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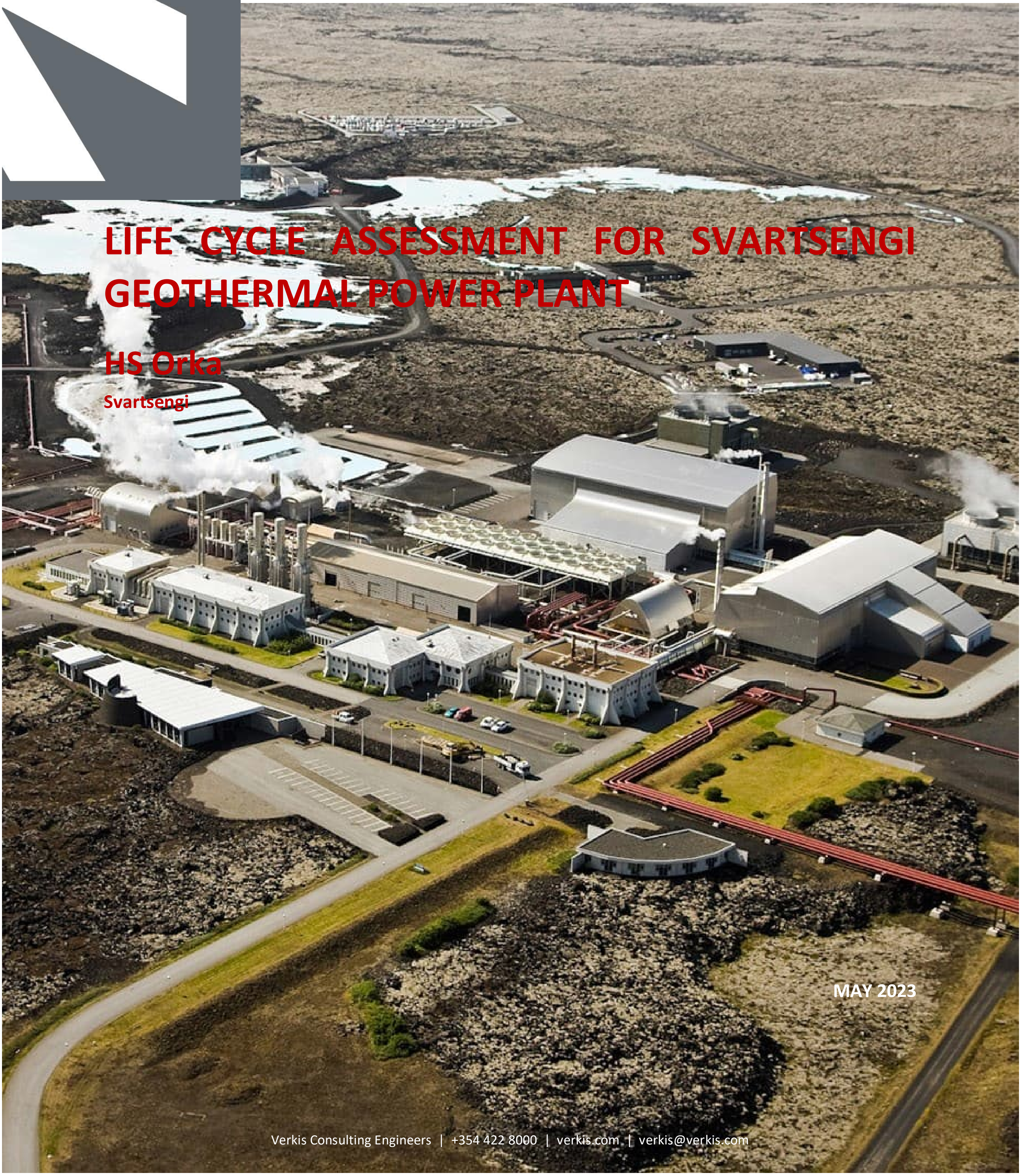

LIFE CYCLE ASSESSMENT FOR SVARTSENGI GEOTHERMAL POWER PLANT

HS Orka

Svartsengi

MAY 2023

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REPORT TITLE:	LCA GREINING RAFORKUFRAMLEIÐSLU HS ORKA_SVA_SKÝRSLA		DISTRIBUTION: ☐ OPEN ☐ CLOSED ☒ SUBJECT TO CLIENT'S APPROVAL
PROJECT:			
REPORT NO.	2	PRODUCT ID: 03062-M	

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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 Svartsengi power plant was determined to be **43.5 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 of the power plant.

KEYWORDS (ENGLISH):
Life cycle assessment, geothermal energy, carbon footprint, global warming potential

KEYWORDS (ICELANDIC):
Lífsferilsgreining, 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 – Svartsengi

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 Svartsengi Geothermal Power Plant and reported in "Life Cycle Assessment for Svartsengi Geothermal Power Plant" (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 Svartsengi 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

Svartsengi geothermal power plant is owned and operated by HS Orka, generating heat and power. The geothermal power plant was commissioned in 1978 and has installed capacity at 75 MW_e and 190 MW_{th}. A new power plant expansion that will begin generating energy in 2025 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 Svartsengi 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 Svartsengi 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. The Svartsengi power plant has a carbon footprint of 43.5 g CO_2-eq. per kWh of energy produced. The main source of the carbon footprint, accounting for 39.7 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 resources, construction and end-of-life, account for 3.7 g CO_2-eq. per kWh, with operational energy usage, drilling, buildings and infrastructure and earthworks being the largest contributor.

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Abbreviations

CO_2	Carbon dioxide
CH_4	Methane
CML	Characterization Factors method; was created by the University of Leiden
CO_2-eq.	Carbon dioxide equivalent
EoL	End of life
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
SVA	Svartsengi power plant
SVA2-6	Svartsengi power plant, current power plant
SVA7	Svartsengi 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 neighbouring municipalities. HS Orka has been steadily expanding since it began generating renewable energy and heat in 1978 (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 analyse the environmental impact of the combined heat and power production of Svartsengi power plant, a GGP owned and operated by HS Orka. Greenhouse gas emission (GHG) from the power plant will be evaluated using a life cycle assessment (LCA) methodology. According to the European Environment Agency a “Life-cycle assessment 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.” (EEA, 2023).

1.2 Svartsengi power plant

The Svartsengi power plant (ice. Svartsengisvirkjun) was constructed in six phases from 1974 to 2008. The power plant is located on the Reykjanes peninsula, see Figure 1.1. The Svartsengi power plant is the first of its kind in Iceland to have combined heat and power production. In the Svartsengi area, three steam wells were originally drilled in 1971; they supplied hot water for a heat exchanger station that was built in 1976.

Six power stations make up the Svartsengi power plant today (SVA1 through SVA6), however SVA1 and SVA3 are no longer in operation. Today, 26 wells are in operation at Svartsengi power plant that provide steam for power stations SVA4, SVA5 and SVA6. Power plant station 2 is the single power station that supplies hot water today (HS Orka, 2023). The two most recently built power stations, SVA5 and SVA6, have been in operation since 2000 and 2007. Power station 7 is in preparations and estimated to be in operation by 2025, and replace SVA4, which began operation in 1989 and is to be replaced to increase efficiency (HS Orka, 2023).

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

Current figures from production and future production with extension of Svartsengi power plant is presented in Table 1.1 and Table 1.2. The figures are based on data for energy capacity and sold energy provided by HS Orka. Future energy production for the years 2023 and 2024 is expected to be the same as in the year 2022. In the year 2025 SVA7 is added and the production from 2026 to 2030 is assumed to be the same as in 2025.

Table 1.1 **Svartsengi power plant total energy production with and without extension.**

Svartsengi power plant	With-out extension (SVA2 - SVA6)	With extension (SVA7)
Installed capacity	75 MW_e	84.9 MW_e
Electricity generation capacity	606 GWh per year	710 GWh per year
Thermal energy sold	973 GWh per year	973 GWh per year

Table 1.2 Installed capacity and installed thermal production capacity for each power station at Svartsengi.

