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The environmental impacts and the carbon intensity of geothermal energy: A case study on the Hellisheiði plant

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ABSTRACT

Geothermal energy, alongside other low-carbon and renewable energies, is set to play a key role in decarbonising the power generation industry to meet the Paris Agreement goal. Thus far the majority of Life Cycle Assessment (LCA) studies focused on enhanced geothermal plants. However, conventional geothermal plants that harness hydrothermal reservoirs dominate the production of electricity from geothermal energy worldwide. This article focuses on Hellisheiði, a combined heat and power double flash geothermal plant located in Iceland, with an installed capacity of 303.3 MW of electricity and 133 MW of hot water. The study has a twofold goal: (i) identify hot spots in the life cycle and, where possible, suggest improvements, and (ii) understand the potential of geothermal energy to decarbonise the power generation industry. First, a detailed LCA study has been performed on Hellisheiði, with cradle-to-grave system boundaries and detailed site-specific data obtained from the literature. The analysis identifies consumption of diesel for drilling and use of steel for wells casing and construction of the power plant as the main hot spots. Second, carbon intensities of electricity production for various possible configurations of the Hellisheiði power plant (including single flash, and power-only production) have been compared with those of other geothermal plants and other energy sources. Different allocation procedures have been used to allocate impacts between electricity and hot water where necessary, and Monte Carlo simulations have been used to estimate uncertainties of Hellisheiði's carbon intensities. The comparison shows that the carbon intensity of Hellisheiði is in the range of 15–24 g CO_2-eq./kWh, which is similar to those of binary cycle geothermal plants, solar (photovoltaic) and hydropower, lower than other geothermal technologies and fossil-based technologies, and higher than nuclear and onshore wind.

1. Introduction

The Paris Agreement, signed in 2015, set a milestone in the battle against anthropogenic climate changes, with a global consensus on limiting global warming to 2 °C and the aspiration to achieve 1.5 °C by 2100 (UNFCCC, 2015). Whilst the goal of 2 °C was found by the IPCC to be too generous to avoid catastrophic environmental consequences, the current trajectory points to a global warming as high as 3 °C in 2100 (Masson-Delmotte et al., 2018). The scientific community is clear that major efforts are necessary. Electrical power generation is in the spotlight because it represents the largest contributor to greenhouse gas emissions and has the potential to decarbonise almost fully and more quickly than other industrial sectors. Renewable energy sources are set to play a key role in its transformation; amongst those, geothermal energy has notable advantages. It is practically ubiquitous (beneath the earth surface, rock temperature increases with depth due to the natural geothermal gradient), it is independent from seasonal and climatic conditions and thus a source of baseload power, and it is cheap (with an average levelised cost of electricity as low as USD 0.07/kWh) (IRENA, 2019), primarily because it makes use of well-known thermodynamic processes for electricity generation.

As for most technologies, harnessing geothermal resources has proceeded from the highest quality and least common resources (steam-dominated hydrothermal systems) to lower quality and more common resources (petrothermal systems, after Schechinger and Kissling (2015)). Technologies for hydrothermal systems extract hot geothermal fluid from natural aquifers at depths varying from about one to about four kilometres. The quality of an aquifer increases with its enthalpy, essentially from liquid-only to steam-only (i.e. dry steam) reservoirs through increasing concentrations of water vapour. By contrast, technologies for petrothermal systems aim to produce hot water at locations where natural aquifers are not present by developing an "engineered reservoir". This technology, also known as enhanced geothermal systems (EGS), is receiving increasing attention because it potentially

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allows harnessing geothermal energy anywhere – though in practice it is economically feasible only in the presence of substantial geothermal gradients.

In 2015, geothermal energy produced less than 0.5% (~73 GWh) of global electricity (Bertani, 2016). However, the total capacity is expected to almost double from 2015 to 2020 to 21 GWe. At present, single flash plants represent around 40% of the total installed capacity; dry steam and double flash technology follow with approximately 20%, whilst binary plants, used in both hydrothermal and petrothermal systems, contribute to 14% (Bertani, 2016).

In recent years, large efforts have been made on assessing the life cycle environmental impacts of enhanced geothermal plants (e.g. Frick et al., 2010; Lacirignola and Blanc, 2013; Pratiwi et al., 2018; Sullivan et al., 2011, 2010; Treyer et al., 2015); however, hydrothermal systems still dominate the current electricity generation, and are set to do so for the near future as well. For this reason, it is essential to assess the life cycle environmental impacts of conventional geothermal technologies (i.e. hydrothermal systems), as done for example by Bravi and Basosi (2014) and Parisi and colleagues (2019) for conditions found in Italy and by Sullivan et al. (2011, 2010) for generic conditions. A review of Life Cycle Assessment (LCA) studies on geothermal power generation technologies was performed by Tomasini-Montenegro and colleagues (2017). The present article presents a comprehensive LCA study based on detailed site-specific literature data on Hellisheiði (Karlsdóttir et al., 2015), a combined heat and power (CHP) geothermal plant in Iceland.

Iceland is the seventh country in the world for electricity production from geothermal (Bertani, 2016), and it is the leading country in annual geothermal energy use for district heating per person (Lund and Boyd, 2016). Due to its location on the mid-Atlantic ridge, Iceland features geological characteristics that favour utilization of geothermal energy. The share of geothermal energy in the primary energy supply of Iceland is about 69%, reaching 90% of all energy used for house heating and standing at 29% for electricity needs (Bertani, 2016). Hellisheiði is the most recent Icelandic geothermal project: electricity generation started in 2006 and hot water production in 2010 (Karlsdottir et al., 2010). The plant is the largest in Iceland and the sixth largest by electric capacity in the world (303 MWe) (IGA, 2015).

