A life-cycle analysis of deep enhanced geothermal systems – the case studies of Reykjanes, Iceland and Vendenheim, France

Abstract

The climate impacts of deep enhanced geothermal systems (EGS) have been understudied in the academic literature. Using life-cycle analysis (LCA) conducted in accordance with ISO 14040 and ISO 14044 standards, this paper explores the climate change impacts of two deep EGS. The first study was in Reykjanes, Iceland, where a single well, IDDP-2/DEEPEGS, was drilled to a depth of 4.6 km for the purposes of additional electricity production from an existing power plant. The second study involved two wells with side-tracks (depth > 5,000 m), drilled to serve a new heat and power co-generation plant located on an old oil field site in Vendenheim, France. Climate change impacts for the sites were estimated in the range 1.6-17.4 gCO2e/kWh and 6.9-13.9 gCO2e/kWh for Reykjanes and Vendenheim, respectively. Although the EGS projects are very different, both outcomes are low when compared to non-renewable alternatives and akin to best-in-class renewable alternatives. The main impact at the Reykjanes demonstration site were the greenhouse gas emissions released from the borehole, an effect that could be avoided by carbon capture and storage/mineralisation/utilisation. In the case of Vendenheim, further reductions in emissions could be achieved via more extensive adoption of circular economy principles in design and procurement.

Keywords: life-cycle assessment; deep geothermal energy; environmental impacts; hotspots; greenhouse gas emissions

1. Introduction

1.1 Utilisation of geothermal energy resources and enhanced geothermal systems

For well over 100 years, geothermal resources have provided base-load electricity around the world (Tomasini-Montegro et al., 2017). Total worldwide installed capacity from geothermal technologies was 15.9 GW in 2019 (Huttrer, 2020), with likely future growth in the utilisation of conventional and enhanced geothermal systems (EGS) (Aghahosseini et al., 2020; Pan et al., 2020). The difference between a conventional geothermal system and EGS is that in principle an EGS could theoretically harness the heat in every place on the earth, by enhancing the properties of the geothermal system so that it can be utilised similarly to conventional systems (Olasolo et al., 2016). EGS reservoirs are deep enough to reach a high-temperature rock, however, usually without any fluid, and need to have an injection well/wells to pump water down to it (Xu et al., 2015). Nevertheless, the rock in the reservoir is either impermeable or has low permeability, preventing any heat extraction (Shao et al., 2015). As a result, the reservoir needs to be stimulated and enhanced for the water to be able to travel through it and heat up before coming back up to the production well and being utilised in a power conversion unit (Huenges and Ledru, 2011; Olasolo et al., 2016).

Since the early 1970s, there have been numerous EGS projects in Europe, the USA, Australia and Japan, which have sought to utilise the energy stored in the fluid-impaired geothermal reservoir at that site (Olasolo et al., 2016). The initial results were that deep high-temperature wells could be drilled and completed in the hard, abrasive rock at these EGS sites. Furthermore, a reservoir could be stimulated to a large enough extent to sustain energy extraction over a long period of time (Tomasini-Montegro et al., 2017). Heat in a reservoir as deep as 5,000m below the surface can be accessed and extracted (Tester et al., 2006). Thus, in finding the most prominent areas for an EGS on a European scale, a map of temperature extrapolated at 5 km depth, conducted by Genter et al. (2003) and modified by the Economic Interest European Group (EIEG), shows the potential feasibility of EGS as a climate change mitigation technology in Europe. The most promising areas are thought to be the Pannonian Basin, French Massif Central, Rhine Graben Basin, the Campidano Graben, Tuscany and a narrow graben in central Greece. Other areas with potential include the Limagne Basin, the Rhine Graben Borders, the Rhone Valley and the Provence, the North German Basin, Urach, Catalonia, the northern part of Bulgaria, and Cornwall in the United Kingdom.

1.2 Environmental impacts of geothermal energy and life-cycle analysis (LCA)

Given the likely expansion in production, increased attention has been directed towards the environmental impacts of the geothermal power sector, particularly in connection with the harnessing of high-temperature fields for electricity generation. Several studies have described the environmental impacts of geothermal power projects and their effects on societal well-being (Ármannsson & Kristmannsdóttir, 1992; Bayer et al. 2013; Shortall et al., 2015; Cook et al., 2020). Bayer et al. (2013) observed that these include direct effects[1], such as land distortion (land use), atmospheric emissions (especially carbon dioxide and hydrogen sulphide), waste heat, solid waste (terrestrial ecotoxicity potential), water consumption (water demand), noise emissions (human toxicity potential), and impacts on biodiversity. However, there also exist a variety of indirect effects specific to the harnessing of geothermal power. These often relate to the materials and energy required over the lifecycle of the power plant (Tomasini-Montegro et al., 2017; Tosti et al., 2020). Therefore, to fully understand the environmental implications of

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[1] Examples of associated LCA impact categories stated in brackets.

geothermal power generation, a product system approach should be favoured, since this facilitates an assessment which is considerate of the impacts of supply chains over a project's life-cycle. Evaluations of this type can be conducted using Life-Cycle Analysis (LCA), which, when conducted according to well-defined ISO norms and procedures, such as ISO 14040 (2006a) and ISO 14044 (2006b), can compile and aggregate all inputs, outputs and environmental impacts of geothermal power generation across a project's lifecycle (Hunkeler et al, 2008; Swarr et al., 2011).

In recent years, given recognition of the need to tackle climate change, the many direct and indirect environmental impacts of power generation have assumed increased importance. Even fairly early examples in the academic literature hint at a breadth of focus in LCA studies with respect to the power sector. They include studies on the greenhouse gas emissions of a coal fuelled power plant (Wu et al., 2018) and substituting switch grass for coal in electricity generation (Ney and Schnoor, 2002), an LCA on a natural gas combined-cycle power system (Spath and Mann, 2000), and LCAs focused on wind turbines (Batumbya et al., 2006; Chen et al., 2011). There are also several LCA studies in the academic literature that focus on geothermal power plants (Karlsdóttir et al., 2015; Paulillo et al., 2019; Karlsdóttir et al., 2020). These include a theoretical study on the potential LCA impacts of EGS (Clark et al., 2012), an applied LCA study on geothermal power generation using supercritical steam (Frank, et al., 2012), a review study on the environmental issues of relevance to geothermal LCAs in the context of a Californian plant (Sullivan et al., 2012), an analysis of how to integrate life cycle analysis and emergy synthesis for a dry steam geothermal plant in Italy (Buonocore et al., 2015), a comprehensive review of existing LCA studies using different geothermal technologies (Tomasini-Montenegro et al., 2017), a study focused on climate change impacts in relation to a power project in the Upper Rhine Valley (Pratiwi et al., 2018), and a comparison of the life-cycle impacts of a geothermal power venture in Italy compared to wind and solar power (Basosi et al., 2020). As far as the authors are aware, there are no applied LCA studies on EGS.

1.3 Aims and case studies

Researchers have dedicated an extensive amount of time in modelling, predicting and optimising the hydraulic and thermal aspects of EGS reservoirs (Aghahosseini et al., 2020; Pan et al., 2020). This research, among others, has contributed to making EGS systems technically feasible today. Their utilisation is therefore increasing. However, in contrast to research on conventional geothermal systems, little is known about the environmental impacts of EGS systems, especially those involve deep drilling to depths of 4-6 km. This paper therefore seeks to use LCA explore two research questions:

- What is the climate change impact of deep EGS and where in the life-cycle do those impacts occur?
- How can the impacts be potentially mitigated?

