MEET
Multi-sites EGS Demonstration

DELIVERABLE D7.2 GEOTHERMAL ENERGY POTENTIAL DEVELOPMENT IN DIFFERENT GEOLOGICAL CONDITIONS

WP7: ECONOMIC AND ENVIRONMENTAL ASSESSMENT FOR EGS INTEGRATION INTO ENERGY SYSTEM

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PUBLIC SUMMARY

This public deliverable D7.2 was prepared within the framework of the MEET project (H2020) and presents site specific analysis of EGS demonstration sites in various geological conditions. Within this activity the geothermal energy development potential will be evaluated from techno-economic perspective using the Decision-Making Support Tool for Optimal Usage of Geothermal Energy (DMS-TOUGE) developed as part of Deliverables D7.1 and D7.10, and Milestone M10. The emphasis of this deliverable is on choosing the most economically feasible and viable projects among different EGS demonstration sites in various geological conditions within existing market environment.

1 EXECUTIVE SUMMARY

The following document entitled “Geothermal energy potential development in different geological conditions” is a Deliverable within Work package 7 “Economic and environmental assessment for EGS integration into energy systems” of the MEET project.

The MEET project (Multidisciplinary and multi-context demonstration of Enhanced Geothermal Systems exploration and Exploitation Techniques and potentials) aims to demonstrate the viability of EGS with electric and thermal power generation in all main kinds of geological settings (crystalline, sedimentary, metamorphic, volcanic).

1.1 DESCRIPTION OF THE DELIVERABLE CONTENT AND PURPOSE

This report provides site specific analysis of various EGS demonstration sites in different geological conditions. The analyses are made by using the decision-making support tool developed for MEET project. Namely, Decision-Making Support Tool for Optimal Usage of Geothermal Energy (DMS-TOUGE) enables investors with different background and level of expertise to conduct comparative analyses of different geothermal energy usage at chosen geothermal site taking into account various influencing criteria. Furthermore, DMS-TOUGE presents holistic approach for techno-economic and socio-environmental assessment of EGS sites that provides the capability of simultaneous site-specific analysis of different sites or usages of geothermal energy at the same site.

The purpose of this report is to identify most economically feasible projects viable within market conditions taking into account different geological setting which highly influences project’s development path and duration.

1.2 BRIEF DESCIPTION OF THE STATE OF THE ART AND THE INNOVATION BREAKTHROUGHS

The growing concern regarding rising energy costs, the dependence on fossil fuels, and the environmental impact of energy supply makes it necessary to find economical and environment-friendly energy alternatives. The largest share in newly installed power capacities around the world is covered by wind and solar power plants. Besides those two renewables, geothermal energy represents large untapped renewable potential and low environmental impact. Despite many other advantages, like a reliable, constant baseload electricity or direct heat usage and a small land area footprint, geothermal energy is nowadays still a small contributor to the primary energy consumption. Its worldwide installed capacity was estimated at 12.9 GW at the end of 2016 [1] and 15.6 GW at the end of 2020 [2] and share in total electricity generation of around 1%. The main reasons are related to the risks and uncertainties of sustained fluid provision from the reservoirs and large upfront costs associated with exploration, well drilling and stimulation [3]. Furthermore, the traditional hydrothermal systems, based on mature and well-known technology, enable the exploitation of mainly high-enthalpy reservoirs, whereas a huge geothermal potential is present in low permeable, low porosity and low to medium enthalpy bedrock. In order to enhance reservoir productivity in low permeable rocks, Enhanced Geothermal Systems (EGS) technology has been developed. The EGS technique consists of creating or reactivating an existing fracture system in the targeted geological formation through which geothermal fluid can circulate. It potentially allows a widespread use of the enormous untapped geothermal energy potential, with a much larger geographical distribution than conventional geothermal energy produced from close-to-the-surface volcanic activity or from highly permeable natural hot aquifers, named hydrothermal systems. The basic concept of the approach is to exploit the heat which is trapped in any geological settings with several configurations for rock composition, tectonic setting and stress field.

The future of EGS in Europe relies on the demonstration of geothermal plant operation in different geological settings with the goal to replicate the solution where the same geologic unit can be found. So far, the only European EGS power plants running are located in the Upper Rhine Graben (URG) where hot fluids are exploited from deep fractured crystalline rocks (Soultz-sous-Forêts and Rittershoffen in France, Bruchsal, Landau and Insheim in Germany), a rare geological setting in EU that limits the replicability of the solution to few new sites such as Cornwall in the U.K at United Downs and EDEN geothermal drilling sites. Hence the focus should be on the most widespread units such as Variscan rocks (crystalline and metamorphic) or even better, sedimentary rocks that are by far the main surface to sub-surface rock type found in the EU and all over the world. Namely, when looking at the global level most of the EGS projects or pilot projects are developed in igneous rocks (mainly granitic), followed by sedimentary [4] (Figure 1).

