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GETEM-Based Decision Support System to Analyse the LCOE of Geothermal Plants Utilising Very Hot or Superhot Georesources

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ABSTRACT

The transition to low-carbon energy sources has heightened interest in very hot or superhot geothermal resources, particularly in Icelandic and Italian perspectives. A Cost Estimator for Surface Plant (CESP) – a decision support system software tool has been developed based on the Geothermal Electricity Technology Evaluation Model (GETEM) framework for estimating and analysing the Levelised Cost of Electricity (LCOE) and other financial metrics of geothermal plants utilising very hot or superhot geothermal resources under site-specific conditions. The CESP incorporates site-specific parameters, including high reservoir temperatures, drilling requirements, permitting and leasing costs, production and injection wells, well field infrastructure, fluid gathering systems, and power plant configurations for cost performance evaluation of the plants. In this study, techno-economic analysis of the representative Icelandic and Italian plants utilising very hot georesources has been conducted, alongside a demonstration of the proposed COMPASS plant utilising superhot georesources, using the CESP tool. The resulting LCOE values were €53.91 per MWh for the Icelandic plant, €51.86 per MWh for the Italian plant, and €24.65 per MWh for the COMPASS plant. The LCOE value of the COMPASS plant is much lower than those of the representative plants utilising very hot georesources. These findings reflect the influence of site-specific geological conditions, drilling technology improvements, infrastructure maturity, and regulatory frameworks. The developed software tool aims to support process engineers and decision-makers by providing insights into cost reduction opportunities and regional feasibility of future geothermal projects utilising superhot georesources.

1 INTRODUCTION

Geothermal energy is the heat stored beneath the Earth's surface. It comes from the Earth's internal structure and the heat transfer occurring in the mantle and crust. This energy is an impressive source of heat and superheated fluids beneath the Earth's surface. Turning it into electrical energy takes skilled engineering and involves major risks and challenges in the geothermal sector. Converting this thermal energy into electricity through geothermal plants has been a major goal for European Union (EU) countries that want to achieve long-term carbon-free energy. Within the EU, a primary objective is to reduce greenhouse gas emissions by 80% by 2050, moving towards nearly zero-carbon electricity generation (Jones and Glachant, 2010). In EU, the annual electrical energy output from geothermal energy is anticipated to range from 100 to 210 terawatt hour (TWh), whereas thermal energy output uses in residential, commercial, industrial, and agricultural sectors could grow to between 880 and 1,050 TWh each year. By the middle of this century, geothermal plants might provide 4 to 7% of Europe's electricity, with a projected investment market totaling 160 to 210 billion US dollars per year (Dalla Longa et al., 2020). Globally, its installed capacity totaled approximately 7.97 gigawatt-electric (GWe) by the year 2000, delivering power at competitive prices (2–10 US¢/kWh) and accounting for a considerable portion of electricity in numerous developing nations (Barbier, 2002). By December 2022, global geothermal installed capacity reached 16.32 GWe across 32 countries and around 198 geothermal fields, representing 0.16% of total worldwide electricity capacity (10,216 GWe). In 2021, geothermal generation totaled 96,552 GWh, accounting for 0.34% of global electricity production and 0.87% of clean energy, including renewables and nuclear (Gutiérrez-Negrín, 2024). In this situation of rising demand for geothermal energy, proper development of geothermal plants is essential. Engineers and researchers focus on identifying cost-effective solutions for geothermal systems, given the high expenses associated with drilling, operation, maintenance, and power plant development (Sanyal, 2004). For cost-effective solutions in geothermal systems, Decision Support Systems (DSS) can perform outstandingly by providing accurate calculations and offering effective solutions to existing problems. The Levelised Cost of Energy (LCOE) is a key indicator that estimates the representative cost of generating electrical power from a plant over its operational lifetime (Short et al., 1995).