The paper answers these questions through two deep EGS case studies, Reykjanes, Iceland and Vendenheim, France, both of which are demonstration sits in the European Union-funded Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business (DEEPEGS) project. DEEPEGS is an innovative four-year project led by the Icelandic power company, HS Orka, alongside other partners in Iceland, France, Germany, Italy and Norway. The project includes the testing of deep EGS projects in Reykjanes, Iceland and Vendenheim, France. The goal of the project was to demonstrate the feasibility of deep EGS in different locations.

An existing 2.5 km deep well at Reykjanes, known as IDDP-2, was deepened to 4.6 km, with drilling completed in late 2017, and well stimulation and testing undertaken thereafter. In theory, drilling to unconventional depths enables access to very high temperatures, i.e. 400-500°C in hydrothermal areas and about 200°C in hot, dry rock areas (Friðleifsson et al., 2014; Friðleifsson et al., 2020). The hypothesis of the DEEPEGS project was that the consequence of deep drilling projects would be a considerable reduction in costs and environmental impacts (Peter-Borie et al., 2019; Friðleifsson et al., 2020). Far fewer wells should, in theory, be required to generate the same power output using regular geothermal boreholes and potentially lower gas emissions from boreholes would result, as was demonstrated by Ármannsson et al. (2010) in the IDDP-1 project in northern Iceland.

The Vendenheim dry steam project is led by Fonroche Géothermie and involves the drilling of two deep wells in excess of 5,000 metres depth, with side-tracks starting below depth of 3,500 metres to increase connectivity between the VDH1 and WDH2 wells, and subsequent construction of power plant infrastructure on the site of a former fossil fuel plant. The demonstration site at Vendenheim constitutes a traditional EGS, as the heat is the only naturally occurring element in the area, utilised by enhancing the resource-enabling fluid through an injection well to pump down the fluid and induce soft stimulation activity, leading to permeability.

The two demonstration sites at Reykjanes and Vendenheim were thus very different EGS, as although they were utilising the same fundamental resource, i.e., energy from within the earth geothermal energy, their accessibility and the project characteristics were dissimilar. In Reykjanes, there was already electrical production from the resource categorised as hydrothermal geothermal energy, i.e. there was access to fluid, heat, and permeability in a naturally occurring geological formation at a depth of about 2.5 km. Unlike Reykjanes, where the aim was to provide additional electricity generation from a single well to an established power plant, the Vendenheim project entailed new co-production of heat and power. Therefore, the results from the two studies cannot be directly compared. Instead, they should be considered as two standalone contributions to the nascent academic literature on the climate change impacts of deep EGS over the duration of project life-cycles.

1.4 Structure

The remainder of this paper is structured as follows. Section 2 details the LCA modelling methodology with respect to the two case studies, including a conceptualisation of their respective processes, description of the operational characteristics of the sites, and detailing of data sources for the purposes of the LCA inventories. Section 3 provides the results and Section 4 discusses these in comparison to other energy-generating technologies and opportunities for further mitigation of impacts. Section 5 outlines a short conclusion and considers options for future research.

2. Materials and methods

2.1 Overarching method

The LCA methodology for these studies was conducted in accordance with the standards outlined by ISO 14040 (2006a) and ISO 14044 (2006b). As described in recent paper by Basosi et al. (2020), there were four chronological stages to the method. These were as follows:

1) Goal and scope definition
2) Life-cycle inventory analysis
3) Life-cycle impact analysis
4) Life-cycle interpretation

In the first stage, the goal of the project and its system boundaries were described, quality requisites of data sources scrutinised, and the functional unit of the analysis determined. Stage two involved the collection of input-output data of relevance to the system, with primary data always preferred wherever possible. In the third stage, the climate change impacts of the respective sites were evaluated through the linking of inventory data with specific LCA impact categories and characterisation factors. The Life-Cycle Impact Assessment (LCIA) was conducted in accordance with the Intergovernmental Panel on Climate Change 2013 method (de Bruyn et al., 2018) to find the climate change impact of the demonstration sites. A comparison was then made between the values of the demonstration sites and results using EU-average data for electricity production. As is customary in LCA studies, sensitivity analysis was also conducted during this third stage using Monte Carlo simulation, ensuring that data uncertainty was accounted for. Fourthly, the results of the LCA models were evaluated in the light of opportunities to reduce greenhouse gas emissions across the life-cycles of the projects.

2.2 Conceptualisation of main operational processes

2.2.1 Reykjanes

The expected higher temperatures from drilling the IDDP-2 well could be used to generate superheated steam, increasing electricity production from the site to levels higher than in conventional geothermal power projects (Friðleifsson et al., 2020). In terms of eventual power output, it was originally expected[2] that this might equate to 25-50 MW from a single well, much more than the typical 4-5 MW from a conventional hydrothermal borehole (Friðleifsson et al., 2020). Figure 1 shows a conceptual drawing of the main processes in the Reykjanes case study as modelled in this work.

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[2] Unfortunately, due to engineering and stimulation complexities, the authors were informed by the DEEPEGS project managers that the most likely power outcome at the end of the project was akin to a conventional geothermal well of 4-5 MW, and the higher expectation of 25-50 MW was desired through further stimulation and other technological innovations, but deemed very unlikely to be attained.

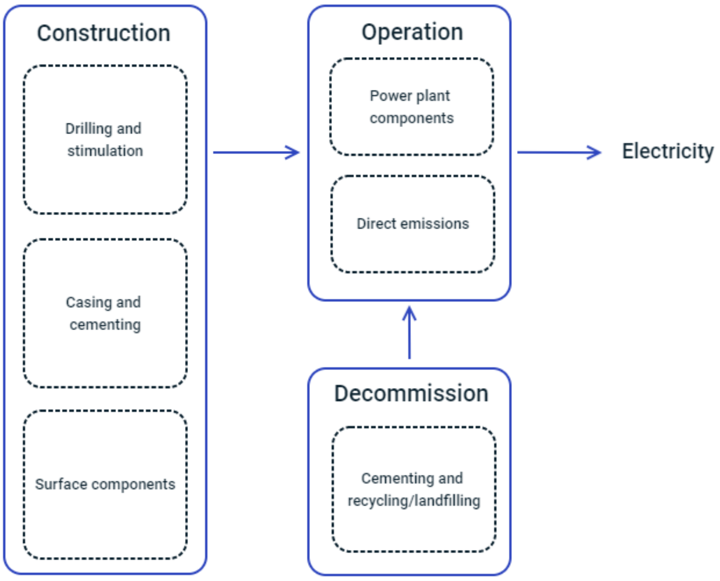

Figure 1. A conceptual drawing of the main processes in the Reykjanes case study.

The product system at Reykjanes is divided in Figure 1 into construction, operation and decommission stages. The main processes in the construction part were drilling and stimulation of the borehole, casing and cementing the borehole, and the surface components. The operational process was divided into power plant components and direct emissions, and included emissions linked to maintenance. Decommissioning involved a process of disposal, including cementing the borehole and recycling/landfilling the surface and power plant components. Table 1 gives an overview of the main operational characteristics of the Reykjanes case study for two power output scenarios: scenario 1 (most likely) and scenario 2 (desired).

