Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Life Cycle Assessment of the Theistareykir Geothermal Power Plant in Iceland

Alexandra KJELD[1], Helga Johanna BJARNADOTTIR[1], Ragnheiður OLAFSDOTTIR[3], Björn HALLDORSSON[3] and Valur KNUTSSON[3]

[1]EFLA Consulting Engineers, Lyngháls 4, Reykjavík, Iceland, [2]Landsvirkjun, National Power Company of Iceland, Háaleitisbraut 68, 103 Reykjavík, Iceland

alk@efla.is

Keywords: life cycle assessment, environmental impact, carbon footprint, geothermal energy, electricity generation, Theistareykir, energy return on energy invested

ABSTRACT

One of Iceland‘s key energy sources, geothermal energy, provides the country with more than 25% of its total electrical energy supply and nearly all of its heating supply. The country‘s latest installation is the 90 MW Theistareykir geothermal power station in Northeast Iceland, owned and operated by the National Power Company, Landsvirkjun. The station has been in full operation since 2018. During its design, preparation and construction the unique nature of the Theistareykir area was taken into consideration and emphasis placed on environmental matters. Additionally, the preparation stage of the project was successfully assessed under the Geothermal Sustainability Assessment Protocol. The goal of this study was to assess environmental impacts associated with electricity generation in Landsvirkjun's geothermal power plants. The assessment is part of a larger project which aims to assess the environmental impact of Landsvirkjun's electricity generation via hydropower, wind and geothermal power. Although geothermal energy is a renewable resource it is not without impacts to its environment. One of the preferred methods to assess environmental impacts from a life cycle perspective is Life Cycle Assessment (LCA). The LCA for Theistareykir power station follows the international standards: ISO 14040, ISO 14044, EN 15804, and product category rules according to ISO 14025 for the preparation of Environmental Product Declaration (EPD) for electricity generation and distribution. The assessment provides numerical results on a variety of environmental impacts throughout the life cycle of the power plant, including the manufacturing of all construction materials and equipment, construction work, operation and end of life.

According to the LCA results, the largest contributors to environmental impacts are direct emissions during the operation of the station during its lifetime, the manufacturing of all station components and fuel use during construction. The carbon footprint of electricity generation at Theistareykir is 13.8 g CO_2-eq per kWh leaving the station, and 14.7 g CO_2-eq per kWh when electricity transmission has been included. This is a relatively small carbon footprint compared to other geothermal projects. The carbon footprint is dominated by direct CO_2 emissions from the geothermal fluid during the 40-year lifetime, amounting to 10.2 g CO_2-eq/kWh or 69%, while the manufacturing and construction of station buildings, infrastructure and machinery accounts for 17% of the carbon footprint. The most carbon intensive units are the wells, in total constituting 8.2% of the carbon footprint. Direct hydrogen sulphide (H_2S) emissions at Theistareykir is the main contributor to the impact category acidification, and an important contributor after applying weighting and normalisation. The results identify many opportunities for improvement of future development projects and for the operational years ahead, including measures to reduce CO_2 and H_2S emissions from the geothermal fluid, improving the station's capacity and/or extending its lifetime with good maintenance. Although there is uncertainty regarding the number of make-up wells needed during the station's lifetime, this LCA identifies opportunities to reduce their environmental impacts. The results of this assessment provide valuable information for the company in its plan to become carbon neutral by 2025, identifying environmental hot spots and highlighting where the largest improvements can be made in terms of eco-design of future projects, environmental impacts from the operational and end-of-life phases and to support sustainable procurement procedures. The results can be compared to LCA results of electricity generation via other energy sources and they form a basis for communication or marketing of results, e.g. using a standardized form such as an EPD.

1. INTRODUCTION

Iceland's energy and electricity needs are nearly fully met by renewable energy sources, hydropower and geothermal power. Due to a high industrial demand, Iceland has the highest power generation per capita globally, as approximately 80% of generated power is used by industries, mainly the production of aluminum and processing of ferro-silicon. Today, geothermal energy provides the population of Iceland with approximately 61% of its entire energy supply, thermal and electric. Most of the country's geothermal energy is used for heating providing nearly the whole population with warm water, delivered by district heating systems from either low-temperature fields or from dual-use power generation and heating plants in high-temperature geothermal fields. Warm water for heating is provided in areas within a reasonable distance from geothermal fields, which is why geothermal power plants in the southwest of Iceland, inhabited by most of the country's population, are generally dual-use. Conversely, geothermal power plants in the rural area in north and northeast of Iceland, such as Theistareykir, are typically single-use and exclusive for electricity generation.

Landsvirkjun is Iceland's largest utility, owned by the Icelandic state, and generates approximately 73% of the country's electricity. Today, the company operates 15 hydropower stations, 2 research wind turbines and 3 geothermal stations, of which Theistareykir is the most recent installation. To date, Landsvirkjun has completed life cycle assessments (LCAs) of 4 of its hydropower stations (EFLA, 2018a and 2018b, 2019 and 2020). To better understand the environmental performance of wind power utilization in Iceland, the company has also completed an LCA of the two research wind turbines at Hafið near Búrfell, in the south of Iceland (EFLA, 2015). To complete the portfolio of utilized energy sources, the company has now undertaken an assessment of its latest installation at Theistareykir (EFLA, 2020a), an important step towards better understanding the environmental performance of its geothermal power utilization.

Theistareykir is a 90 MW ‘single flash’ geothermal power plant in the northeast of Iceland, currently generating approximately 738 GWh per year and is the country’s latest geothermal installation. It is owned and operated by Landsvirkjun with a potential for future capacity up to 200 MW. The area has been researched since the 1970s and the first wells were installed in 2000 for production capacity research. The design stage started in 2011 after the conclusion of an EIA and the initial planning process in 2007-2010. The main investment phase began in 2014 and included the drilling of several production wells, the construction of a steam supply system, powerhouse with adjacent cooling towers and service buildings, and a re-injection system. Construction began in 2015, reaching its peak in 2016-2017, and concluded in autumn 2018 when the second 45 MW turbine-generator unit was launched. The preparation stage of the project was the first to undergo an assessment under the Geothermal Sustainability Assessment Protocol (Hartmann, 2017), which concluded successfully in 2017. The protocol, still in development, is based on a similar global rating system as the Hydropower Sustainability Assessment Protocol for hydroelectric power plants..

At Theistareykir, geothermal fluids are harnessed from deep wells extending up to 2.5 km each, see Figure 1. Superheated fluid at over 250°C comes up under its own pressure and boils while reaching the surface. At each well there is a well silencer that can be used when electricity generation needs to be halted momentarily or when wells are being tested. The geothermal fluid is a mixture of steam, and water and geothermal gases and is transported from the wellheads to a separator station via a network of pipelines. The separator station, followed by a secondary demister, ensure that the geothermal water is separated from the steam. If required, a valve station with silencers can shut down steam supply to the plant. The separate water is reinjected to the reservoir while the dry steam ‘flashes’ through two sets of turbine-generators for the generation of electricity. The steam is then transported to a cooling tower (condenser) where gases are separated from the steam and ejected, while the steam is condensed and turned into condensate water. The condensate water is then added to the separated water and reinjected to the reservoir.