This article is organised as follows: Section 2 reports goal and scope of the LCA study, impact categories analysed and the approach used for allocation and uncertainty analysis; Section 3 presents results of the LCA study in terms of hot spot analysis and carbon intensity of electricity production[1]; the results are discussed in Section 4 and the key conclusions summarised in Section 5.

2. Methods

The environmental impacts of the CHP plant at Hellisheiði and its carbon intensity of electricity production have been quantified from a life-cycle perspective following the LCA standardised methodology (ISO, 2006a, 2006b). Gabi software version 8 has been used for the computations.

2.1. Goal and functional unit

This study has a twofold goal. First, it quantifies and evaluates the environmental impacts associated with the Hellisheiði geothermal plant with the objective of identifying hot spots in the life cycle, and propose, where possible, improvements. The calculated absolute environmental impacts refer to the amount of electricity and hot water that are produced during the operation of the Hellisheiði plant for one second, which equal ~303 MJe and 133 MJth[2] respectively. This quantified description is in LCA commonly referred to as Functional Unit.

Second, this study quantifies and compares the carbon intensity of electricity production at Hellisheiði with respect to other geothermal plants and other energy sources. The aim is to understand the potential of geothermal energy to contribute to the Paris Agreement goal and the decarbonisation of the power generation industry.

The LCA study follows an attributional approach whereby the average environmental impacts of the plant in its current configuration are quantified; the possible environmental impacts associated with potential decisions based on the conclusions of this study are not considered. (For more specific definitions of attributional LCA see e.g. Curran et al., 2005; Finnveden et al., 2009; JRC, 2010).

2.2. Scope

Fig. 1 reports the system boundaries of the LCA study: they are cradle to grave and include the three typical phases of construction, operation and end-of-life. The exploration stage prior to construction was not considered due to lack of data. This study adopts the pragmatic distinction between foreground and background systems, whereby the former is defined as “the set of processes whose selection or mode of operation is affected directly by decisions based on the study” and the latter as “all other processes which interact with the foreground, usually by supplying or receiving material or energy” (Clift et al., 2000).

The Hellisheiði power plant is a double-flash combined heat and power plant that generates electricity by means of high- and low-pressure turbines. The high-pressure turbines use geothermal fluid steam separated by means of flash separation and have a combined capacity of 270 MWe, whilst the low-pressure turbines generate additional 30.3 MWe using steam separated in a second flash separator. The heating station recovers the remaining thermal energy in the geothermal fluid to produce hot water for district heating, with an installed capacity of 133 MJ/s.

The construction phase includes drilling of production and injection wells, construction of pipelines that transport geothermal fluid from the wells to the power plant; and construction of facilities and machineries for the power generation plant and the heating station, including cooling towers. During the operational phase, the plant uses geothermal fluid to produce electricity, which is sent to the grid, and hot water, which is used for district heating. Additional activities are required to maintain the operation of the plant; these include drilling of make-up wells and construction of additional collection pipelines. Maintenance of machineries and facilities was however not considered. Finally, the end-of-life phase consists of closure of the geothermal wells and dismantling of the power plant and the heating station.

2.3. Life cycle inventory

The process of data collection has been guided by the distinction between foreground and background systems mentioned in Section 2.2. Where possible, site-specific data have been used for the foreground system, whilst the background system has been described by the Ecoinvent database version 3.4 (Wernet et al., 2016). Iceland specific datasets have been used when available in the Ecoinvent database, otherwise activities have been described by European or generic global datasets. The cradle-to-grave perspective is adopted for all activities in the background system.

The foreground system primarily relies on the comprehensive inventory developed for the Hellisheiði geothermal plant by Karlsdóttir and colleagues (Karlsdóttir et al., 2015). The inventory covers both

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[1] Carbon intensity is defined as the life-cycle emission of greenhouse gases expressed in terms of CO_2 equivalents (i.e. in terms of their potential to contribute to global warming) per kWh of electricity produced.

[2] Thermal energy of hot water has been calculated based on heat difference between 90 and 40 °C.

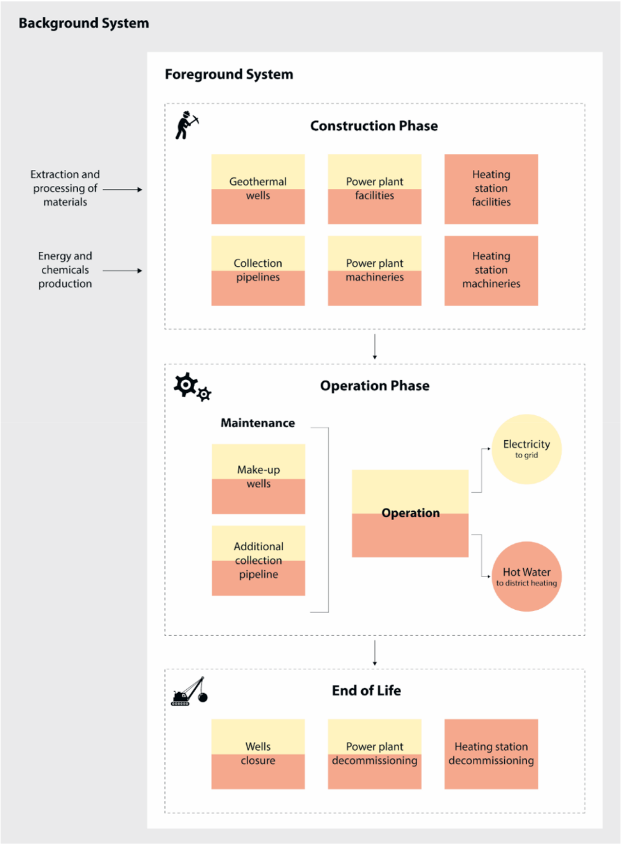

Fig. 1. System boundaries for the combined heat and power geothermal plant at Hellisheiði. Rectangular boxes identify processes, whilst oval shapes represent products. The colour system highlights the allocation strategy: single coloured processes are allocated to either electricity or heat; double coloured processes are partitioned between the two products. Elementary flows are not reported for clarity.