	Installed capacity [MW_e]	Installed thermal production capacity [MW_{th}]
SVA2	-	75.0
SVA3	6.0	-
SVA4	8.5	30.0
SVA5	30.0	75.0
SVA6	30.0	-
SVA7	24.9	40.0

2 Life cycle assessment

2.1 Goal

The goal of this life cycle assessment is to analyse the environmental impact and greenhouse gas (GHG) emission per kWh of energy production of the Svartsengi 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. The 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 were also considered. For the environmental impact assessment, the study uses the CML methodology (CML-IA 2012) based on values reported by IPCC (Guinée, et al., 2002). 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 analyse and evaluate the carbon footprint of electricity and heat production in HS Orka´s GGP, Svartsengi 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 Scope

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

A lifetime of 30 years is assumed for the analysis, from the year 2000 until 2030. This is based on the lifetime of the former power stations at Svartsengi (HS Orka, 2023). This study will consider all production, operations, and activities that takes place over the 30-year lifetime. That implies production from SVA2, SVA3, SVA4, SVA5, and SVA6, as well as the anticipated production from SVA7. Power station 1 ended almost all operation before 2000 and will therefore be excluded from the study. The timeline represented in Figure 2.1 demonstrates the lifespan of the Svartsengi power plant, the end- and starting point of this study's 30-year lifetime. The study's timeline will not include power production operations from the years 1970 to 2000. However, geothermal wells that were drilled before year 2000 and will still be in operation within the study’s lifetime will be within the system boundary, as well as all production, implementation, operation and maintenance of the wells.

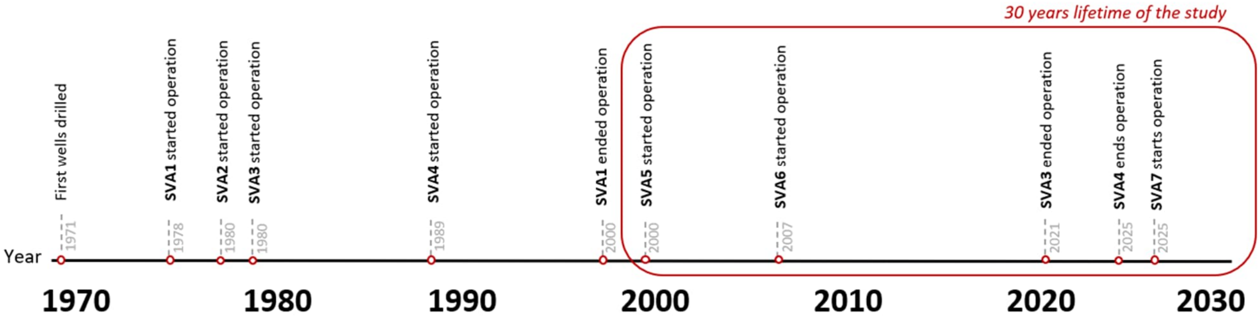

Figure 2.1 **Timeline of Svartsengi geothermal power plant area from 1970-2030.**

The system boundary is described with the process flow diagram in Figure 2.2. 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. All power stations will be included in the resource and construction phase and the operation phase, except for SVA1. End-of-life phase will apply for SVA3 as it stopped operation in 2021 as well as SVA4, which is assumed to stop operating in 2025 when SVA7 takes over.

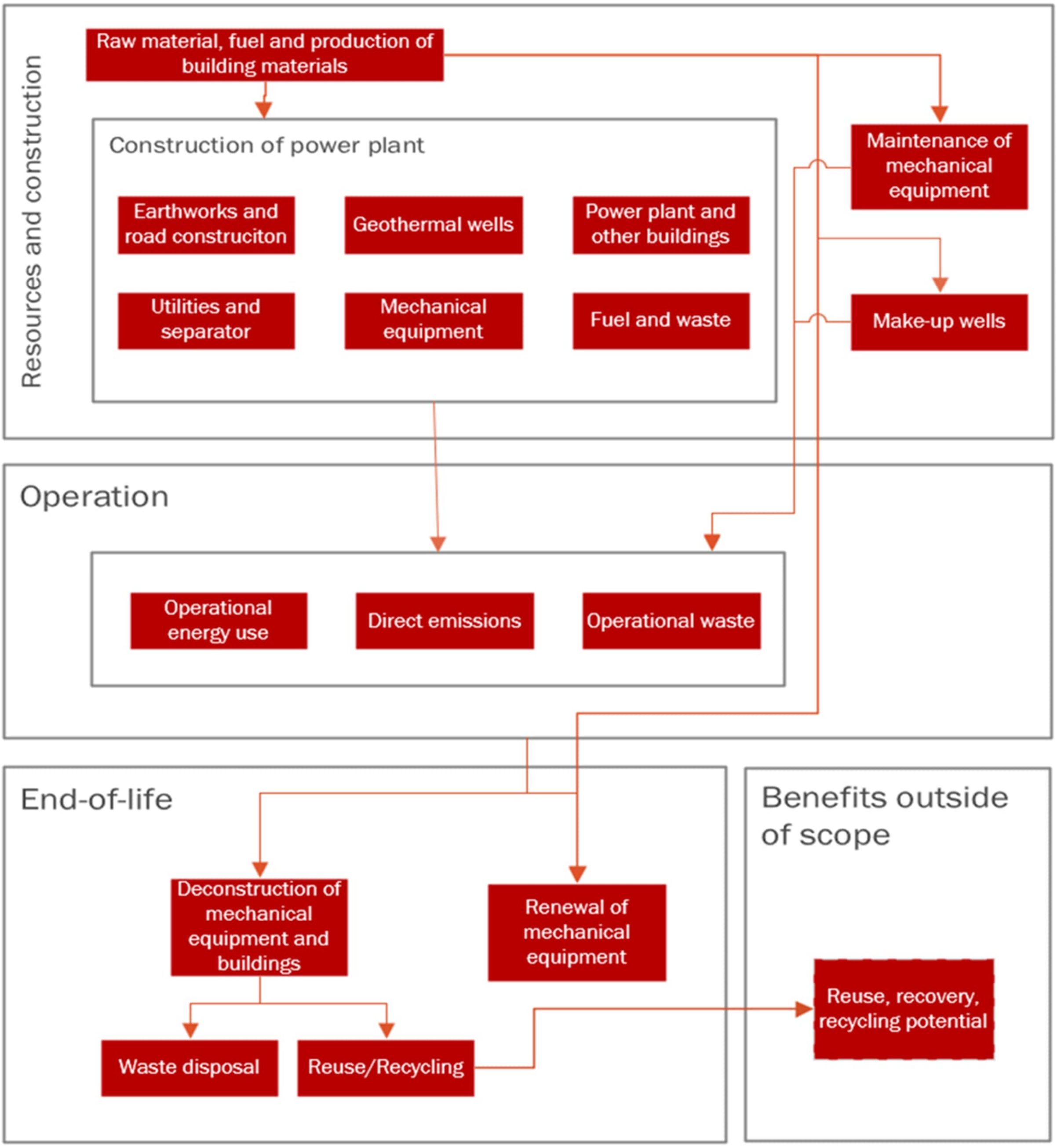

Figure 2.2 **The main unit processes set up to describe the production of electricity and heat from Svartsengi power plant.**

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 since the electrical grid is outside the system boundary. For this study physical allocation procedure was used, however no allocation is done between the heat and electricity. Table 2.1 shows the total energy production figures the study is based on.

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

Svartsengi power plant	Total over 30 years lifetime [TWh]
Electricity generation capacity	16.05
Thermal energy sold	27.57
Total energy production	43,62

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 Svartsengi GPP is approximately 50 years old and the oldest power station (SVA2) that is included in this study was constructed over four decades ago. For the older power stations (SVA2, SVA3 and SVA4) assumptions were made based on available data, input from specialists or recent data. Also, there are some uncertainties regarding the effect of the SVA7 expansion on the operation phase. In this chapter, the quality of the data is classified as high (h), medium (m) or low (l), 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 as well as transport and treatment of construction waste

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

For the newest power stations 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 for SVA5, SVA6 and SVA7. In case that production and implementation data was not found in primary data the study "Life cycle inventory data set for power plants, with or without combined heat production" by Karlsdóttir et al. was used for scaling of values in this study (Karlsdóttir, et al., 2015). That applies for the older power stations as well as figures that were not found in primary data. Data for the environmental impact to produce building materials and fuel for Svartsengi power plant is based on European production unless otherwise stated.

