An environmental life cycle cost assessment of the costs of deep enhanced geothermal systems – the case studies of Reykjanes, Iceland and Vendenheim, France

Abstract

Environmental life cycle costing (ELCC) is a tool which aggregates five categories of monetary costs across a project's life cycle: investment, operation, maintenance, end-of-life, and externalities. This paper summarises the results from the first two ELCC studies involving deep enhanced geothermal systems (EGS). The ReCiPe method was used to transform life cycle impact factors into economic costs for externalities. The two case studies are the pilot EGS project in Reykjanes, Iceland and the Vendenheim co-generation plant in France. The ELCC of the Reykjanes project is estimated in the range 14.47-15.78 million euros, with investment and well drilling projected to constitute 83% of these amounts. An ELCC in the range 91.90-113.97 million euros is estimated for Vendenheim, with the production plant, well drilling, and operations and maintenance costs accounting for the majority. The levelized costs of energy associated with Vendenheim (mean €45.0/MWh/year) and Reykjanes (mean €16.5/MWh/year) are at the lower end of the range normally reported for geothermal power projects. Although the case studies cannot be directly compared since Reykjanes involves the drilling of a single well and Vendenheim a co-generation plant and two wells, the outcomes suggest that deep EGS projects may involve cost-savings compared to conventional geothermal power ventures.

Keywords: decision-making; valuation; deep geothermal energy; environmental impacts; costing

1. Introduction

1.1 Life cycle costing and environmental life cycle costing

As a concept, life cycle costing (LCC) began in the mid-1960s when the US Department of Defence began an assessment of the long-term cost effects of military products (Lindholm et al., 2018). In recent years, the use of LCC has expanded in breadth considerably, especially among public authorities, who are often tasked with making cost-efficient investment decisions (Stark, 2015; Cheung et al., 2015; Kerzner and Kerzner, 2017; Kambanou et al., 2020). When comparing between options delivering the same project outcome, decision-makers are likely to prefer the least-cost or most cost-effective option (Stark, 2015). LCC seeks to provide a solid evidence base for making such decisions, endeavouring to account for all of the costs incurred by a project over its entire lifecycle (Jackson and Ostrom, 1980; Lindholm et al., 2017; Heralova, 2017). In general, conventional LCC methods account for and aggregate four categories of costs: investment, operation, maintenance and end-of-life disposal (Luttenberger and Luttenberger, 2016; Heralova, 2017). LCC has been defined by the International Organization for Standardization standard, Building and Constructed Assets, Service-life Planning, Part 5: Life-cycle Costing (ISO 15686-5) as an *"economic assessment considering all agreed projected significant and relevant cost flows over a period of analysis expressed in monetary value. The projected costs are those needed to achieve defined levels of performance, including reliability, safety and availability."* A broader perspective than LCC is offered through environmental life cycle costing (ELCC). This method accounts for all of the four categories of costs addressed by LCC, but also the external environmental costs of a project across its lifecycle (Swarr et al., 2011).

Accounting for such impacts has become an increasingly critical component of decision-making in relation to the award of public procurement contracts in the EU. Article 67 of the EU Procurement Directives[1] asserts that contracting authorities must base the award of public contracts on the most economically advantageous tender, using a cost-effectiveness approach such as life cycle costing (Luttenberger and Luttenberger, 2016). The best 'price-quality ratio' of various tenders may be applied as a decision-making criterion, to include the costs of their environmental and social implications. Consequently, Article 67 stimulates a subtle but discernible shift in decision-making emphasis – from evaluating project tenders based on 'lowest price' to 'lowest cost' (Van den Abeele, 2014). In addition, the EU Procurement Directives have further embedded the importance of environmental soundness into decision-making processes by stipulating that project economics cannot be the only criterion contracting authorities apply. The award of contracts can also be based on various criteria of relevance to life cycle analysis (LCA), including production processes, sourcing of raw materials, water or energy consumption, or biodegradability (ICLEI, n.d.). Article 68 of the EU Procurement Directives further reinforces the importance of the LCC concept in public procurement, specifically enshrining the need to account for environmental externalities across a project's lifecycle, such as pollution, greenhouse gas emissions and recycling costs, provided their monetary value can be determined and verified.

1.2 LCA studies on geothermal power generation

For well over 100 years, geothermal resources have been harnessed to provide base-load electricity around the world (Tomasini-Montegro et al., 2017). Globally, the total installed

[1] 2014/23/EU (the Concessions Directive), 2014/24/EU (the Public Sector Directive) and 2014/25/EU (the Utilities Sector Directive)—hereafter simply referred to as the 2014 Directives.

capacity from geothermal technologies increased by 3.649 Gigawatt equivalent (GW_e) in the period 2015-2020, a 27% increase. A further increase of 19% is projected over the period 2020-2025 (Huttrer, 2020). Given the likely expansion in production, increasingly attention has been directed towards the environmental impacts of the geothermal power sector, particularly in connection with the harnessing of high-temperature fields for the purposes of electricity generation. In addition, there are also environmental impacts from exploration and some natural background emissions of greenhouse gases and hydrogen sulphide, from geothermal areas (Ármansson, 2018; Bayer et al., 2013; Paulilo et al., 2019; Santoyo et al., 2018). A variety of studies have been undertaken to explore the environmental impacts of geothermal power projects and their impacts on societal well-being (Bayer et al. 2013; Shortall et al., 2015; Cook et al., 2020). Bayer et al. (2013) articulate that these include direct effects, such as land distortion, production of geological hazards, atmospheric emissions, waste heat, solid waste, water consumption, noise emissions, and impacts on biodiversity. However, in addition to these impacts, there exist a variety of indirect effects specific to the harnessing of geothermal power. These occur in relation to the materials and energy required over the lifecycle of the power plant (Tomasini-Montegro et al., 2017). Therefore, in order to fully understand the environmental implications of geothermal power generation, a product system approach should be favoured, since this facilitates an assessment that is considerate of the supply chains of the life cycle in this industrial sector. In so doing, information is provided about the environmental impacts pertaining to the whole system, as opposed to a single process in the geothermal industry. Evaluations of this type can be conducted using LCA, which, when conducted according to well-defined ISO norms and processes (such as ISO 14040, 2006a; ISO 14044, 2006b), can compile 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, with greater 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 regards to the power sector. They include a study on the greenhouse gas emissions of 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 an LCA of a wind turbine (Batumbya et al., 2006). Several LCA studies can be found in the academic literature that have focused on geothermal power plants. These include but are not limited to:

- 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 energy synthesis in respect of 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);
- An LCA on a geothermal power plant linked to the Southern German Molasse Basin's hydrothermal resource (Menberg et al., 2021).
- An LCA assessment on the combined heat and power double-flash geothermal power plant of Hellisheiði in Iceland (Colucci et al., 2021).