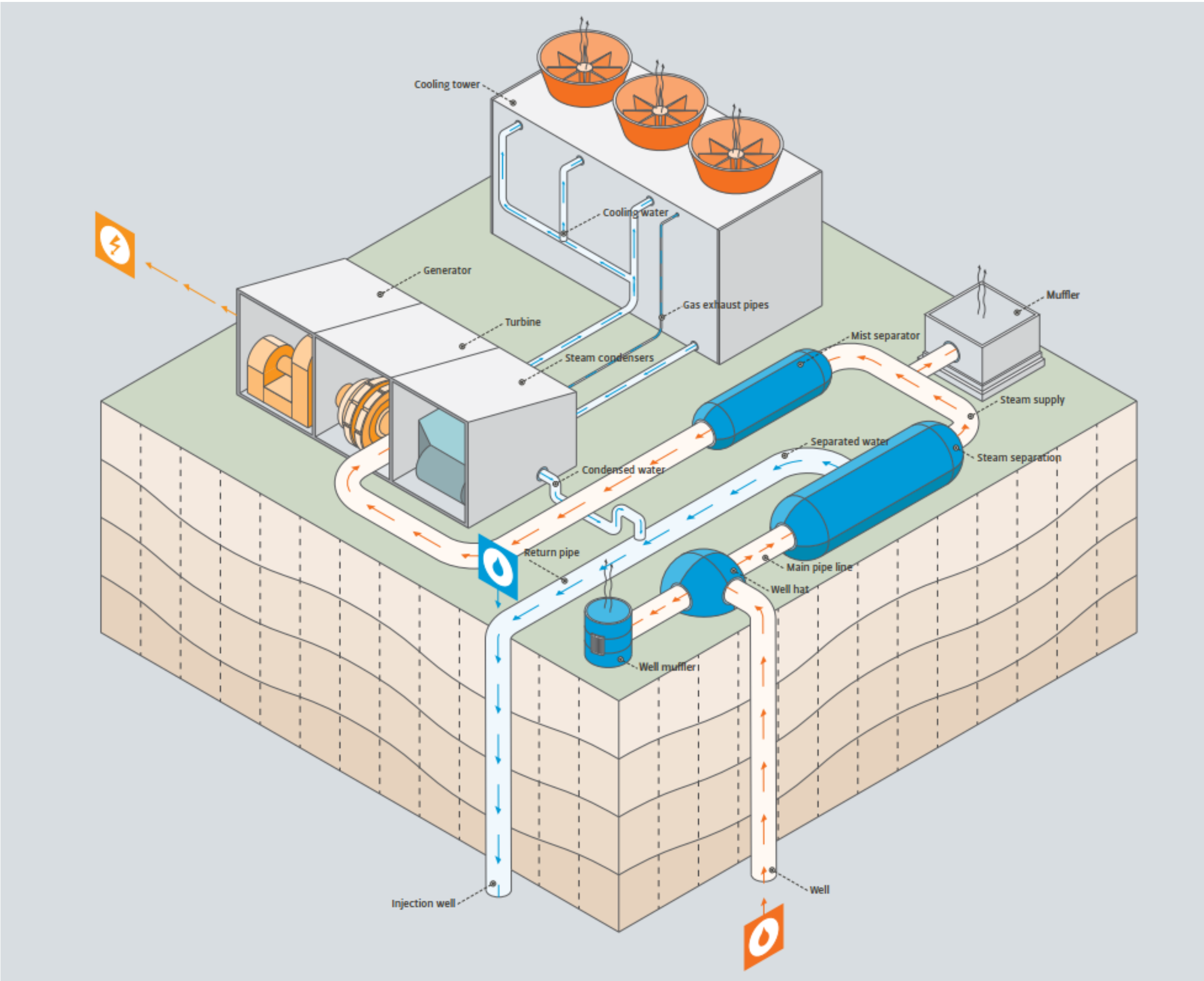

Figure 1: Schematic of the Theistareykir Geothermal Power Project (Landsvirkjun).

Although a proportionally large share of the world’s geothermal energy utilization is generated through single flash plants (Bertani, 2016), little attention has been given to the evaluation of its environmental impacts from a life cycle perspective (Tomasini-Montenegro et al., 2017). The aggregation of life cycle inventory data in this study, scaled with site specific parameters and representing the technology used at Theistareykir, is a contribution to the literature for single flash geothermal plants, globally. It is furthermore an addition to the country’s LCA literature. Thus far one life cycle inventory (LCI) study has been published for a combined heat and power plant in the south of Iceland (Karlsdóttir et al, 2015 and 2020).

2. LCA METHODOLOGY

Life cycle assessment (LCA) is a methodology to assess the environmental impacts of a product, encompassing the whole life cycle (cradle to grave). Hence, the environmental impacts of a product or service are evaluated from the initial resource extraction to material production, product manufacturing, use of the product and up to its disposal, including production wastes. The general procedure of conducting an LCA has been standardized in ISO 14040 and ISO 14044 (2006). A European standard EN 15804 on the sustainability of construction works has also been prepared (EN 15804, 2012), as defined in ISO 14025 for Type III environmental declarations (ISO, 2015). Lastly, the study also takes into consideration recommendations of the Product Category Rules for electricity generation, as defined by The International EPD System (2020).

2.1 Goal and scope of the study

The objective of this study is to use the LCA methodology to evaluate the environmental impacts of electricity generation at the Theistareykir geothermal power plant in northeast Iceland. This assessment provides numerical results on environmental impacts for seven environmental impact categories, where the contribution of each life cycle stage and its different components to each impact category is identified. Although site specific and technology specific, the standardized results allow for a comparison to be made between different geothermal power projects in Iceland and different energy sources. Also, in completing this study, Landsvirkjun will have performed an overall assessment of its main power stations for different sources of energy, complying with one of its environmental policy targets as defined according to the accredited environmental management system ISO 14001, where the results of LCAs shall be used to improve efficiency in the use of natural resources and to reduce impacts on the environment. A completion of a life cycle assessment is furthermore a prerequisite for the publication of an Environmental Product Declaration (EPD) if considered feasible.

2.2 Functional unit

The functional unit of the study is defined as 1 kWh of electricity generated at the Theistareykir geothermal power station and delivered via a transmission system. The lifetime of the station is defined as 40 years as recommended by Product Category Rules, but for comparison purposes a sensitivity analysis is carried out for a variable lifetime. The electricity generation capacity at Theistareykir is 738 GWh per year, amounting to a total generation of 29.5 TWh in a 40-year lifetime.