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

Works	Contract	Explanation
Building structures	**SVA7-P101**	Involves all work on the construction of the power plant, incl. earthworks, plumbing, ventilation, concrete, steel structures, timber structures, interior and exterior finishing.
Earthwork	**SVA7-P102**	Consisted of pre-earthwork in the construction area, mainly excavation and filling for the foundations of the power station and cooling tower.
Installation of electrical equipment	**SVA7-P103**	Involves the construction and installation of one 65 MVA 132/11 kv transformer and one 10 MVA 11/11 kv transformer, distribution cabinets and high voltage cables. Supply and installation of power and control cables.
Installation of machinery	**SVA7-P104**	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.
Prefabrication of machinery	**SVA7-P116**	Manufacturing and construction of one steam separators and other machinery connected to machinery.
Installation of machinery	**F0215-100 SVA6**	Installation of machinery, devices and pipes in the station building and its immediate vicinity.
Quantity	**SVA6**	Quantity list for earthwork, pipes, building construction, steel works and timber works.
Installation of machinery	**HS-98012 SVA5**	Installation of machinery, devices and pipes in the station building and its immediate vicinity.
Installation of machinery – Separation station	**HS-99010 SVA5**	Installation of pressure vessels and pipes in the separator and silencer, the laying of steam pipes and condensate pipes.
Steam Separators	**HS-981436 SVA5**	Work consists of material procurement, construction, testing and transportation of separators and steam hoods.

3.1.1 Building materials

Buildings at Svartsengi Power Plant consist of a powerhouse, substation houses and houses for the separators and cooling facilities. There are six powerhouses with a steel-frame structure and one powerhouse currently under construction, also a steel-frame structure. Figure 3.1 shows power station six under construction. The footprint for SVA5, SVA6 and SVA7 is approximately 13,500 m², however the footprint of older power houses in the area is unknown. To estimate quantities of building material for the older power stations, SVA2, SVA3, and SVA4, secondary data was required. The approach from Karlsdottir 2015, was applied to determine the quantity of building material, where quantities of material are estimated in relation to the installed electrical production capacity and installed thermal production capacity of the power stations (Karlsdóttir, et al., 2015). Table 3.2 shows the amounts of material used in construction of the power plant.

Figure 3.1 **Power station 6 under construction June 2006.**

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

Material	Unit	Total amount	Data quality
Concrete	Tonnes	34,825	*m*
Steel	Tonnes	5,109	*m*
Glass	Tonnes	5,1	*m*
Rockwool	Tonnes	81	*m*
Aluminium	Tonnes	122	*m*
Rebar	Tonnes	470	*m*
High voltage wires (copper)	Tonnes	43	*l*
Plastic and other material	Tonnes	146	*l*

3.1.2 Collection pipelines

The total length of collection pipes for those power plants is approximately 35 km with different pipe sizes: DN350, DN400, DN450, DN700, DN1000. The collection pipelines consist of pipes from boreholes, separators, power plant and a pipe from the power plant to the sea. The collection pipes are made of steel, insulated with mineral wool, and cladded with aluminum sheets, see Figure 3.2. Data was collected in tender documents and from HS Orka. Amount for mineral wool and aluminum was estimated according to Karlsdottir 2015 (Karlsdóttir, et al., 2015). The total amount of materials is summarized in Table 3.3.

Figure 3.2 **Installation of pipeline to Arfadalsvík.**

Table 3.3 Key figures for materials in collection pipelines.

Material	Unit	Total amount	Data quality
Steel	Tonnes	6.545	*h*
[a] **Aluminum**	Tonnes	1.517	*l*
[a] **Mineral wool**	Tonnes	1553	*l*

a (Karlsdóttir, et al., 2015)

3.1.3 Machinery

The machinery in Svartsengi is made mostly from steel. It was transported to Iceland by sea from Germany, Japan, Netherlands, and Italy. Information about the machinery was found in tender documents and case/work specifications, the total amount of materials and origin is summarized in Table 3.5. Due to the difficulty in obtaining papers and case/work requirements for the oldest power stations, Karlsdottir 2015 approach was applied to assess the amount of main machinery materials for SVA2 and SVA3 (Karlsdóttir, et al., 2015).

Table 3.4 Main machinery in Svartsengi power plant.

Power station	List of main machinery, their capacity and origin
SVA4	• Three water-cooled Ormat 1,2 MW each (Ormat Technologies) • Four air cooled Ormat 1,2 MW each (Ormat Technologies) • Four 2 MVA transformer (Efacec) • Three 1 MVA transformer (Efacec)
SVA5	• One 30 MW Turbine (Fuji Electric) • One 30 MW Condenser (Balcke Dürr) • One 30 MW Generator (Fuji Electric) • 40 MVA transformer (Koncar) • 25 MVA transformer (Koncar)
SVA6	• One 30 MW Turbine (Fuji Electric) • One 30 MW Condenser (Balcke Dürr) • One 30 MW Generator (Fuji Electric) • 40 MVA transformer (Tamini) • 2,5 MVA interconnection transformer (Tamini) • 1,6 MVA interconnection transformer (Tamini)
SVA7	• One 30 MW Turbine (Fuji Electric) • One 30 MW Condenser (Balcke Dürr) • One 30 MW Generator (Fuji Electric) • 65 MVA transformer (Tamini) • 10 MVA transformer (Tamini)

Table 3.5 **Machinery in Svartsengi power plant.**

Material	SVA2-4 [tonnes]	SVA5-7 [tonnes]	Total amount [tonnes]	Data quality
Stainless steel	77 [a]	196	273	*m*
Steel	182 [a]	894	1076	*m*
Copper	5 [a]	54	59	*m*
Aluminum	5[a]	22 [a]	27 [a]	*l*

[a] (Karlsdóttir, et al., 2015)

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 Svartsengi.

Data about the origin of raw materials was found in the tender documents, in absence of this data the most common origin for the raw material was assumed. Table 3.6 and Table 3.7 show origin of material and transport distances.

Table 3.6 **Origin of material and transport distances from manufacturer to Svartsengi.**

Material	Origin	Transport on land, international and domestic [km]	Transport on sea [km]
Cement	Denmark	170	2,500
Concrete	Iceland	70	-
Rockwool	Iceland	70	-
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 3.7 **Origin of machinery and transport distances from manufacturer to Svartsengi.**

Material	Origin	Transport on land, international and domestic [km]	Transport on sea [km]
Transformers	Tamini, Italy	1,470	2,190
Transformers	Efacec, Portugal	400	3,111
Transformers	Koncar, Croatia	1,470	2,190
Ormat machinery	Ormat, USA	842	13,200
Turbines/ Generators	Fuji Electric, Japan	206	21,000
Condensers	Balcke-Dürr, Germany	567	2,190

3.1.5 Earthworks

Earthworks involves excavation for the buildings on-site, cold-water tank, and filling to and under these structures as well as excavation and filling for ditches where cables and pipelines are laid, see Figure 3.3.

No available data exists on petroleum fuel consumption during the construction phase. Therefore, it was based on secondary data. The project plan was used for one specific power plant to find out the hours dedicated for machinery work. The amount of soil excavated along with the typical petroleum fuel consumption of the primary machinery used for this kind of structure, were then used to calculate an average. The figures for average petroleum fuel consumption are according to 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, based on a similar project and fuel consumption and engine load factors of equipment (Mannvit, 2021). The total fuel consumption is assessed based on those plans, and the estimated petroleum fuel use for all earthwork in Svartsengi GPP is 20.4 million L.