As part of the Icelandic Deep Drilling Project (IDDP) and the EU funded project COMPASS (Gunnarsson et al., 2024), an LCOE framework was developed using the Geothermal Electricity Technology Evaluation Model (GETEM) (Mines, 2016). This framework was integrated with the Cost Estimator for Surface Plant (CESP). The CESP model was turned into an Application Programming Interface (API) to connect it with the Decision Support System (DSS) (see architecture overview in Figure 1.1). After developing the CESP tool, techno-economic analyses were carried out using three case studies (Icelandic, Italian and COMPASS). These studies represented a variety of geological and operational conditions. The Icelandic case study focuses on the geothermal resource in the Hengill area of Iceland. It uses very high-temperature wells with maximum temperatures of around 250°C to 300°C (Sveinbjornsson and Thorhallsson, 2014). The Italian case study looks at the geothermal resource in the Tuscany region of Italy, with temperatures of about 325 °C (Ebigbo et al., 2016). These case studies help us assess site-specific factors like drilling depth, resource temperature, power plant capacity, and operation and maintenance (O&M) costs. The COMPASS case study, focused on a geothermal plant that uses superhot resources, was also considered.

The studies examined the operational performance and financial aspects of the representative geothermal plants, as well as a demonstration of the proposed COMPASS plant. The Icelandic and Italian case studies aimed to find out the main reasons for variations in LCOE and to identify the parameters influencing these differences.

Previous studies have extensively analysed geothermal project economics using models such as GETEM and GEOPHIRES; however, there remains a research gap in developing an integrated Decision Support System (DSS) capable of dynamically linking techno-economic models through APIs for real-time evaluation and optimisation of geothermal systems e.g.,(Beckers et al., 2013; Beckers and McCabe, 2019; Chadwick Holmes et al., 2022; Fleckenstein et al., 2023). In particular, while web-based spatial DSS approaches, such as those applied for optimised siting of geothermal wells in the Olkaria Geothermal Field, have addressed well location optimisation, they do not integrate detailed LCOE calculations or enable comprehensive financial assessment for case studies using GETEM or similar models (Fleckenstein et al., 2023). Therefore, there is a need for a system that combines real-time techno-economic modeling with site-specific case study data to support informed decision-making and cost optimisation in geothermal project planning.

To address this gap, this report presents and analyses the cost performance outcomes from three case studies: the Icelandic, Italian, and COMPASS plants. The analysis demonstrates the capabilities of the CESP tool to simulate realistic operational scenarios, identify key cost drivers, and support data-driven decision-making for both existing geothermal systems and proposed developments. Furthermore, the CESP tool enables “what-if” scenario testing, allowing researchers and engineers to assess alternative configurations, resource utilisation strategies, and investment options.

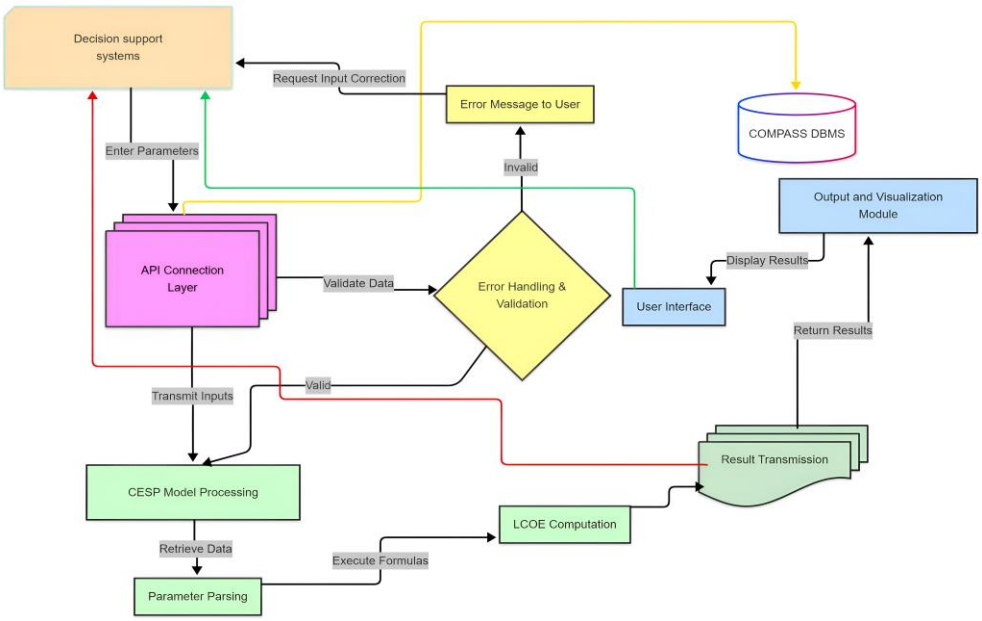


Figure 1.1. Workflow and system architecture showing the integration of the Levelised Cost of Energy (LCOE) model with the Decision Support System (DSS) via API, including user input, model processing, result transmission, and visualization modules.

