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Life Cycle Assessment of Geothermal Energy: a case study on Hellisheiði, Iceland

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ABSTRACT

Power generation is the industrial sector with the highest potential to reducing carbon emissions, and thus contributing to reaching the goals established in the Paris Agreement. To this end, geothermal energy is set to play a key role. But to what extent? And, what about environmental impacts other than global warming? This study provides tentative answers to these questions by means of the Life Cycle Assessment (LCA) methodology. LCA is a standardized methodology, widely used to support decisions and development of policies, which quantifies and assesses the environmental impacts of products (i.e. goods or services) from a life cycle perspective, i.e., from the extraction of raw materials to the disposal of wastes. The present LCA study relies on publicly-available data regarding the Hellisheiði geothermal plant in Iceland, which co-generates electricity and hot water for district heating. A detailed hot-spot analysis is presented to identify the key sources of impacts. The carbon intensity of the Hellisheiði plant is compared against other energy technologies.

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). The power generation sector is in the spotlight because it has the potential to almost fully decarbonise. Renewable energy sources are set to play a key role in its transformation; amongst these, geothermal energy has notable advantages. It is often considered ubiquitous (beneath the earth surface, rock temperature increases with depth due to the natural geothermal gradient), it is independent from seasonal and climatic conditions, hence a source of baseload power, and it can be cheap (IRENA, 2018), primarily because it makes use of well-known thermodynamic processes for electricity generation.

The exploitation of geothermal resources is proceeding from the highest quality, and least common, resources to lower quality and more common resources. Hydrothermal systems extract hot geothermal fluid from natural aquifers at depths varying from ~ two to four kilometres. The quality of an aquifer increases with its enthalpy, from liquid-only to steam-only (i.e. dry steam) reservoirs. By contrast, petro-thermal systems aim to produce hot water at locations where natural aquifers are not present by developing an "engineered reservoir". The latter technology, also known as enhanced geothermal systems (EGS), is receiving increasing attention because it allows exploitation of geothermal energy in principle anywhere. In recent years, large efforts have been made on assessing the life cycle environmental impacts of enhanced geothermal plants (Frick et al., 2010; Lacirignola and Blanc, 2013; Paulillo et al., 2020a, 2020b; Pratiwi et al., 2018). However, because hydrothermal systems still dominate the current electricity generation, and are set to do so for the near future as well, it is important to assess their life cycle environmental impacts. This paper presents a Life Cycle Assessment (LCA) study based on detailed site-specific data on Hellisheiði (Karlsdóttir et al., 2015), a combined heat and power (CHP) geothermal plant in Iceland; the complete results of the study are reported and comprehensively discussed in Paulillo et al. (2019a, 2019b)

Iceland is the sixth country with the highest electricity generated from geothermal in the World (Bertani, 2016), and the leading country in annual geothermal energy use for district heating (Lund and Boyd, 2016). Due to its location on the mid-Atlantic ridge, Iceland features geological characteristics that favour the exploitation of geothermal energy. The share of geothermal energy in the primary energy supply of Iceland is ~70%, reaching 90% of all energy used for house heating and standing at 29% for electricity needs (Bertani, 2016). Hellisheiði is one of 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 third largest by electric capacity in the world (303 MWel).

This article is organised as follows: Section 2 introduces the Life Cycle Assessment (LCA) methodology and reports the main features of this study; LCA results in terms of hot spot analysis and carbon intensity of electricity production are presented and discussed in Section 3; the key conclusions are summarised in Section 4.

2. LIFE CYCLE ASSESSMENT

LCA is an ISO (International Organisation for Standardisation) standardised and widely used methodology for quantifying the potential environmental impacts associated with products and services (ISO, 2006a, 2006b). The main feature of LCA is that it considers the whole life cycle of a process/product, that is from the extraction of raw materials to management and disposal of wastes. LCA explicitly quantifies several environmental impacts, including but not limited to global warming, e.g. acidification, eutrophication, ozone layer depletion, human and environmental toxicity. This perspective enables the identification of trade-offs when multiple alternatives for obtaining the same product are compared. The standardised LCA framework, shown in Figure 1, consists of four phases, namely Goal and Scope Definition, Inventory Analysis, Impact Assessment and Interpretation.