Figure 3.3 **Earthwork for power station 6 in July 2006.**

3.1.6 Geothermal wells

The energy production at Svartsengi GPP is based on the 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 are included in the scope are 22, and they are listed in Table 3.8. The wells in Svartsengi are on average about 1020 m deep, however some can reach depths of approximately 2500 m (Orkustofnun, 2022) (HS Orka, 2022). According to drilling plans from HS Orka until 2030, a total of two make-up wells are anticipated to be drilled within the lifetime of the study.

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.

Table 3.8 **Number of wells drilled in the Svartsengi area, the year they are drilled, depth and name of drill used. Þór is the only electrical drill, other drills are powered with diesel.**

Well number	Year drilled	Depth (m)	Name of drill used
SV-07	1979	1438	Dofri Gufubor
SV-08	1980	1603	Dofri Gufubor
SV-09	1980	994	Dofri Gufubor
SV-10	1980	425	Dofri Gufubor
SV-11	1980	1141	Dofri Gufubor
SV-13	1981	60	Höggbor 6
EV-1	1982	63	Höggbor 6
EV-2	1982	1265	Dofri Gufubor
SV-14	1994	612	Narfi
SV-15	1992	15	Glaumur
SV-16	1998	448	Jötunn
SV-17	1998	1253	Jötunn
SV-18	1998	1838	Jötunn
SV-19	1998	1600	Jötunn
SV-20	2000	430	Sleipnir
SV-21	2001	1475	Jötunn
SV-22	2008	862	Óðinn
SV-23	2008	700	Sleipnir
SV-24	2008	1086	Óðinn
SV-25	2015	2004	Þór
SV-26	2016	2537	Þór
EV-3	2018	100	Nasi

The quantities for material use, energy use and waste from drilling of an average well are summarized in Table 3.9. 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. According to an experience from a drilling specialist at Icelandic drilling in Reykjanes and Svartsengi geothermal area (ice. Jarðboranir), the estimated average amount of diesel oil used while drilling is 100,000 L per well (Sigurjónsson, 2022). The amount of concrete and steel in well casings is estimated by an expert for an average well in Svartsengi power plant area (Gunnarsson, 2022). The data for waste generated during geothermal well drilling was obtained from an LCA study on the most recent GGP in Iceland, Þeistareykir (Efla, 2020).

Table 3.9 **Key figures for material use and waste for each well in Svartsengi power plant. The estimated total amount is based on twenty-two drilled wells with casing.**

Material	Unit	Average per well	Total amount	Data quality
Concrete	Tonnes	400	8800	m
Steel	Tonnes	204	4492	m
Diesel oil	Thousand L	100	2200	m
Electricity [a]	MWh	363	725	m
Waste				
Disposable waste	Tonnes	2	44	l
Timber	Tonnes	4	88	l
Metals	Tonnes	3	66	l
Hazardous waste	Tonnes	4	88	l

[a] Total of 2 wells drilled with electricity

3.1.7 Direct emission

Although 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 tangible results, indicating an increase or decreased in emissions. 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. In this study, the GHGs CO_2 and CH_4 will be considered, however, not H_2S as it is not considered a GHG and therefore does not affect the GWP. Methane will also be included due to its potential to absorb significantly more energy than CO_2, which could potentially cause larger reflection in the GWP (EPA, 2022). Since CH_4 emission were not monitored until 2006, values prior to that were estimated proportionally to CO_2 emission.

All emission from the wells within the lifetime of the study are counted in the operation phase. To estimate the total direct gas emission from Svartsengi GPP, the concentration of gas has been multiplied by the yearly production from each well. Each well is sampled, for geochemical monitoring, every 1-3 years and the samples are sent to ÍSOR's geochemical laboratory for analysis. The rate of sampling is not every year since the reservoir has been very stable for the last decade. The results from ÍSOR are used to calculate the deep liquid concentration. In Svartsengi, the Russell-James method has shown to be a very good method to estimate the total production from each well. There are some variations between years in the emission. The reason for this is that emissions from a geothermal area are not constant and naturally have some variations. A common trend that can be seen in geothermal areas is the emissions are high first after drilling and then gradually lower and peak again once new wells are drilled.

The Svartsengi power plant began operating in 1977, the power plants SVA2, SVA3, SVA4, and SVA5 were constructed before the study's timeframe. New wells are drilled when a new power facility is constructed, and direct emissions are released from the wells. To allocate the direct emission during construction of the power plants, each power plant's construction period is expected to take two years, based on past experience at Svartsengi GPP. As a result, the direct emissions that were emitted during those two years will be allocated for each power plant. The total direct emission during the construction phase of following power plants is represented in Table 3.10. The data quality for direct emission is high as it is based on measured, published figures.

Table 3.10 Direct emission during construction phase.

Gas	Total direct emission [tonnes]
CO_2	67,591
H_2S [a]	831
CH_4 [b]	6

[a] Not a GHG, does not affect 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 or gravel. The total area of paved asphalted roads and parking lots is approximately 34,000 m². Gravel roads and spaces are also to be found on site and the total area is approximately 6,200 m². 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

At Svartsengi, SVA6 is the latest power plant, constructed in 2007. Waste generation from construction was not being monitored at that time. HS Orka has nevertheless monitored waste during the construction of their newest power plant at Reykjanes geothermal power plant (ice. Reykjanesvirkjun), called REY4. HS Orka uses an external system called Klappir to keep track of their waste disposal. The waste monitored by REY4 will be used to estimate the waste for the extension of SVA7 as well as the construction of the power plants SVA2 to SVA6, see Table 3.11. The quantities of construction waste were estimated based on installed capacity of each of the power plants. Given the different construction period and building sizes of REY4 compared to example SVA2 and SVA3, the data quality is poor since it cannot be considered to be truly accurate.

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

	SVA2-6 [kg]	SVA7 [kg]	Total amount [kg]
General waste	17,587	2828	20,416
Treated wood for recycling	139,293	22,400	161,692
Metals for recycling	31,573	5077	36,651
Hazardous waste for incineration	2,055	330	2,385
Gypsum or rubble	22,891	3681	26,572
Inert waste	15,047	2420	17,466

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 combined energy use for Reykjanes and Svartsengi power plants 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 use of non-renewable energy is fuel for cars or machinery.

The electricity use is calculated as the difference between produced and sold electricity. A limitation in the software, OneClickLCA, where specific electricity mix based on IEA for Iceland must be used, with the GWP of 0.0288 kg CO_2-eq. per kWh.

The average energy use over the three years was used and estimated according to installed capacity of Svartsengi, see in Table 3.12. The energy use was similar over the three years reported and since the figures are high, a small change does not have a significant effect on the results. 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.

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

Year	Non-renewable energy [MWh]	Electricity [MWh]
Average per year	245	23,821
Total over lifetime	7,357	714,641

3.2.2 Waste

Waste generated during the operation of the power plant has been monitored by HS Orka since 2017, through Klappir. 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 average waste per year and for the 30-year lifetime is represented in Table 3.13. The data quality is low for the operational waste.

Table 3.13 Key figures for operational waste at Svartsengi power plant.

	Yearly average based on 2017-2021 [kg]	Total amount [kg]
General waste	10,547	316,410
Treated wood for recycling	37,506	353,280
Metals for recycling	11,776	1,125,168
Hazardous waste for incineration	4,955	148,644
Plastic	41,810	1,087,060

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 3.1.6 with the exception of diesel use as it is assumed that all make-up wells are drilled with an electric drill. The make-up wells are assumed to be two throughout the lifetime of the study. The quantities for material use, energy use and waste from drilling of make-up wells are summarized in Table 3.14.

Table 3.14 Amount of material and waste for make-up wells.

Material	Unit	Average per well	Total amount
Concrete	Tonnes	400	800
Steel	Tonnes	204	408
Electricity	MWh	363	725
Waste			
Disposable waste	Tonnes	2	4
Timber	Tonnes	4	8
Metals	Tonnes	3	6
Hazardous waste	Tonnes	4	8

3.2.4 Direct emission

Annual emissions during operations are reported to the National Energy Agency (NEA) (Orkustofnun, 2022). The monitoring is done manually at each wellhead once a year and the results extrapolated over one year. Based on these years, the average emission per year is estimated. The reported emission for the years 2000 to 2022 are used in the study, and the average value was estimated for 2023 to 2030, 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 emission tends to vary from year to year.