Table 1: Main operational characteristics of the Reykjanes project – scenarios 1 and 2.

Characteristic	Value (scenario 1)	Value (scenario 2)	Unit
Massflow	50	50	kg/s
Lifetime	30	30	years
Power output	5	30	MW
Steam ratio	18%	100%	
CO_2	2,328	202	mg/kg steam
CH_4	0.22	0.02	mg/kg steam
Capacity factor	0.8	0.8	
Annual electricity production	35,040	210,240	MWh
Annual steam production	227,059,200	1,261,440,000	Kg

All data on the most likely scenario was provided by HS Orka, the Icelandic operator of the Reykjanes power plant. The most likely scenario assumed that the inflow to the borehole was from the same reservoir as the existing power plant at Reykjanes, and the desired scenario assumed that the inflow is sourced from a deeper reservoir. In the most likely scenario in Table 1, the power capacity is around 5 MW, and the gas emissions are 2,328 mgCO_2/kg steam and 0.22 mgCH_4/kg steam. The steam ratio in the mass flow is about 18%. In the optimal scenario, based on estimations derived from the preceding IDDP-1 project in northern Iceland, the power capacity is around 30 MW, and the gas emissions are 202 mgCO_2/kg steam and 0.02 mgCH_4/kg steam. The steam ratio in the mass flow is 100%. These values were formed from the difference between the “deep” borehole and other boreholes in the area (Ármannsson et al., 2014).

2.2.2 Vendenheim

The Vendenheim site involved drilling two boreholes with side-tracks for increased connectivity between the wells to a depth of approximately 5 km, where the temperature is 200°C. It will be a three-legged doublet system and a combined heat and power plant. The expected electrical efficiency is about 16.5%, resulting in 6-12 MW electricity generated to the grid, with a heat supply capacity factor of approximately 50%. Figure 2 illustrates a conceptual drawing of the main processes in the Vendenheim case study as modelled in this work.

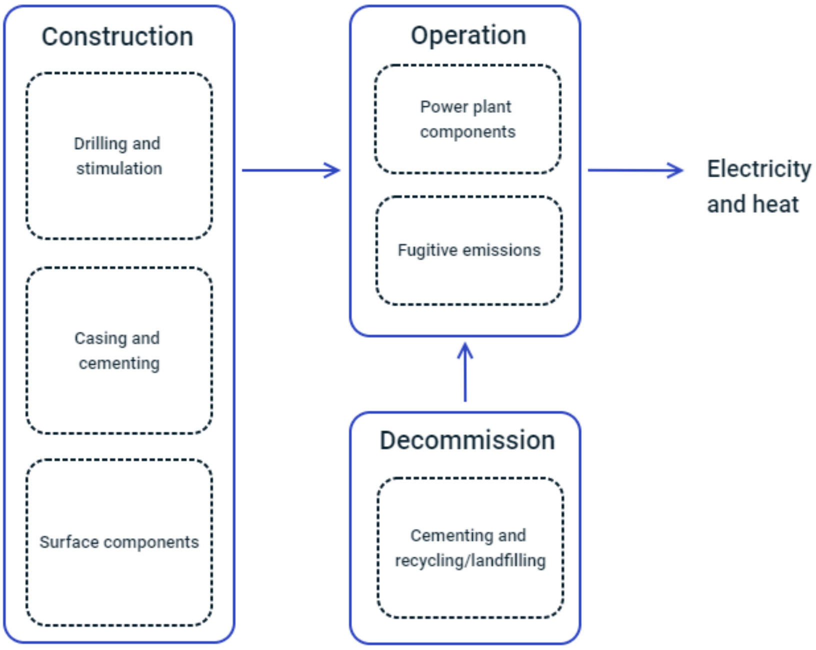

Figure 2. A conceptual drawing of the main processes of the Vendenheim case study.

As per the Reykjanes case study, the Vendenheim product system is divided into construction, operation (including emissions from maintenance) and decommission phases. The main processes in the construction part are the same, apart from a higher number of boreholes compared to the Reykjanes case study. The power plant components represent an Organic Rankine Cycle power plant, and the decommissioning part involves cementing the boreholes and recycling/landfilling the surface and power plant components. Table 2 provides an overview of the main operational characteristics of the Vendenheim case study for two power output scenarios: scenario 1 (lower) and scenario 2 (upper).

Table 2. Main operational characteristics of the Vendenheim project – scenarios 1 and2.

Characteristic	Value (Sc. 1)	Value (Sc. 2)	Unit
Wells	3	3	Items
Legs	2	2	Items
Temperature at wellhead	200	200	Degrees Celsius
Massflow	80	160	kg/s
Lifetime	30	30	Years
Gross power	40.1	80.3	MW

Electrical efficiency	16.5%	16.5%	
Auxiliary power downhole pump	0.4	0.9	MW
Auxiliary power reinjection pump	0.3	0.6	MW
Power output	5.9	11.8	MW
Heat output	13.4	26.8	MW
Capacity factor electric	0.8	0.8	
Capacity factor heat	0.5	0.5	
Annual electricity production	41,369	82,739	MWh
Annual heat production	58,605	117,210	MWh

The working fluid in the Organic Rankine Cycle was 1233 RZ, which has a low global warming potential. The main difference between the scenarios concerned the expected flow rate in the production wells. The production well flow rate is a measure of the enhancing success, i.e. how well the stimulation activities work to create permeability and induce connection to the injected fluid from the injection wells. The upper and lower limits were determined based on the findings of Lacirignola and Blanc (2013).

2.3 Functional unit and LCA modelling approach

As the construction of the demonstration site in Reykjanes was (and is) ongoing, the life-cycle perspective was estimated by modelling the complete product system according to the 1 kWh electric functional unit. The model then computes results in mean, upper and lower bounds using Monte Carlo simulation for the two case studies (Metropolis & Ulam, 1949; Mooney, 1997). With respect to the scenarios described in Tables 1 and 2, the differences between them are mainly productivity and emissions from the borehole as described. This is where most of the uncertainty is in the operational phase, as these parts of the product system are not completed yet. Figure 3 is a conceptual drawing of the modelling and simulation approach, from the gathering of technical data and process descriptions through to impact assessment calculations.