The first phase, Goal and Scope Definition, frames the study: the goal includes the reason for carrying out the study and its intended application, whilst the scope establishes the focus of the study in terms of the processes to be included in the analysis. Inventory Analysis collects physical flow information in terms of input of resources, materials, semi-products and by-products and of outputs such as emissions, waste and the final product. The Impact Assessment phase "translates" the physical flows of the product system into potential impacts on the environment and human populations, using knowledge from models from environmental and medical science. Finally, in the Interpretation phase, the results of the study are checked for consistency and completeness, and conclusions and recommendations based on the results of earlier phases are developed.

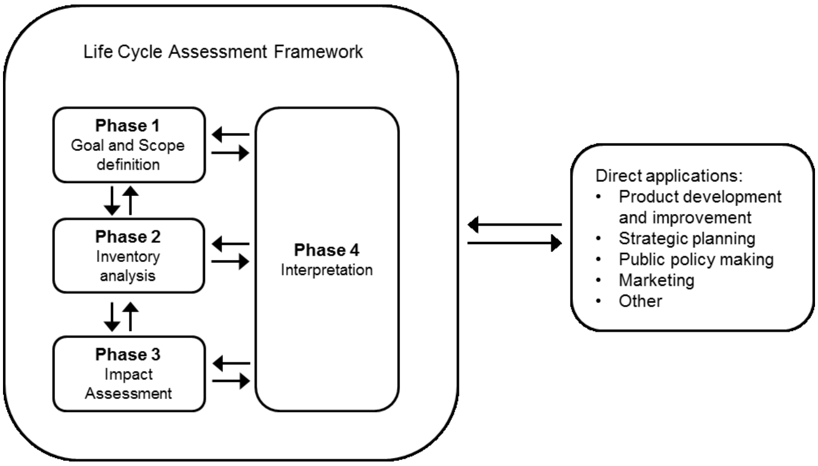

Figure 1 – Phases of Life Cycle Assessment (ISO, 2006a).

2.1 Goal of this study

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. 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 MJ and 133 MJ, respectively. This quantified description is in LCA commonly referred to as Functional Unit. Second, this study compares the carbon intensity of electricity production at Hellisheiði with respect to alternative energy sources, with the aim of understanding the potential of geothermal energy to contribute to the decarbonisation of the power generation industry.

2.2 Scope of the study and life-cycle inventory

Figure 2 reports the system boundaries of this LCA study. We adopt the pragmatic distinction between foreground and background systems developed by Clift et al. (2000). The former identifies all those processes that are the main focus of the study and that may be directly affected by decisions based on the study's results; the latter encompasses all other processes that exchange materials and energy with the foreground, usually through a homogenous market. The system boundaries are cradle to grave and include the three typical phases of construction, operation and end of life.

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 MWel. The low-pressure turbines generate additional 30.3 MWel 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 thermal capacity was calculated based on the energy difference of water between 90 and 40 °C.)

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 production of electricity during the life time of the plant; these include drilling make-up wells and construction of additional collection pipelines. The end-of-life phase includes dismantling of the power plant and the heating station, and assumes closure of the geothermal wells.

The foreground system primarily relies on the comprehensive inventory developed for the Hellisheiði geothermal plant by Karlsdóttir and colleagues (2015), which for instance includes the assumption that the technical lifetime of the plant (including both the power plant and the heating station) equals 30 years. The inventory covers both single and double flash configurations, and both combined heat and power, and power-only production. The background system has been described by average, market data obtained from the Ecoinvent database version 3.4 (Wernet et al., 2016).