It should be noted that CO_2, H_2S and CH_4 in geothermal areas is emitted even though no drilling has taken place, nevertheless how much is unknown. The amount of direct emission comprises the emission that would have occurred naturally in the absence of the construction of the power plant.

Table 3.15 **Direct emission over the lifetime.**

Gas	Total amount [tonnes]
CO_2	1,660,117
H_2S*	28,638
CH_4	142

*Not a GHG, does not affect GWP

**No data for CH_4 were published before 2006. Estimated values before 2006 are proportional to CO_2 emission

3.2.5 Maintenance

A report that looks at the financial aspects of a geothermal power plant the maintenance cost is calculated as 1.5% – 2.5% of the total installation cost (Chatenay & Jóhannesson, 2018). Based on this, 2% extra for all raw materials for buildings and infrastructure was assumed. Since information about maintenance is very limited and the effect of the 2% addition assumed is negligible this is excluded from the analysis.

3.3 End of life

For the end of life in this study, SVA7 is expected to replace SVA4, which will cease operation in 2025. Power stations 2, 5 and 6 are expected to continue operation, this assumption is based on the history of geothermal power plants in Iceland (Orkustofnun, 2022). Svartsengi power plant has been extended and machineries and buildings renewed to increase the lifetime of the power plant.

Machinery from SVA3 was sent to recycling in 2021 and machinery from SVA4 will be as well, and the buildings currently are and will serve new purposes. All geothermal wells will continue in operation and no make-up wells will be needed at the end of life. New machinery for SVA7, that will replace SVA4, is represented in Table 3.4.

4 Results

4.1 Environmental impact during the life cycle of Svartsengi Power Plant

The results show that the total GWP of the power production is 43.5 g CO_2-eq. released per 1 kWh produced over the whole 30 year 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. 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 carbon footprint for direct emission is 39.7 g CO_2-eq. per kWh. As a result, the other factors within the GPP life cycle stages contributes to 3.7 g CO_2-eq. per kWh, with earthworks being the second biggest contributor, followed by wells and, building and infrastructure.

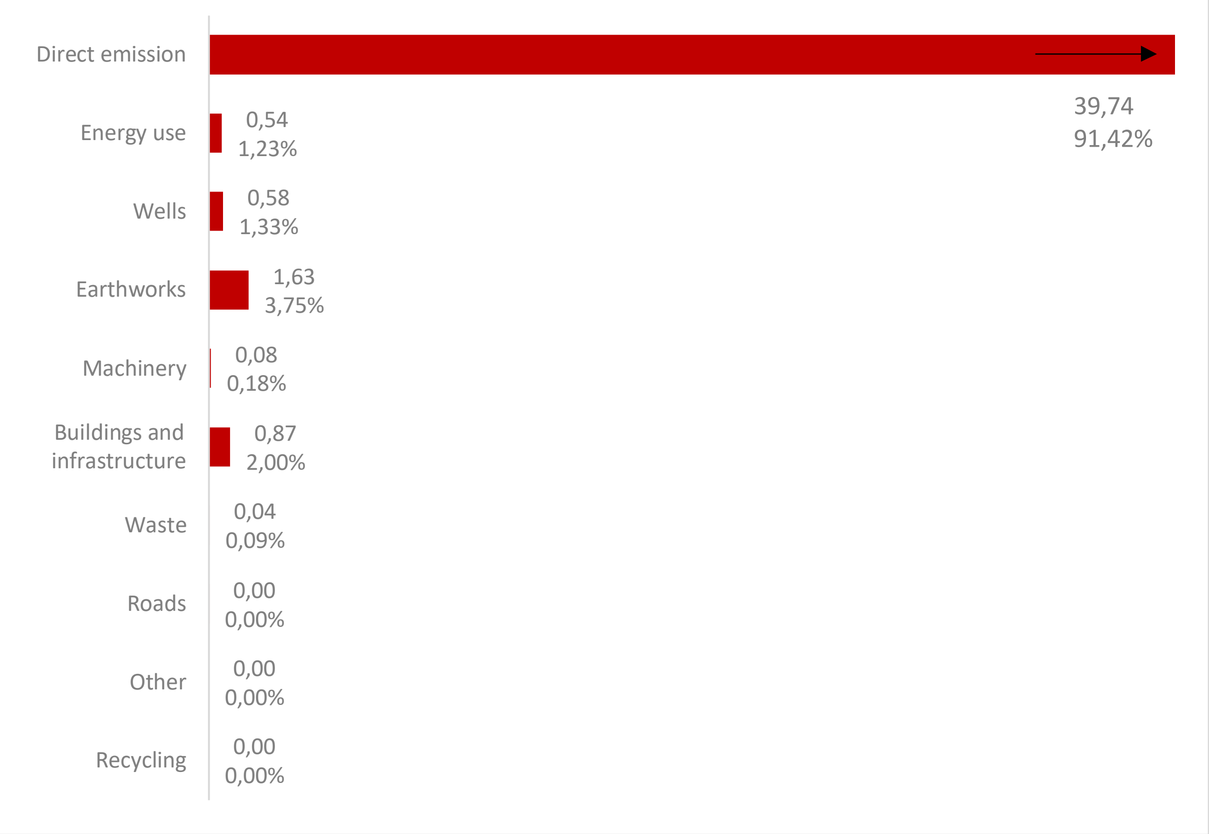

Figure 4.1 Global Warming Potential total showing both carbon footprint above [g CO_2-eq./kWh] and ratio below [%] of each factor in Svartsengi power plant. Note that direct emission is much larger than shown in the figure.

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

The total GWP for each life cycle stage of Svartsengi power plant is represented in Figure 4.2. The majority of GHG emissions occur during the operation life stage, making this stage of the life cycle the most significant GWP contributor, with total of 38.8 g CO_2-eq./kWh. Construction and resources life stages also has an impact on the GWP. The GWP for the end-of-life stage and external impacts stage are negligible.

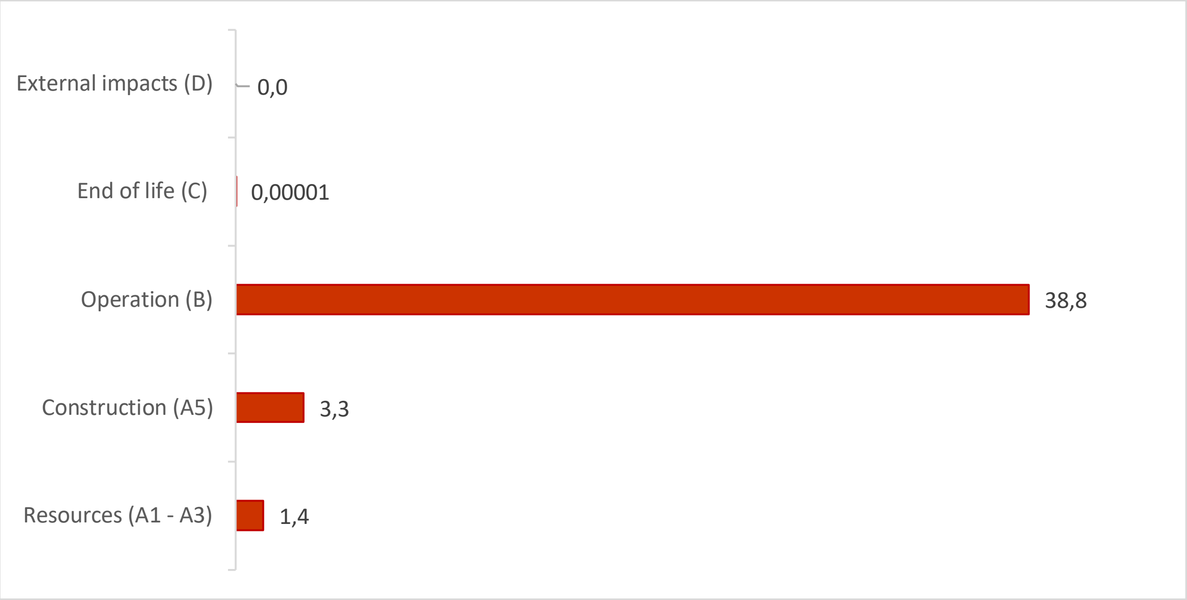

Figure 4.2 Carbon footprint [g CO_2-eq./kWh] for each life cycle stage of Svartsengi power plant.