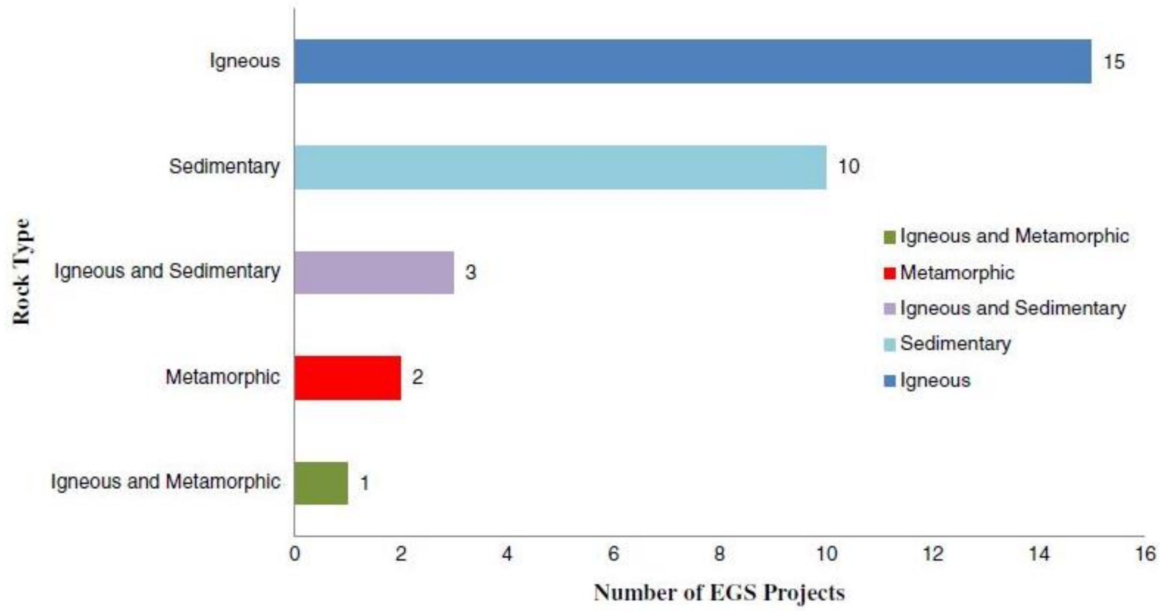

Figure 1. EGS projects on global level classified based on rock type (source: [4])

Running EGS sites and ongoing projects are mainly found in granitic/crystalline rocks which is the most studied environment. However, there is room for optimization especially for reservoir productivity and stimulation techniques. There is also a great effort to understand the other geological settings, i.e., sedimentary and metamorphic, where EGS can be deployed with large opportunity for replicability on more than 70% of EU surface, introducing new players on geothermal market such as Spain, France, Germany, UK and eastern EU countries.

1.3 CORRECTIVE ACTION (IF RELEVANT)

Decision-making support tool, that is prerequisite for deliverables D7.2 “Geothermal energy potential development in different geological conditions”; D7.3 “Upscaling of already existing geothermal provinces and coproduced oil fields” and D7.4 “Optimal usage of geothermal potential on already existing geothermal pilot sites”, verification and validation took place later than previously intended. In fact, due to the COVID-19 crisis, the foreseen tool validation and analysis of real site data in cooperation with partners had to be postponed. Therefore, the first version of the tool was only internally verified and validated by UNIZG-FER team. Namely, the decision-making support tool has been modelled to be used for comprehensive analysis of geothermal site and this demands a complete data set, i.e. input parameters for a particular site with more or less details. Team from UNIZG-FER made two visits for the purpose of tool verification and validation: first in June 2021 to Vermilion and second in July 2021 to ESG. As it was expected, certain adjustments and modifications in the tool should have been made and that took additional time.

1.4 IPR ISSUES (IF RELEVANT)

N/A

2 DELIVERABLE REPORT

2.1 MEET DEMONSTRATION SITES

The site-specific analyses conducted for the purpose of this deliverable strongly depended on the work and outcomes from various demonstration sites of the MEET project since many input parameters related to each demo site and necessary for proper and comprehensive evaluation resulted from several work packages (WP3, WP4, WP5, and WP6).

Four reservoir's rock types based on different geological settings were chosen for the analysis and are as follows. On the Figure 2, the demo sites within the MEET H2020 project which replicate the stated reservoir rocks are shown.

- Meta-sedimentary rocks,
- Volcanic rocks,
- Crystalline rocks, and
- Sedimentary rocks.

Figure 2. Demonstration sites in various geological settings chosen for the analysis

As reported in Deliverable D7.6, the demo sites from which the main data are extracted can be classified according to reservoir's rock type in four main groups as shown in Table I. In further text, different reservoir rock types, i.e., will be called demo sites.

Table I. Classification of analysed demo sites according to their reservoir rock type

Demonstration site	Reservoir's rock type
Havelange (Belgium)	meta-sedimentary rocks
Grásteinn (Iceland)	volcanic rocks
UDDGP (UK)	crystalline rocks
Cazaux (France)	sedimentary rocks

2.1.1 Meta-sedimentary reservoir rocks

This kind of rocks represents one of the rare cases of exploration borehole investigating the deep structure of Lower Devonian formations in the external Variscan fold-and-thrust belt. The Havelange site is located far from any younger extensional structure in the central part of the Dinant Synclinorium, which is a regional unit of the Rhenohercynian fold-and thrust belt in Belgium [5].