- The LCA studies on the deep enhanced geothermal systems of Reykjanes and Vendenheim, on which these LCC studies are largely based, are reported in Sigurjónsson et al. (2021).

1.3 LCC and ELCC studies on geothermal power generation

In general, the economic efficiency of power plants continues to be assessed using standard cost-benefit analysis, which is not extended to account for the economic costs of environmental and social effects of projects (Cook et al., 2016), and levelized cost analysis, which often suffers from the same pitfall (Ebenhoch et al., 2015). It is likely that this is largely due to reasons of complexity deriving from the challenges in (a) estimating the costs of projects with a long lifespan, and (b) converting environmental impact factors into economic cost values. Very few LCC or ELCC studies, which seek to incorporate the economic value of environmental externalities, have occurred linked to the harnessing of geothermal energy resources. The paper by Martínez-Corona et al., (2017) appears to provide the first study which has sought to link LCA inventories and impact values to monetary valuation in the context of high-temperature geothermal power plants. Based on a power project in Wairakei, a comparison was formed concerning different environmental assessment methods for geothermal plants based on either physical or monetary data. Yilmaz (2020) conducted both an LCC and levelized cost assessment of hydrogen production via geothermal power. Park et al., 2020 explore the impact of risk on the levelized cost of geothermal technologies. Other life cycle cost studies in the context of geothermal power have focused on low temperature geothermal technologies, such as ground source heat pumps (Chiasson, 2006; Habibzadeh-Bigdarvish et al., 2019).

1.4 Deep EGS and the DEEPEGS case studies of Reykjanes, Iceland and Vendenheim, France

In theory, drilling to unconventional depths in EGS projects enables the sourcing of water at 400-500°C, some 25-50% hotter than in conventional hydrothermal drilling projects in volcanic regions (Friðleifsson et al. 2018; Friðleifsson et al., 2020). The higher temperatures potentially associated with EGS projects could be used to generate superheated steam, which can then be utilised to create electricity. Assuming success, an anticipated consequence of deep drilling projects is a considerable reduction in costs and environmental impacts, since far fewer wells would be required to be drilled to generate the same power output using regular geothermal boreholes. Since the harnessing of geothermal energy can result in changes to land surface manifestations, noise effects and visual blight from pipelines (Shortall et al., 2015; Cook et al., 2020), the drilling of fewer wells, including make-up wells, would reduce the scale of these effects and the environmental impacts of drilling. In this respect, this ELCC study acts as a starting point in providing a comparison in cost per unit of power output between conventional and EGS projects.

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. An existing 2.5 km deep well at Reykjanes, known as IDDP-2, has been deepened to 4.6 km, with drilling completed in late 2017, and well stimulation and testing undertaken thereafter. 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 a depth of 3,500 metres to increase connectivity between the VDH1 and WDH2 wells, and the subsequent construction of power plant infrastructure on the site of a former fossil fuel plant. Unlike Reykjanes, where the aim was to provide additional electricity generation, the Vendenheim project entailed the co-production of heat and power from a geological area with heat in the range of 180-210 °C from the deep wells (Sanjuan et al., 2020). Although, these are much lower temperatures than at commensurate depths in Iceland, in the context of mainland Europe, where there is different geology, the Vendenheim site is a very hot resource. Thus, site-specific differences make it difficult to compare the two case studies.

1.5 Aims, research questions and structure

The limited number of LCA/LCC/ELCC studies in the academic literature with respect to geothermal power projects, and complete absence in the context of deep EGS ventures, motivates this study. There are thus considerable opportunities to enhance knowledge concerning the lifecycle costs of different types of geothermal power projects. This will enable better knowledge of the lifecycle costs of geothermal power compared to alternative energy-generating technologies and ultimately help to inform cost comparisons between different geothermal technologies and design parameters. In particular, the highlighting of the economic value of environmental hotspots across the lifecycle of geothermal power project provides important information for supply chain and project managers.

The aim in this study is not to form direct cost comparisons between the two case studies, since one is a new project and the other an extension of an existing venture, but rather to add to the knowledge base concerning the economic costs of geothermal power ventures. It applies the two cases studies in pursuit of answers to the following three research questions:

1) What are the environmental life cycle costs and how do these affect the levelized costs of deep EGS power projects?
2) What represent the main cost components in deep EGS power projects?
3) How do the environmental life cycle costs of deep EGS power projects compare to conventional geothermal power ventures?
4) What other environmental and socio-cultural impacts to human well-being should be accounted for beyond those incorporated in the ELCC?

This paper applies the LCA model (Sigurjónsson et al., 2021) developed in relation to the DEEPEGS site at Reykjanes and Vendenheim to conduct an ELCC, translating environmental impacts into monetary values using state-of-the-art methods. Section 2 of this paper sets out the methodology for the ELCC study on the DEEPEGS project in Reykjanes, Iceland, including how it accounts for environmental externalities and conducts a sensitivity analysis concerning the discounting of probabilistic cost components. Section 3 sets out the estimated results according to the range of discount rates explored, and then discusses the main outcomes from the study, including some of the wider decision-making implications of LCC, and the extent to which the approach accounts for all environmental and social costs linked to the project. Section 4 provides a brief conclusion and considers the potential for future related research.

2. Methodology

2.1 Components of ELCC

Within LCC and ELCC, some costs can be classed as deterministic and others probabilistic. Deterministic costs include mainly those outlays relating to acquisition and disposal. Most probabilistic costs relate to the reliability and maintenance needs of a project’s system, including the costs of repairs, spare parts and downtime (Barringer, 2003). This paper adopts the following seven-component formula for calculating the ELCC of the DEEPEGS case studies at Reykjanes and Vendenheim, as set out in Fig. 1. Unlike traditional LCC, ELCC incorporates an additional category of costs involving environmental externalities linked to the operations of a project, for instance greenhouse gases and other pollutants (Luttenberger and Luttenberger, 2017). ELCC thus accounts for both the internal and external environmental externalities of a project. It is calculated as follows:

$$ELCC = C_{pio} + C_{wd} + C_{pp} + C_{ret} + C_{de} + C_{om} + C_{ex} \quad \text{(eq. 1)}$$

Where:

ELCC = the aggregate environmental life cycle costs expressed in present value and across the likely lifespan of the project (30 years)
C_{pio} = Project planning, upfront infrastructure and operational
C_{wd} = Well drilling
C_{pp} = Production plant
C_{ret} = Reservoir engineering (including stimulation) and testing
C_{de} = Decommissioning
C_{om} = Operations and maintenance
C_{ex} = Environmental externalities of operations

Note that not all the cost elements in equation (1) applied to both case studies. For example, there was no production plant (C_{pp}) in relation to the Reykjanes site, as one with 100 MW_e capacity already operated at the site, drawing energy from existing multiple conventional wells of 2.2-2.5 km depth. The DEEPEGS well at Reykjanes was the first deep well drilled into the deeper, higher-temperature zone.