Figure 4.3 represents the total GWP of processes within each life cycle stage. The GWP is slightly impacted by waste transport at the end-of-life stage; otherwise, the impact is minimal. 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 38.2 g CO_2-eq./kWh. Operational energy use process, releasing 0.5 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 3.3 g CO_2-eq./kWh. Raw material extraction and processing is also a significant factor in the life stage, accounting for 1.3 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 factor; installation into the building is the largest factor; due to fossil fuels used in machinery and transport during earthworks and constructure of all the power stations. Other factors that impact the GWP fossil are raw material and extraction and processing factor as well as operational energy use. Figure 4.5 shows the non-fossil GWP for processes within each life cycle stage, where the uses, and application process dominates, other processes are negligible. Again, this is a result of CO_2 being accounted for as a direct emission from the GPP during operation.

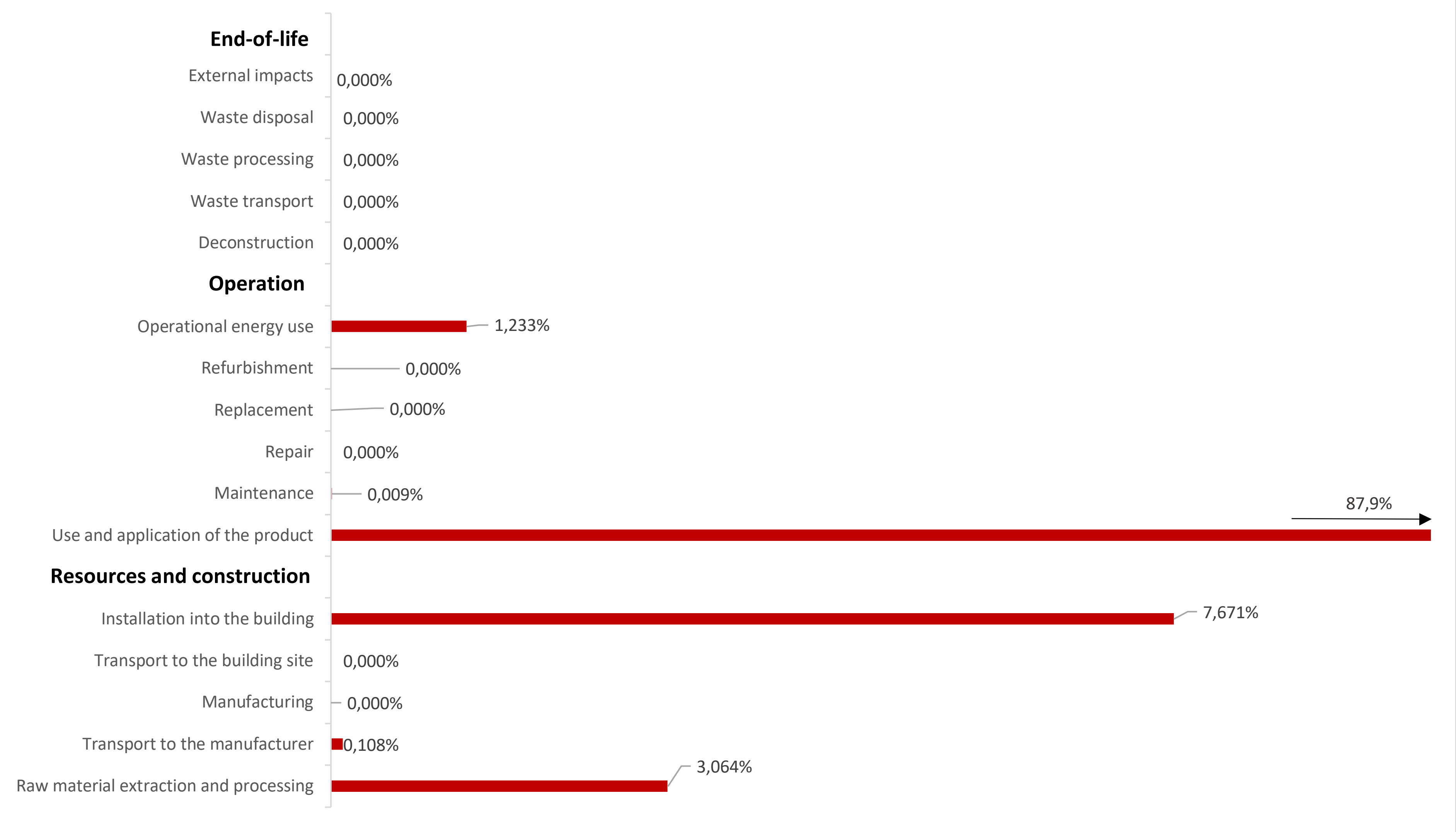

Figure 4.3 **Global warming potential total ratio for each life cycle stage. Note that use and application of the product is much larger than shown in the figure.**