Existing infrastructure at the chosen site includes deep borehole (5,648 m) that was drilled in the early 1980's as an exploration well targeting gas resources potentially trapped below the main Variscan external thrust (Midi-Eifel Fault). Up to now it is the deepest borehole in Belgium. Of particular interest is the quartzite members showing permeability indicators related to fractures that were drilled in Havelange at a depth of ~ 4.5 km with a recorded temperature of approximately 126°C.

The Havelange demo-site is located in a rural environment (Figure 3). The energy valorisation options are therefore constrained to specific heat demands to be developed or to target electricity production.

Figure 3. Landscape view from the Havelange demo site

2.1.2 Volcanic rocks

Grásteinn is at the end of a 5,000 year old lava field (Hellisheiðarhraun b/c) and on top of a 10,000 year old lava field (Hellisheiðarhraun a). The site is a low-temperature geothermal field. From 1995 to 2008, a 440 m deep well was adequate for household heating, but a natural earthquake drastically reduced the well's output and it's depth needed to be increased. This was done in 2010 and the action increased both the flow and temperature of the fluid coming from the well.

Recent production temperature is 115°C and mass flow rate of around 875 m^3/d.

2.1.3 Crystalline rocks

Site UDDGP in Cornwall, United Kingdom is located at places where acidic to intermediary intrusive rocks (e.g., granites) form massive parts of the subsurface and at some place they are covered by a sequence of sediments. Therefore, the UDDGP site is chosen as demonstration site for such fractured crystalline rock type. Namely, the Carnmenellis granite is a sub-circular composite intrusion and forms part of the Variscan Cornubian batholith. The Porthtowan fault zone (PTF) belongs to a family of NW-SE striking structures cross-cutting SW England. The PTF is a sub-vertical strike-slip fault zone penetrating both killas (metamorphic rocks) and granite. Foliated and mylonitised granites give evidence for PTF being active during granite emplacement (Figure 4). No active movement is documented along this fault.

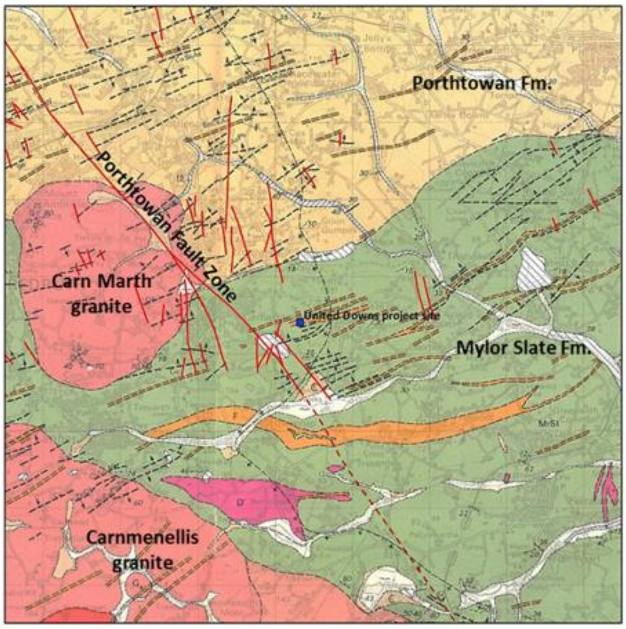

Figure 4. Mapped structures in the vicinity of the UDDGP site (source: [6])

2.1.4 Sedimentary rocks

Demonstration sites for sedimentary rocks are located in oil- and/or natural gas-bearing sedimentary basins of Mesozoic age. The Cazaux Purbeckian field was chosen for further analysis. It was discovered in 1961 and is located 3,200 m deep. Cross section of West Cazaux is shown in Figure 5.

Average temperature from single well is around 110°C at the surface with an average flow of 300 m^3/d.

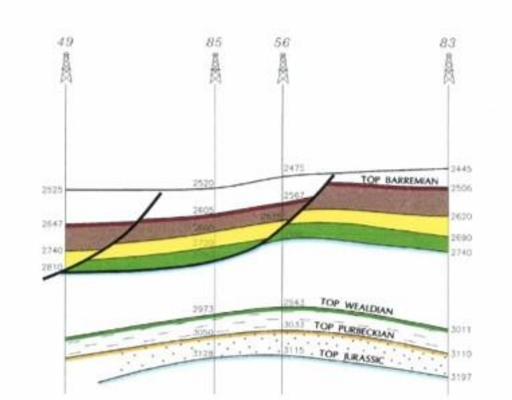

Figure 5. Cross section of West Cazaux (source: [7])

2.2 METHODOLOGY

The geothermal energy development potential was evaluated from techno-economic perspective using the Decision-Making Support Tool for Optimal Usage of Geothermal Energy (DMS-TOUGE) developed as a part of Deliverables D7.1 [8] and D7.10 [9]. The emphasis of the conducted analysis was on choosing the most economically feasible and viable projects among different EGS demonstration sites in various geological conditions within existing market environment. DMS-TOUGE is used for conducting techno-economic analysis, alongside with environmental and social impacts of enhanced geothermal system (EGS) projects. Based on the input data provided by the user and pre-defined default values, DMS-TOUGE allows for evaluation of different scenarios and estimates costs related to generating electrical power, thermal energy or both, i.e. combined heat and power production (CHP). The projected costs throughout the project's lifetime and annual energy sales are used to interpret one of the various economic outputs, such as the levelized cost of energy (LCOE) and net present value (NPV) of the project.