Table 1
Key model parameters. The complete inventory is reported in Karlsdóttir et al. (2015).

Parameter	Unit	Value
Power plant		
Electric capacity – double flash	MWe	303.3
Electric capacity – single flash	MWe	270
Heat capacity	MWth	133
Load factor	–	0.87
Lifetime	years	30
Wells		
Number of production and injection wells	#	64
Number of make-up wells	#	16
Average depth	m	2150
Operation		
Geo-fluid flow	kg/s	1050

single and double flash configurations, and both combined heat and power, and power-only production. Only key parameters are reported in this article (Table 1). Data for cooling towers are based on those reported by Schulze et al. (2019). The amount of drill cuttings (with 50% water) is estimated to be equal to ~450 kg per metre of well.

Up to present, the plant load factor, i.e. the ratio between the actual power output and the installed capacity, has been 0.87. The lifetime of the plant is projected to be 30 years. For the installed capacity, 64 wells primary (production and injection) have been drilled with an average depth of 2150 m. Additionally, 16 make-up wells are estimated to be required during the plant lifetime (approximately one new well every two years). The plant uses around 1050 kg of geo-fluid per second for producing 303 MW of electricity and 133 MW of hot water.

Table 2
Parameters used for exergy- and economic-based allocation.

Parameter	Unit	Value
Temperature of hot water	°C	90
Temperature of surrounding environment	°C	10
Price of electricity	kr/kWh *(USD/kWh)*	5.9 *(~0.05)*
Price of hot water	kr/m^3 *(USD/m^3)*	149.9 *(~1.23)*

Because the plant is still in operation, data on the end-of-life phase is not yet available. This study assumes that at the end of the lifetime, the geothermal wells are filled with cement and gravel and sealed with a concrete slab, according to the inventory included in the Ecoinvent database. We assumed that only large metal (copper and steel) parts of the transformers, which are easy to dismantle, and reinforced concrete from the plants' facility are recycled. Treatment of the remaining materials is based on the Ecoinvent database of market activities.

2.4. Allocation

Allocation is the procedure used in LCA to apportion the environmental impacts to each function of a multi-functional process such as a combined heat and power plant. In this study, allocation has been used to quantify the carbon intensity of electricity production at Hellisheiði.

The procedure involved two steps. First, the processes that could be associated to only one function have been identified; these include the construction and the dismantling of the heating station facilities and machineries, which are solely associated to the function of hot water production. The environmental impacts of the remaining processes have been partitioned between the two functions of electricity and hot water production according to three strategies. Partitioning factors have been developed to reflect either the energy or the exergy content of the product streams, or their economic value. Table 2 reports the main parameters used for calculating partitioning factors, whilst partitioning factors for electricity are included in Table 3. (The underlying modelling equations are included in the Supporting Information.) For economic allocation, Iceland-specific prices for hot-water and electricity have been taken from Veiture, a utility company (Veiture, 2019).

2.5. Uncertainty analysis

LCA results can be uncertain for a number of reasons; a general distinction is usually made between parameter, model and scenario uncertainty (Huijbregts et al., 2003). Here we focus on parameter uncertainty, which reflect inherent variability or incomplete knowledge on inventory data, due for instance to imprecise measurements, (expert) estimations and assumptions.

The Monte Carlo method has been used to propagate uncertainties from the life-cycle inventory data to LCA results. Uncertainty ranges have been taken from Karlsdóttir and colleagues, who for each model parameter reported a high, medium or low level of accuracy, which indicate respectively a likely under- or over-estimation of 5%, 10% and 25% (Karlsdóttir et al., 2015). Model parameters have been assumed to be independent and normally distributed, with a standard deviation equal to a third of the range of variability[3]. The Monte Carlo simulation has been performed in the Gabi software, version 8, with a number of iterations equal to 10,000 (Huijbregts et al., 2003).

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[3] It is an empirical rule that nearly all values, 99.7%, lie within three standard deviations of the mean.

Table 3
Partitioning factors for electricity.

Strategy	Single flash	Double flash
Energy	0.66	0.69
Exergy	0.69	0.71
Price	0.99	0.99

Table 4
Impact categories analysed. Only the impact categories reported in bold are included in the main text. The results for the other impacts are reported in graphical form in the SI and in numbers in Paulillo et al. (2019).

Impact category	Metric
Acidification	**Mole of H + eq.**
Climate Change	**kg CO_2 eq.**
Ecotoxicity freshwater	**CTUe**
Eutrophication freshwater	**kg P eq.**
Eutrophication marine	kg N eq.
Eutrophication terrestrial	Mole of N eq.
Human Toxicity, Cancer effects	**CTUh**
Human Toxicity, Non-Cancer effects	**CTUh**
Ionizing Radiations	Bq U235 air eq.
Ozone Depletion	kg CFC-11 eq.
Particulate Matter/Respiratory Inorganics, human health	**kg PM2.5 eq.**
Photochemical Ozone Formation, human health	**kg NMVOC**
Resource Depletion, mineral, fossils and renewables	**kg Sb eq.**
Resource Depletion, water	m^3 eq.

2.6. Impact categories

The Impact Assessment phase of LCA translate the emissions and resources use quantified in the inventory phase into impacts. Two general approaches are available, using so-called mid-points or end-points (Clift, 2013). In this study the mid-point approach based on the ILCD (International Life Cycle Data System) recommendations has been used (JRC, 2011, 2012). All impact categories, but land use and ionising radiation, have been included. The former has been considered irrelevant due to lack of data for the foreground system; the latter has been replaced by a more recent and comprehensive category developed by Paulillo (Paulillo, 2018). Table 1 reports the impact categories considered in this study along with their metrics; a brief description of each category is included in the Supporting Information.