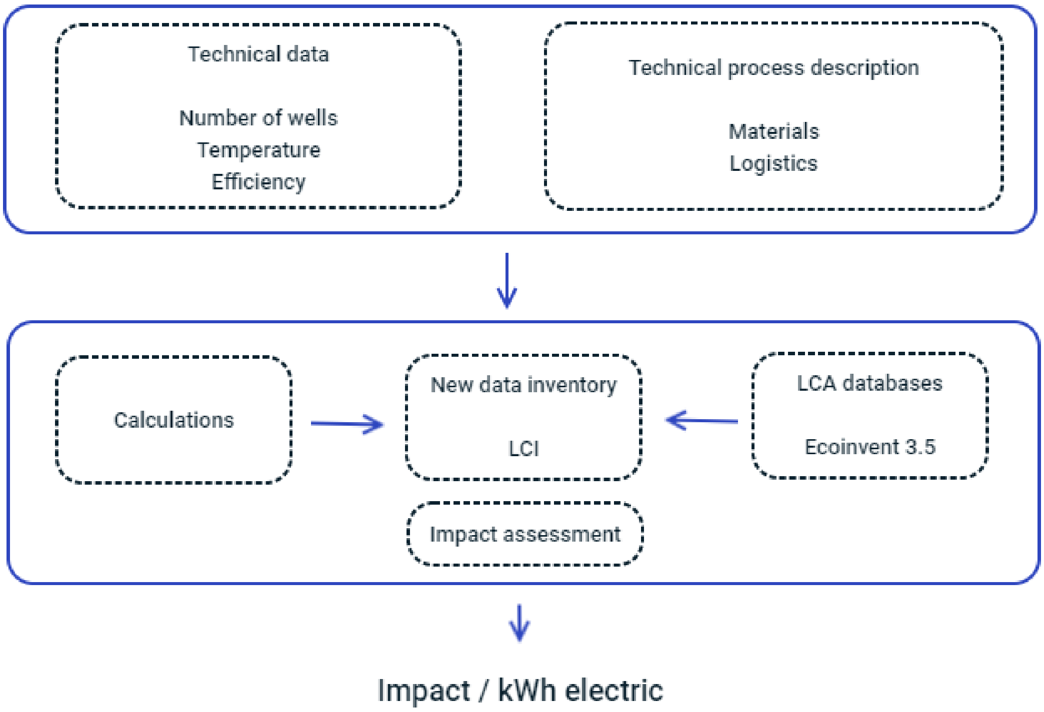

Figure 3. Conceptual drawing of the modelling and simulation approach.

This work relied on the information given by the DEEPEGS partners: HS Orka and Fonroche for the Reykjanes and Vendenheim case studies, respectively. Technical data and technical process descriptions were gathered from those partners, which then formed the foundation of the life-cycle inventory. All scenarios relied on a base model for the life-cycle inventory that was modelled using actual and estimated data inputs based on the construction status of the demonstration sites. The base model represents parts of the life-cycle additional to the operational phase, since that part is more uncertain and depends on the enhancement success, as was described earlier. All data inputs have been given an uncertainty distribution based on data quality using the Pedigree matrix (Ciroth et al., 2013; Ciroth et al., 2016; Muller et al., 2016). The model's likelihood was then assessed using the Monte Carlo simulation.

2.4 Life-Cycle Inventory

This section gives an overview of the main inputs in the life-cycle inventory for the life-cycle assessment. In addition to the data for the main operational characteristics, these inputs are used to find the estimated impact for the two case studies and all scenarios. Tables 3-8 are included in the Appendix and outline the primary material, energy, and transportation processes in the construction, operation and decommission parts of the products' systems.

The inputs in Tables 3-8 were then normalised into the functional unit, i.e. 1 kWh of electricity produced. The values used to normalise are stated in Tables 1 and 2 for the two cases and all scenarios. These values were divided by the annual electricity production then multiplied by the assumed lifetime of the power projects, which was a duration of 30 years.

The main differences in Tables 3-8 concern the volume of materials used. These were far greater in the case of Reykjanes, since this project involved the drilling of two new boreholes and a sidetrack. Additionally, gas emissions in the Reykjanes case study are significantly higher than the fugitive emissions in the Vendenheim case study, which results in a very different operational impact.

3. Results

The results are presented separately for the Reykjanes and Vendenheim case studies and their respective power output scenarios. The two power output scenarios for the Reykjanes site were 5 MW (lower) and 30 MW (upper); the two power output scenarios (co-generated heat and electricity) for Vendenheim were 40.1 MW and 80.3 MW. Monte Carlo simulation results detail the impacts of the construction phases of the two cases, giving a range for the operational scenarios described in the methods section. The life-cycle impact of greenhouse gas emission hotspots is compared to the carbon intensity of average electricity production in Europe.

3.1 Reykjanes

The life-cycle impact category hotspots for the Reykjanes case study were split as follows: climate change (45%); particulate matter formation (29%); terrestrial acidification (14%); and human toxicity (8%). For all these impact categories, the impact of average European electricity production is considerably higher than in the Reykjanes case study.

Figure 4 gives the results of the Monte Carlo simulation for the construction part of the DEEPEGS project at Reykjanes. It includes the borehole construction, stimulation and above-ground equipment.

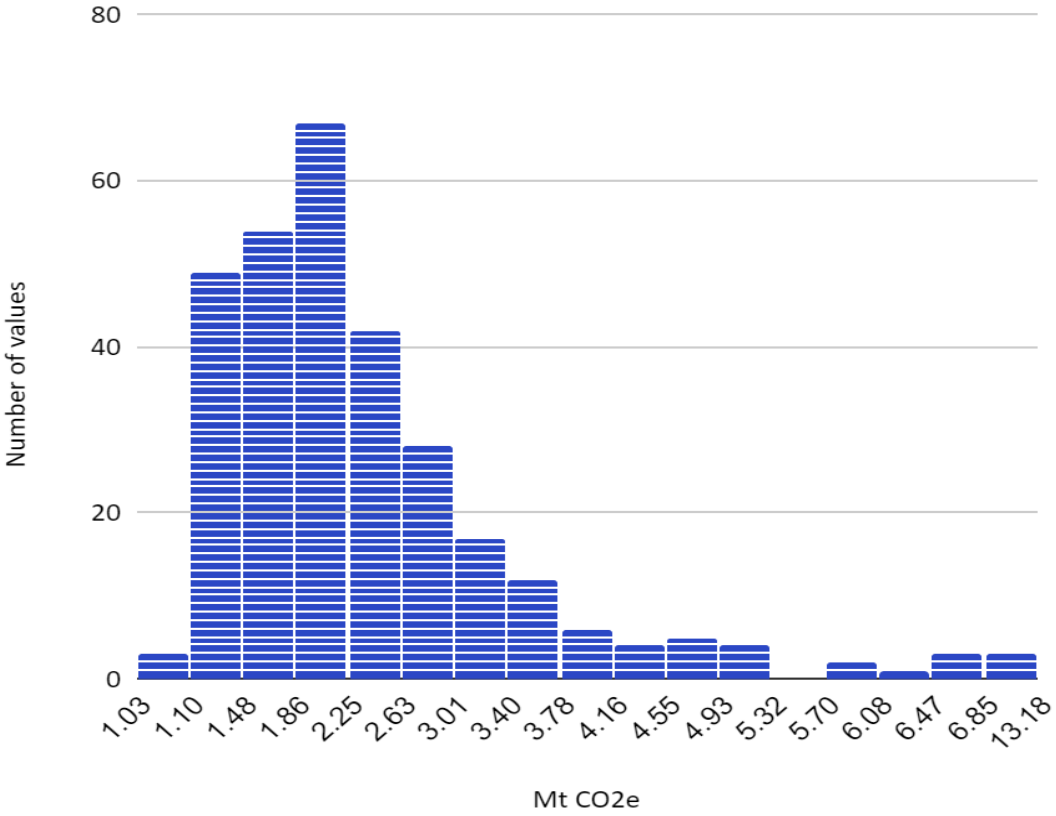

Figure 4. Monte Carlo simulation results of the Reykjanes case study in MtCO$_2$ equivalents.