Physical impact data was extracted from LCA studies on the two case studies conducted by the University of Iceland (Sigurjónsson et al., 2021). The system boundaries and constraints for the ELCC studies are set in accordance with the LCA studies reported by Sigurjónsson et al. (2021). The system boundaries related to costs and impacts occurring at the construction site, except for externalities, which constitute spill over effects on surrounding populations. Aggregate cost data for the various deterministic and probabilistic cost components (excluding environmental externalities) was provided by the developers responsible for the respective sites. The exception to this was the cost in respect of decommissioning in the case of the Reykjanes project, where, in the absence of a developer estimate, 'rule of thumb' data was applied from Huenges et al. (2010).

2.2 Accounting for environmental externalities of operations

The concept of external costs, or negative externalities, was first introduced by the British economist, Arthur Pigou, who sought to address such effects through market mechanisms, including environmental taxes. Rebitzer and Hunkeler (2003, p.253) define externalities as costs that *include "the monetised effects of environmental and social impacts not directly billed to the firm, consumer, or government, etc. that is producing, using, or handling the product. The so named "externalities" are outside the economic system, though inside the natural and social system"*. In a lifecycle costing context, environmental externalities include costs already paid for by an entity along the value chain and not included in market transactions (e.g. municipal waste disposal, increased safety features), as well as costs that have been paid for and can be monetised (e.g. greenhouse gas emissions and pollutants) (Hunkeler et al., 2008).

As the results and discussion section of this paper acknowledges, there are also external costs that are difficult to monetise using lifecycle costing, such as impacts to the aesthetics of geothermal landscapes.

Several different techniques can be applied to account for environmental externalities. One approach to calculating environmental externalities specific to life cycle costing is set out in the European Union's Clean Vehicles Directive (2009/33/EC). This Directive requires contracting authorities to account for energy consumption, greenhouse gas emissions and pollutant emissions. A set of standardised costs for carbon dioxide, nitrogen oxide, non-methane hydrocarbon and particulate matter emissions from road transport is listed in the Appendix to the Directive, which requires adjustment to reflect current rather than 2007 prices. More recently, the European Commission has issued a new LCC Tool known as ReCiPe, inclusive of direct and some indirect (environmental externalities) costs. ReCiPe first translates the relevant items of a product's lifecycle (e.g. its electricity consumption) into a resource and emissions profile using publicly available life cycle inventory data, converts these environmental impacts using LCA, before finally applying monetisation factors, such as the social cost of carbon and damage function, to the computed environmental impacts and aggregating (Estevan and Schaefer, 2017) (see Fig. 1). External costs were calculated using monetary impact values from several air pollutants (Gunnlaugsson et al., 2018; Sigfússon et al., 2018) and a social cost of carbon study (Sigfússon et al., 2018) focused on geothermal power, which assumes a value of 20 euros/tonne.

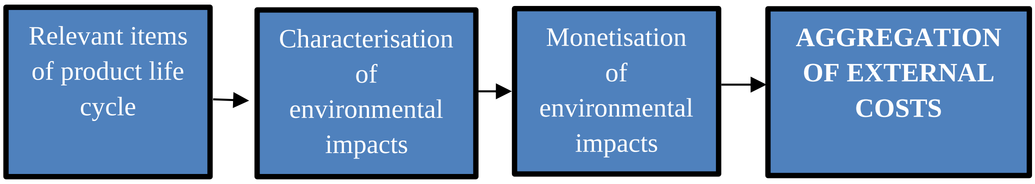

Fig. 1. EU's ReCiPe method to account for environmental externalities.

2.3 Discounting for probabilistic costs and sensitivity analysis

An important issue in any ELCC study concerns the treatment of probabilistic costs relating to costs not occurring upfront. The academic literature includes several studies focused on the optimisation of probabilistic components, with much of the focus on operations and maintenance costs (Tsang et al., 2006; Campbell et al., 2011). However, in an ELCC context, much less attention has been given to the importance of discounting probabilistic costs, most likely due to the issue of uncertainty. In order to be able to aggregate and compare costs that occur at different points in the lifecycle of projects, these need to be made time-equivalent. This is even more important when projects have an extended lifecycle, such as infrastructure ventures. Discounting accounts for the time value of money (Jaggi et al., 2016; Chakrabarty & Chaudhuri 2017). In LCC or ELCC studies, discounting converts future probabilistic costs into present values (Goh and Sun, 2016; Islam et al., 2016). This enables future costs to be compared with upfront outlays, and an overall aggregation of total costs to occur in present value terms. The interest rate selected to discount future costs is an arbitrary value but is most often selected based on an investor's opportunity cost of money over time (Ciambrone, 2018). In other words, the return that an investor wants to achieve is at least as high as the next best alternative investment. In this paper, three discount rates are applied to the probabilistic costs in the

DEEPEGS ELCC model, including 2% (low), 5% (medium) and 8% (high). This sensitivity analysis ensures that the results account for various degrees of risk and uncertainty.

In addition, a further sensitivity analysis was conducted with respect to the anticipated social cost of carbon in future years. The same approach was followed as per the study by Helgason et al. (2020). Although the starting point social cost of carbon was 20 euros per tonne as per Sigfússon et al. (2018), cost curves for future years then followed assumptions of low, medium and high per annum annual increments across the thirty-year period of this study. The increments are in accordance with estimates by the EIB (2015) and are set out in Table 1. Depending on whether low or high annual increments are assumed, the range of social carbon estimates in the year 2050 are from a low of 50 euros/tonne up to 200 euros/tonne.

Table 1. Incremental increases in shadow prices for greenhouse gas emissions from 2020-2050 (2018 euros) (sourced with permission from Helgason et al., 2020).

