon footprint, therefore it is particularly sensitive to the amount of GHG released.

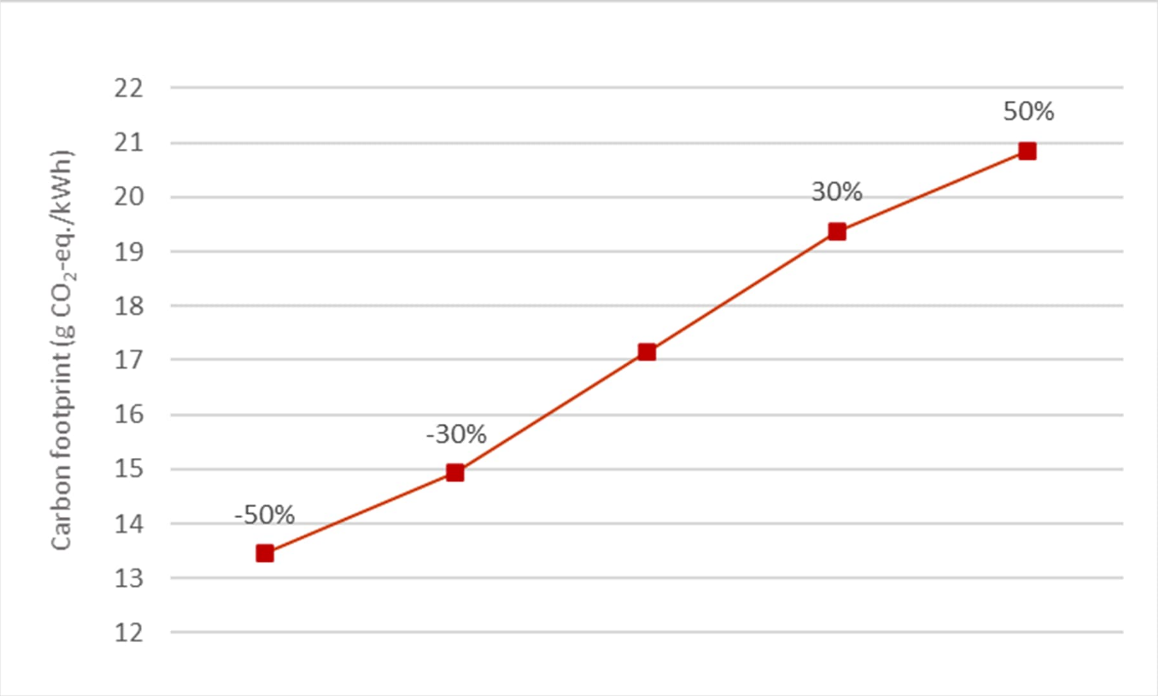


**Figure 5.1 Sensitivity analysis on direct emission of $CO_2$ and $CH_4$ from Reykjanes power plant. Represented in GWP.**

## 5.2 Drilling of wells

The total GWP of the power plant increased to 17.3 g $CO_2$-eq. per 1 kWh when it was assumes that all future drilling would be conducted using diesel rather than electricity as energy source, see Figure 5.2. That is a change in the GWP of less than 1%. The GWP fossil increases from total of 2.1 g $CO_2$-eq./kWh to 2.2 g $CO_2$-eq./kWh. As results show the power plant's carbon footprint is not significantly impacted by the energy source used for future drilling.