The main paper focuses on nine impact categories (reported in bold in Table 4); these have been selected based on their normalised impacts (reported in graphical form in the Supporting Information and in numbers in Paulillo et al. (2019)), which represent the contributions to the overall impact per person of Europe.

3. Results

The following Sections present a hot spot analysis for the combined production of heat and power in a double flash configuration at Hellisheiði, and a comparison of the carbon intensity of electricity production at Hellisheiði with other geothermal studies and energy technologies. The complete LCA results are reported in Paulillo et al. (2019).

3.1. Hot spot analysis

Fig. 2 shows contributions of each of the three phases – construction, operation and maintenance (reported separately), and end-of-life (see Fig. 1) - of the life cycle of the Hellisheiði power plant for the production of electricity and heat in a double flash configuration. The construction phase, which includes drilling of the wells, construction of collection pipelines and commissioning of the CHP plant, contributes to over 80% of the impact score in all impact categories but climate change and ecotoxicity. The climate change category is dominated by atmospheric emissions of CO_2 occurring during the operation of the plant. The operational phase has also a small contribution to the photochemical ozone formation category due to methane emissions (see Supporting Information and Paulillo et al. (2019)). On the other hand, nearly half of the ecotoxicity category score is associated with the end-of-life phase, which in turn is primarily due to end-of-life treatment of copper used in electrical wires in the plants' facilities. The end-of-life phase has negligible contributions to the remaining impact categories (included those reported in the Supporting Information and in Paulillo et al. (2019).) Finally, maintenance of the plant, which includes the construction of make-up wells and additional collection pipelines, contributes to around 10–20% of impact categories with the exception of climate change.

The impacts of the construction phase are analysed in more details in Fig. 3 and Fig. 4. These report hot spot analyses of the primary geothermal wells and of the CHP plant, whose combined contribution amounts to over 80% of the impact of the construction phase in all impact categories.

With respect to the geothermal wells, the results presented in Fig. 3 show that production of steel, which is used for wells casing, and production of diesel and its use on-site in a diesel-electric generating set for powering the drilling rig represent the two key sources of environmental impacts. Together they contribute to over 85% of the categories acidification, climate change, particulate matter/respiratory inorganics, photochemical ozone formation and depletion of minerals, fossils and renewables and to over 50% of the remaining categories reported in Fig. 3. (Notably, they also dominate the impact categories reported in the Supporting Information and in Paulillo et al. (2019) with the exception of depletion of water.). Diesel production and use is modelled by a generic global dataset, whilst steel production is based on a European-specific dataset. Besides diesel and steel, treatment of drilling wastes has substantial contributions (20–40%) in the categories eutrophication (freshwater) and human and environmental toxicity. Waste drilling treatment is also modelled by a generic global dataset and includes landfarming and disposal in a residual material landfill; the impact is primary due to landfarming and is due to emissions to industrial soils of metals (for the toxicity categories) and of phosphorus (for the eutrophication category). Cement production for wells casing represents a significant contribution (~10%) to the climate change category. Aluminium (used in wellheads), drilling mud components including water, lignosulfunite and bentonite, and other materials have minor impacts in the categories reported.

The hot spot analysis for the construction of the CHP plant in Fig. 4 reveals a more diversified situation. Steel (in various forms) and copper result in being the major sources of impacts. Reinforcing steel contributions range between ~10 and ~40%, stainless steel and steel (low alloyed) have significant (~20%) contributions to human toxicity (cancer effects) and particulate matter categories. Copper, on the other hand, yields contributions higher than 40% in the categories ecotoxicity and eutrophication (marine) and human toxicity (non-cancer effects). Other notable sources of impacts are titanium to the category depletion of minerals, fossils and renewables, glass fibre reinforced plastic and concrete to the category climate change.

3.2. Comparison of carbon intensities for selected geothermal studies and energy sources

In Fig. 5 and Fig. 6 we compare the carbon intensity of the Hellisheiði geothermal plant with those of other geothermal plants and other energy sources, respectively. Fig. 5 includes Hellisheiði carbon intensities for both single (SF) and double (DF) configurations and for both the case of combined heat and power (according to three allocation strategies) and power-only production[4]. A box-and-whisker plot is used to display uncertainties: the vertical line indicates median values,

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[4] Note that the system boundaries for power-only production does not include construction and dismantling of the heating station (see Fig. 1).

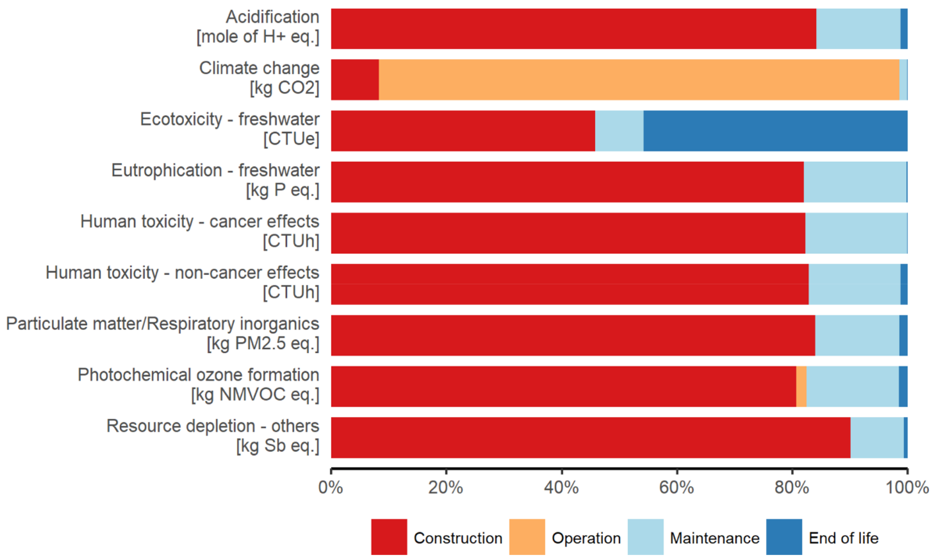

Fig. 2. Hot spot analysis of the product system depicted in Fig. 1. “Resource Depletion – others” is used in place of “Resource Depletion, minerals, fossils and renewables” for clarity of displaying.