2.3 System boundary

The life cycle assessment for the Theistareykir geothermal power plant is a cradle to grave analysis. The system boundaries include raw material extraction, manufacturing of all components, transport, construction of the power station and geothermal wells, operation and maintenance during the designated lifetime and dismantling and disposal or recycling at the end of life stage. The life cycle stages covered in this study are in accordance with current PCRs, modules of the EN 15804 standard and recent guidelines, see Figure 2.

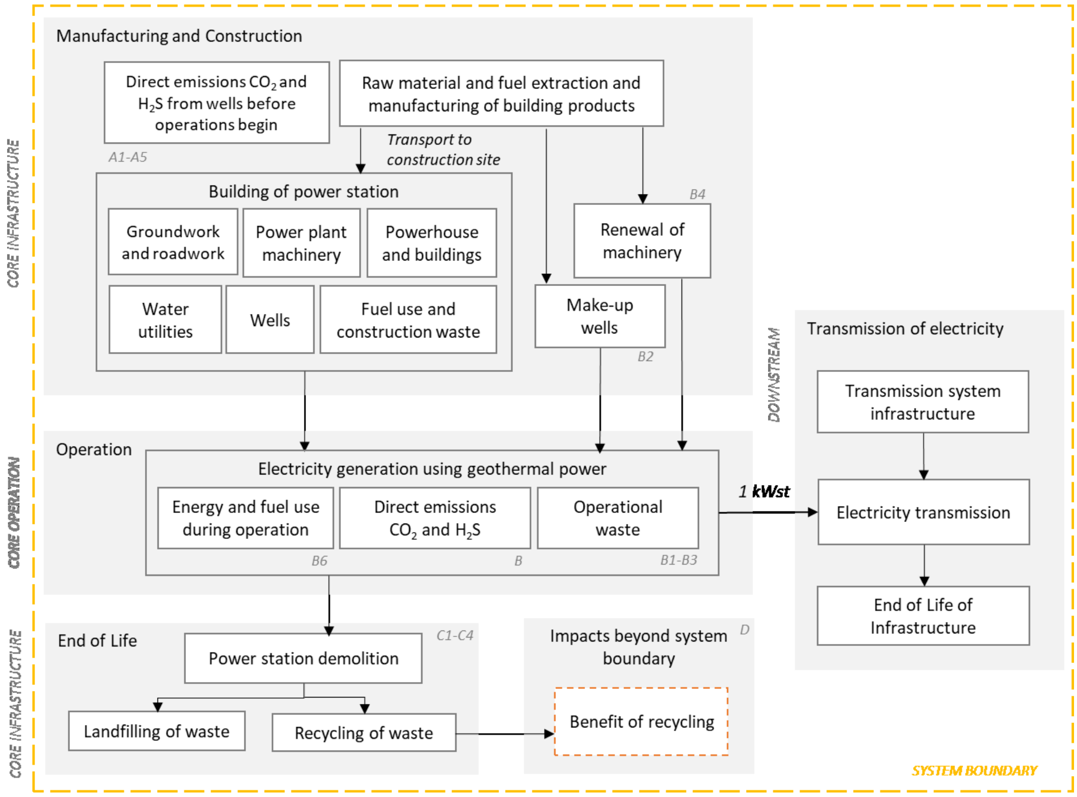

Figure 2: Simplified system boundaries for the life cycle assessment of the Theistareykir geothermal power station. Life cycle stages (core and downstream processes) according to Product Category Rules (The International EPD System, 2020) are in vertical, which is also in accordance with the first version of harmonized guidelines to perform environmental assessment for geothermal systems based on LCA and non LCA impact indicators (Blanc et al., 2020). Grey letters (A-D) indicate life cycle stages in accordance with EN 15804.

2.4 Environmental impact categories

The following environmental impact categories are used to present results in the Life Cycle Impact Assessment (LCIA), in accordance with current requirements for disclosure of information in Environmental Product Declarations (The International EPD System, 2020) and EN 15804.

- Global warming
- Ozone depletion
- Acidification
- Eutrophication
- Photochemical ozone creation
- Depletion of abiotic resources (elements)
- Depletion of abiotic resources (fossil)

In addition to these categories, other energy related impact categories were also assessed, namely Primary energy demand (PED), Energy return on energy invested (EROI) and Energy payback time.

3. LIFE CYCLE INVENTORY

The data collection procedures for the assessment are described below. Data was collected or estimated for the manufacturing of all power plant components. Information on transports, construction practices and operational emissions were collected from Landsvirkjun, its suppliers and contractors. Background information on manufacturing processes, global and local electricity use and fuel use and transport were acquired from international LCA databases from GaBi and published EPDs. More details on the life cycle inventory can be found in Landsvirkjun's final LCA report for Theistareykir (EFLA, 2020a).

3.1 Manufacturing and construction

3.1.1 Overview

The project was broken down in accordance with work, supply and service contracts that Landsvirkjun made with different contractors and suppliers, see Table 2.

Table 1: Manufacturing and construction components of the Theistareykir Power Station.

• Geothermal wells	• Steam separators
• Roadwork	• Power plant machinery
• Powerhouse foundation and groundwork	• Transformers
• Steam supply system	• Station auxiliaries
• Powerhouse construction	•
• Water utilities	• Post-construction landscaping

Information on transport and locations of origin was based on information from Landsvirkjun's suppliers. Transport distances are summarized in Table 3. In general, in this study it is assumed that construction materials and power station components are transported an average 100 km by land and then shipped from the nearest harbor to Húsavík harbor in northeast Iceland, before being transported to the building site at Theistareykir, unless otherwise stated.

Table 3: Origin and transport of key manufacturing and construction components of the Theistareykir Power Station.

Building material	Location of manufacturing	Road transport outside Iceland	Shipping	Road transport in Iceland
Cement	Norway/Denmark	100 km	3,000 km	30 km
Silica flour	Belgium	100 km	3,000 km	30 km
Bentonite	USA	3,500 km	5,000 km	30 km
Steel casing	Japan/China	500 km	21,500 km	30 km
Precast concrete	Iceland	-	-	400 km
Cast iron	Poland	100 km	3,000 km	30 km
PP pipes	Germany	100 km	3,000 km	30 km
Steel pipes and structural steel	Germany	100 km	3,000 km	30 km
Mineral wool	Iceland	-	-	220 km
Reinforced steel	Belarus	1,400	3000 km	30 km
PEX	Sweden	100 km	3000 km	30 km

3.1.2 Powerhouse foundation, groundwork and roadwork

Powerhouse foundation construction and groundwork was carried out in the year 2014 and includes access roads and earth work. According to the green accounting compiled by Landsvirkjun and provided by the contractors, a total of 443,000 litres of diesel oil was used during the construction work.

The preparation stage also includes the construction of a 27 km access road from Húsavík to Theistareykir, north of the power station, and a 17.1 km road from Theistareykir to Kísilvegur, south of the power station. To assess fuel and material used during road construction, a recent LCA study on a similar rural road construction in Iceland was used (EFLA, 2013).