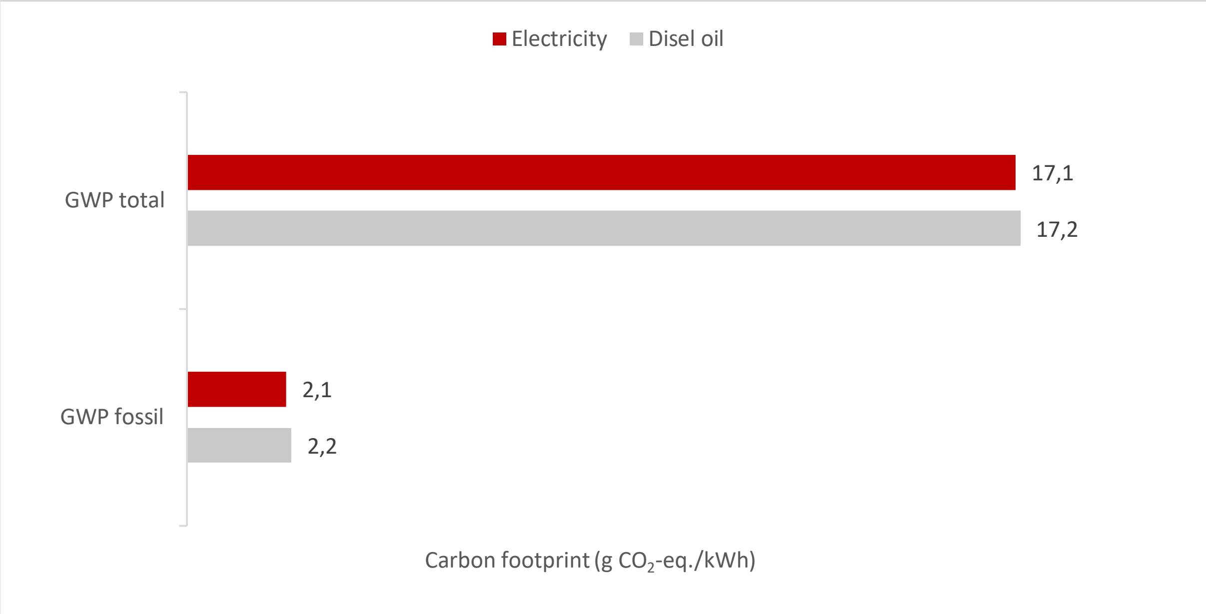


**Figure 5.2 Systems sensitivity on energy source used when drilling wells. Wells drilled with diesel oil compared to the LCA study baseline of electricity drilling.**

Due to 20% uncertainty in the oil consumption during drilling the effect of this was considered. The total GWP altered by less than 1% when the oil consumption during drilling of wells was increased or decreased by 20%, as shown in Table 5.2. When GWP of fossil was examined, the difference between 20% increase and 20% decrease of oil consumption, the GWP fossil altered by 7%. According to the results, the oil consumption when drilling does not significantly affect the power plant's carbon footprint.

**Table 5.1 The GWP total and GWP of fossil when oil consumption of wells drilling is modified.**

| Change | Oil volume (L) | GWP total (g CO2-eq./kWh) | GWP fossil (g CO2-eq./kWh) |
|---|---|---|---|
| **0%** | 5,200,000 | 17.14 | 2.05 |
| **20% decrease** | 4,160,000 | 17.06 | 1.98 |
| **20% increase** | 6,240,000 | 17.21 | 2.13 |

## 5.3 Variation in lifetime

The lifetime was changed to 40 years, 50 years, and 60 years with alterations to the direct emissions, the number of make-up wells and the total energy production and the carbon footprint was calculated for each scenario. The results were plotted and extrapolated (see Figure 5.3). This shows the carbon footprint is slightly lower for a longer lifetime but increases again around the 60- or 70-year mark. Based on this the carbon footprint would increase again after reaching a minimum unless the energy production is increased or optimized.