The result of the simulation is a mean value of 2.4 gCO_2e/kWh, and a standard deviation of 1.3 gCO_2e/kWh. The upper limit based on the 95th percentile is 4.8 gCO_2e/kWh, and the lower limit based on the 5th percentile is 1.2 gCO_2e/kWh. These results were then articulated with respect to the functional unit (1 kWh electricity produced) and combined with the operational impact based on the two scenarios defined in the methods section. The mean result for scenario 1 (most likely) is that the impact of the Reykjanes case study is expected to be 17.4 gCO_2e/kWh, with an upper limit of 19.7 gCO_2e/kWh and a lower limit of gCO_2e/kWh. The results for scenario 2 (desired) imply a considerably lower impact – the mean impact is expected to be 1.6 gCO_2e/kWh, with an upper limit based on the 95th percentile of 2.0 gCO_2e/kWh and a lower limit based on the 5th percentile of 1.4 gCO_2e/kWh.

Figures 5 and 6 show the distribution of impacts from different processes within the product system based on scenarios 1 and 2, respectively, which can help to identify opportunities for improvements in sourcing and processing.

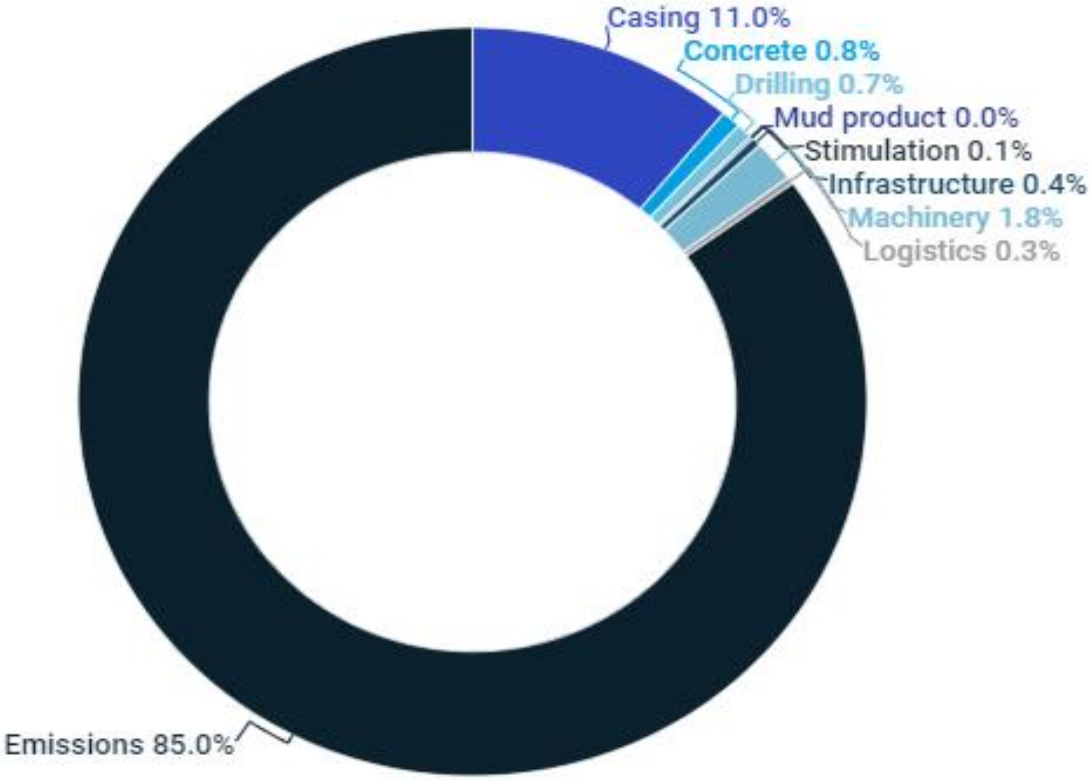

Figure 5. Distribution of climate change impact in scenario 1 of the Reykjanes case study.

As Figure 5 above shows, 85% of the climate change impact is from operational emissions i.e. the gas emissions (CO_2) from the borehole which are derived from the geothermal reservoir. Most of the other impacts relate to borehole construction, especially from the steel material (11%) used in the casing.

Figure 6 below reveals a slight difference in the distribution of climate change impacts between the two scenarios. Operational emissions are relatively less prevalent, and about 20% of the effects are from steel production used in the casing in the borehole. However, when analysing the distribution of impacts from other impact categories for both scenarios, most of the impact is from steel production for the casing i.e. 62% of the particulate matter formation impact and

64% of the human toxicity impact, except for the terrestrial acidification impact where 64% of the impact is due to operational ammonia emissions from the borehole and only 23% from the steel material used in the casing.

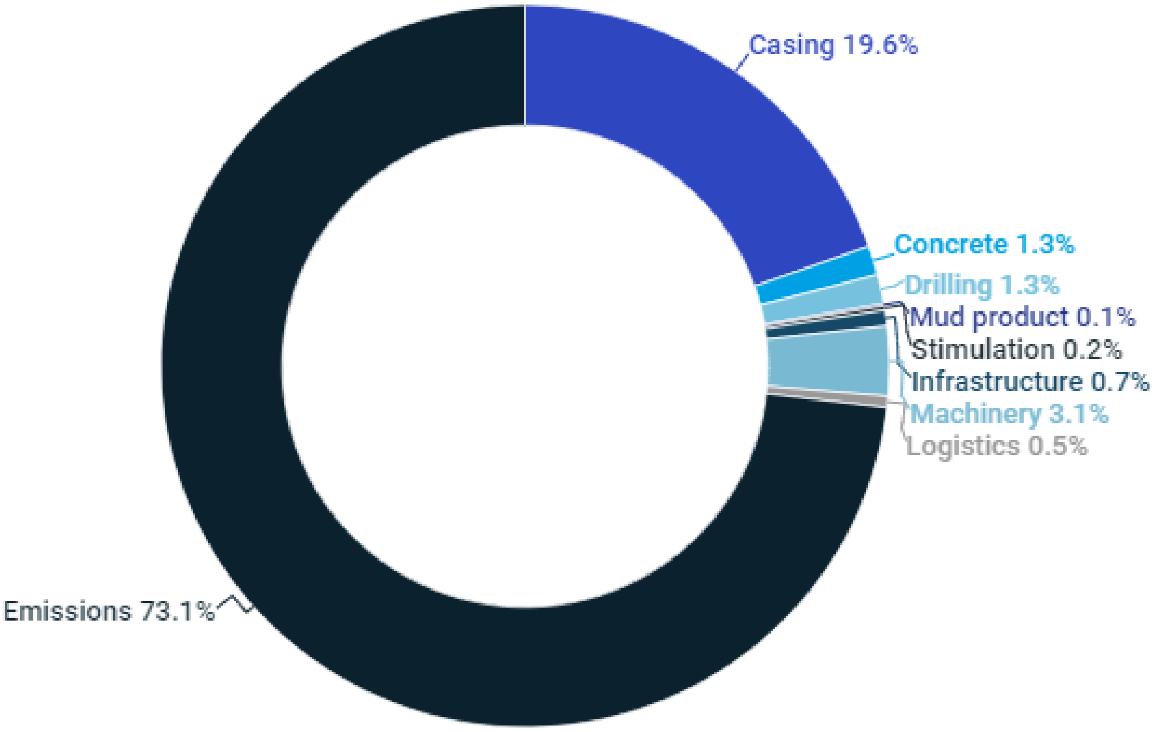

Figure 6. Estimated climate change impact in scenario 2 of the Reykjanes demonstration site.