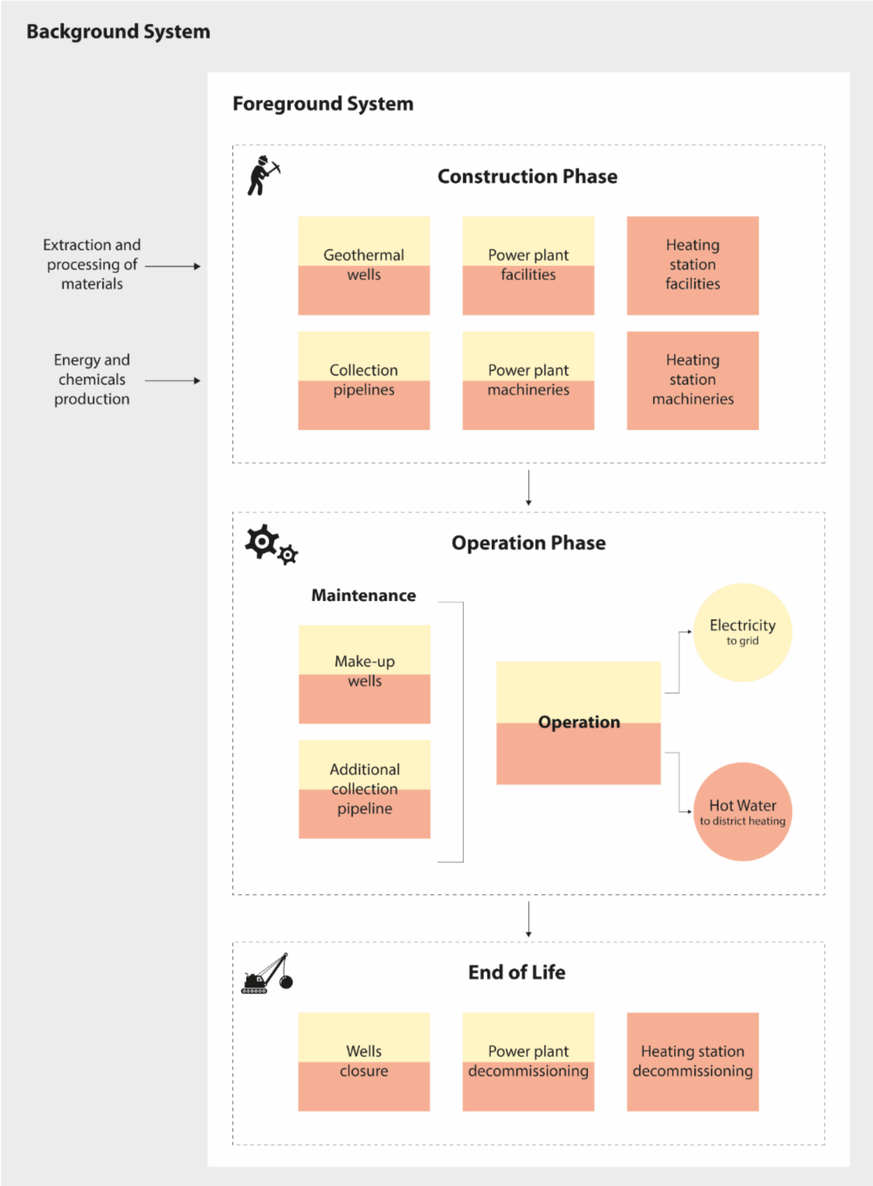

Figure 2 – System boundaries for the combined heat and power geothermal plant at Hellisheiði (Paulillo et al., 2019a). Rectangular boxes identify processes, whilst oval shapes represent products. The colour system highlights the allocation strategy: single-coloured processes are allocated to either electricity or heat; double-coloured processes are partitioned between the two products.