3.1.3 Geothermal wells

The geothermal wells at Theistareykir are up to 2800 m deep, directionally drilled with a 20-40° angle. Included in the inventory is fuel use during drilling and casing, and materials used for well casing, including cement, mud and steel, and wellhead materials. A total of 17 operational wells have been drilled and prepared with casings and wellheads with an average well length of 2400 m. In the year 2019, 12 out of 17 wells were being utilized for electricity generation, while others are still being tested or not used. Total use of fuel and materials for each well was assessed using drilling reports from contractors for 8 wells that were drilled between 2015 and 2018, see Table 4. Approximately 1% of the mass weight of well materials was not accounted for in the inventory, namely polymers and sealants, due to lack of information. On average, more steel for casings was used per well at another geothermal power plant Iceland, Hellisheiði, than at Theistareykir, but less cement and diesel oil (Karlsdóttir et al., 2015).

Table 4: Estimated material and fuel use per well at Theistareykir geothermal power plant.

MATERIALS	UNIT	AVERAGE PER WELL	ESTIMATED TOTAL AMOUNT
Bentonite	tonnes	96	1,633
Silica	tonnes	82	1,390
Cement	tonnes	248	4,214
Barite	tonnes	12	196
Perlite	tonnes	4	70
Steel casing (API 5CT standard)	tonnes	176	3,000
Steel well housing	tonnes	3	51
FUEL USE	**UNIT**		
Diesel oil	thous. litres	183	3,107
Lubricants	thous. litres	1.5	26
WASTE	**UNIT**		
Mixed waste	tonnes	2	42
Wood (coloured and uncoloured)	tonnes	4	65
Hazardous waste	tonnes	4	68
Metals	tonnes	3	56

During the initial well testing and construction period, gas emissions were measured and reported, although natural emissions are difficult to discern from emissions due to testing and/or utilization, particularly in the early stages. Gas emissions during this period can be seen in Table 5. The release of drilling mud and/or separated water was minimized during the construction period and well testing via use of swallowing pits. It is estimated that a very limited amount of discharge liquid dissipated into groundwater during this period and is therefore not set within system boundaries of this study.

Table 5: Direct gas emissions during the first well testing and construction period 2008 – 2017. All numbers are in tonnes.

GAS	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2008-2017
CO_2	964	1,654	656	827	1,863	672	895	2,345	770	2,922	13,568
H_2S	613	462	523	570	246	136	391	971	150	787	4,849
CH_4	-	-	-	-	1	-	1	1	-	2	5

3.1.4 Steam supply system, steam separators and water utilites

Construction work for the steam supply system was carried out by the contractor LNS Saga. Key figures can be seen in Table 6.

Table 6: Key figures in the life cycle inventory of the steam supply system, steam separators and cold-water utilities at Theistareykir.

MATERIALS	TOTAL AMOUNT	
Concrete	tonnes	7.045
Steel	tonnes	2.100
Steinless steel	tonnes	375
Mineral wool	tonnes	150
Plastics	tonnes	317
Aluminium	tonnes	77
Other materials	tonnes	28

3.1.6 Powerhouse

Key material figures for the construction of the powerhouse and other building components for cooling towers and steam supply system, for a total of 8,000 m^2, can be seen in Table 7. Civil works were carried out by the contractor LNS Saga.

Table 7: Key figures in the life cycle inventory of the powerhouse

MATERIALS	TOTAL AMOUNT	
Concrete	tonnes	17.275
Steel	tonnes	1.466
Glass	tonnes	270
Mineral wool	tonnes	114
Aluminium	tonnes	32
Cast iron	tonnes	21
Tar fabric	tonnes	11
Stainless steel	tonnes	10
Plastics and other materials	tonnes	12

3.1.8 Power plant machinery, turbines and station auxiliaries

The main components of the power plant's machinery are two power-generating turbine and generator units and cold-end equipment including steam surface condenser, cooling tower, gas extraction system and pump and spare parts, see Table 8. Origins of manufacturing and transport distances are provided in Table 9. The units were procured from Fuji Electric (Japan) and Balcke Dürr (Germany). Station auxiliaries provide a direct current and distribution system for electricity and were procured from Icelandic contractor Rafeyri. Included in this inventory, but not present in Table 10, are also 4 power transformers from Tamini (Italy), using inventory data from a previous LCA (EFLA, 2018a), and three powerhouse transformers, using previously published EPDs (ABB, 2006).

Table 8: Key figures in the life cycle inventory of the power plant machinery, turbines and station auxiliaries

MATERIALS	TOTAL AMOUNT	
Cast iron	tonnes	81
Steel	tonnes	428
Stainless steel	tonnes	529
Aluminium	tonnes	39
Plastics	tonnes	98
FRP	tonnes	119
Concrete	tonnes	30
Mineral wool	tonnes	6
Other materials	tonnes	2

Table 9: Origin and transport of power plant machinery of the Theistareykir Power Station.

MATERIALS	MANUFACTURER	ROAD TRANSPORT OVERSEAS	SHIPPING	ROAD TRANSPORT ICELAND
Transformers	Tamini, Italy	983 km	3,048 km	30 km
Machinery: steam turbine and generator	Fuji Electric, Japan	136 km	22,273 km	30 km
Machinery: condenser, cooling tower and pipes	Balcke-Dürr, Germany	280 km	2,900 km	30 km
Station auxiliaries and powerhouse transformers	Germany / Poland	100 km	3,000 km	30 km

3.1.9 Construction of power station

The building of the power station began in 2015, but by that time 9 wells had already been drilled and tested. Construction work culminated in 2016-2017. Table 10 provides an overview of total fuel use for different units of the Theistareykir power station up until the year 2018, when work terminated with post-construction landscaping. Not present in table 10 is the inventory for roadwork, see chapter 3.1.2. A detailed inventory of construction waste and disposal methods can be found in Landsvirkjun's final LCA report (EFLA, 2020a).

Table 10: Use of fuel oil and lubricants for the building of the Theistareykir geothermal power station, excluding roadwork. All figures are in total litres.

CONSTRUCTION UNIT	DIESEL OIL	GASOLINE	KEROSENE	LUBRICANTS	ANTI-FREEZE
Earthwork	443,435	-	-	-	-
Construction of powerhouse and steam supply system	384,247	1,364	1,200	254	381
Wells	3,107,039	-	-	25,936	43
Installation of machinery	23,807	13,438	225	326	
Cold water utilities	63,565			509	
Post construction landscaping	17,536				

3.2 Operation and maintenance

The operation and maintenance phase of the power station commences after construction and includes operational electricity and fuel use and waste generation, direct gas emissions from geothermal utilization, the drilling of make-up wells to maintain a 90 MW generation capacity and the renewal of machinery during the station's 40-year lifetime.

The power station's own use of electricity and generation of waste was estimated using data from Landsvirkjun's geothermal power stations in northeast Iceland (Krafla and Gufustöðin), see table 10.