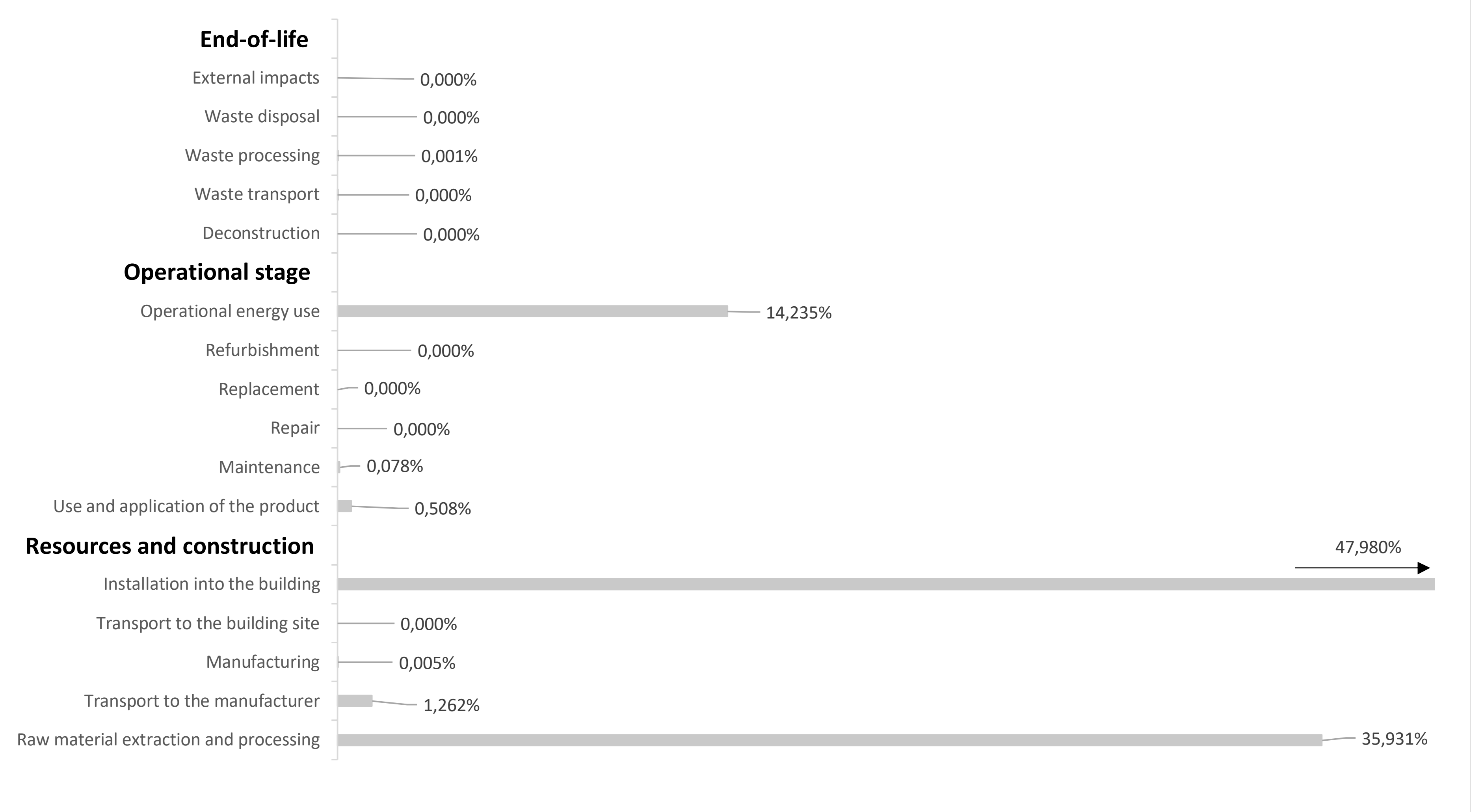

Figure 4.4 **Global warming potential fossil ratio for each life cycle stage.**

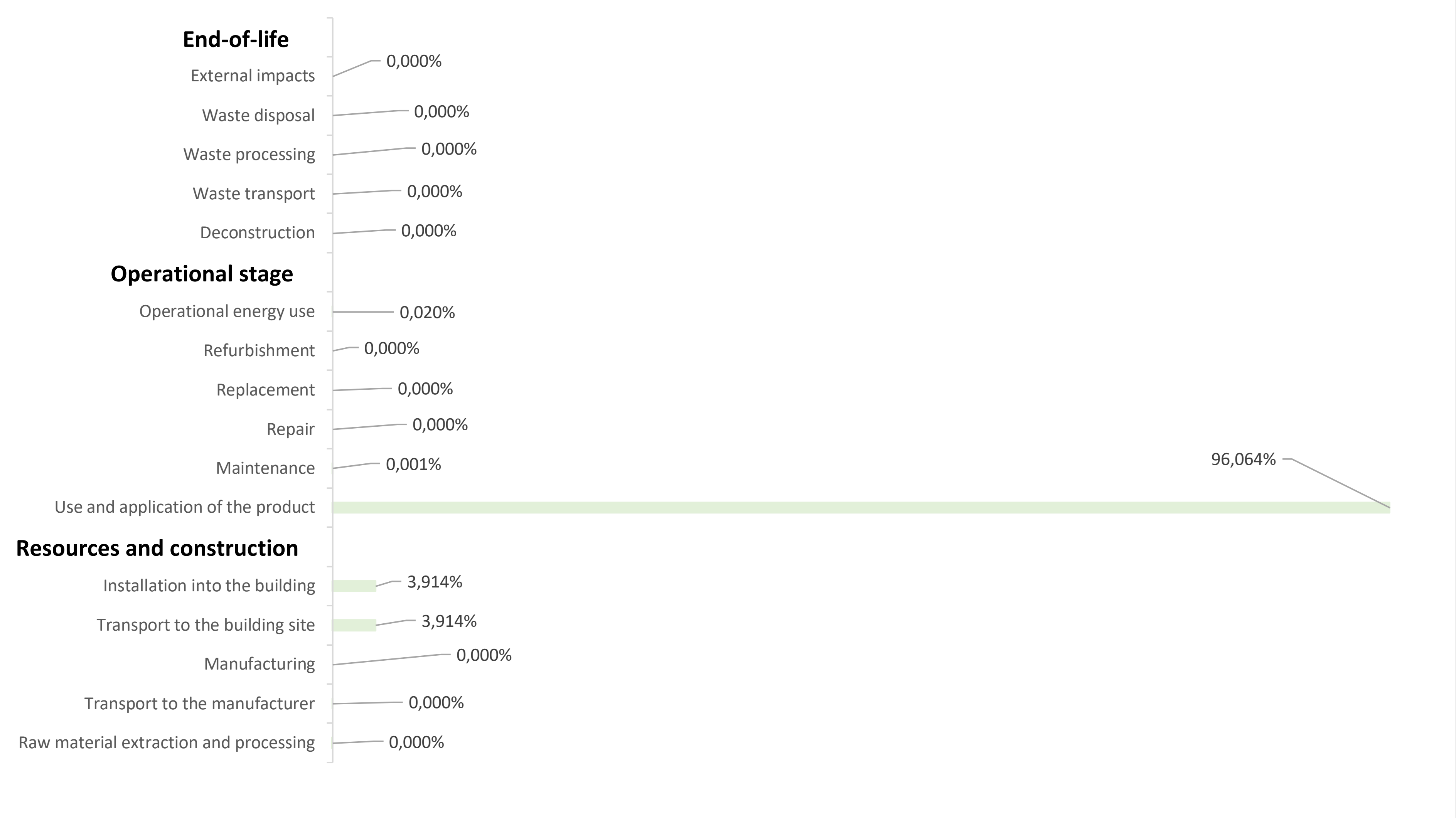

Figure 4.5 Global warming potential non-fossil ratio for each life cycle stage

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 8 years, since direct emission generally decreases over time in geothermal areas.
- Petroleum fuel use as estimated at 100,000 L per well with some percentage uncertainty. For that reason, fuel consumption during drilling in this study was both increased and decreased by 20%.
- Lifetime was increased to 90-years. In correlation, make-up wells were added, 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 are known, the estimate for future emission was modified to see the effect on the carbon footprint. By increasing and decreasing the direct emission during operation by 30% the GWP of the power plant per 1 kWh increased by 3.7 g CO_2-eq. and decreased by 2.4 g CO_2-eq. respectively, see Figure 5.1. When the direct emission was increased to 50% for the next 8 years the GWP increased by 5.7 and decreased by 4.5 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.

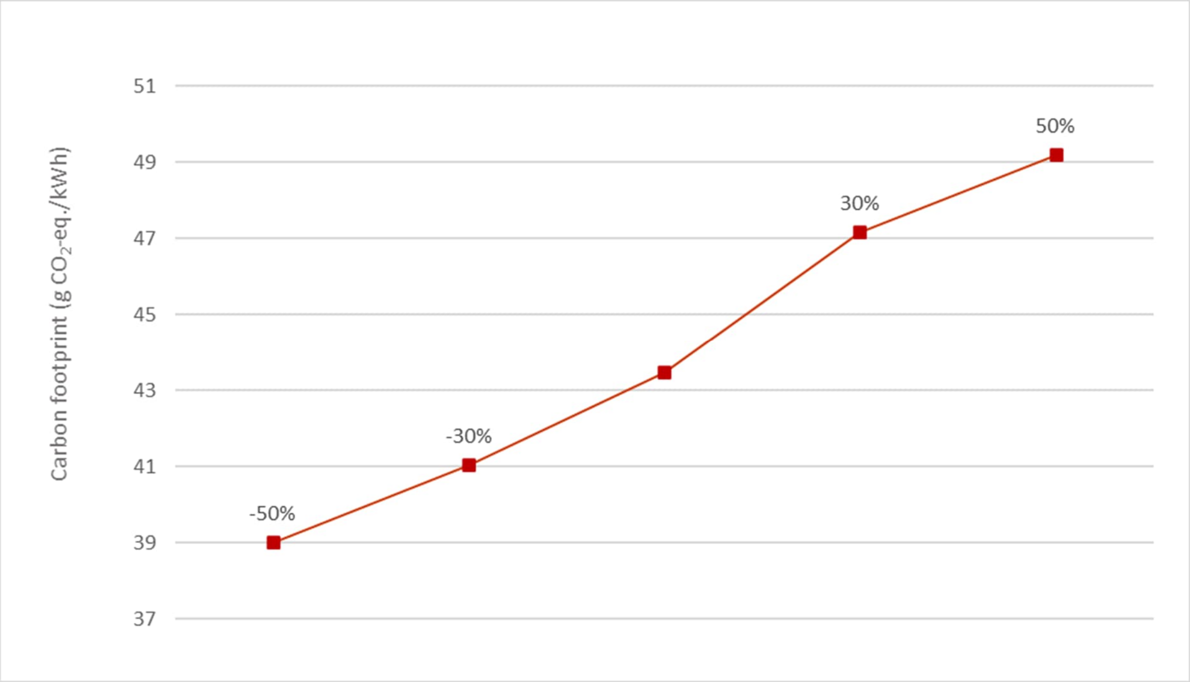

Figure 5.1 **Sensitivity analysis on direct emission of CO_2 and CH_4 from Svartsengi power plant. Represented in GWP.**