2.3 Allocation of environmental impacts

To quantify the carbon intensity of electricity production (Section 3.2), the environmental impacts of the product system depicted in Figure 2 are partitioned between the two functions of electricity and hot water production. We calculated allocation factors based on three strategies to reflect either the energy or the exergy content of the product streams, or their economic value. For economic allocation, Iceland-specific prices for hot-water and electricity have been taken from Veiture, a utility company (Veiture, 2019).

2.4 Uncertainty

We used the Monte Carlo method to propagate uncertainties from model parameters 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 normally distributed, with a standard deviation equal to a third of the range of variability (it is possible to calculate from the probability density function of a normal distribution that nearly all values, 99.7%, lie within three standard deviations of the mean). The Monte Carlo simulation has been performed in the Gabi software with 10,000 iterations.

2.5 Environmental impact categories

This study uses the ILCD impact assessment approach (JRC, 2012, 2011) and covers nine impact categories, which are introduced in what follows, based on Rosenbaum et al. (2017) and Baumann and Tillman (2004):

Acidification
Metric: Mole of H^+ eq.
Description: The "acidification" category quantifies the impact of pollutants with the potential of causing acidifications of soil or aquatic ecosystems. Acidifying pollutants are mainly released by combustion processes occurring in thermal power plants, combustion engines, waste incinerators, e.g. sulphur and nitrogen oxides and hydrochloric acid, and agriculture, which is the main contributor to emissions of ammonia. Following the release, acidifying compounds are trapped by water in the form of rain, fog and snow, and then deposited onto different receptors. Because of their high solubility in water, the atmospheric residence time of acidifying pollutants is limited to a few days, and therefore acidification represents a regional effect.

Climate change
Metric: kg CO_2 eq.
Description: The "climate change" category expresses the impact of greenhouse gas (GHG) emissions based on the extent to which they increase radiative forcing in the atmosphere. The portion of the sunlight that is not reflected back into space heats up the planetary surface and is released back into the atmosphere as infrared radiation with a longer wave-length than the absorbed radiation. This infrared radiation is partially absorbed by GHGs and kept in the atmosphere instead of being expelled into space, explaining why the temperature of the atmosphere increases with its GHGs content. The major anthropogenic contributions to the greenhouse effect are represented by emissions of CO_2, methane and nitrogen oxides, mainly from burning fossil fuels and deforestation.

Freshwater ecotoxicity and human toxicity
Metric: CTUe, CTUh
Description: Any substance emitted may lead to toxic impacts depending on a number of factors including mobility, persistence, exposure patterns and bioavailability, and toxicity. The toxicity impact categories account for these four factors and focus on the impact on freshwater ecosystems and human beings.

Freshshwater eutrophication
Metric: kg P eq.
Description: The "freshwater eutrophication" category describes the impact of macro nutrients, the most important being nitrogen (N) and phosphorus (P), on freshwater ecosystems. Excessive levels of nutrients in the aquatic ecosystem trigger a cause-effect chain that causes growth and blooming of algae and other aquatic plants, and reduction of oxygen availability, leading to degradation of water quality, altered species composition and loss of biodiversity. For terrestrial systems, eutrophication primarily causes changes in the function and species composition of nitrogen-poor ecosystems and also damages to crops and forests leading to reduced yields. Because of these environmental mechanisms, eutrophication is a regional impact category, highly dependent on local conditions.

Particulate matter/respiratory inorganics
Metric: kg PM2.5 eq.
Description: The category of "particulate matter/respiratory inorganics" quantifies toxicity-related effects on human health caused by Particulate Matter (PM). Exposure to PM leads to numerous detrimental effects including chronic and acute respiratory diseases, cardiovascular diseases, chronic and acute mortality and lung cancer. PM can be distinguished according to formation type (primary and secondary) and aerodynamic diameter (respirable, coarse, fine and ultrafine). Primary PM includes particles that are directly emitted (e.g. from transport vehicles or power plants), whilst secondary PM refers to particles formed by reactions with precursor substances such as nitrogen oxides, sulphur oxides, ammonia and Volatile Organic Compounds (VOCs).