2 METHODOLOGY

For the COMPASS project, a Levelised Cost of Energy (LCOE) framework has been developed using the GETEM calculator. Key formulae and equations come from the GETEM manual (Mines, 2016). The Cost Estimator for Surface Plant (CESP) tool was included in this framework to perform detailed techno-economic analyses. The estimation of capital costs was structured across four major phases which include the Exploration phase, the Drilling to complete the well field phase, the Field gathering system phase, and the Power plant construction phase. Input parameters for these phases were obtained from the corresponding case study project partners and secondary data sources, including literature, COMPASS project datasets, and site-specific data from the Icelandic, Italian, and COMPASS case studies. In the CESP tool, the total exploration cost is evaluated expressed by Eq. (1):

$$Total\ Capital\ Cost = \sum (\mathrm{E}xploration\ \mathrm{phase} + \mathrm{Well\ field\ phase} + \mathrm{Field\ gathering\ system\ phase} + \mathrm{Power\ plant\ construction\ phase}) \quad (1)$$

After calculating the plant capital cost, CESP tool employs levelised royalties, levelised capital expenses, and levelised O&M costs to determine the Levelised Cost of Electricity (LCOE). This comprehensive approach ensures that all relevant financial aspects are taken into account (Aldersey-Williams and Rubert, 2019). The calculations $LCOE_{capital\ cost}$ used are expressed in the following Eq. (2):

$$LCOE_{capital\ cost} = \frac{(Total\ Capital\ Cost) \times \frac{(1-\tau \times PV\ (\mathrm{D}epreciation))}{(1-\tau)}}{PV\ (Q)} \quad (2)$$

Where τ (%) is the effective tax rate, $PV(\mathrm{D}epreciation)$ is the present value of depreciation, and $PV(Q)$ is the present value of total energy generated, calculated from the discounted power sales over the project lifetime expressed by Eq. (3):

$$\mathrm{PV(Q)} = \sum_{\mathrm{n=1}}^{\mathrm{project\ life}} \frac{(\mathrm{Power\ Sales})_{\mathrm{n}}}{(1+\mathrm{d})^{\mathrm{n}}} \quad (3)$$

PV(Q) is calculated from the present value of power sales throughout the project's life. This is the total of the sales, which are discounted using a specific discount rate over that time. Here, n denotes the project lifetime in years, and d represents the discount rate expressed as a percentage.

Power sales refer to the difference between the plants' output and are also influenced by the plant's net capacity factor. The net capacity factor represents the actual energy output as a percentage of the maximum possible output over a given period. Variations in resource availability, plant efficiency, and operational downtime all affect the capacity factor (Grubert, 2020). Consequently, these factors directly impact the total power sales and the overall economic performance of the geothermal project LCOE.

The operation and maintenance costs (O&M) costs contributing to the LCOE include labour for both the plant and field, maintenance of the plant, wells, reservoir, gathering system, and production pumps. Additional costs include makeup water, taxes, insurance, and royalties. These factors are important for evaluating overall operational expenses (Asjad et al., 2013). The contribution of operating and maintenance (O&M) costs is determined using Eq. (4):

$$LCOE_{O\&M} = \frac{PV(annual\ O\&M\ costs) \times \frac{((1+d)^{plant\ life}-1)}{(d \times (1+d)^{plant\ life})}}{PV(Q)} \quad (4)$$

Where, $PV(annual\ O\&M\ costs)$ represents the present value of the annual operating and maintenance expenses, plant life denotes the operational lifetime of the geothermal plant, and $PV(Q)$ is the present value of the total energy produced during the plant's lifetime. Operating and maintenance (O&M) costs include labour costs, maintenance costs for the plant, maintenance costs for the well field and reservoir, maintenance costs for the field gathering system, water makeup costs, production pump maintenance costs, taxes and insurance, and royalties (Allan, 1998).