Table 10: Estimated use of electricity (including losses) and fuel oil and waste generation during yearly operations

YEARLY OPERATION	AMOUNT	
Electricity use and losses	%	4.7
Gasoline	litres/year	1,001
Diesel oil	litres/year	11,193
Biodiesel	litres/year	4,636
Waste generation	tonnes/year	58

Geothermal fluids carry a mixture of gases. Natural geothermal areas emit these gases, but emissions are typically increased by geothermal exploration and generation. The main gases emitted at the Theistareykir geothermal area are CO_2, H_2S, N_2, H_2 and CH_4, of which the latter three are in trace amounts. The year 2018 was the first full operational year. The first part of the year the station operated on one 45 MW turbine generator and the second one was put online in April of the same year. As there is yet relatively little experience from the operation of the power station, the emissions estimation for a 40-year operational lifetime is based on the years 2018 and 2019, see Table 11. A yearly average emission factor for CO_2 emissions is chosen as 7,500 tonnes/year and for H_2S as 3,000 tonnes/year.

Table 11: Gaseous emissions during the operation of the Theistareykir power station.

GAS	EMISSIONS 2018 *tonnes*	ESTIMATED EMISSIONS 2019* *tonnes*	ESTIMATED YEARLY EMISSIONS *tonnes/year*	ESTIMATED YEARLY EMISSIONS *g/kWh*
CO_2	7,909	6,139	7,500	10.2
H_2S	3,304	2,826	3,000	4.1

** Emissions in the year 2019 are based on autumn measurements and an upper limit is estimated at 6,300 tonnes.*

It is estimated that an additional 13 wells have to be drilled to maintain a 90 MW generation capacity during a 40 year lifetime, or on average a new well every three years. The same amount of well material use as current wells is assumed (Table 4), except fuel oil will be replaced by electricity generated at the station, in line with the company's carbon policy of replacing fuel powered vehicles and machines with sustainable counterparts. It is furthermore assumed that turbines, generators and transformers will need to be replaced once during the station's lifetime.

3.3 End-of-life stage

The end of life stage includes the decommissioning and demolition of all eligible aboveground power station components, and the collection, transport and recycling of steel materials in the powerhouse and steam supply system. As there is a high level of uncertainty regarding use and source of energy for the demolition work, in this study we assume the same energy use and waste generation as during the construction process for the powerhouse and supply system. Disposal methods, retrieval and recycling rates are also difficult to estimate, but in this study, it is assumed that 100% of above-ground materials are retrieved. A value-corrected substitution factor (scrap to virgin) is used to calculate the avoided burden from the recycling of steel (0.37), aluminium (0.69) and copper (0.81). All other materials are assumed to be landfilled at their end of life.

3.4 Transmission of electricity

To extend the life cycle inventory beyond a 'cradle-to-gate' analysis, the electricity generated at Theistareykir must be delivered to the user via a transmission system. In Iceland, the transmission system operates on an up to 220 kV voltage level, delivering electricity to either power-intensive consumers or distribution systems for urban areas. For the inventory, data from an LCA of the Icelandic transmission system was used (EFLA, 2018c). The transmission of one kWh of electricity includes the building and operation of powerlines, towers and substations, and transmission losses.

4. RESULTS

4.1 General LCA results

A summary of results by life cycle phase can be seen in Figure 3. According to the results, the largest contributors to environmental impacts are direct emissions during the operation of the station during a 40-year lifetime, manufacturing of all station components and fuel use during construction. Direct CO_2 emissions are the largest contributor (69%) in the global warming potential category, while H_2S emissions are by far the largest contributor (91%) to the Acidification Potential category. A more detailed account of LCIA results can be found in Landsvirkjun's final LCA report for Theistareykir (EFLA, 2020a).

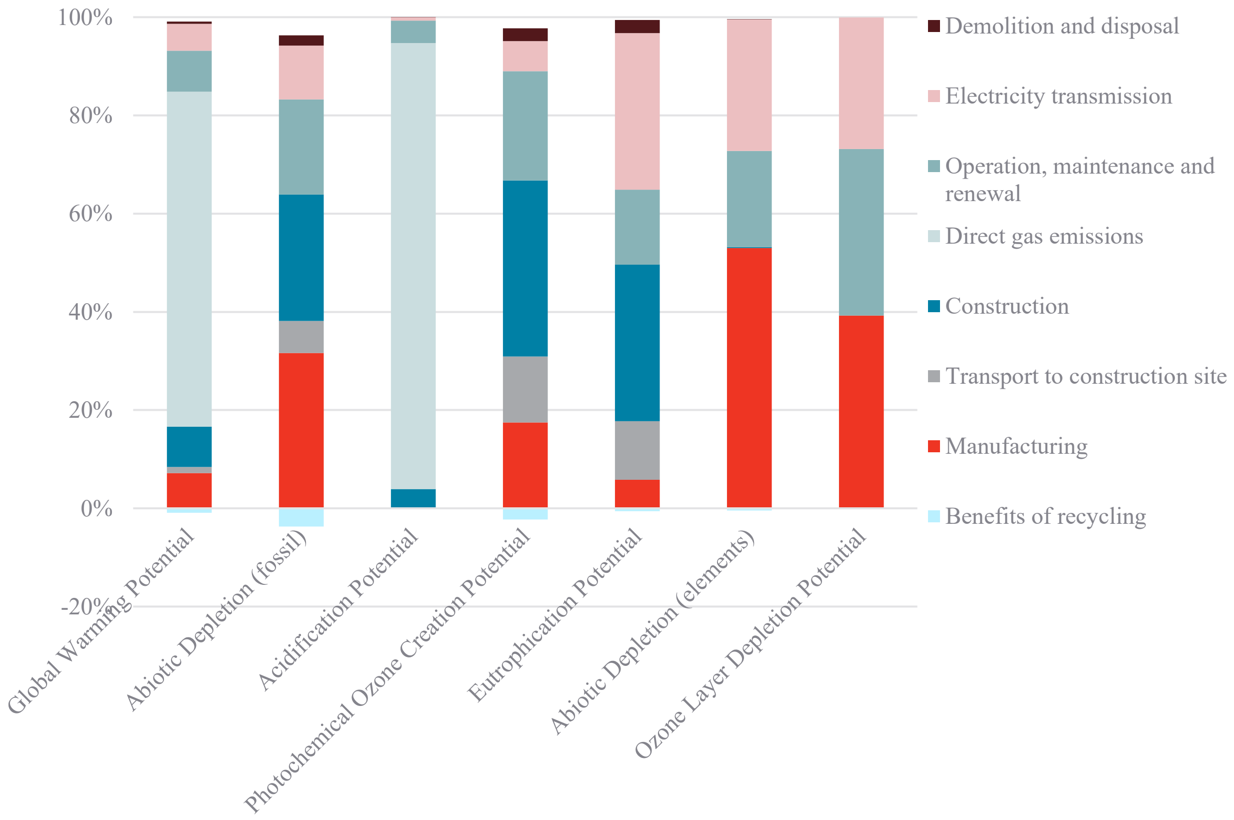

Figure 3: An overview of results for the life cycle assessment of 1 kWh generated at the Theistareykir geothermal power station, identifying the relative share of each life cycle stage during a 40 year lifetime within seven different impact categories.