For each geothermal site, several probable scenarios for brine flow rate were considered. Additionally, a scenario for each end-use application was created by modification of input parameters. After obtaining all performance and economic results, the multi-criteria decision-making analysis (MCDM) was done, which is an additional feature of the DMS-TOUGE. The MCDM as a subprocess of the DMS-TOUGE enables a comprehensive understanding of the interaction between economic, geological, social, environmental and technical uncertainties. Usage of this additional feature is completely decision-makers choice. Namely, the MCDM feature enables investors with different background and point-of-view to evaluate geothermal projects (with emphasis on EGS). However, this evaluation is directly influenced by preferences of the decision-maker and consequently can vary noticeably. Namely, the decision-maker creates the preferable ranking of determined influencing criteria by giving more importance to specific criteria. This is obtained with the usage of Analytic hierarchy process (AHP) method. Namely, decision makers are more reluctant to make gut decisions based of feelings and hunches, and instead prefer to use analytic and quantitative tools, and base and analyse their decisions on a solid ground. Many methods stemming from applied mathematics and operations research have proved useful to help decision makers making informed decisions, and among these methods there are also those requiring, as inputs, subjective judgments from a decision maker or an expert. It is in this context that the Analytic Hierarchy Process (AHP) becomes a useful tool for analysing decisions [10]. Although the utility of the AHP is not limited to the following, it is safe to say that it has been especially advocated to be used with intangible criteria and alternatives, and thus used to solve multi-criteria decision making (MCDM) problems, which are choice problems where alternatives are evaluated with respect to multiple criteria [10]. The AHP method allows decision-makers to put emphasis, i.e. more importance to specific criteria, therefore this method is selected as suitable for the purpose of this Deliverable. Namely, it can be used to somehow take into account different geological setting and belonging main characteristics into account which highly influence the outcome of decision related to the potential investment. Therefore, the emphasis on different geological settings was accomplished by using (AHP) method. The MCDM is briefly described in Section 2.2.1.

2.2.1 Multi-Criteria Decision-Making

In order to somehow compare seemingly incomparable demo sites, taking into account wide range of criteria, the multi-criteria decision-making (MCDM) analysis is used as an additional feature. At its core, MCDM is useful for:

- Dividing the decision into smaller, more understandable parts;
- Analysing each part;
- Integrating the parts to produce a meaningful solution.

Multi-Criteria Decision-Making (MCDM) analysis is performed and used to grade each of the chosen demo sites with the emphasis on geological setting parameters. Namely, for evaluating different EGS options, a set of criteria is defined and used. All identified influencing criteria can be divided into five main groups: geological setting, technology, economy/finance, society and environment. Additionally, for the evaluation of relative importance of each criterion in decision making, the weight is associated with each criterion. The weights for each criterion are obtained by using the AHP method.. The general AHP method is depicted in Figure 6.