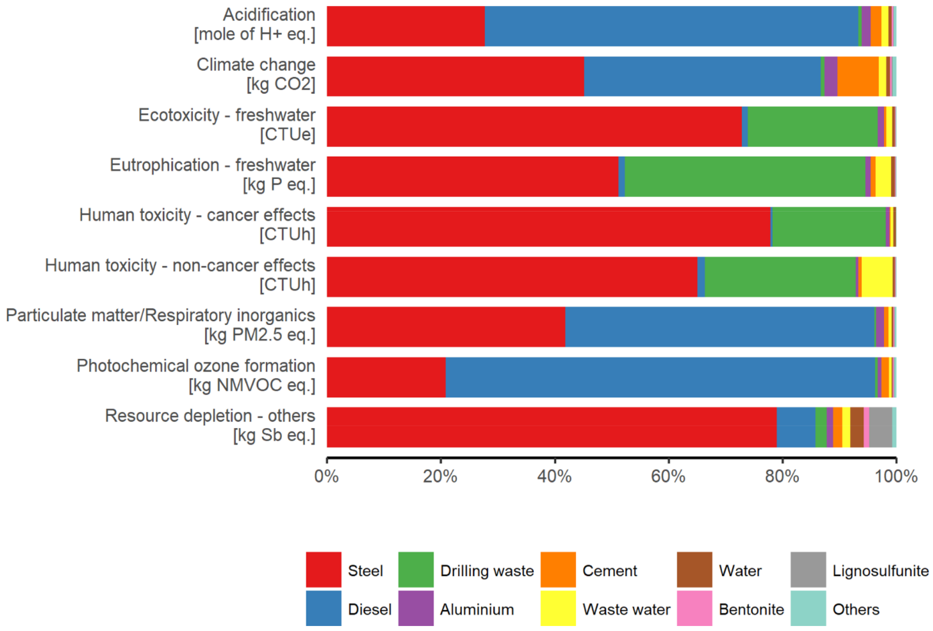

Fig. 3. Detailed hot spot analysis of the construction of primary geothermal wells. “Resource Depletion – others” is used in place of “Resource Depletion, minerals, fossils and renewables” for displaying purposes.

the box represents the 25th and 75th percentiles, whilst the whiskers the 10th and 90th percentiles (numerical values are included in Paulillo et al. (2019)). Median values for SF and DF configurations range between 18 and 24 g CO_2-eq./kWh and 15–23 g CO_2-eq./kWh respectively, with the lowest value for energy allocation and highest for power-only production.

With respect to other geothermal plants, we found ten life-cycle studies in the literature that report climate change impact scores. Of these, five focused on binary cycles (Frick et al., 2010; Lacirignola and Blanc, 2013; Martín-Gamboa et al., 2015; Pratiwi et al., 2018; Rule et al., 2009), three on double flash plants (Atilgan and Azapagic, 2016; Hondo, 2005; Marchand et al., 2015), and one on single flash (Bravi and Basosi, 2014) and on dry steam (Buonocore et al., 2015) technologies. The Hellisheiði carbon intensities are slightly lower than median values of double flash plants (47 g CO_2-eq./kWh, with a range of 15–63 g CO_2-eq./kWh) and similar to that of binary cycles plant, featuring a median value of 25 g CO_2-eq./kWh (and a range of 2–25 g CO_2-eq./kWh). Life-cycle studies on dry steam and single flash technologies report values as high as ~250 and ~770 g CO_2-eq./kWh respectively.

Carbon intensities estimated for other energy sources have been obtained from the fifth assessment report of the IPCC (Schlömer et al., 2014). Fig. 6 reports median values, together with minimum and maximum ranges for conventional fossil-fuels technologies such as coal (pulverized coal-fired plant) and natural gas (burnt in a combined cycle plant), low-carbon technologies such as nuclear, and renewable sources such as onshore wind, solar photovoltaic and hydropower; numerical values are reported in Paulillo et al. (2019). The carbon intensity performance of the Hellisheiði power plant is reported as a range between the minimum and maximum values associated with different configurations and allocations (light blue area). The chart shows that Hellisheiði has performances similar to that of hydropower (median