Royalties play a crucial role in determining the financial viability of geothermal projects (Malafeh and Sharp, 2015). They are typically based on the revenue generated from the power produced and can significantly impact on the overall cost structure. The contribution of royalties to the LCOE is calculated using the following Eq. (5):

$$LCOE_{roylaties} = LCOE_{Total} \frac{[RR_{initial} \times PV\ Power_{initial} + RR_{final} \times (PV\ Power_{life} - PV\ Power_{initial})]}{PV\ Power_{life}} \quad (5)$$

Where,

- $RR_{initial}$ refers to the royalty rate applied during the initial phase (first 10 year), generally 1.75%
- $PV\ Power_{initial}$ represents the present value of the power generated during this initial phase, typically covering the first 10 years.
- RR_{final} is the royalty rate applied after the initial phase (after 10 year), generally 3.5%.
- $PV\ Power_{life}$ Present value of the power generated over the entire project life

In the calculation of the LCOE of a plant, GETEM uses the levelised royalties, levelised capital costs and levelised O&M costs as using Eq. (6):

$$\text{LCOE} = \frac{(LCOE_{capital\ costs} + LCOE_{O\&M})}{(1 - LCOE_{royalties})} \quad (6)$$

The above LCOE equations describe the processes involved in calculating LCOE of a geothermal plant. During the LCOE calculation, numerous process parameters are considered. When utilising the CESP tool, the first step is to define the scenario by specifying various process parameters from the perspective of a geothermal plant. Several default values from GETEM are applied to represent Icelandic, Italian, and COMPASS case scenarios in geothermal plant systems, some of which are presented in Table 2.1.

Table 2.1 Default Values of Geothermal Plant Systems for the Icelandic, Italian, and COMPASS Plants

Description	Unit	Icelandic	Italian	COMPASS
Do you want to evaluate a hydrothermal or EGS resource?		Hydrothermal		
Resource temperature	°C	268	325	375
Average production well depth	m	2150	2270	2800
Average injection well depth	m	1500	1500	2000
Resource type being developed	-	Field expansion	Field expansion	Greenfield
Conversion technology	-	Flash	Flash	Flash
Flash type	-	Double-flash	Double-flash	Double-flash
Evaluation based on power sales/number of production wells?	-	Power sales	Power sales	Power sales
Power sales	MW	303.3	60	350
Contingency	%	15	15	15
Royalty (thru Yr 10)	%	1.75	1.75	1.75
Royalty (after Yr 10)	%	3.5	3.5	3.5
Discount Rate During Operation	%	7	7	7
Effective Tax Rate	%	30	30	30
Average production well flow rate per well	kg / s	53.4	40.1	100
Productivity Index	lb/hr-psi	2980	2190	3650
Injectivity Index	lb/hr-psi	2500	1800	3000
Capacity factor	%	87	90	90
Project Life (Period of Operation)	y	30	40	40

3 RESULTS AND DISCUSSIONS

For the Icelandic representative plant, we chose the Hellisheidi geothermal power plant. It uses a hydrothermal resource with an average reservoir temperature of 268 °C and an average production well depth of about 2150

m (Karlsdóttir et al., 2015). These parameters, together with the values presented in Table 2.1, were incorporated into the different stages of plant development alongside default data from GETEM (Mines, 2016).

Following the established methodology, the cost estimation model was implemented using the Python programming language. All relevant equations and calculation procedures were translated into Python scripts and integrated into the COMPASS Decision Support System (DSS) through an Application Programming Interface (API). Figure 3.1 shows the interface of the Cost Estimator for Surface Plant (CESP). These modules cover scenario definition, economic parameters, permitting and exploration data, drilling characteristics, reservoir information, geofluid gathering system, power plant construction, and operation and maintenance (O&M) details. Each module has several process parameters that work together to calculate the Levelised Cost of Energy (LCOE).