Photochemical ozone formation
Metric: kg NMVOC
Description: The "photochemical ozone formation" category addresses the impacts caused by ozone and other reactive oxygen compounds; these are formed as secondary contaminants in the troposphere by the oxidation of the primary contaminants, mainly Volatile Organic Compounds (VOC) and carbon monoxide, in the presence of nitrogen oxides and under the influence of light. The most important source of emissions of VOC derives from road traffic and use of organic solvents; whilst carbon monoxide is mainly emitted from combustion processes with insufficient supply of oxygen, including road traffic. The VOC's negative impacts are associated with their reactive nature, which enables VOC to oxidise organic molecules: when inhaled they can cause damages to the respiratory tract tissue and trigger respiratory diseases in humans; or they can attack plants leaves damaging the photosynthetic organs.

Resource depletion, mineral, fossils and renewables
Metric: kg Sb eq.
Description: Natural resources can be classified according to their origin into biotic and abiotic, that is whether resources are or are not living at the moment of extraction, or according to their availability into stock (resources with a finite and fixed reserve), fund (resources that are regenerated but can be depleted if the extraction rate exceeds regeneration) and flows (resources that are provided as flows, e.g. solar radiation and wind). The most widely accepted method for quantifying impacts of resource use focuses on depletion of abiotic resources (stocks)[1], using either the total estimated reserves of the resource (ultimate reserves approach) or only that part that has reasonable potential to become economically and technically feasible to exploit (reserve base approach).

[1] It must be noted that stocks do not include geothermal reservoirs.

3 RESULTS AND DISCUSSION

3.1 Hot-spot analysis

Figure 3 shows contributions of each of the three phases – construction, operation and maintenance (reported separately), and end of life (see Figure 2) - to the life cycle's impacts 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. Maintenance, which includes the construction of additional make-up wells and additional collection pipelines, contributes to around 10-20% of impact categories with the exception of climate change and ecotoxicity. The climate change category is dominated by atmospheric emissions of CO_2 occurring during the operation of the plant, whilst impacts in the ecotoxicity category originate in the end-of-life phase and are due to treatment of copper used in electric wires in the power plant facilities.

The results presented in Figure 4 focus on the geothermal wells and show that over 80% of the score in the categories acidification, climate change, particulate matter/respiratory inorganics, photochemical ozone formation and depletion of mineral, fossils and renewables, and over half of the score in the remaining categories can be attributed to two sources: production of steel, which is used for wells casing, and the production of diesel and its use on-site in a diesel-electric generating set for powering the drilling rig. Steel production dominates the impact categories of freshwater eutrophication, environmental and human toxicity (both cancer and non-cancer effects), and depletion of minerals, fossils and renewables. Diesel dominates the remaining categories. The impact of other activities (which also include production of cement for wells casing drilling mud elements like lignosulfunite and bentonite, and disposal of drilling mud) is primarily dominated by the disposal of drilling waste, which has significant impacts in freshwater ecotoxicity and human and environmental toxicity.