		Time period		
		2018-2030	**2031-2040**	**2041-2050**
Low cost increase p.a.	Euros	0.5	1	2
Central cost increase p.a.	Euros	1	2	4
High cost increase p.a.	Euros	2	4	8

3. Results and discussion

3.1 Results

Table 2 summarises the ELCC calculation for the two case studies. A breakdown of the aggregate costs is detailed according to the various components provided in the methodology, including the respective percentage contributions. Figs. 2 and 3 display pie charts relating to these cost components. Both Table 2 and Figs. 2 and 3 are based on an assumed discount rate of 5% for all probabilistic cost components, including future costs relating to the imminent well stimulation, and these were assessed across a 30-year time horizon. Process externalities for the well drilling and stimulation components include all production and transport-related emissions, and these are derived directly from the LCA study on this project. Assessed environmental externalities for Reykjanes include carbon dioxide emissions (CO_2) and hydrogen sulphide emissions (H_2S). CO_2 and H_2S emissions, although much lower in scale than fossil-fuel alternatives, are considered to be by far the largest constituents of all steam vapour gases emitted by geothermal power plants, in Iceland and around the world (Júlíusson et al., 2015; Sigfússon et al., 2018). No fugitive emissions are assumed in relation to the operations of the Vendenheim project.

Table 2: ELCC calculation – Reykjanes and Vendenheim

	Reykjanes		Vendenheim	
Cost Component	**Cost (million euros)**	**Percentage of total costs excluding environmental externalities of operations**	**Cost (million euros)**	**Percentage of total costs excluding environmental externalities of (operations**
Project planning and upfront infrastructure and operational	6.87	46.83	5.40	5.39
Well drilling	5.44	37.09	31.52	31.43
Construction-related climate impacts (includes well drilling and stimulation	0.15	1.08	0.03	0.03
Production plant	0.00	0.00	34.30	34.20
Discounted well engineering and testing	1.15	7.83	2.57	2.57
Discounted decommissioning	0.31	2.13	0.50	0.50
Discounted operational and maintenance	0.74	5.02	25.97	25.89
Total costs excluding environmental externalities of operations	**14.67**	**100.00**	**100.29**	**100.00**
Environmental externalities of operations	0.21		0.0	
Total costs including environmental externalities of operations	**14.88**		**100.29**	

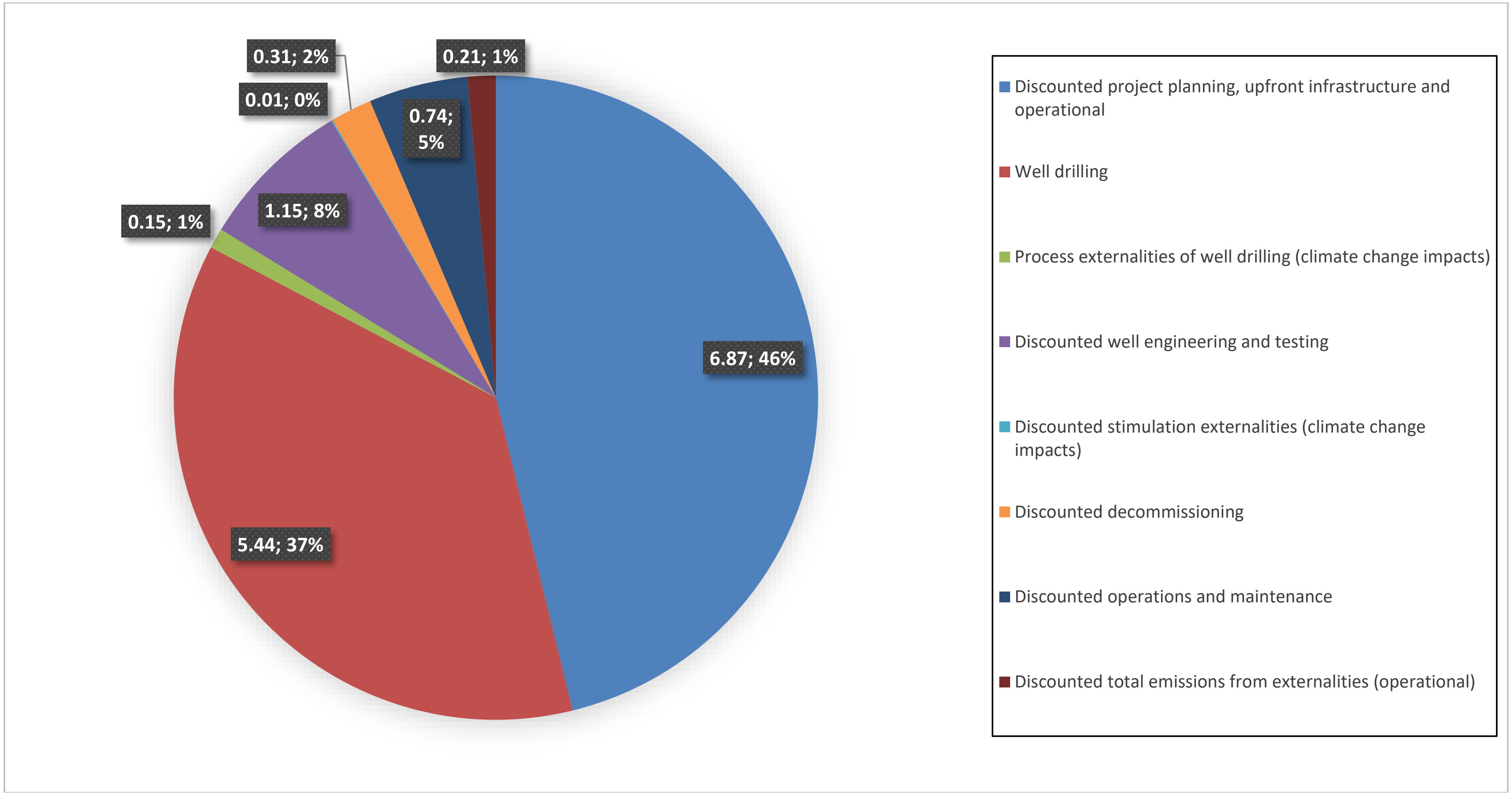

Fig. 2: ELCC pie chart – breakdown of cost components, Reykjanes (million euros)