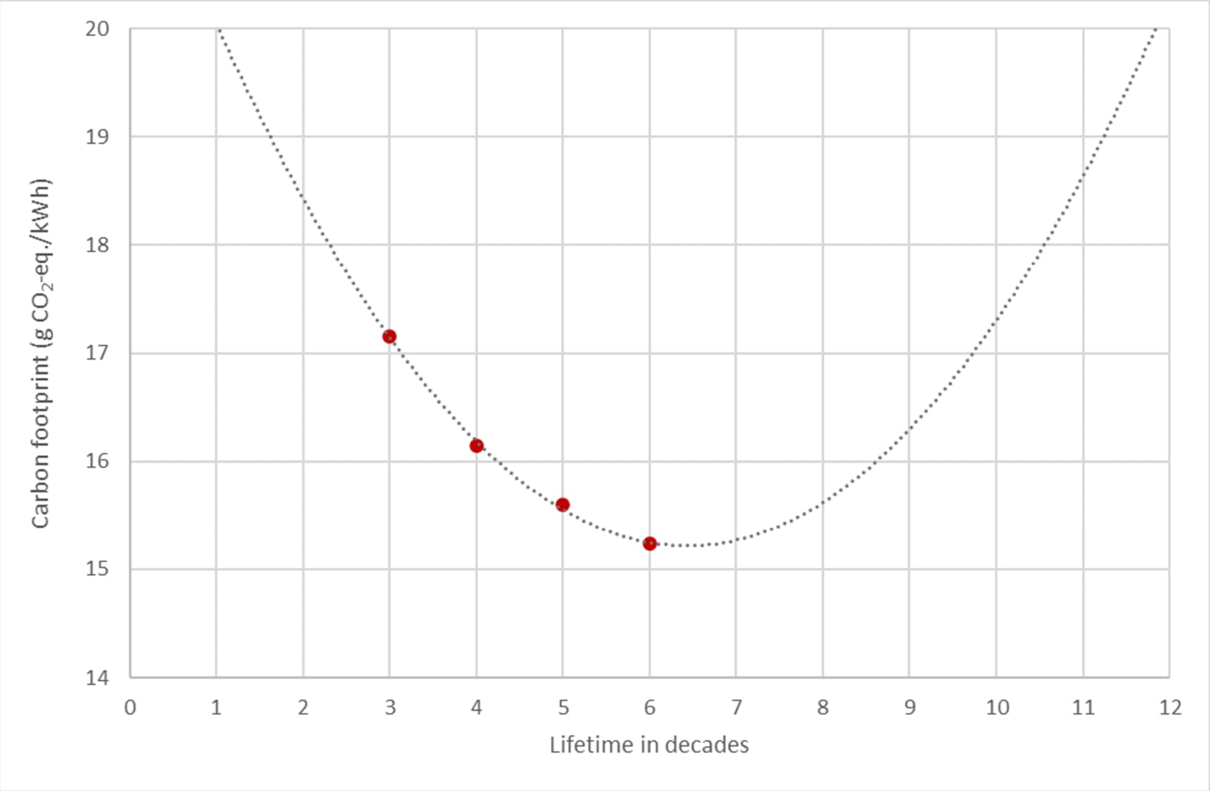


**Figure 5.3 The carbon footprint as a plot of lifetime in years, calculated for 30, 40, 50 and 60 years and the results extrapolated.**

## 5.4 Change in electricity mix

The electricity mix was modified to the power plants own electricity. When the power plant's own electricity requirements are met by the electricity generated by the power plant itself, the electricity will not pass through a transmission system. The total GWP altered by 2% when calculations are based on the electricity produced at Reykjanes power plant. Table 5.2 shows that the system is not sensitive to electricity source. Although it must be noted that Iceland energy is 99% renewable, the impact might change with other electricity mixes.