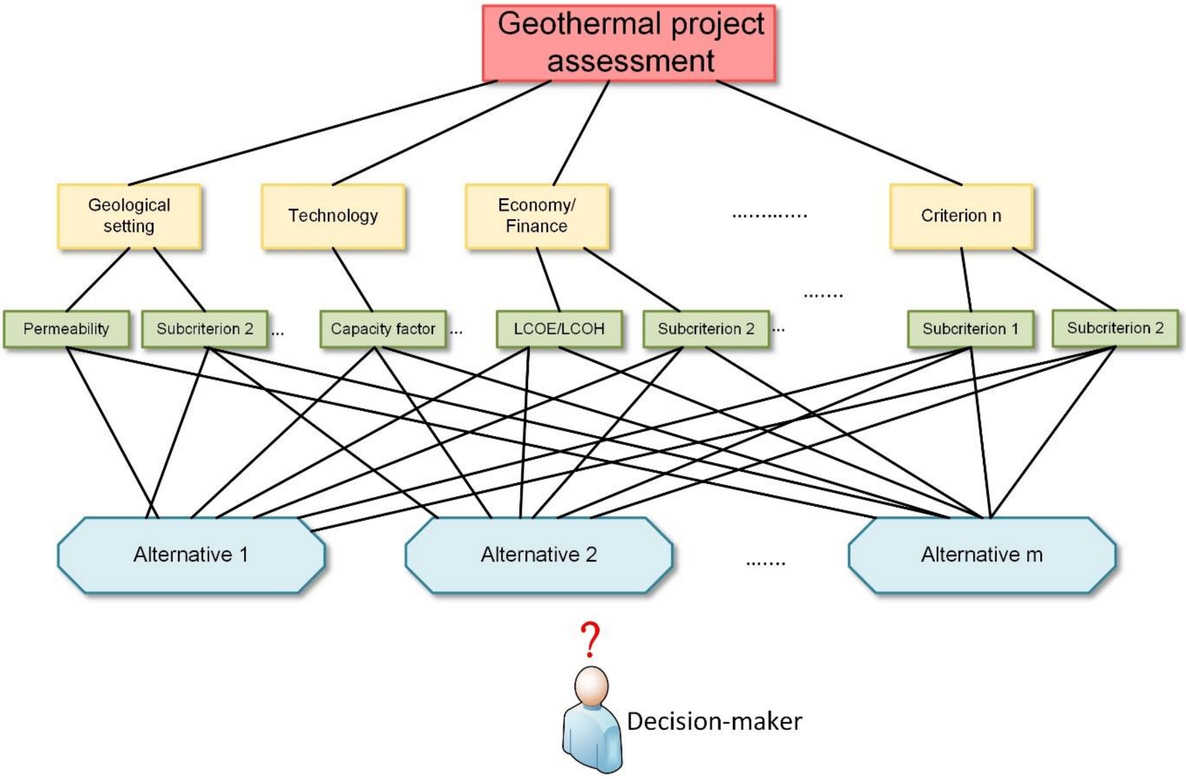

Figure 6. General depiction of used AHP method for evaluation of relative importance of selected criteria

The Analytic Hierarchy Process (AHP) has been conducted for several influencing groups such as geological setting, technology, economy/finance, society and environment. The parameters within each group encompass the influencing factors required for the development of a geothermal project. The geological setting group of criteria was intentionally given the highest importance compared to other groups. The purpose was to highlight the influence of different geological settings characteristics. Such decision environment should be taken with a certain carefulness having in mind that the geological setting characteristics are the main focus of this Deliverable report, followed by economic criteria as shown in Figure 7. Any change in the ranking of the defined influencing criteria will result in different final grading of each demo site, and consequently slightly different conclusions. Obtained local weights for each influencing criteria in each group of criteria are shown in Figures 8, 9, 10, 11, and 12. The final (global) weights of each criteria are shown in Figure 13 where the emphasis is on the geological settings where it can be observed that the reservoir temperature, fluid specific heat capacity, permeability, etc., have the greatest influence when evaluating the geothermal project.