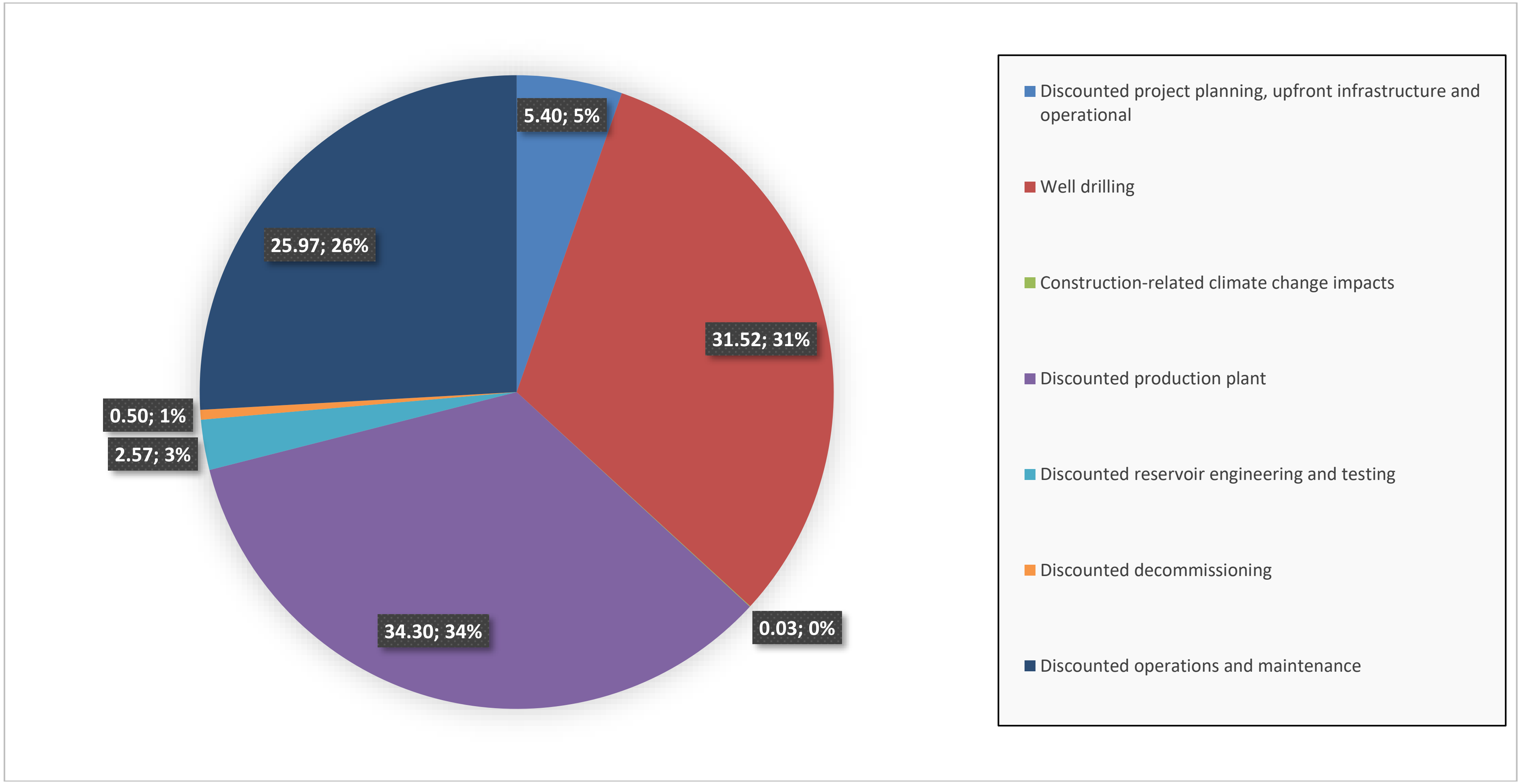

Fig. 3: ELCC pie chart – breakdown of cost components, Vendenheim (million euros)

The total life cycle costs (excluding environmental externalities from operations) for Reykjanes are 14.67 million euros. Including the environmental externalities of operations, this figure is marked up by 1.43% to 14.88 million euros. Given the capital intensity of all geothermal power projects and the relatively low greenhouse gas emissions in comparison to fossil fuel alternatives, it is perhaps unsurprising that environmental externalities of operations form a relatively insignificant component of the ELCC. Of the aggregate present value of 0.21 million euros (based on a 5% discount rate) ascribed to the environmental externalities of operations, these were dominated by greenhouse gas emissions associated with the well drilling phase (0.15 million euros), especially relating to transportation of materials and equipment.

A significant proportion (83%) of the total lifecycle costs at Reykjanes related to the well drilling phase and linked upfront costs concerning the procurement of equipment, labour, travel and miscellaneous components. This is a high proportion, but broadly in line with estimates in the academic literature given the specifics of this project and its speculative nature. The study by Huenges and Ledru (2010) found that 74% of the overall lifecycle costs of a geothermal power plant related to well drilling and investments linked to well drilling. Overall, probabilistic cost estimates constituted a slight contribution to the aggregate costs compared to deterministic components. The combined end of life, operations and maintenance, and environmental externalities of operations costs were 1.26 million euros, equating to 8.47% of the total costs inclusive of environmental externalities. Although the evaluation by Huenges and Ledru (2010) did not seek to account for the environmental externalities of operations, much higher operations and maintenance and decommissioning costs are associated with geothermal plants, compared to a single well, and accordingly, these reduce the proportion of total lifecycle costs derived from well drilling.

The total life cycle costs for Vendenheim are 100.29 million euros. The results for Vendenheim are fairly typical of geothermal power projects, with 73% of costs amassed in relation to upfront activities, well drilling and the production plant. Construction-related externalities formed a very low proportion (0.03%) of the total estimated costs. Probabilistic cost estimates constituted 26.47 million euros in relation to decommissioning and operations and maintenance. These two elements were equivalent to 26.39% of the total costs of the Vendenheim project, dominated by the 25.97 million euros of discounted costs in relation to operations and maintenance.

Table 3 outlines the range of likely ELCC estimates according to the three selected discount rates of 2% (low), 5% (medium) and 8% (high). Fig. 4 provides a bar chart comparing these outcomes for both Reykjanes and Vendenheim.