5.2 Drilling of wells

Due to uncertainty in the petroleum fuel consumption during drilling the effect of this was considered. The total GWP was altered by less than 1% when the fuel consumption during drilling of wells was increased or decreased by 20%, as shown in Table 5.1. When GWP of fossil was examined, the difference between 20% increase and 20% decrease of fuel consumption, the GWP fossil altered by less than 1%. According to the results, the fuel consumption when drilling does not significantly affect the power plant's carbon footprint.

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

Change	Diesel oil volume (L)	GWP total (g CO_2-eq./kWh)	GWP fossil (g CO_2-eq./kWh)
0%	1,800,000	43.47	3.70
20% decrease	1,440,000	43.49	3.68
20% increase	2,160,000	43.43	3.73

5.3 Variation in lifetime

The lifetime was changed up to 100 years with alterations to the direct emissions, the number of make-up wells, the total amount of energy production, and the carbon footprint was calculated for each scenario. The results were plotted and extrapolated (see Figure 5.2). The results demonstrate that the GPP's carbon footprint peaks at 40 years of lifetime, in the amount of 47.1 g CO2-eq. per kWh. The carbon footprint begins to decline slowly and evenly after 40 years, then stabilizes between 90- and 100-year lifetime.

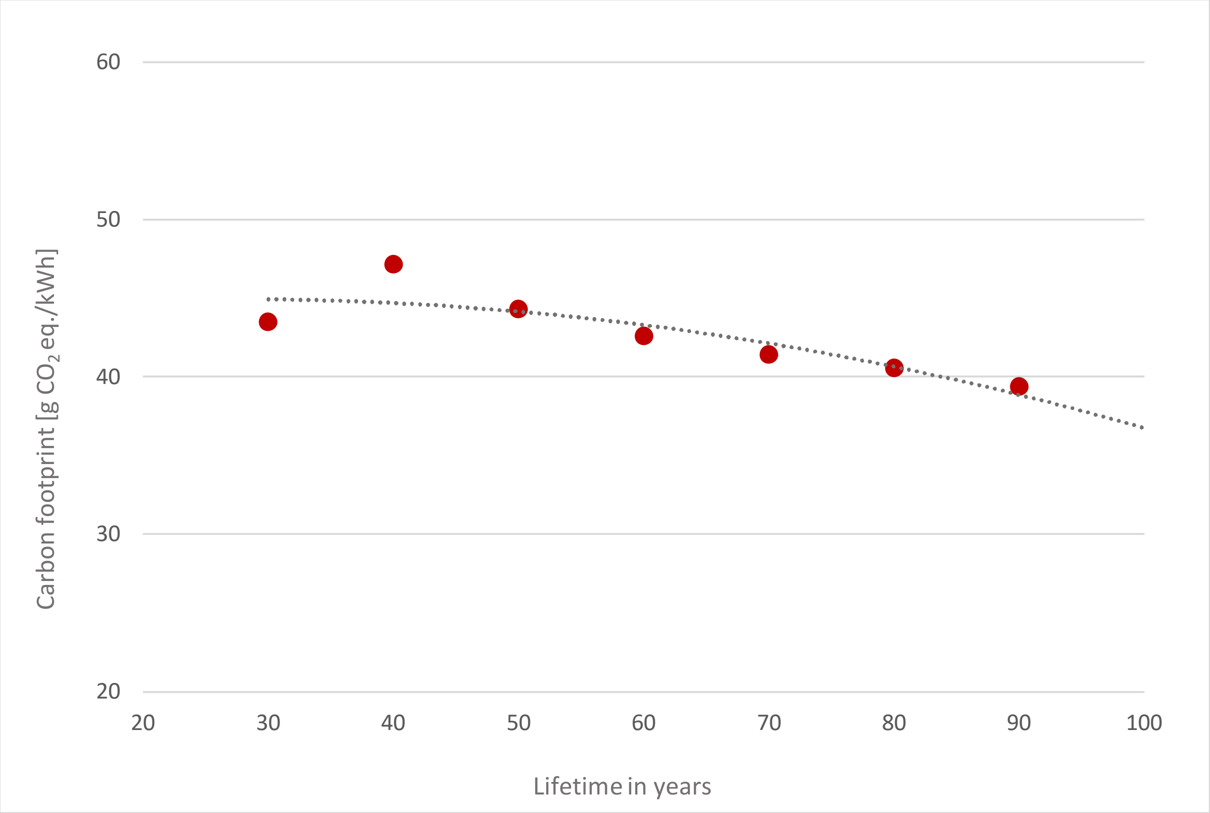

Figure 5.2 The carbon footprint as a plot of lifetime in years, calculated from 30 to 100 years and the results extrapolated.

5.4 Change in electricity mix

The electricity mix was modified to the power plants own electricity. When the power plant's own electricity needs are met by the electricity generated by the power plant itself, the electricity will not pass through a transmission system, with possible internal losses. Additionally, the carbon footprint for electricity traveling via transmission system will be somewhat higher due the infrastructure required for the system. The total GWP for Svartsengi GPP was altered by 0.4% when calculations are based on the electricity produced at Svartsengi power plant. Table 5.2 shows that the system is not sensitive to the 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	43.47
Svartsengi power plants own electricity	43.64

6 Discussion

Most impactful life cycle stages

Total GWP

When the total GWP for each life cycle stage of the study is evaluated, 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 natural release of gases from surface venting in 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 change if it could be determined how much greenhouse gas is in fact emitted naturally. If it were determined that all gas release would occur independent of the GPP and at the same rate as currently, drilling, earth works, and energy use would then be the main factors affecting the GWP. Currently, with natural emissions being unknown, direct emission from the GPP are the most significant data source. Although the data's high quality for the emissions is based on annual measurements over the previous 22 years, an estimate for the upcoming 8 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 22 year, and the estimate for next 8 years is based on that. This variation is therefore included in the estimate.

Earthworks during the resources and construction stage has the second-largest overall GWP. This is affected by several factors, fuel consumption during machine operation and transportation during earthworks as well as drilling of wells. Additionally, the usage of raw material extraction and processing for infrastructure and pipelines are also part of this stage. The number of power stations located in the Svartsengi GPP area explains the excessive fuel consumption and raw material usage during excavation and infrastructure activity. The amount of petroleum fuel consumption during well drilling operations has a minor effect on the carbon footprint, regardless of 20% uncertainty in the total amount of fuel consumption over the power plant's history.

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 fuel during earthworks and drilling as well as machine operation and transportation. Fuel consumption during operation stage is due to transport and other machinery driven by fuel. 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. Based on this, it is necessary to increase and optimize production while optimizing the existing facility in order to maintain a low carbon footprint in the next years. This is the strategy for upcoming decades, according to the HS Orka sustainability report (HS Orka, 2022). The Svartsengi power plant is already close to 50 years old and is frequently refurbished and renovated rather than being demolished, demonstrates that Iceland's GPP lifespan is substantially longer than 30 years.

Summary

The information used for this LCA of the Svartsengi power plant’s construction and operation is based on a variety of data. Since some of the data is more than 50 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 substantially affect the results. 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 1 One Click LCA report – Results of the study