4.2 Carbon footprint

A breakdown of the global warming potential or carbon footprint can be seen in Figure 4. The station's carbon footprint during a 40-year lifetime, excluding electricity transmission, is 408 kt CO_2-equivalents or 13.8 g CO_2-eq per kWh generated at the station. Once electricity transmission has been added, the carbon footprint is 14.7 g CO_2-eq/kWh. Proportionally, the largest contributing factor to global warming due to material use is material and fuel use for the geothermal wells used at Theistareykir. This corroborates with findings of other LCA studies, as the drilling of wells is both energy and resource intensive and has thus far required large amounts of fuel oil, cement and casing steel. This has highlighted the importance of these factors for future operation of the station, as future operation will require regular drilling and maintenance of make-up wells. The other largest contributors to global warming are the steam supply system and powerhouse infrastructure, mainly due to large amounts of steel, concrete and fuel needed for the construction, roadwork, mainly to due fuel use for the construction of access roads to the station, and powerhouse machinery which is material intensive.

Out of all of the construction materials accumulated within different units of the power station, the manufacturing of different grades of steel has the highest carbon footprint or 4,6%, as it plays an important role in well casings, the construction and for all the station's machinery. Concrete and steel contribute to 1.3% of the carbon footprint, plastics and aluminium 0.3% each. Transport of building products and machinery accounts for 1.3% of the carbon footprint (Fig.3), geothermal CO_2 emissions during construction period 3.2%, fuel use and waste generation during construction 5.2% (Fig.3), and electricity, fuel use and waste generation during operations accounts for 4.9% (Fig.4).

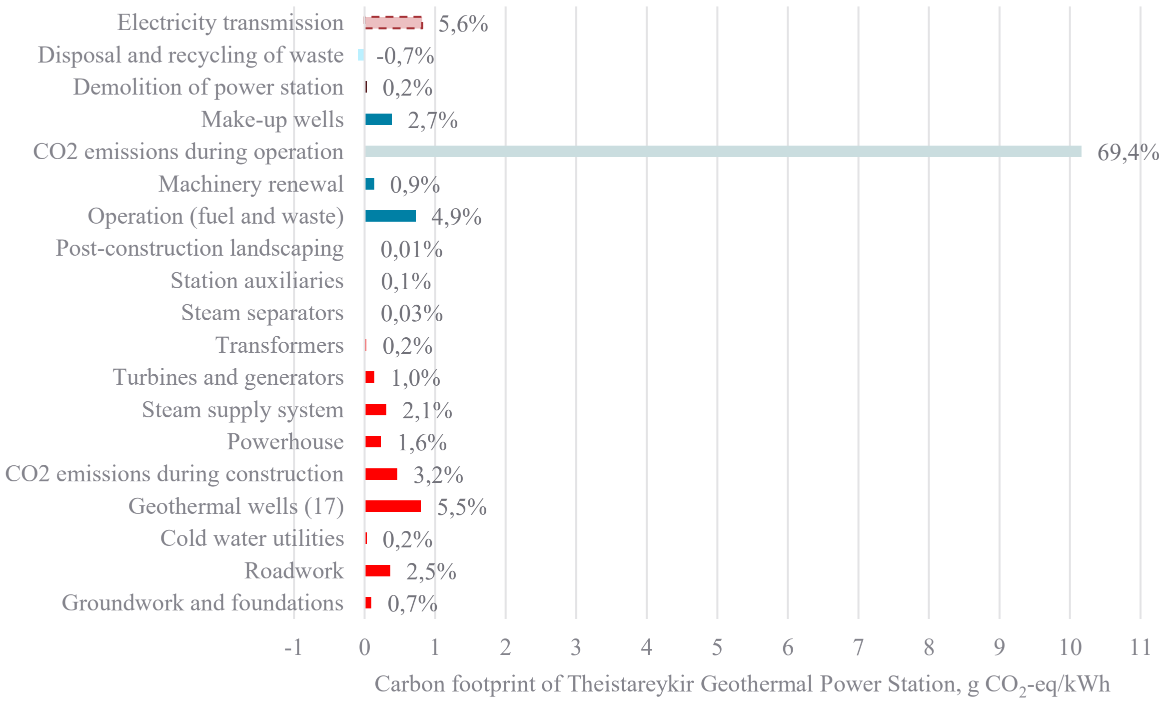

Figure 4: The share of different life cycle components within the carbon footprint (Global Warming Potential) of Theistareykir Power Station during a 40 year lifetime.

5. DISCUSSION AND CONCLUSION

5.1 Weighting and normalisation

The importance of the seven environmental impact categories were assessed employing weighting and normalization via the CML method, where LCA results for Theistareykir were stacked up against anthropogenic emissions in Europe and weighting factors assigned to impact categories by worldwide LCA specialists. Weighting and normalization results imply that out of these seven impact categories, Theistareykir by far contributes the most to the impact category acidification, which can be attributed to H_2S emissions from the geothermal fluid. The category second most impacted by the station is the impact category global warming potential or climate change, also attributable mostly to direct CO_2 emissions from the geothermal fluid.

5.2 Energy performance

The energy performance of the Theistareykir power station can be seen in Table 12. The primary energy demand (PED) of the Theistareykir power station is the acculumated energy demand throughout the station's life cycle, from renewable and non-renewable energy sources. The harvest factor is the ratio between energy generation and energy demand during the life cycle of the power station and is 109 for Theistareykir power station, which is far higher than the published range 2- 14 for geothermal stations in IPCC's special report on renewable energy sources (Sathaye et al., 2011) and more fitting to the range 6 – 280 for hydropower stations. After 5 months of operation (0.4 years), the station has generated the equal amount of energy needed for its entire life cycle, which is also lower than the published range of 0.6 – 3.6 years for geothermal stations and resembling the lowest energy payback times for hydropower stations (0.1 – 3.5).

Table 12: Energy performance of the Theistareykir power station.

	UNIT	AMOUNT
Primary energy demand	GWh	1,550
Energy generation for 40 years	GWh	29,520
Harvest factor / Energy return on invest	-	109
Energetic payback time	years	0.4

5.3 Quality and uncertainties

The life cycle impact assessment results highlight where the largest improvements can be made, whether it be from a planning, design or operational point of view. These include areas for consideration during the development phase, e.g. on key technologies or material use and can equally prove useful during the construction or operational phases. The information and data used in this study is of high quality, acquired from final construction reports, Landsvirkjun's suppliers and machine manufacturers. Operational information and assumptions are based on more than 40 years of experience with geothermal stations in northeast Iceland. All key factors within the station's life cycle are considered within the system boundaries, leaving few or no gaps, in accordance with the ISO 14040 and ISO 14044 standards. Many of these factors are not typically within system boundaries in other published LCAs for geothermal stations, e.g. roadwork, transport and end of life processes.