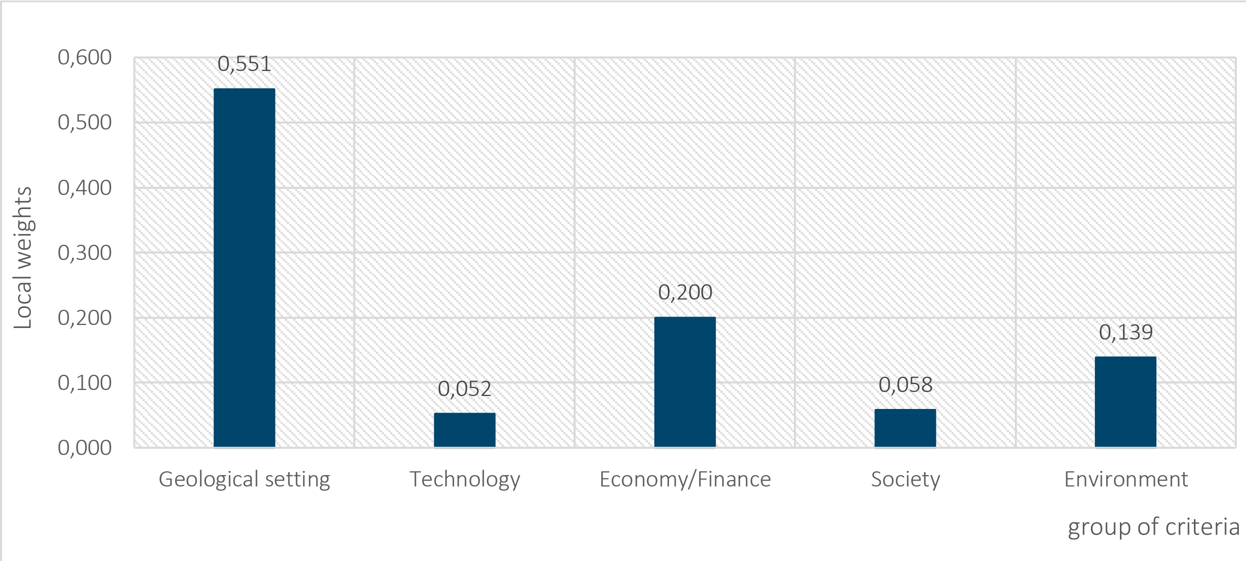

Figure 7. Obtained local weights of group of criteria

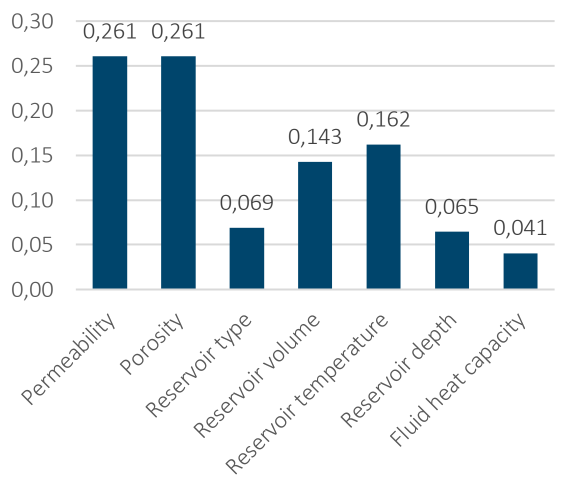

Figure 8. Obtained local weights of geological setting criteria

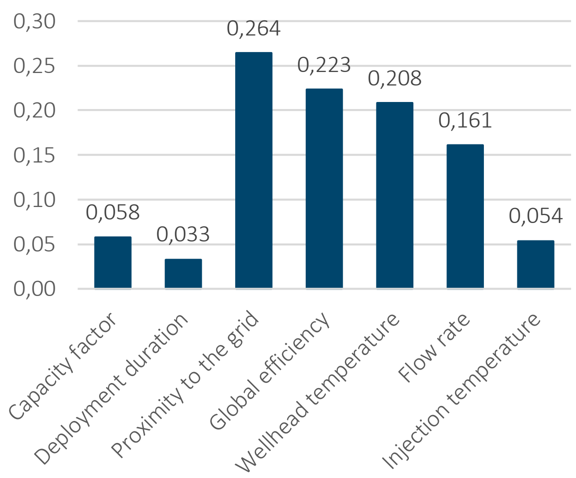

Figure 9. Obtained local weights of technology group of criteria

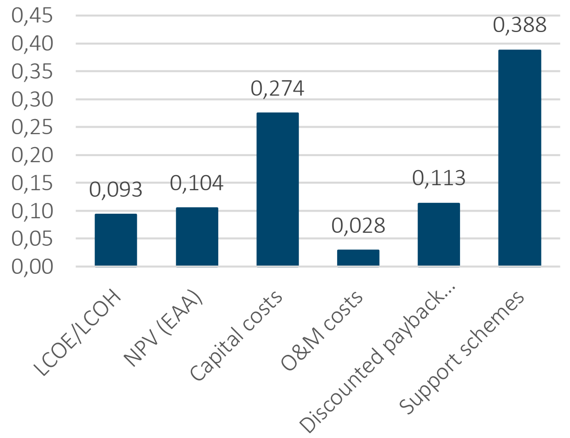

Figure 10. Obtained local weights of economic group of criteria

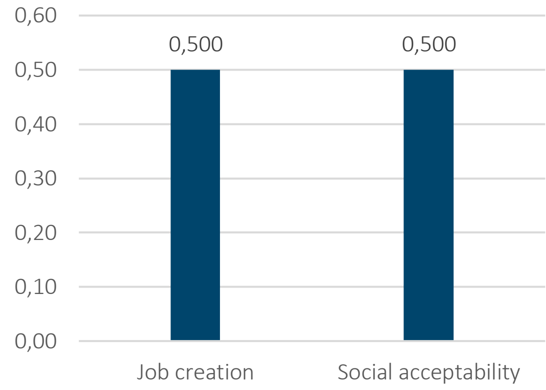

Figure 11. Obtained local weights of society group of criteria

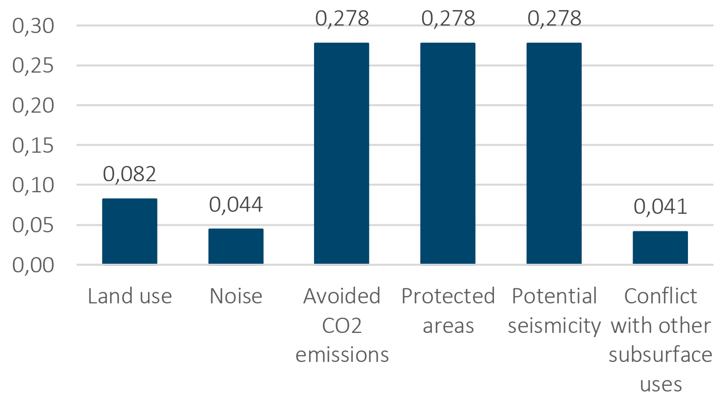

Figure 12. Obtained local weights of environment group of criteria

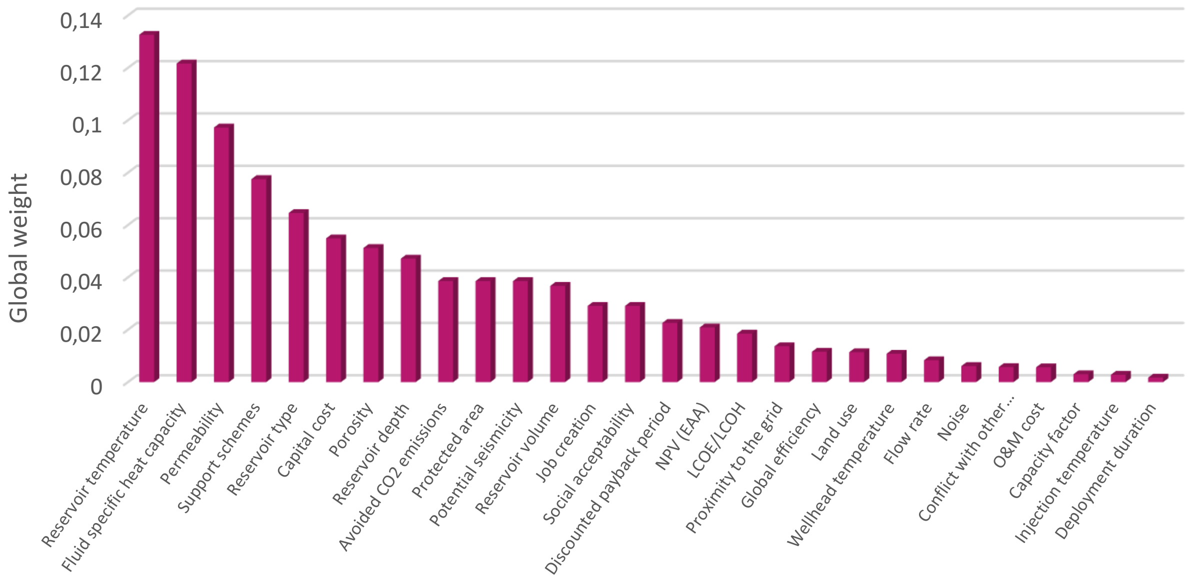

Figure 13. Sorted influencing factors of conducted AHP analysis (global weights of criteria)

After obtaining global weights, each weight (Figure 13) is multiplied with corresponding grade that was given to each influencing criterion. Namely, each criterion was graded based on the value, which was either input value, calculated value or default value in case if the first two mentioned techniques were not applicable for a certain demo site. Finally, the final grade for each demo site was calculated. The final grade can range from 1 to 5. The final grades for each scenario and each demo site are shown in Results analysis sections (Section 2.3.1.1, Section 2.3.2.1, and Section 2.3.3.1).

2.2.2 General information

Table II. Main characteristics of chosen demonstration sites which replicate the different geological settings

PARAMETER	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Location	Teste de Buch (France)	Öflus (Iceland)	Cornwall (UK)	Wallonia (Belgium)
Project status	In operation	In exploitation	Under development (stimulation, testing, plant construction)	Abandoned exploration well (natural gas)
Reservoir rock type	sedimentary rocks	volcanic rocks	crystalline (faulted granite)	meta-sedimentary rocks (paleozoic)
Number of wells	23 production wells 10 injection wells	1 production	1 production well 1 injection well	1 (exploration)