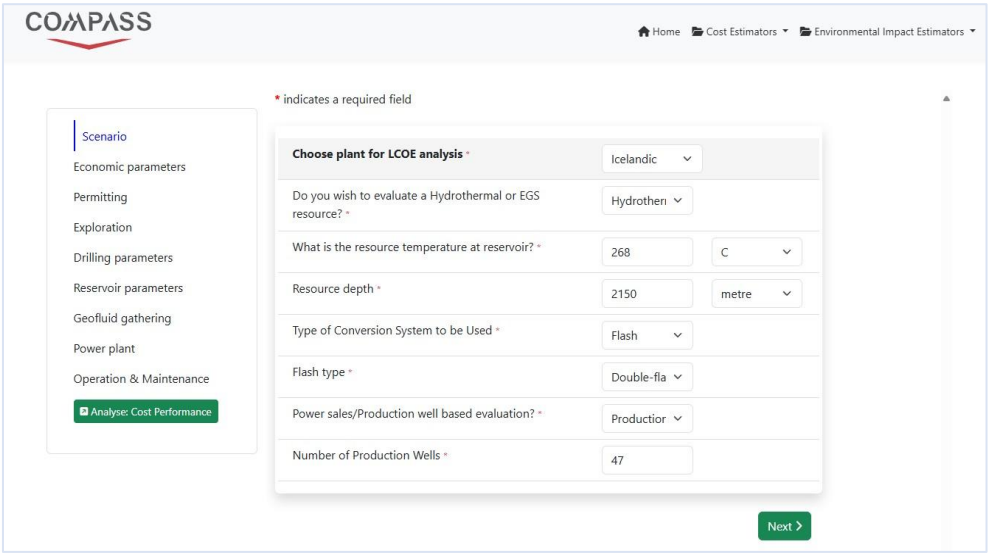


Figure 3.1 User Interface of the Cost Estimator for surface plant displaying scenario-based input modules for financial evaluation of the plant.

The calculated LCOE for the Icelandic representative plant is € 53.91 per MWh of electrical energy production. The total capital cost is about € 854.99 million, including contingency. The annual operation and maintenance (O&M) cost is about € 24.68 million.

For the Italian representative plant, the Bagnore geothermal power plant was examined. It uses a hydrothermal resource with an average reservoir temperature of 325 °C and a production well depth of about 2270 m (Tosti et al., 2020). The calculated LCOE for the Italian representative plant is € 51.86 per MWh of electrical energy production. The total capital cost is about € 167.88 million, including contingency. The annual O&M cost is approximately € 5.16 million.

For the COMPASS enabled geothermal plant, the estimated LCOE is € 24.65 per MWh, with a total annual O&M cost of about € 15.58 million. The lower LCOE value compared to the Italian (Bagnore) and Icelandic (Hellisheidi) representative plants primarily comes from the higher installed capacity of 350 MW utilising superhot georesources. This capacity is supported by just ten high-output production wells, each contributing 35 MW, and a high resource temperature of 375 °C. These factors together improve thermal efficiency, reduce the necessary number of wells, and significantly lower both capital and operating costs per unit of electrical energy production.

The financial assessment results for all three case studies are summarised in Table 3.1. At a depth of 2000 m, the LCOE for the Icelandic (Hellisheidi) plant is approximately €52.85 /MWh, increasing to €78.56 /MWh at 4000 m—an overall rise of more than 48%. A similar trend is observed for the Italian (Bagnore) and COMPASS plants. Although the COMPASS plant consistently demonstrates the lowest LCOE values across all depths, primarily due to its higher resource temperature and greater production well output of 35 MW per well, it also exhibits a gradual increase in LCOE with depth. This rise reflects the escalating drilling and operational challenges associated with deeper wells, which contribute to higher capital and maintenance costs. Overall, the analysis highlights that while deeper wells can access hotter resources and enhance energy production, they substantially increase drilling expenditures. Therefore, optimising well depth is crucial to achieving cost-effective and sustainable geothermal power generation (Kassem and Moscariello, 2025).