Table 3: ELCC cost estimates (million euros) according to sensitivity analysis – DEEPEGS, Reykjanes

	Reykjanes		Vendenheim	
Discount rate	**ELCC (exc. operational environmental externalities)**	**ELCC (inc. operational environmental externalities)**	**ELCC (exc. operational environmental externalities)**	**ELCC (inc. operational environmental externalities)**
2%	15.48	15.78	113.97	113.97
5%	14.68	14.88	100.29	100.29
8%	14.31	14.47	91.90	91.90

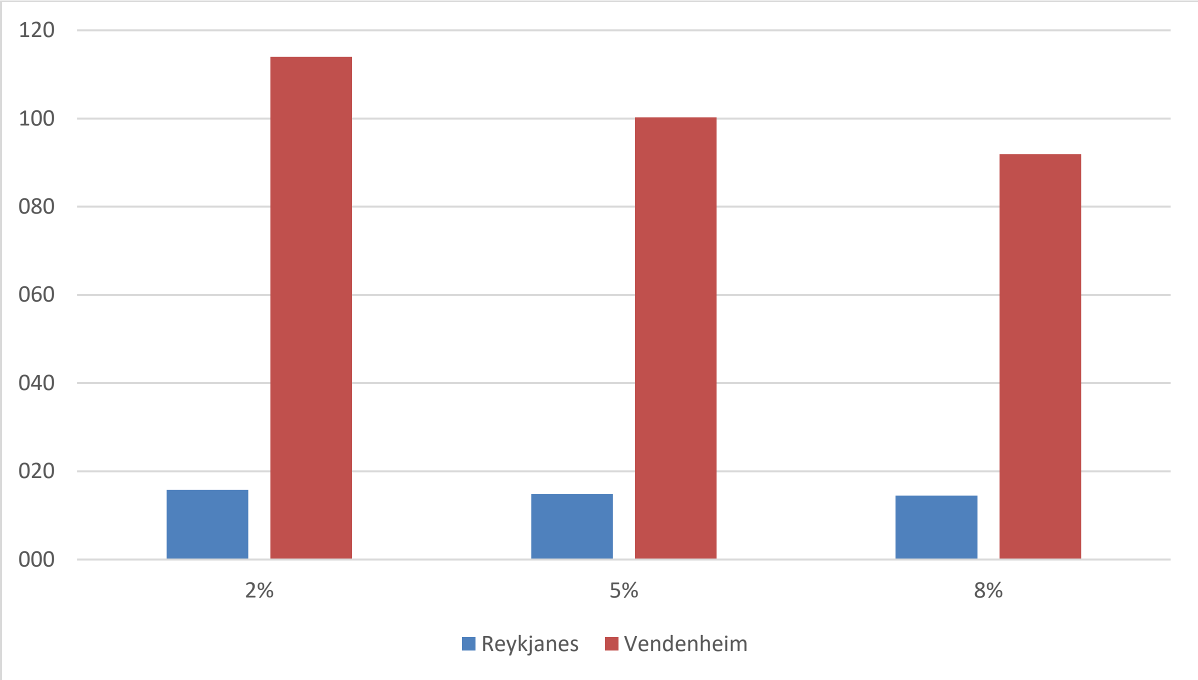

Fig. 4: Bar chart comparing ELCC estimates (including environmental externalities) according to sensitivity analysis – Reykjanes and Vendenheim (million euros)

The relatively small contribution of probabilistic cost elements ensures that the choice of discount rate has a relatively insignificant effect on the outcomes in the sensitivity analysis. Based on the discount rates applied, the total ELCC for Reykjanes are in the range 14.47 to 15.78 million euros. There is a difference of 1.31 million euros (9.05%) between these estimates. The total ELCC for Vendenheim is in the range 91.90 to 113.97 million euros depending on the respective discount rate. This is a differential of 22.07 million euros (24.02%). The greater variance in the ELCC estimate for Vendenheim can be attributed mainly to the higher proportion of costs relating to probabilistic cost elements, especially the operations and maintenance of the new power plant facility.

Finally, a further sensitivity analysis was conducted by varying the social cost of carbon in accordance with the annual increments set out in Table 1. Based on the highest increments estimated by EIB (2020), the ELCC for Reykjanes, inclusive of operational externalities, increases to the range 15.13-17.05 million euros. The contribution of environmental externalities to the total was 1.57 million ISK in the scenario of lowest discount rate (2%) and highest social cost of carbon (average of 125 euros per tonne across the thirty-year horizon). This was equivalent to 9.21% of the total ELCC, an increase on the 1.94% contribution to the total ELCC (2% discount rate) when a non-varying social cost of carbon of 20 euros/tonne was assumed across the thirty-year horizon. There were no implications for Vendenheim's ELCC due to the zero greenhouse gas emissions for the operations phase in the LCA by Sigurjónsson et al. (2021), and thus it is not possible to compare the relative effects of this part of the sensitivity analysis between the two study sites.

3.2 Comparison of outcomes to similar studies

There are currently no comparable ELCC studies related to a single geothermal well, such as Reykjanes, in existence. Although other studies, such as Huenges and Ledru (2010), have provided indicative rule-of-thumb estimates in relation to geothermal power plants deriving from EGS, those outcomes cannot be directly compared to this study as they include very large costs related to power plant infrastructure, ongoing operations and maintenance costs, and they also assume the drilling of multiple wells.

An additional way of considering the outcomes from this study is to consider these in terms of the levelized cost of energy (LCOE), where multiple studies have focused on the economic costs of geothermal power. LCOE is an economic measure describing the cost of generating a MWh of electricity averaged over the lifetime of the power plant or energy-generating technology. In other words, it averages the total ELCC over the production period, which in this study was assumed to be 30 years.

The LCOE for the Reykjanes and Vendenheim projects were estimated to be €16.5/MWh/year and €45.0/MWh/year, respectively, based on a 5% discount rate (see Fig. 6). Considerable caution should be expressed with regards to these estimates, given that they were made prior to commencement of production at both sites. Thus, various assumptions had to be made, such as those relating to power outputs, capacity factors and future variable costs. Although it was largely self-evident that the LCOE for the deep geothermal well at Reykjanes would be lower than usual estimates for geothermal power projects, the same is also true – to a much lesser degree – for the co-production project at Vendenheim. Recent estimates of the LCOE for geothermal power, based on no subsidies, are in the range of US$ 71-111/MWh/year, which equates to approximately € 65-102/MWh/year (Lazard, 2018). Another study by IRENA (2018) arrived at a a LCOE of geothermal power estimate in the range 40 to 140 US $ per MWh per annum (approximately € 37-94/MWh/year, and thus, the Vendenheim estimate is at the lower end of the reported range. The outcome also compares favourably with LCOE estimates for geothermal power projects in Iceland, which have been estimated in the range € 37-92/MWh/year (Ólafsson, 2016). The estimate for Reykjanes is even lower, but it is incomparable to other estimates in the literature, since it did not include the costs of production plant infrastructure, which in turn led to lower than normal projected costs for decommissioning and operations and maintenance.