**Table 5.2 Sensitivity analysis on the GGP electricity mix.**

| Electricity mix | GWP (g $CO_2$-eq./kWh) |
|---|---|
| IEA specific electricity mix for Iceland | 17.1 |
| Reykjanes power plants own electricity | 16.7 |

# 6 Discussion

## Most impactful life cycle stages

### *Total GWP*

When each life stage of the LCA is evaluated, based on total GWP, the operation stage has significantly higher carbon footprint than any other stage. The single largest contributor to the carbon footprint of the power plant is the direct emission of $CO_2$ from the GPP. Direct emission of $CH_4$ had almost no impact on the GWP, due to the trace-minimal amount of $CH_4$ released into the atmosphere during operation. This is in line with other life cycle assessments that have been performed for GPPs. Due to lack of research on release of gases from geothermal areas it cannot be confirmed that the direct emissions counted in this study are directly related to the GPP. The environmental impact would potentially be reduced if it could be determined how much greenhouse gas is in fact emitted naturally through surface venting in geothermal areas and whether there is an emission surplus due to the GPP. Drilling, earth works, and energy use would then be the main factors affecting the GWP whereas currently, with natural emissions being unknown, direct emission are the most significant data item. Although the data's high quality for the emissions is based on annual measurements over the previous 15 years, an estimate for the upcoming 15 years had to be made. Future emissions were evaluated in a sensitivity analysis in which they were both increased and decreased. Figure 5.1 illustrates how the results are affected by changes in the direct emissions. It should be noted that direct emission from geothermal areas can vary, they usually lower over time and peak again once new wells are drilled. Nonetheless, that is represented in the measurements for the past 15 year, and the estimate for next 15 years is based on that. This variation is therefore included in the estimate.

Energy use during the operation life stage has the second largest environmental impact. This is affected by a variety of factors, including electricity use and fuel consumption during machine operation, transportation, and maintenance. Because of software limitations, which require the use of a specific electricity mix based on the IEA for Iceland, the GWP of the electricity is overestimated. This causes some uncertainty in the results, but the carbon footprint, as described in chapter 5.4, would not be significantly affected.

After the operation life cycle stage, the construction life stage is the stage that most significantly contributes to the carbon footprint of a power plant. This is largely attributable to the 26 wells that have been drilled over the past several decades using diesel oil for drilling. In the assessment it is assumed that all future wells will be drilled using electricity and not diesel. Overall, any uncertainty in energy use during construction does not affect the carbon footprint substantially. The amount of oil consumed during well drilling operations has a minor effect on the carbon footprint, regardless of whether there is a 20% uncertainty in the total amount of oil consumption over the power plant's history or if diesel oil is used to power drilling operations in the future.

### *Fossil and non-fossil GWP*

Operational energy use and installation of building are the main contributors to the fossil GWP. That is because, as was already mentioned, a great amount of diesel oil is required for well drilling as well as for machine operation, transportation, and maintenance. Regarding the non-fossil GWP, which is primarily impacted by direct $CO_2$ emissions, all the other factors are negligible except for manufacturing during construction stage. However, that is once more a result of the direct $CO_2$ emissions, because direct emission is included as soon as wells are drilled and measurements began, even before the geothermal energy power plant was put into service.

## Lifetime

In chapter 5.3, the effect of change in lifetime is presented. The carbon footprint is reduced with longer lifetime. However, it reaches a minimum and at that point it would be crucial to increase or optimize the energy production to keep the carbon footprint low. Even though a longer lifespan has some impact on the carbon footprint, it cannot be reduced below approx. 15.2 $CO_2$-eq. g/kWh. However, it is preferable to maintain the power plant to extend its lifespan, instead of demolishing it and constructing a new one. History also reveals that the lifetime for GPP in Iceland is exceeds 30 years considerably, the oldest GPP are currently around the age of 50 years.

## Summary

The information used for this LCA of the Reykjanes power plant's construction and operation is based on a variety of data. Since some of the data is more than 15 years old, its quality varies. However, as was already mentioned, the study's overall data quality for the major contributing elements to the GWP is high including the key parameters. Certain assumptions had to be made, but sensitivity analysis reveals that it does not affect the results substantially. The limitations of the study did not affect the results of the carbon footprint. Even though the data listed as low quality would have been better, it would not have had a significant effect on the result since it does not contribute to a large portion of the GWP. Therefore, any uncertainty in that data is not considered to be impactful.

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# Appendix: Calculations from OneClickLCA