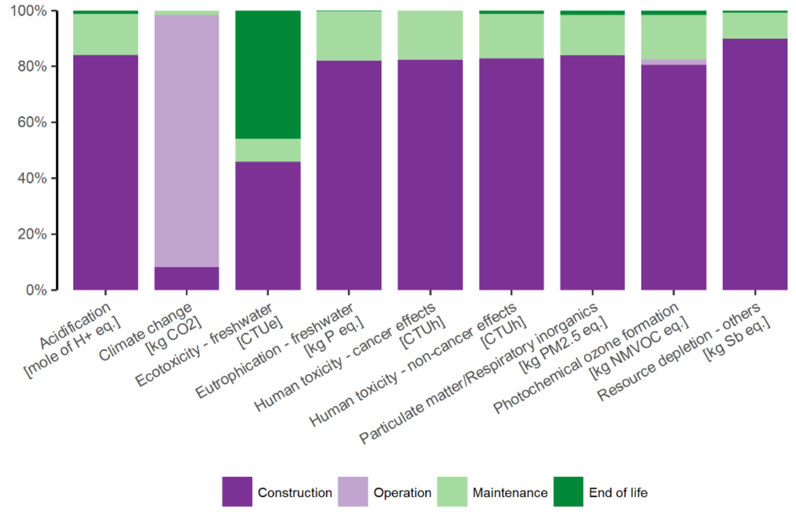

Figure 3 - Hot spot analysis of the product system depicted in Figure 2. "Resource Depletion – others" is used in place of "Resource Depletion, minerals, fossils and renewables" for clarity of displaying.

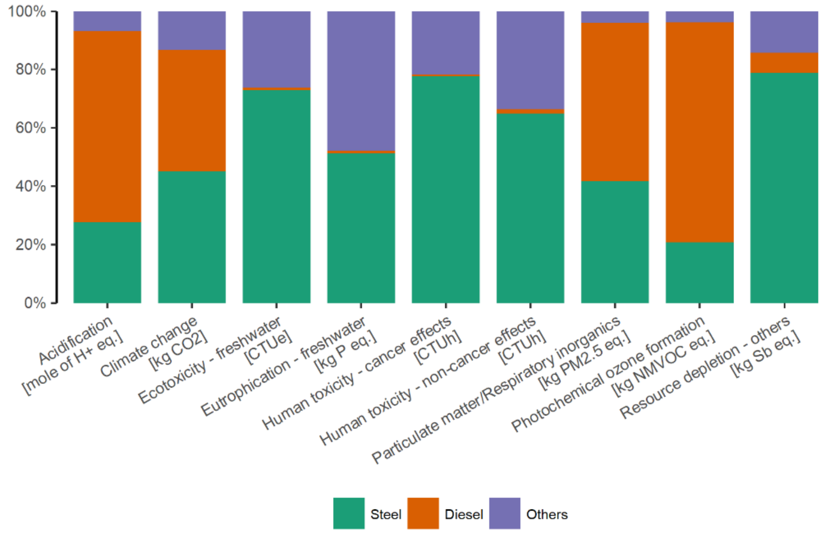

Figure 4 - Detailed hot spot analysis of the construction of primary geothermal wells. "Resource Depletion – others" is used in place of "Resource Depletion, minerals, fossils and renewables" for displaying purposes.

The results shown in Figures 3 and 4 are in line with those obtained by other LCA studies in identifying the construction phase, and specifically steel production and diesel consumption as the environmental hot spots. It was not possible to perform a detailed comparison with other LCA studies because life-cycle data (especially for drilling) is often not reported. 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 lifetime of the plants and the geothermal reservoirs would significantly reduce the environmental impacts of geothermal energy. 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).

3.2 Carbon intensity

The carbon intensity represents the life-cycle emissions 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. Here we compare the carbon intensity of electricity produced at the Hellisheiði with those of key energy technologies obtained from the fifth assessment report of the IPCC (Schlömer et al., 2014). In Figure 5 we report 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. The carbon intensity performance of the Hellisheiði power plant is reported as a box-and-whisker plot, according to the three allocation strategies of energy, exergy and price.