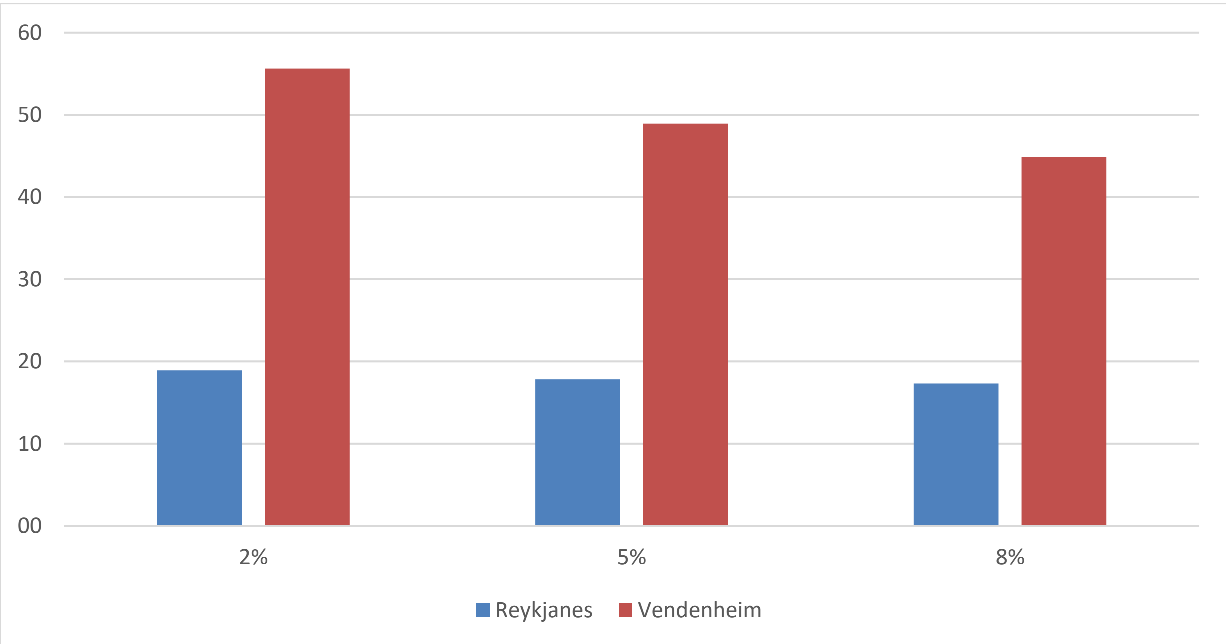

Fig. 6: LCOE estimates for Reykjanes and Vendenheim (US $ per MWh per annum)

3.3 Reflection on other cost components – social LCA and non-use value – and integration of alternative cost estimation approaches

The results from this study are based upon a cost methodology designed to estimate the economic and environmental implications of the DEEPEGS project. These are two dimensions in a sustainability analysis of a project's cost consequences, but they omit social implications, which in many nations constitute one of the main barriers to geothermal utilisation (Barich et al., 2021). Social LCA (S-LCA) was first conducted in the 1990s but it has yet to be developed to the extent of LCA or ELCC approaches (Iofrida et al., 2018). In practice, where such studies are available, S-LCA assessments often involve merging or comparing outcomes in terms of social impacts with quantitative results from separate assessments, such as LCA or ELCC (Sala et al., 2015; Iofrida et al., 2018). Rather than representing a single technique, S-LCA is currently considered to be a set of methods focused on assessing the potential or real social impacts of projects in relation to human capital, human well-being, cultural heritage and social behaviour (Chhipi-Shrestha et al., 2014). Outcomes in terms of impacts are expressed using either qualitative or quantitative data, or both. In contrast to LCA and ELCC methods, S-LCA has added complexity due to the need to incorporate the underlying values and valuations of multiple stakeholder interests, including individuals, communities, governments, business and NGOs (Sala et al., 2015). This is especially complex in situations where different cultural elements, values and lifestyles apply, and these are dynamic factors across the lifecycle of the product or project. It is likely for these reasons that, as far as the authors are aware, no S-LCA studies have been conducted in the published literature in connection to geothermal power plants.

Alternative economic approaches to valuing socio-cultural impacts are emerging in a geothermal context, and these have been focused on the integration of an ecosystem services perspective. This links impacts to ecosystems and changes in human well-being to either monetary or non-monetary information, with the former comparable to the other costs and benefits of the project. Landsberg et al. (2011) conducted a review of the extent to which Environmental Impact Assessment data could be used to quantify the value of multiple, and often simultaneous, impacts to human well-being. The conclusion of the authors was that the approach had potential in terms of stimulating greater stakeholder integration into decision-making, with the increased likelihood of stakeholders retaining well-being benefits when developments took place.

In recent times, researchers have sought to apply non-market valuation techniques to elicit preferences and estimate the economic value of preserving geothermal landscapes. Such studies have focused on eliciting single value aggregate cost estimates for the preservation of geothermal landscapes, in so doing forming a cost estimate suitable for inclusion in a cost-benefit analysis for the project, and/or as a complement or addition to ELCC. Often the contingent valuation is applied to survey the economic value of sites where few or no people live or visit, or ever intend to visit. However, individuals will often still hold a preservation value for landscapes, and this is known as 'non-use value'. Geothermal landscapes are a classic example of sites with likely non-use value due to their aesthetical rarity, diversity and distinctness. Despite controversy, largely centred around its reliance on constructed markets, the contingent valuation method is a survey-based technique that has been implemented to estimate willingness to pay for the preservation of geothermal areas. The first study by Thayer (1981) estimated the economic value of preserving a geothermal area in the Jemez Mountains of Santa Fe National Forest in New Mexico. More recently, the second and third contingent valuation surveys were conducted to estimate the economic value of preserving the Eldvörp and Hverahlíð geothermal fields in Iceland, the location of the former site is approximately ten kilometres from the Reykjanes project (Cook et al., 2018). The studies provided survey participants with real development scenarios in the form of likely geothermal power projects at the study sites, together with a summary of their environmental and socio-cultural implications. Total willingness to pay for preservation, aggregated across the affected Icelandic population, was 2.10 and 1.77 billion ISK for Eldvörp and Hverahlíð, respectively. These values were found to be equivalent to approximately 2% of the total construction costs of the Hellisheiði Geothermal Power Plant, Iceland's largest and the world's third biggest in installed capacity. No such studies have yet been conducted in the context of EGS or the development of a new well on a site with an existing power plant, so these cost estimates should not necessarily be considered indicative of the likely scale of the impacts at the DEEPEGS case study sites in Reykjanes and Vendenheim.