To summarise the results of the life-cycle perspective for the Reykjanes case study, the most critical impact categories are climate change, particulate matter formation, terrestrial acidification and human toxicity. As this study has been conducted when the Reykjanes demonstration site is still under construction, the impact analysis was conducted using Monte Carlo simulations, and the uncertainty distribution was found using the Pedigree method as described in the methods section. The impact is then estimated over a range for the two scenarios, giving expected results in the range 1.4-19.7 gCO_2e/kWh[3].

3.2 Vendenheim

The life-cycle impact category hotspots for the Vendenheim case study were split as follows: particulate matter formation (30%); human toxicity (25%); climate change (14%); ionising radiation (13%); terrestrial acidification (8%); and terrestrial ecotoxicity (5%). For all these impact categories, the impact of average European production is considerably higher than in the Vendenheim case study.

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[3] Today, based on feedback from the operator, HS Orka, it is considered more likely that the impact when the project is operational will be closer to the 19.7 gCO2 equivalents, similar to the current situation at Reykjanes power plant as accessing a deeper reservoir has potentially been unsuccessful.

Figure 7 depicts the results of the Monte Carlo simulation for the DEEPEGS project at Vendenheim. It includes the borehole construction, stimulation and above-ground equipment.

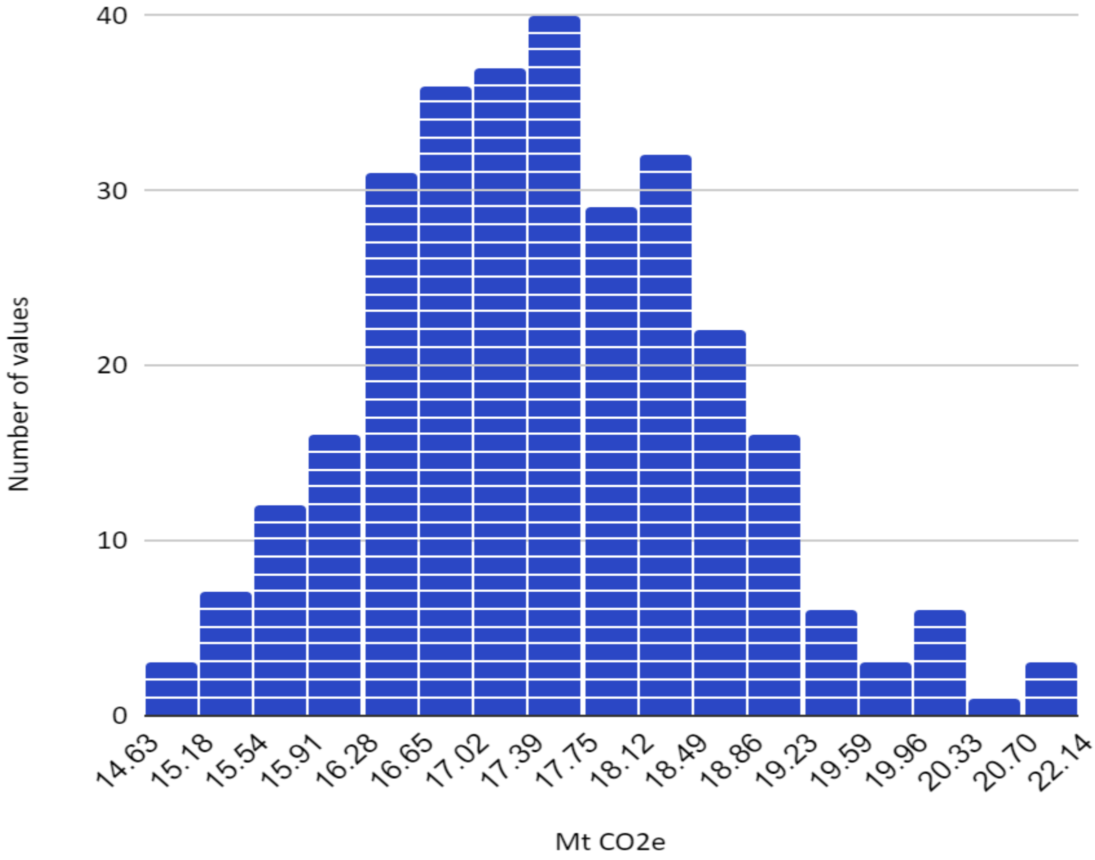

Figure 7. Monte Carlo simulation results of the Vendenheim demonstration site in MtCO$_2$ equivalents.

The result of the Monte Carlo simulation is a mean value of 17.2 gCO$_2$e/kWh, and standard deviation of 5.8 gCO$_2$e/kWh. The upper limit based on the 95th percentile is 19.3 gCO$_2$e/kWh, and the lower limit based on the 5th percentile is 15.8 gCO$_2$e/kWh. These results were then calculated with respect to the functional unit (1 kWh electricity produced) and combined with the operational impact based on the two scenarios defined in the methods section. For scenario 1 (lower), the mean result is that the impact of the Vendenheim case study is expected to be 13.9 gCO$_2$e/kWh, with an upper limit based on the 95th percentile of 15.6 gCO$_2$e/kWh and a lower limit based on the 5th percentile of 12.7 gCO$_2$e/kWh. The results for scenario 2 (upper) reveal a considerably lower impact, with the mean expected to be 6.9 gCO$_2$e/kWh, with an upper limit of 7.8 gCO$_2$e/kWh (95th percentile) and a lower limit (5th percentile) of 6.4 gCO$_2$e/kWh.

Figure 8 shows the distribution of impacts to different processes within the product system for both scenarios as the difference between them is negligible. The result shows where most of the impacts are sourced from, which can help identify opportunities for improvements.