Depth of wells	avg. 3,200 m	586 m	4,500 m (production) 2,000m (injection)	5,648 m
Production temperature	110°C	158°C	175°C (expected)	126°C
Reinjection temperature	55°C	draining system (discharged onto the surface)	70°C (designed)	not applicable
Flow rate	-	7.5 l/s	20 - 60l/s	3.47 l/s (average well)

Main characteristics of chosen demonstration sites that are real measurements or estimated values based on experts' knowledge are presented in the Table II.

The reliability level of economic and performance results that were obtained by using the DMS-TOUGE highly depends on the certainty level of input data. Therefore, for those sites where no or little geological and geophysical data and no reliable numerical reservoir and models exist, several probable scenarios for brine flow rate were considered. Additionally, since the status of each demonstration site differs from each other, available data is also different. Therefore, when analysing the results, one should take into account that some data are real measurements and other are either evaluations based on real screenings, samples etc. or evaluations based on experts' knowledge of analogue sites.

2.3 EVALUATION OF CONDUCTED SCENARIOS

To evaluate different directions of geothermal energy potential development in different geological conditions three scenarios for each demonstration site have been modelled and analysed: only heat production, only electricity production, and combined heat and power production (CHP), respectively. Finally, the four demonstration sites are compared for each scenario using the MCDM analysis and AHP method described in Section 2.2.1. The AHP method is used to give relative importance to the criteria, and for the purpose of this Deliverable the highest importance was given to the geological setting criteria enabling thereby the comparison of geothermal energy potential development in different geological conditions. The geological input data of each demo site is shown in the Table III.