3.4 Decision-making consequences of study

Outcomes from LCC or ELCC studies such as this one have considerable implications in terms of supply chain management. Slightly more than 83% of the costs for the Reykjanes site related to the well drilling phase, and a further 8% were projected to derive from the well stimulation. Given Iceland's remote, island location in the North Atlantic, some shipping costs relating to imported materials, such as the steel well casing, will be difficult to reduce. However, experience gained from this inaugural, speculative project, will greatly assist in future purchasing decisions and the determination of resource allocations, likely enabling knowledge gained from this project to lower future ELCC outcomes for EGS ventures in Iceland, France and elsewhere. In particular, there may be opportunities to lower the costs of operational externalities in future projects, perhaps via the integration of proven carbon and hydrogen sulphide capture technologies, such as those demonstrated in the CarbFix and SulFix projects in Iceland (Karlsdottir et al., 2020; Kristjánsdóttir, 2014).

Some cost components in this study would also be of relevance to any cost benefit analysis conducted for the Reykjanes or Vendenheim projects. Traditional forms of cost benefit analysis seek to account for most cost components studied in this project, however, they are rarely, if ever, extended to account for the economic value of environmental impacts. Thus, all costs in this study relating to process-based 'internal' environmental externalities and those from operations are normally omitted. Although relatively small in comparison to the total ELCC estimate (especially so in the case of Vendenheim), these costs are non-negligible for Reykjanes since they comprise more than 1% of the total. Moreover, if impacts to other ecosystem services, such as non-use value, were also accounted for, then the likelihood increases that the economic value of environmental and social impacts could have a decisive impact on the welfare gains or losses of a project, as assessed in cost benefit analysis. These impacts could be considerable in the context of projects introducing new production plant facilities, with potential visual and aesthetic impacts over a wide geographical area. However, they may equally be less significant when the production site is a former fossil fuel plant facility, as per Vendenheim.

Additionally, there are sometimes wider issues pertaining to the valuation of ecosystem service impacts from developing geothermal resources, which ensure that not all costs and impacts should be estimated using monetary information, as has already been briefly discussed in the context of S-LCA. Although unlikely to apply to the case of either Reykjanes or Vendenheim, environmental and social impacts often occur in relation to a wide range of stakeholders, including indigenous communities. Where indigenous societies, such as the Kenyan Maasai or New Zealand's Maori, hold deep and resonant values in relation to a geothermal resource, leading to ecosystem services such as spiritual enrichment or community identity, these will typically be formed on a collective rather than individual basis (Cook et al., 2019; Cook et al., 2020). Although it is possible to estimate their value using either qualitative or quantitative data, the use of a money metric to value individual preferences and willingness to pay is an inappropriate means of estimating impacts to collectively formed non-material well-being. This, in turn, means that it is not sufficient for decision-makers to simply be informed about a geothermal power project's direct economic costs and benefits – for example, using cost benefit analysis and/or an ELCC outcome – prior to determining whether to proceed with the venture. Rather, advanced decision-support platforms need to be utilised, which embed and integrate monetary and non-monetary information concerning the welfare implications of the power project. This theme is explored in more detail in an earlier paper by Cook et al. (2019), in which Multi Criteria Decision Analysis (MCDA) is advanced as a potentially suitable platform for this endeavour. A review is conducted of the extent to which existing MCDA analyses of geothermal power projects evaluate stakeholder interests and seek to account for an array of values in decision-making, both monetary and socio-cultural. It is evident that a small number of MCDA studies have ranked or prioritized variables (technical, economic, environmental and social), including those by Borzoni et al., (2014); Jesus, (1997) and Polatidis et al. (2015). However, other MCDA studies in the review by Cook et al. (2019) tended to have a limited focus on only economic variables and were lacking in-depth stakeholder consultation.

3.5 Study limitations

Akin to the results from the LCA studies pertaining to the two sites, caution should be expressed with regards to the ELCC estimates in this paper, given that they are made prior to commencement of production from the new wells at both sites. Thus, various assumptions had to be made, particularly those relating to power outputs, capacity factors and future variable costs. The range of discount factors (2-8%) may also be insufficient to represent the risk associated with deep EGS projects, which is a speculative technology in its infancy, and the assumed duration of both projects of 30 years may be too conservative. In addition, although ultimately intended to address four environmental impact categories – human health, ecosystem, resource availability and climate change – the current ReCiPe tool only monetises externalities linked to climate change. ReCiPe is thus an emerging approach, lacking data and not yet sufficient in scope to account for the full spectrum of externalities from a geothermal power project. In addition, certain costs, such as impacts to socio-cultural values are not covered by the four categories of costs that the ReCiPe method seeks to address, and these were thus not included within these studies. This has also been the case with other, widely popularised approaches to capturing external costs, such as the European Commission's ExternE project from the 1990s.

4. Conclusion

This study has provided the first estimates (non-comparable) of the environmental life cycle costs of developing deep EGS at Reykjanes, Iceland and Vendenheim, France. Inclusive of environmental externalities, the levelized cost of energy for the Reykjanes and Vendenheim sites is 16.5 and 45.0 €/MWh/year, respectively. The outcomes from this study are of interest and relevance to public procurement agencies, supply chain managers, purchasers and other decision-makers, including EU funding agencies who call for such studies to be carried out. Cost components linked to externalities, both 'internal', related to well drilling and stimulation processes, and external, relating to operations after production commences are of particular relevance to decision-making processes. Together, these contributed more than 2% of the total environmental lifecycle costs in the case of the Reykjanes site. More work is needed to ensure that the social costs of developing geothermal power projects are accounted for in ELCC studies, perhaps involving the use of S-LCA alongside LCA and ELCC. Moreover, the necessity of providing decision-makers with an array of monetary and non-monetary information concerning the environmental and social implications of geothermal power projects promulgates the need for advanced platforms to integrate such data. In this study, Multi-Criteria Decision Analysis is briefly discussed as being one such tool, however, more research and advancement is needed in order to ensure that such tools adequately reflect stakeholder interests and impacts to multiple and diverse values linked to geothermal areas.

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