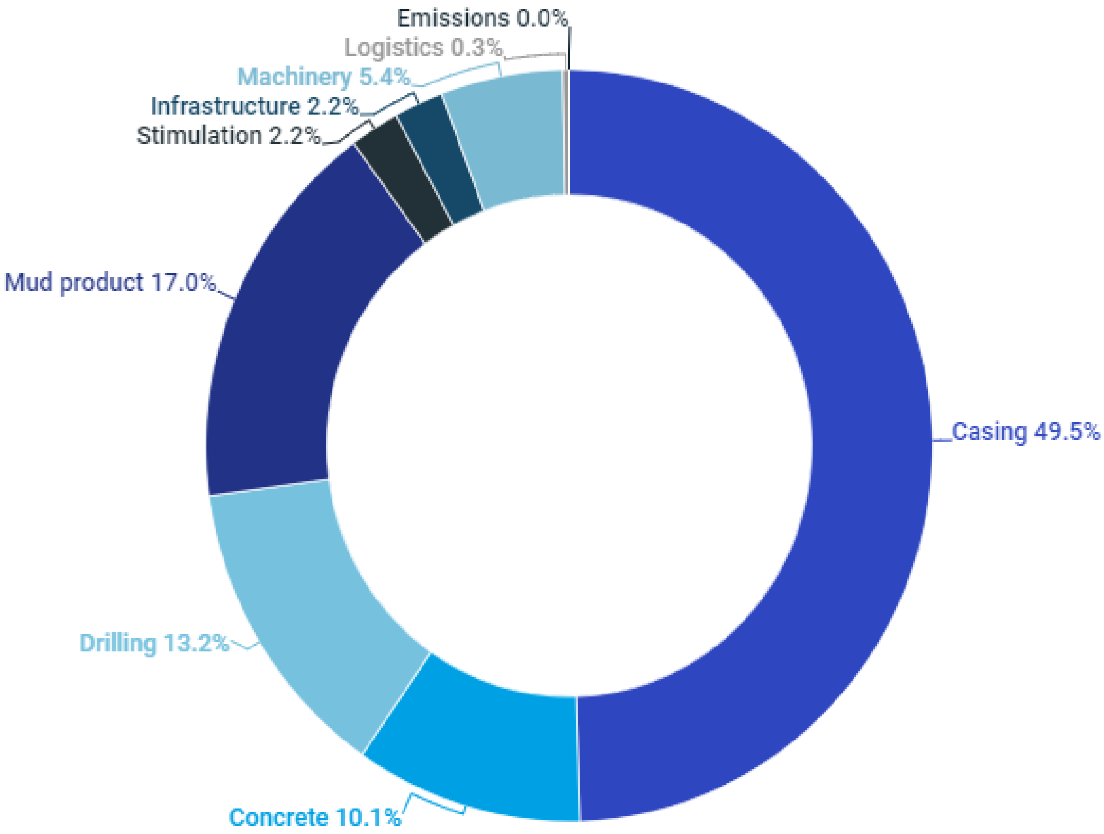

Figure 8. Estimated climate change impact of scenario 2 in the Vendenheim demonstration site.

As Figure 8 above shows, 50% of the climate change impact is derived from the steel material used in the casing, followed by the mud products needed for drilling, then by the energy use in drilling and the concrete. All these aspects are involved in the borehole construction phase of the demonstration site. For the other impact categories, the same applies to particulate matter formation and terrestrial acidification. However, the greatest human toxicity impacts are due to the drilling waste and ionising radiation relating to the use of nuclear power plants to produce the electricity used in drilling. However, when analysing the impact, it is interesting to see the potential consequences of the co-product district heating in Vendenheim. If the district heating supply is from the EGS power plant, it could substitute heating from other sources, e.g. natural gas. It is assumed that the heating capacity factor is about 50%, as described in the methods section. If natural gas utilisation is substituted, it could result in an avoided climate change impact of about 304 gCO_2e for every 1 kWh of electricity that is produced, equal to about 15.9 Mt CO_2e on an annual basis.

To summarise the results of the life-cycle perspective for the Vendenheim case study, the most critical impact categories are particulate matter formation, human toxicity, climate change, ionising radiation and terrestrial acidification. As the study is conducted when the Vendenheim demonstration site is still under construction, the impact analysis was conducted using Monte Carlo simulations, and the uncertainty distribution was found using the Pedigree method, as was conducted for the study of the Reykjanes demonstration site. The impact is then estimated over a range for the two scenarios, giving results between 7.7 and 15.4 gCO2e. Today, it is considered more likely that the impact when operational will be closer to 11.0 gCO2e based on the currently expected flow rate and net electrical efficiency.

4. Discussion

4.1 Comparison to climate impacts of alternative electricity-generating technologies and EU-wide decision-making implications

The life-cycle perspective of the two demonstration sites was compared with the life-cycle perspectives of various electricity production alternatives and the EU-27 average (EEA, 2020). As shown in Fig. 9, the two demonstration sites have a fractional climate change impact from a life-cycle perspective compared to non-renewable alternatives and a comparable effect to renewable options such as hydropower, wind energy and biomass.

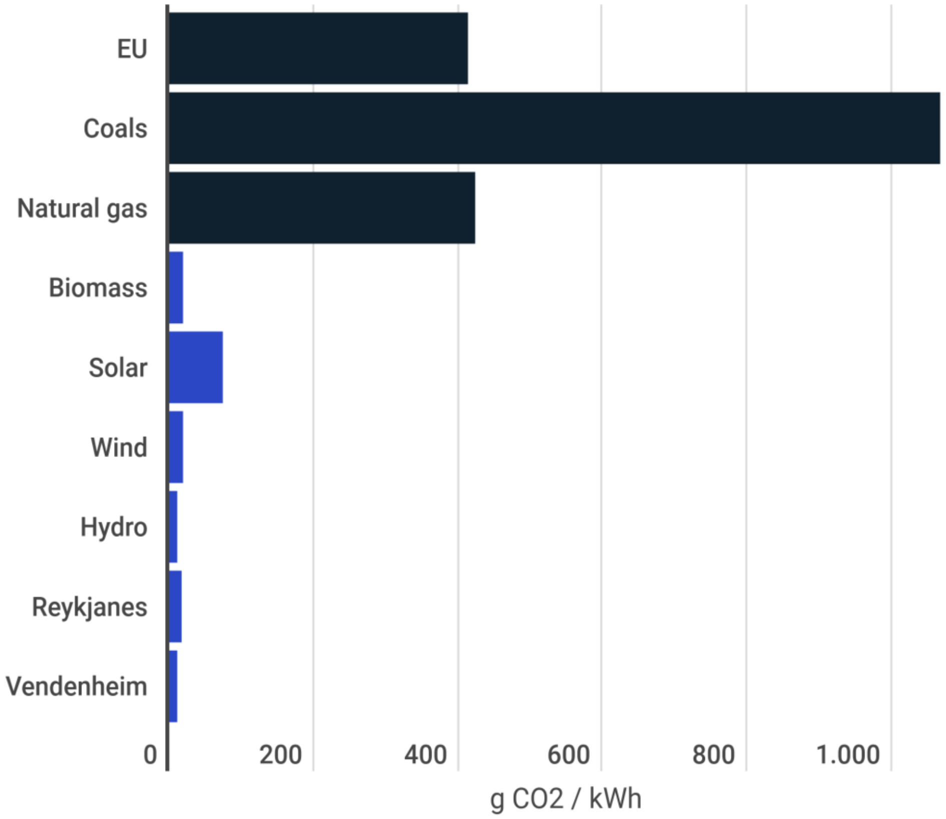

Figure 9. Climate change impact of various electricity production alternatives and the EU-27 average.[4]

These results underscore the importance of electricity generation from EGS as a climate-mitigating activity. It is even more important when considering that many of the renewable alternatives are intermittent sources that can be hard to control without a storage system. EGS electricity generation can support biomass utilisation and hydropower to provide renewable

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[4] Sourced from EEA (2020).

baseload in the EU’s future renewable energy system. There is also the added benefit of being able to provide heating as well as minimising reliance on natural gas or biomass.