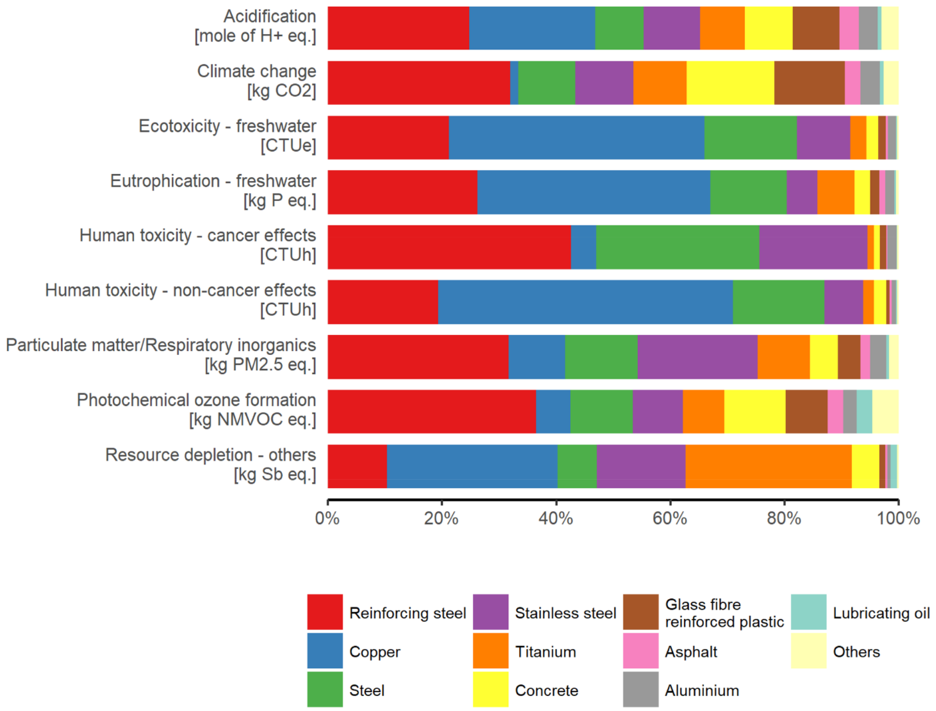

Fig. 4. Detailed hot spot analysis of the construction of the combined heat and power (CHP) plant. “Resource Depletion – others” is used in place of “Resource Depletion, minerals, fossils and renewables” for displaying purposes.

value = 24 g CO_2-eq./kWh), lower than the median value of solar photovoltaic (48 g CO_2-eq./kWh), but higher than onshore wind and nuclear (11 and 12 g CO_2-eq./kWh respectively). Fossil-based energy technologies feature carbon intensities over 50 times higher than that of Hellisheiði, and binary and double flash plants (median value for coal and natural gas equals ~500 and ~800 g CO_2-eq./kWh), but similar to that of dry steam and single flash technologies.

4. Discussion

4.1. The life-cycle hot spots

The hot spot analysis performed over the life cycle of the Hellisheiði plant for a co-production of electricity and heat (Section 3.1) revealed that the majority of impacts stem from the construction phase, specifically from the drilling and the casing of primary geothermal wells, and

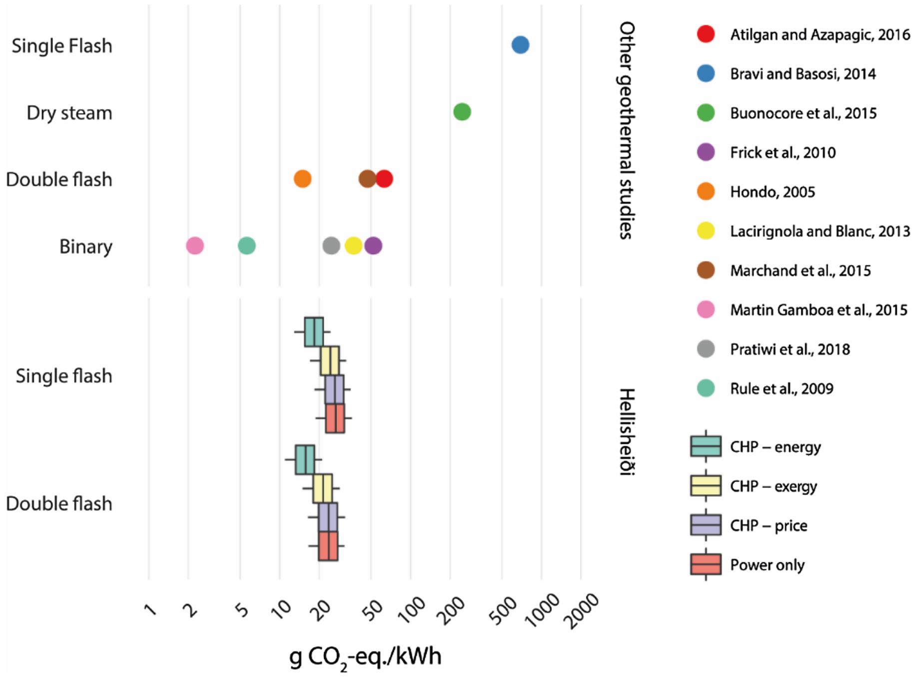

Fig. 5. Comparison of climate change impacts (g CO_2-eq.) between Hellisheiði and other geothermal. Values for Hellisheiði are reported for combined heat and power (according to energy, exergy and price allocation) and power-only production. The box-and-whisker plots report the 10th, 25th, 50th, 75th and 90th percentiles.

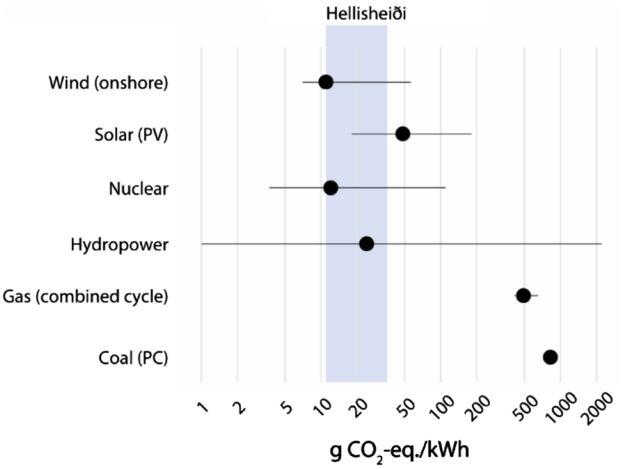

Fig. 6. Comparison of climate change impacts (g CO_2-eq./kWh) between Hellisheiði and other energy sources. The blue area identifies the minimum and maximum carbon intensity of Hellisheiði according to different configurations and allocations strategies (Fig. 5). The carbon intensity of other energy sources is reported in terms of median values (dots) and minimum and maximum ranges (lines).

from the construction of the CHP plant. A further significant contribution arises from the construction of make-up wells required to compensate for reductions in the productivity of primary wells; 16 make-up wells are projected to be drilled compared to an initial 64 primary wells. More specifically, the analysis reveals that diesel, used for powering the drilling rig, and steel, used for wells casing as well as for facilities and machineries of the CHP plant, represent the major sources of impacts. The life-cycle inventory used reports an average consumption of diesel of 2 MJ/m (calculated using a lower heating value of 42.6 MJ/kg) and an average use of steel of 100 kg per metre of well.