Table 3.1 Summary of financial assessment results for the Icelandic, Italian, and COMPASS geothermal case studies.

Items	Unit	Icelandic	Italian	COMPASS
LCOE	€/ MWh	53.91	51.86	24.65
Power sales	MWe	303.3	60.00	350
Total capital cost w/o contingency	€	792,264,937	155,584,410.78	416,645,964.69
Total capital cost with contingency	€	854,992,083	167,883,753.87	464,311,377.86
Exploration Drilling Costs (full-sized)	€	20,994,459	21,757,015.04	27,028,904.24
Exploration Drilling Costs (small diameter)	€	2,173,366	458885.37	2,173,366.30
Non-Drilling Exploration Costs	€	458,885	265,947.94	458,885.37
Permitting & Leasing Costs	€	734,110	1,145,106.05	248,719.52
Other Indirect Costs	€	1,104,971	25,800,320.70	1,422,573.91
Total exploration cost w/o contingency	€	25,465,793	458885.37	31,332,449.34
Total drilling cost w/o contingency	€	372,884,179	55,770,780.10	76,840,110.80
Total field gathering system cost w/o contingency	€	42,540,622	6,350,944.63	14,637,139.33
Total Power plant & Transmission cost w/o contingency	€	351,374,342	67,662,365.34	293,836,265.22
Total Annual O&M cost	€	24,677,749	5,160,777.64	15,583,254.95

Table 3.2 Literature-based comparison of geothermal plant Levelised Cost of Energy (LCOE) across multiple regions (Hernandez et al., 2016).

Plant	Location (State/Country)	LCOE ($ / MWh)	LCOE (€ / MWh)
San Emidio	Nevada, USA	89.37	80.43
Hellisheidi	Iceland	59.90	53.91
Galena 2	Nevada, USA	47.50	42.75
Bagnore	Italy	57.62	51.86
Desert Peak 2	Nevada, USA	49.50	44.55
Raft River	Idaho, USA	53.61	48.249
Geysers	California, USA	17.76	15.984
COMPASS	Iceland	27.39	24.65
McGinness Hills 1 & 2	Nevada, USA	85.58	77.02
Don A. Campbell Phase II	Nevada, USA	81.3	73.17
Salton Sea	California, USA	72.75	65.475

Table 3.1 Summary of financial assessment results for the Icelandic, Italian, and COMPASS geothermal case studies. The financial assessment results for the Icelandic, Italian, and COMPASS geothermal case studies also compared with literature data from geothermal plants in Europe and beyond. Table 3.2 presents the LCOE values for various geothermal plants across different regions, while Figure 3.2 visualises these data in a comparative bar chart. The values are sourced from literature (Hernandez et al., 2016) and reflect reviewed Power Purchase Agreement (PPA) data, accounting for site-specific and contractual conditions. Among the plants considered, the highest LCOE is observed at San Emidio with 80.43 € / MWh, and the lowest at The Geysers with 15.98 € / MWh. The COMPASS plant demonstrates a comparatively low LCOE of 24.65 € / MWh.