In June 2020, a political agreement between the European Parliament Taxonomy Regulation set in motion the imminent creation of a “green list” classification system for sustainable economic activities. It details a general framework that will allow for the progressive development of an EU-wide classification system for environmentally sustainable economic activities (European Commission, 2020). The formalities of this general framework are, however, still being developed and will take a few years. The proposed green list is as follows: climate change mitigation, climate change adaptation, sustainable use and protection of water and marine resources, a transition to the circular economy, pollution prevention and control, and protection and restoration of biodiversity and ecosystems. Based on the low LCA impacts of the demonstration sites at Reykjanes and Vendenheim, deep EGS ventures could provide a significant contribution to at least two of these six objectives, i.e. climate change mitigation, and pollution prevention and control, as well as fulfilling wider policy objectives linked to the decarbonisation of economies, for example, the emissions reduction objectives of the Paris Accord.

4.2 Further reducing the impacts of deep EGS power projects

Since the main impacts at the Reykjanes demonstration site, and other hydrothermal geothermal energy sites, are greenhouse gas emissions from the borehole itself, these effects could be largely avoided by carbon capture and mineralisation/utilisation, while the same approach is also possible for hydrogen sulphide emissions. There are commercial solutions available that have been tested for hydrothermal geothermal energy systems e.g. the CarbFix and Sulfix projects at Hellisheiði in Iceland, where the gases react with basaltic sub-surface rocks to form stable minerals for safe, long-term storage of the injected gases (Gíslason et al., 2010; Matter et al., 2011; Sigfússon et al., 2018) and the Carbon Recycling International methanol plant nearby at Svartsengi in Iceland, where renewable methanol from carbon dioxide and hydrogen is produced using water electrolysis (Helgason et al., 2020; Stefánsson and Sigurbjörnsson, 2019).

The latter solution is using captured carbon dioxide emissions from another power plant operated by HS Orka, and currently the CarbFix and Sulfix projects capture about 10,000 tonnes of CO_2 and 5,000 tonnes of H_2S, respectively, injecting them back into the geothermal reservoir, corresponding to 34% and 68% of the annual emissions from the plant in 2017 (Sigfússon et al., 2018). The carbon available at these power plants differs as the amount of carbon emitted from geothermal boreholes is very site-specific, but in general, the annual quantity is quite low compared to natural gas or coal-fuelled power plants. This is a strength, since it is easier to store small amounts than substantial quantities of carbon. However, carbon capture from hydrothermal geothermal energy systems could also be combined with other utilisation solutions that are also available e.g. bioenergy systems acting as a carbon boost to increase the quality of the syngas or carbon, which could be used to make utilisation with captured carbon more economically attractive than it is already by supplementing each other. Together, bioenergy and geothermal energy could be part of the 100% renewable energy solution (Connolly et al., 2016) in the future smart energy system (Sigurjónsson and Clausen, 2018).

In comparison to previous studies on EGS systems, the results at Vendenheim show lower climate change impacts from a life-cycle perspective. The reason is that the borehole drilling uses electricity as its primary driver. The power used in France has a relatively low carbon intensity compared to the EU average (Ang and Su, 2016). Although it is mostly not from renewable sources, it has a significant impact on the overall impact of the Vendenheim demonstration site. The improvements available at Vendenheim and likely other hot, dry rock geothermal energy sites are mostly related to a transition to circular economy practices, as most of the impacts are from materials or energy used during construction. As noted above, sourcing the electricity used during drilling from low carbon sources is essential, and it is even better if it is sourced from renewable energy sources. This could be extended to adopt a circular supply chain, i.e. use of renewable energy, bio-based or potentially wholly recyclable materials. Reducing the impacts of the steel and cement used in the borehole construction is likely a challenge in the short to medium term. As the findings by Arens et al. (2017) suggest, efforts to reduce greenhouse gas emissions in the steel industry through new processes are unlikely to be available in time to help meet the United Nations' climate targets for 2030, as these technologies will take decades to develop and introduce. However, low carbon cement alternatives are already available, as noted by Naqi and Jang (2019), and should be considered for use in the geothermal energy sector.

The lower carbon intensity of deep EGS projects in comparison to fossil fuel alternatives and most other renewable energy solutions could increase the attractiveness of these innovative technologies as a means of decarbonising the French and Icelandic energy systems. In the case of the latter, the Icelandic electricity system is almost entirely fuelled by renewable energy, however, Iceland's new energy and climate policies stress the importance of further harnessing of renewable energy resources to provide electricity for the expanding electric car market and its charging infrastructure, and in ports (MENR, 2020; MII, 2020). Meanwhile, the results in this study provide further evidence in support of the contentions of Chavot et al. (2018) who asserted that deep EGS could form an important part of the energy transition in France, in which the carbon intensity of the electricity supply is further reduced in the period to 2030. This would help France to comply with it targets under the Paris Accord, which are to reduce non-Emissions Trading Scheme greenhouse gas emissions by 36% over the period 2005 to 2030 (European Commission, n.d.).

4.3 Study limitations

The main limitation of this study is that both case studies represented demonstration sites in the middle of construction. This means that actual data could not be used for parts of the assessment, requiring Monte Carlo simulation for the construction phase. However, this was mitigated by using estimates based on previous studies in a similar type of plant and area as the demonstration sites. The widely used Pedigree Matrix was used to estimate uncertainty for the input values that were assumed.

Additionally, several of the environmental and socio-cultural impacts of geothermal power projects were not captured in this assessment, most of which are traditionally overlooked in LCA studies. These include impacts to the aesthetics of geothermal areas, increased risk of land subsidence and earthquakes – as have recently been evident at the Vendenheim site (Think Geoenergy, 2020), noise emissions, and short and long-term biodiversity implications. These also need to be accounted for in decision-making, and this can be done using tools such as social-LCA, cost-benefit analysis, Environmental Impact Assessment and Multi-Criteria Decision Analysis (Cook et al., 2017; Cook et al., 2019).

5. Conclusion

The geothermal industry continues to grow in significance in many nations around the world. Increasingly, EGS are utilised as a means of providing low carbon sources of energy, contributing to the fulfilment of climate-related goals, such as those of the Paris Accord and the Sustainable Development Goals, especially Goals 7 (Affordable and Clean Energy) and 12 (Responsible Production and Consumption). This study set out to provide the first LCA studies in the academic literature pertaining to deep EGS, using the case studies of the DEEPEGS demonstrator sites at Reykjanes, Iceland and Vendenheim, France to explore the climate change impact of deep EGS projects, deciphering where in the life-cycle the impacts occur, and reflecting on opportunities to mitigate greenhouse gas emissions.

The study found evidence that the greenhouse gas emissions of deep EGS projects across their life-cycle are considerably lower than fossil fuel alternatives for electricity generation, and comparable in emissions per unit of energy to renewable energy solutions such as hydropower, wind energy and biomass. Climate change impacts for the sites were estimated to be in the range 1.6-17.4 gCO2e/kWh and 6.9-13.9 gCO2e/kWh for Reykjanes and Vendenheim, respectively. The main options for reducing greenhouse emissions at Reykjanes related to the carbon capture and mineralisation of effluent carbon dioxide, as has been practiced elsewhere in Iceland in recent years. The dry, hot rock project of Vendenheim had opportunities to reduce greenhouse gas emissions by advancing its adoption of circular economy principles relating to the procurement of materials, as most of the climate impacts derived from materials and energy used in construction.

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