These results are in line with those obtained by other LCA studies in identifying the construction phase, and specifically steel and diesel as the environmental hot spots. It was not possible to perform a detailed comparison with the life-cycle data (especially for drilling) used by other LCA studies. Average steel use is rarely reported in the literature: Pratiwi et al. (2018) are one exception, reporting steel consumption for Enhanced Geothermal Systems (EGS) in the range of 95–130 kg/m. On the other hand, average diesel consumption is reported by multiple studies focusing on EGS, and ranges between 4 and 9 MJ/m (Frick et al., 2010; Lacirignola and Blanc, 2013; Pratiwi et al., 2018; Treyer et al., 2015). These values, however, are not immediately comparable with those relevant for hydrothermal systems because of the different geology of the host rock through which wells are drilled.

The disposal of drilling waste also has substantial impact in eutrophication (freshwater) and toxicity categories. Because the impacts are primarily due to landfarming, the analysis suggest that disposal in landfill is a more environmentally friendly practice. A further significant hot spot is represented by the end-of-life treatment of copper for the ecotoxicity category. In this study we made the conservative assumption that only large metal parts of the transformers and reinforced concrete from the facilities are recycled. Copper used in electrical wires in the power plant and heating station facilities is assumed to be sent to incineration as part of larger items, with the resulting ash residue disposed in landfill. The impacts to the eco-toxicity category are due to long-term emissions of metallic copper from the landfill to fresh water systems.

Because the majority of the impacts stem from the construction phase, the environmental performance of the geothermal plant is considerably dependent on its lifetime. Extending the plants lifetime would significantly reduce the environmental impacts of geothermal energy. This study has assumed a lifetime of 30 years, in accordance with the assumptions of Karlsdóttir et al. (2015). Typical values found in the literature range between 20 and 40 years (note that similar values are used for other types of power-generating plants); one exception is the study by Rule and colleagues who assumed an exceptionally high lifetime of 100 years (Rule et al., 2009). A further key consideration concerns the management of geothermal reservoirs. If geo-fluids are extracted and re-injected at sustainable rates so as to balance the natural process of replenishment, a new equilibrium condition could be established that allows a production to go well beyond 30 years (Rybach, 2007). However, if extraction rates are higher than replenishment, the geothermal reservoir will be depleted in less than 30 years. Hence, maintaining sustainable production rates would extend the plants lifetime, and reduce considerably the life-cycle environmental impacts.

Other strategies to reduce the environmental impacts of geothermal energy should focus on either reducing consumption of diesel and steel or replacing them with more sustainable alternatives. Consumption of diesel could be reduced by means of revolutionary non-contact drilling technologies, which have higher penetration rates and thus can achieve lower specific energy requirements (energy per metre drilled) than conventional rotary drilling (Menberg et al., 2016; MIT, 2006; Ndeda et al., 2015). Using biodiesel or electricity to replace diesel seems the most straightforward solution. However, the advantages of biodiesel over traditional fossil-based diesel are still debated and are generally limited to climate change impacts and fossil fuel consumptions (Vedel Hjuler and Balle Hansen, 2017); whilst the benefits of using electricity, especially for climate change, depends on the degree of "decarbonisation" of the grid mix (Menberg et al., 2016). Steel, which makes up the wells casing, has two important functions: it prevents the well from collapsing and avoids unintentional exchanges between surrounding formations and the wells (Di Pippo, 2016). Hence, the amount of steel used for casing cannot be substantially reduced without impairing the normal functioning of the well. However, steel with higher recycled content can be used to avoid the environmentally high-impact activities of ore extraction and processing – although the benefits of increasing the recycled content depends on the end-of-life allocation method (Allacker et al., 2017). The environmental impacts of strategies for replacing steel and diesel, generally and for Iceland, must be investigated in detail by means of LCA.

4.2. Allocation of environmental impacts

The strategy implemented for allocating impacts between electricity and hot water can affect the environmental performance of geothermal energy compared to that of other technologies. This study shows that if allocation is based on energy content, approximately ~65–70% of the impacts are to be attributed to electricity. Taking into account the quality of energy using the concept of exergy increases the allocation of impacts to electricity to 90%. If allocation is based on the revenues associated with electricity and hot water sales, the environmental impacts are in practice to be attributed solely to electricity, whilst hot water is produced "impact-free". In this case, the environmental performance of electricity from a cogeneration plant is similar to that of a power-only configuration. It should be noticed that these considerations depend on the price of electricity and hot water. Although Icelandic-specific prices have been used, these considerations can, with a good degree of confidence, be extended to the rest of Europe. The choice of an allocation strategy in LCA studies represents yet an arbitrary choice. Our results demonstrate that such choice is crucial, and emphasize the importance of standardising the allocation procedure in LCA. It is not the aim of this article to recommend a specific allocation strategy for geothermal systems; rather we use different allocation strategies to quantify a range of environmental impacts of electricity production from geothermal in Iceland.