The largest factors of uncertainty in the study are direct geothermal emissions of CO_2 and H_2S during the lifetime, the number of make-up wells needed to sustain the generation capacity and assumptions made for the station's end of life; dismantling and material recycling. Direct geothermal emissions of CO_2 and H_2S are the single largest impact factors in the life cycle assessment for two impact categories, climate change and acidification. This study is based on emissions during the two first years of operation and it is highly uncertain how the geothermal reservoir will develop in the future, in response to geothermal utilization. There is also a level of uncertainty regarding the station's lifetime, the renewal of machinery and fuel use during operation. The oldest Icelandic geothermal power plants have been in operation since the early and late 70's and have already reached a 50-year lifetime. They still have years of operation ahead of them. A more detailed discussion of results, including a sensitivity analysis for the station's lifetime and geothermal gas emissions and how these factors impact the carbon footprint, can be found in Landsvirkjun's final LCA report (EFLA, 2020a).

5.4 Geothermal gas emissions

Gas concentration in geothermal fluids is highly variable between geothermal reservoirs and is to changes over time and also during utilization. In many places, a reduction in emissions can be observed until utilization reaches balance with the reservoir. In Berthani & Thain's review (2002) of 85 geothermal stations in 11 different countries, a high range of emissions was reported or 4 – 740 g CO_2/kWh, with the average 122 g CO_2/kWh. Since then stations with even higher emissions have been reported (Aksoy et al., 2015) and country emissions 106 g CO_2/kWh in USA in 2002, 330 g CO_2/kWh In Italy in 2013 (Friðriksson et al., 2016) and 76 g CO_2/kWh in New Zealand in 2018 (McLean & Richardson, 2019). In Iceland, average CO_2 and H_2S emissions per generated kWh have been decreasing during the past years and was 26 g CO_2/kWh and 3.3 g H_2S/kWh in 2018, see Figure 5. While it is still a subject of discussion in the scientific community to what extent utilization contributes to natural emissions from geothermal areas, measurements in Iceland have indicated either an increase in emissions or little or no change (Ármannsson, 2018). A measurement campaign in 2015 in the Theistareykir geothermal area (Kristinsson et al., 2017) indicated overall emissions of 110,000 t CO_2 per year. This would mean that measured emissions due to utilization, set within the scope of this study, would account for 7% of the total GHG emission of the area.

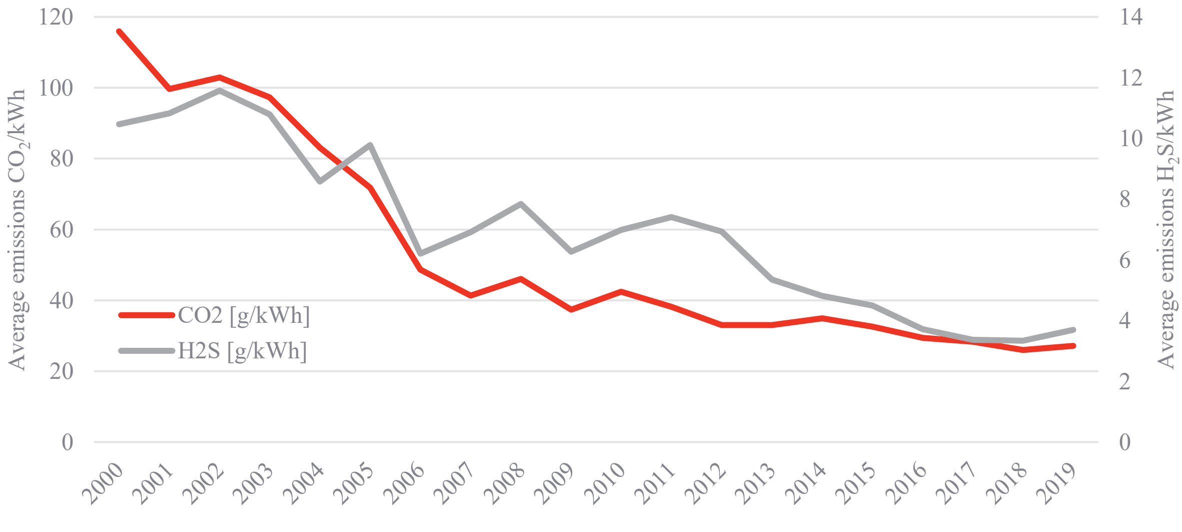

Figure 5: Average CO_2 and H_2S emissions per generated kWh from geothermal power stations in Iceland that generate electricity, 2000-2018 (National Energy Authority, 2020).

5.5 Comparability with other studies

It can be difficult to compare the results of this study with other LCA studies for geothermal stations for several reasons. Firstly, different technologies are employed to best suit the temperature and nature of different geothermal reservoirs (e.g. single or double flash, binary, dry steam or enhanced geothermal systems), and there is also a fundamental difference between stations generating electricity only or generating both heat and electricity (combined heat and power stations, CHP). Lastly, although many key factors are similar between previously published LCA studies, system boundaries have not been harmonized and many studies have gaps in their inventory for different life cycle stages. A stringent set of requirements is made for Environmental Product Declarations (EPDs), third party verified declarations of environmental impacts based on LCAs. These must adhere to Product Category Rules, a set of requirements set by all major stakeholders in the energy sector. This allows for at least a fair comparison between different stations of the same or different energy sources, with a greater level of confidence. Work is also currently underway within the EU to harmonize guidelines for LCAs for geothermal systems (Blanc et al., 2020).

The carbon footprint of Theistareykir geothermal power station is low compared to published values for geothermal stations in Sathaye et al., 2011, which range from 6 to 79 g CO_2-eq/kWh and with a median of 38 g CO_2-eq/kWh. These values are substantially lower than average emission values for non-renewable energy sources such as coal and natural gas, with medians 820 and 490 g CO_2-eq/kWh respectively. A wider range for geothermal stations, or 5 – 898 g CO_2-eq/kWh, was reported in a recent review (Blanc et al., 2020). Although different technologies are employed for different purposes, the carbon footprint for Theistareykir is similar to that of the Hellisheiði power plant, a combined heat and power plant in the south of Iceland (Karlsdóttir et al., 2020), which reports 11.4 – 15.9 g CO_2-eq/kWh_e for electricity and 11.2 – 15.8 g CO_2-eq/kWh_{th} for heat, depending on whether current CarbFix injection measures are considered or not, and calculated for a 30 year lifetime (electricity transmission excluded). According to a sensitivity analysis performed for Theistareykir (EFLA, 2020a), a lifetime of 30 years instead of 40 years would result in an increase of 7% to the carbon footprint, from 13.8 g CO_2-eq/kWh to 14.7 g CO_2-eq/kWh.