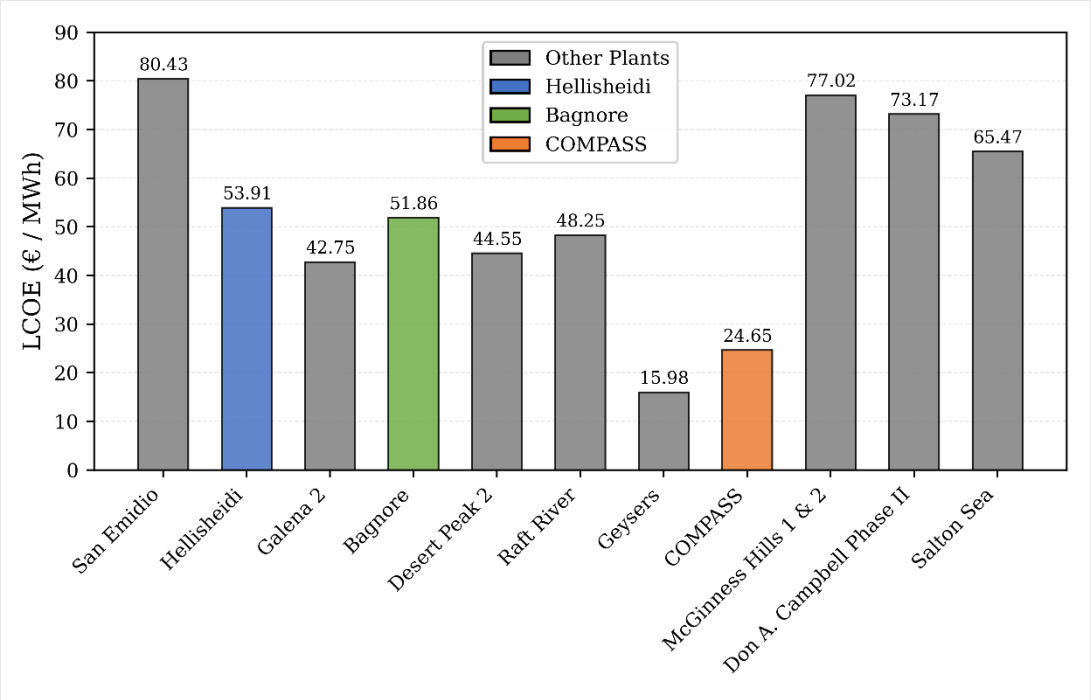


Figure 3.2 Bar chart showing the comparison of LCOE values for geothermal plants in various regions.

According to the IRENA report (Renewable Energy Agency, 2017), flash-type geothermal plants typically have capacities between 0.2 MW and 80 MW, with resource temperatures above 180 °C. These plants use full-size well drilling technologies at depths exceeding 1600 m. They show LCOE values from $0.04 to $0.14 per kWh, which is about €0.036 to €0.126 per kWh. In comparison, the CESP tool uses default scenario with a single flash conversion system, a resource temperature of 180 °C, a depth of 2600 m, and power sales of 80 MW, gives an LCOE of €0.119 per kWh. This value is within the range reported by IRENA, indicating that the CESP tool is consistent with similar geothermal conditions. Minor differences in LCOE can result from variations in resource temperature, well depth, conversion efficiency, and the economic assumptions used in each model.

A future study using the CESP tool using the parameters reported by (Beckers et al., 2014), which included a reservoir temperature of 325 °C, a geofluid flow rate of 40 kg/s, a well depth of 5000 m, a flash system, and four production wells reported a base-case LCOE of 10.6 ¢/kWh, while the CESP tool calculated an adjusted LCOE of 12.467 ¢/kWh using the same input parameters.

For comparison,(Mines and Nathwani, 2013) report that LCOE values calculated using GETEM vary between 13 ¢/kWh and 76 ¢/kWh. These values correspond to geothermal gradients ranging from 40 to 70 °C/km, bottom-hole temperatures between 100 and 325 °C, and a mass flow rate of 40 kg/s per production well.

According to the study (TNO, 2013), the Levelised Cost of Energy (LCOE) for geothermal electricity in the European Union is expected to decline over time, reaching below 200 €/MWh by 2020, 150 €/MWh by 2030, and 100 €/MWh by 2050. As shown in Figure 3.3, the report LCOE: Energy Costs, Taxes, and the Impact of Government Interventions on Investments (Thierry Badouard et al., 2020) indicates notable declines in geothermal power generation costs across the EU27 countries. Based on 13 data points, LCOE has dropped by about 50% since 2013. In 2018, values ranged from €30 to €100 per MWh. For non-EU G20 countries, with 22 observations, LCOE decreased by roughly 30% between 2010 and 2018. The costs in 2018 were between €40 and €50 per MWh.