4.3. Carbon intensity

This study shows that regardless of the allocation strategy chosen, the carbon intensity of electricity production of the Hellisheiði power plant is slightly lower than the median value of other double flash (DF) plants, and similar to that of binary plants (Fig. 5). Compared to other energy sources, Hellisheiði performs as well as hydropower, and slightly better than solar photovoltaic (Fig. 6).

As highlighted by the hot spot analysis, the greatest portion of greenhouse gas emissions occurs during the operational phase. This is due to non-condensable gases that are carried by the geo-fluid and are released during condensation prior to reinjection. Typically, CO_2 makes up over 90% of non-condensable gases, with the rest being shared by primarily hydrogen sulphide, and other gases such as hydrogen and methane (Arnorsson et al., 2007; Fridriksson et al., 2016). Because in binary plants the geo-fluid flows in a virtual closed-cycle, there are no direct emissions of greenhouse gases during operation; this is why binary cycles generally yield lower climate change impacts. However, it must be noted that this advantage is partly offset by the fact that binary cycles usually require deeper wells, with higher impacts in the construction phase, and have lower conversion efficiencies, primarily because they use reservoirs of a lesser quality. The good performance of the Hellisheiði plant is due to low concentrations of CO_2 in the geo-fluid, with emissions per kg of geothermal fluid amounting to 1.4 g (Karlsdóttir et al., 2015). This is not restricted to Hellisheiði, but it is a feature of all reservoirs in Iceland, which on average have direct CO_2 emissions of around 34 g/kWh (Baldvinsson et al., 2011) compared to a world average of 123 g/kWh (Bertani and Thain, 2002).

In some cases, however, the content of CO_2 in the geo-fluid can be so high to make geothermal energy's carbon intensity comparable to that of fossils-based energy sources such as coal and natural gas. The LCA studies that focused on geothermal plants in the Italian region of Tuscany, for example, estimated greenhouse gas emissions as high as 250 and 700 g CO_2-eq/kWh (Bravi and Basosi, 2014; Buonocore et al., 2015). The high content of CO_2 in the geo-fluid is thought to be due to carbon-rich rocks present at the level of the reservoir, and perhaps also to anomalous deep mantle degassing (Frondini et al., 2009). Unlike Tuscany, Icelandic rocks are primarily igneous and contain lower amounts of carbonates (Fridriksson et al., 2016); this does not only mean lower greenhouse gas emissions, but it also enables permanent disposal through mineralization of captured CO_2 as demonstrated by the CarbFix project (Matter et al., 2016). The importance of local characteristics of the geosphere entails that the low performances of dry steam and single flash plants should not be attributed solely to the technology used for energy conversion.

The key role that CO_2 dissolved in the geo-fluid plays towards the environmental performance of geothermal plants raises a further point of discussion, that is whether geo-fluid dissolved CO_2 should be considered an anthropogenic or natural source. In effect, the release of greenhouse gases from geothermal/volcanic systems is a natural process that would occur also in the absence of geothermal operations – natural CO_2 emissions are in fact orders of magnitude higher than those from geothermal plants (Ármannsson et al., 2005). But it is still unclear whether geothermal operations can accelerate this process. Whilst some studies (Allis, 1981; Fridriksson et al., 2010; Óladóttir and Fridriksson, 2015; Rissmann et al., 2012) showed that geothermal operations have increased CO_2 emissions; other studies that focused on Tuscany maintain the opposite (Bertani and Thain, 2002; Frondini et al., 2009). As a result of the latter, at present Italy does not include geothermal greenhouse gas emissions in its national inventory (Ármannsson et al., 2005; Fridriksson et al., 2016).

To investigate whether natural CO_2 emissions and geothermal operations are linked, it is essential that the natural background emissions from a geothermal field are established prior to the development of a new geothermal project, and are continually monitored during operation. If enough studies confirmed that geothermal operations do not accelerate natural processes of greenhouse gas emissions, the carbon intensity of geothermal energy would be considerably reduced. In the extreme case where it was demonstrated that all CO_2 emitted during the operation phase would be released anyway, geothermal energy would entail carbon intensities lower than 10 g CO_2-eq/kWh, i.e. lower than those expected from wind and nuclear energy.

5. Conclusions

This article presented a detailed and comprehensive LCA study on Hellisheiði, a combined heat and power, double-flash geothermal plant located in Iceland, with an installed capacity of 303.3 MW of electricity and 133 MW of hot water. The hot spot analysis showed that the majority of the environmental impacts originate in the construction phase - notably, from the consumption of diesel consumed by the drilling rig, and steel used for casing of wells, and construction of the power plant. Therefore, the most effective strategy to reduce the environmental impacts consists in extending the operational lifetime of the plant and, most importantly, of the geothermal reservoir by maintain sustainable levels of geothermal fluid production.

The life-cycle emissions of greenhouse gases per kWh of electricity produced (carbon intensity) of the Hellisheiði plant were compared with those of other geothermal plants and energy sources, considering different allocation strategies and inventory data uncertainty. The comparison showed that the environmental performance of Hellisheiði (18–24 g CO_2-eq./kWh and 15–23 g CO_2-eq./kWh for single and double flash configurations) is slightly higher than that of other double flash plants, and similar to that of binary cycle geothermal plants, solar photovoltaic and onshore wind. This is due to low concentrations of CO_2 dissolved in the geo-fluid, a feature of Icelandic reservoirs.

The results demonstrate that geothermal energy, alongside other alternative and renewable sources, can play a substantial role towards achievement of the Paris Agreement goal and the decarbonisation of the power generation industry. Further work should investigate the relation between utilization of geothermal energy and the natural release of greenhouse gases from geothermal systems.

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Declaration of Competing Interest

The authors declare no conflicts of interest.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105226.

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