5.6 Opportunities ahead and conclusion

The life cycle inventory of this study is based on current manufacturing and construction methodologies. Many opportunities for improvement are identified within the results for the operational phase in the years ahead, such as the use of alternative energy sources during the drilling of make-up wells. It is likely that the use of fossil fuel during construction and drilling work will be substituted in the very near future by electricity, with society heading towards energy transition. The use of cement and steel for well casing is another area for potential improvements. A portion of the cement can be substituted by other materials, and a greater consideration can be made in the sourcing or procurement of steel, as the carbon footprint of steel differs greatly between methods of manufacturing (blast furnace vs electric arc furnace) and locations of manufacturing (energy grid mix in use). Likewise, the end-of-life stage has many unknowns and iterations can be made regarding the ratio of retrieved materials and the choice of materials that will have end-of-life value.

Landsvirkjun is now working on its climate plan to become carbon neutral in 2025. This includes reducing emissions due to geothermal utilization, whether by injection, or utilization. Although Theistareykir generates more electricity, net emissions are higher from the Krafla geothermal station and this is where the first measures will be implemented to reduce emissions.

The results of a life cycle assessments can be used as a part of a comprehensive decision process in the design phase, construction preparation, procurement and in operational stages, with the purpose of reducing environmental impacts of geothermal power utilization. The LCA thus proves as an important tool in environmental management and eco-design for continuous improvement. A life cycle assessment is furthermore required for the publication of a certified Environmental Product Declaration (EPD) on geothermal electric power generation. The LCA's results can therefore be of direct use for Landsvirkjun's customers when estimating their products' or services' overall environmental performance.

REFERENCES

ABB T&D S.p.A. (2006): Environmental Product Declaration. Large Distribution Transformer 16/20 MVA (ONAN/ONAF).

Aksoy, N. Gok, O.S., Mutlu, H. & Kilinc, G. (2015): CO2 Emission from Geothermal Power Plants in Turkey. Proceedings World Geothermal Congress 2015, Melbourne, Australia.

Ármannsson, H. (2018): An overview of carbon dioxide emissions from Icelandic geothermal areas. Applied Geochemistry, vol. 97, pp.11-18.

Bertani, R., Thain, I. (2002): Geothermal power generating plant CO2 emission survey. International Geothermal Association (IGA) News

Bertani, R. (2016): Geothermal power generation in the world 2010-2014 update report, *Geothermics* 60: 31-43

Blanc, I., Damen, L., Douziech, M., Fiaschi, D., Harcouët-Menou, V., Manfrida, G., Mendecka, B., Parisi, M.L., Perez Lopez, P., Ravier, G., Tosti, L. (2020): First version of harmonized guidelines to perform environmental assessment for geothermal systems based on LCA and non LCA impact indicators: LCA Guidelines for Geothermal installations. GEOENVI.Deliverable number: (D.3.2).

EFLA (2013): Vistferilsgreining fyrir veg – Rannsóknarverkefni Vegagerðarinnar 2012. Rannsóknarskýrsla. Vegagerðin.

EFLA (2015): Vistferilsgreining raforkuvinnslu með rannsóknarvindmyllum á Hafinu við Búrfell. Landsvirkjun LV-2015-129.

EFLA (2018a): Vistferilsgreining raforkuvinnslu með vatnsafli. Búðarhálsstöð, Landsvirkjun LV-2018-048.

EFLA (2018b): Vistferilsgreining raforkuvinnslu með vatnsafli. Fljótsdalsstöð. Landsvirkjun LV-2018-064.

EFLA (2018c): Vistferilsgreining fyrir flutningskerfi raforku. Flutningskerfi Landsnets rekið á 66 kV, 132 kV og 220 kV spennu. Landsnet.

EFLA (2019): Vistferilsgreining raforkuvinnslu með vatnsafli. Blöndustöð. Landsvirkjun LV-2019-030.

EFLA (2020a): Vistferilsgreining raforkuvinnslu með jarðvarma. Þeistareykjastöð. Landsvirkjun LV-2020-034.

EFLA (2020b): Vistferilsgreining raforkuvinnslu með vatnsafli. Búrfellsstöð II. Landsvirkjun LV-2020-035.

EN 15804:2012 (2012): Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products, *CEN/TC 350*.

Friðriksson, Þ., Mateos, A., Audinet, P. & Oruco, Y. (2016): Greenhouse gases from geothermal power production. Energy Sector Management Assistance Program (ESMAP) technical report; 009/16. World Bank Group.

Hartmann, J. (2017): Geothermal Sustainability Assessment Protocol. Theistareykir Power Project, Iceland. Project Stage: Preparation. Final report.

International Organization for Standardization (2006): ISO 14040:2006, Environmental management – Life cycle assessment – Principles and Framework, Second edition.

International Organization for Standardization (2006): ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines, First edition.

International Organization for Standardization (2015): ISO 14025:2006, Environmental labels and declarations – Type III environmental declarations – Principles and procedures.

Karlsdóttir, M.R., Pálsson, Ó.P., Pálsson, H., Maya-Drysdale, L. (2015): Life cycle inventory of a flash geothermal combined heat and power plant located in Iceland. *Int J Life Cycle Assess* 20; p. 503-519.

Karlsdóttir, M.R., Heinonen, J., Pálsson, H., Pálsson, Ó.P. (2020): Life cycle assessment of a geothermal combined heat and power plant based on high temperature utilization. *Geothermics*, b. 84, p. 101727.

Kristinsson, S.G., Óskarsson, F., Óladóttir, A.A., Ólafsson, M. (2017): Háhitasvæðin í Kröflu, Námafjalli og á Þeistareykjum. Vöktun á yfirborðsvirkni og grunnvatni árið 2017. LV-2017-123, ÍSOR-2017/086.

McLean, K. & Richardson, I. (2019) Greenhouse gas emissions from New Zealand geothermal power generation in context. New Zealand Geothermal Association

National Energy Authority - Orkustofnun (2020): OS-2020-T002-01: Gas Emissions of Geothermal Power Plants and Utilities 1969-2019 (data file).

The International EPD System (2020): Product Category Rules according to ISO 14025. Product Group Classification: UN CPC 171 and 173. Electricity, Steam and Hot/Cold Water Generation and Distribution. Version 4.11

Tomasini-Montenegro, C., Santoyo-Castelazo, E., Gujba, H., Romero, R.J., Santoyo, E. (2017): Life cycle assessment of geothermal power generation technologies: An updated review. *Applied Thermal Engineering* 114: p. 1119-1136.

Sathaye, J; Lucon; O., Rahman; A., Christensen; J., Denton; F., Fujino; J., Heath; G., Kadner; S., Mirza; M., Rudnick; H., Schlaepfer, A. and Shmakin, A. (2011): Renewable Energy in the Context of Sustainable Development. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press.