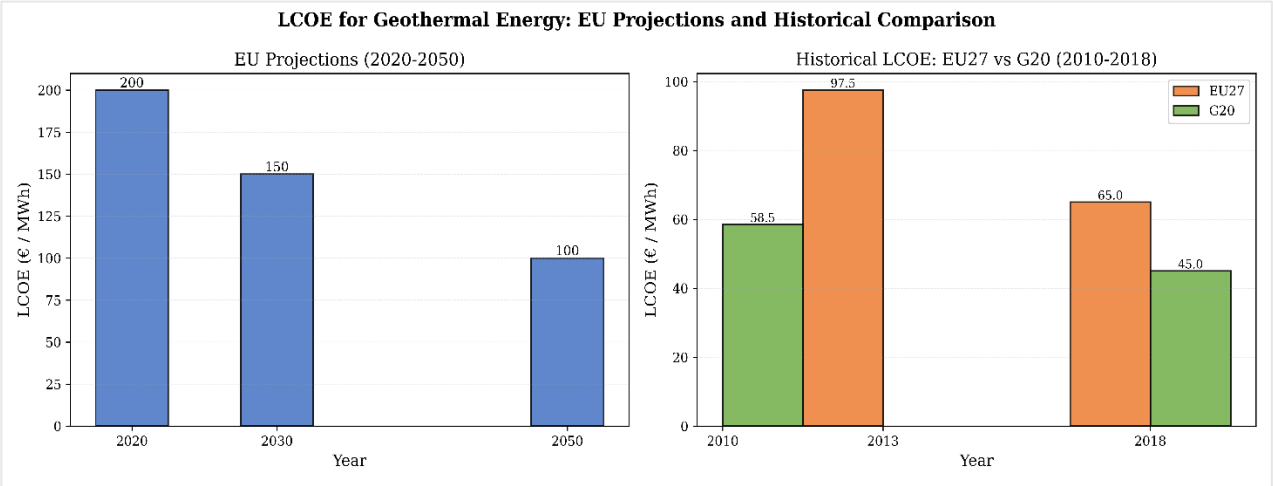


Figure 3.3 Comparison of Projected and Observed Trends in Levelized Cost of Energy (LCOE) for Geothermal Electricity in the EU and Non-EU G20 Countries (2010–2050)

The projected LCOE results suggest that geothermal electricity costs are likely to decrease over time in the EU. This will improve its competitiveness against other energy sources. Geothermal energy provides a clean and dependable addition to Europe's future energy mix. In the COMPASS project case studies, the projected LCOE values indicate even lower costs, showing the economic benefit of the proposed high-temperature geothermal plants.

4 CONCLUSIONS

This study presents the development and application of the Cost Estimator for Surface Plant (CESP) tool to evaluate the Levelised Cost of Electricity (LCOE) for geothermal plants using very hot and superhot resources. The tool was applied to three case studies: the Icelandic plant at Hellisheidi, the Italian plant at Bagnore, and the proposed COMPASS plant. The estimated LCOE values are approximately 54 €/MWh for Hellisheidi, 52 €/MWh for Bagnore, and 25 €/MWh for the COMPASS plant. The lower LCOE for the COMPASS plant is mainly attributed to its high installed capacity of 350 MW, achieved with only 10 high-output wells and the utilisation of superhot geothermal resources. The geothermal reservoir temperatures are about 268 °C for Hellisheidi, 325 °C for Bagnore, and 375 °C for the COMPASS plants, corresponding to an approximately 40% and 15% increase of temperature relative to the Icelandic and the Italian plant, respectively, highlighting the enhanced resource quality of the COMPASS site.

Although Decision Support Systems (DSS) integrating the GETEM model have been studied, there is no research work applying them to site-specific case studies in the representative Icelandic & Italian, and the COMPASS enabled plants, making this work novel. The analysis shows that improving process parameters such as resource temperature, well depth, plant capacity, and specific site conditions can significantly reduce the cost of generating geothermal electricity. While some inputs used standard GETEM values because of limited actual plant data, the CESP tool provides a reliable framework for a thorough techno-economic assessment.

Future work should focus on optimising the calculation procedures and overall modeling framework, particularly for parameters directly influencing the costs associated with drilling and construction phases, which play a critical role in determining the Levelised Cost of Energy (LCOE).

In summary, the developed CESP tool successfully mimics real-world situations, highlights important cost factors, and helps with data-driven decision-making. It serves as a helpful and flexible support system for researchers and engineers who want to improve the performance and cost-effectiveness of geothermal energy projects, particularly those that use high-temperature and superhot resources.

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