Energy-based allocation yields the lowest carbon intensity (and thus the highest environmental performance) amongst the allocation strategies considered, with a median value of ~ 16 g CO_2-eq/kWh. Exergy and economic allocations yield lower performances, with median values of carbon intensity of 21 and 20 CO_2-eq/kWh respectively. The allocation of environmental impacts based on the energy content of the products relies on the assumption that heat and electricity represents the same "quality" of energy. However, heat is deemed of lower quality because it cannot be transformed into other forms of energy without losses. The exergy concept takes into account the quality of energy and assigns a higher share of the environmental impacts to electricity. Allocation based on price apportions slightly lower impacts to electricity on the basis that this represents the highest source of revenues of the Hellisheiði plant; for electricity we used a price of ~6 kr/kWh and for hot water of ~150 kr/m^3. The performance of Hellisheidi is similar to those of onshore wind and nuclear (median values of 11 and 12 g CO_2-eq/kWh respectively) when impacts are allocated according to the energy content, and similar to that of hydropower (median value of 24 g CO_2-eq/kWh) when either exergy or economic allocations are used. However, for every allocation strategy the performance of Hellisheidi is higher than that of solar photovoltaic (median value of 48 g CO_2-eq). Fossil-based energy technologies feature carbon intensities over 50 times higher than that of Hellisheiði, (median values for coal and natural gas of ~500 and ~800 g CO_2-eq.).

As shown in Figure 3, the greatest portion of greenhouse gas emissions occurs during the operational phase of Hellisheiði, and it is due to non-condensable gases that are carried by the geo-fluid and are released during condensation prior to reinjection. Therefore, the good performance of the Hellisheiði plant in terms of carbon intensity compared to other power-generation technologies is linked to low concentrations of CO_2 in the geo-fluid. Notably, 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, like for example the geothermal plants in Tuscany, Italy, 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.

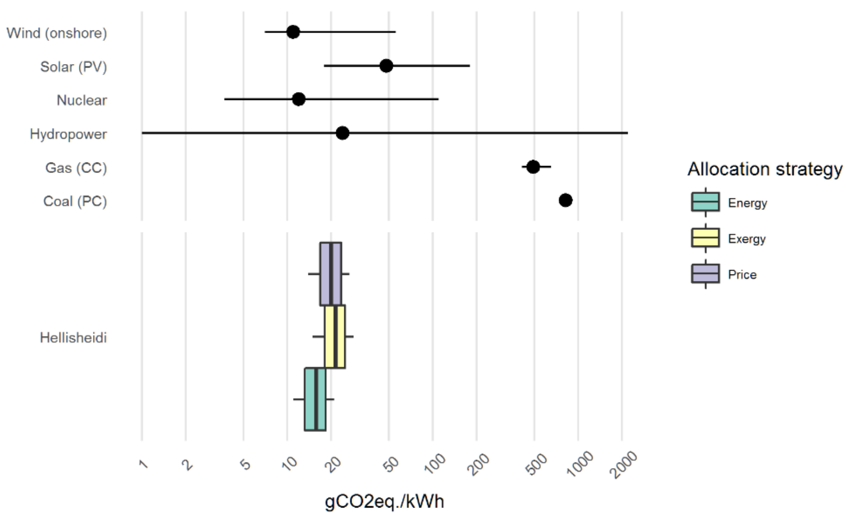

Figure 5 – Comparison of climate change impacts (g CO_2-eq.) between Hellisheiði and other energy sources. The box-and-whisker plots report the 10th, 25th, 50th, 75th and 90th percentiles for Hellisheiði according to different partitioning factors. The carbon intensity of other energy sources is reported in terms of median values (dots) and minimum and maximum ranges (lines).

4. CONCLUSIONS

This article presented a Life Cycle Assessment (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 study focused on nine environmental impact categories and aimed at i) identifying the life-cycle hot-spots and ii) comparing the carbon intensity of the Hellisheiði power plant with those of alternative energy technologies.

The hot spot analysis revealed 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 related to this plant consists in extending its operational lifetime and, most importantly, that of the geothermal reservoir by maintaining sustainable levels of geothermal fluid production.

The comparison of carbon intensities showed that according to the allocation strategy the environmental performance of Hellisheiði is similar to that of onshore wind and nuclear or that of hydropower; and that for each strategy Hellisheiði's performance is higher than solar photovoltaic and fossil-based technologies. The good performance of Hellisheiði 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, depending however on the physical properties of the reservoir and of its fluid.

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