Table III. Main geological input data for each type of geological setting, i.e., demo site

PARAMETER	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Matrix permeability	1×10^{-15} m^2	2.96×10^{-12} m^2	9.97×10^{-17} m^2	1.21×10^{-13} m^2
Fracture permeability	4.93×10^{-13} m^2	5.92×10^{-12} m^2	9.97×10^{-15} m^2	1.21×10^{-13} m^2
Matrix porosity	8%	7.5%	0.4%	2%
Fracture porosity	11%	15%	1%	2%
Reservoir pressure	468.75 bar	15 bar	467.29 bar	474.7 bar
Density of the fluid	990 kg/m^3	980 kg/m^3	990 kg/m^3	998 kg/m^3
Specific heat capacity of the fluid	3,800 J/kgK	3,890 J/kgK	3,800 J/kgK	4,250 J/kgK
Fluid concentration	100 NaCl g/kg	80 NaCl g/kg	100 NaCl g/kg	25 NaCl g/kg

Matrix and fracture permeability, porosity, and the rest of the data for sedimentary rocks was derived from the measurements of the core sample, as well as for the volcanic rocks demo site. The matrix permeability and porosity of meta-sedimentary rocks was taken from the [11] where the group of authors gathered geologic, hydrogeologic, thermal, and paleoclimatic data and used them for performing the hydro-geothermal modelling of the temperature and heat flow. The data about the crystalline rocks demo site were derived from the [12] and [13]. The data that did not have the exact value were estimated in the correspondence of the experts who are in contact with the site. For the reservoir pressure of each site, an exact value, pressure gradient, or estimation based on the geological setting was used to approximate the reservoir pressure at the certain depth. The fluid specific heat capacity was estimated based on the [14] where the influencing factors were fluids temperature and concentration of sodium chloride.

2.3.1 Only heat production scenario

In this scenario the direct usage of geothermal energy was analysed and compared for four different geological conditions. For the sites to be comparable, the same well depth (both production and injection wells) is targeted, except in the volcanic setting where the production well is expected to be at lower depth due to the higher geothermal gradient. So, when equalizing sites according to the depth is not possible, the equalizing according to the wellhead temperature is applied. The main input parameters for each geological setting are shown in the Table IV. The depth of the injection well is the same as the depth of the production well.

Table IV. Main input parameters for each demo site

Parameter	Sedimentay rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Usage	Greenhouse heating	Greenhouse heating	Greenhouse heating	Greenhouse heating
Flow rate (total)	0.03 m^3/s	0.03 m^3/s	0.03 m^3/s	0.03 m^3/s
Depth of production wells	5,000 m	560 m	5,000 m	5,000 m
Wellhead temperature	140°C	140°C	134.10°C	175°C
Reinjection temperature	70°C	70°C	70°C	70°C
Temperature drawdown	0.3 %	0.3 %	0.3 %	0.3 %
Distance to the heating network	1,000 m	1,000 m	1,000 m	1,000 m
Power plant availability	90%	90%	90%	90%
Month of maintenance	July	July	July	July

To bring the geological features to the fore, the flow rate, reinjection temperature, yearly temperature drawdown, distance to the heating network, power plan availability, and month of maintenance are the same. The heat demand is modelled as greenhouse of approximate 3 ha with the supply and return temperatures heat demand shown in the Figure 14 and mass flow rates Figure 15.

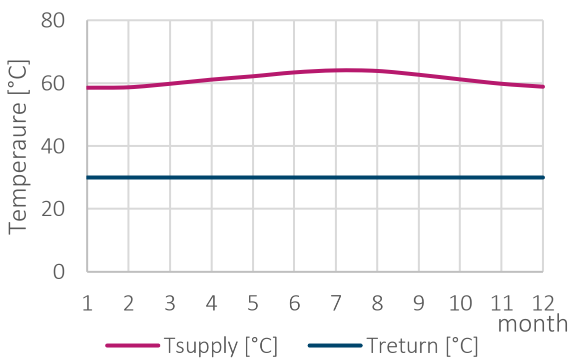

Figure 14. Supply and return temperatures of only heat production scenario (monthly values)

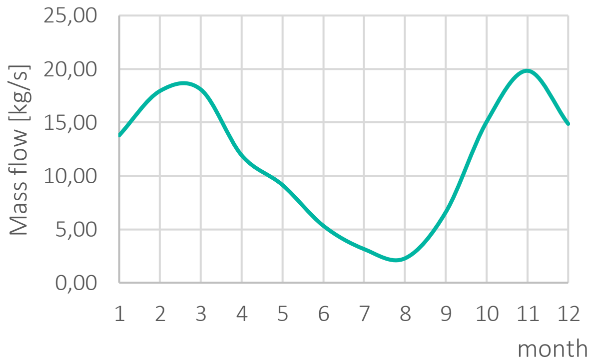

Figure 15. Mass flow of only heat production scenario (monthly values)

In the Table V, the main data about the production and injection pumps are shown.

Table V. Input data about the production and injection pumps for each demo site

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
ESP power	350 kW	11 kW	350 kW	290 kW
ESP depth	550 m	75 m	550 m	470 m
ESP cost	1,223,704 €	46,358 €	1,223,704 €	1,093,136 €
Injection pump power	130 kW	130 kW	130 kW	130 kW
Injection pump cost	424,000 €	424,000 €	424,000 €	424,000 €

For the production and injection pump used for the calculation in this deliverable, the methodology developed in Deliverable 4.5 [15] within the MEET project for the production and injection pump design is used. The mentioned methodology enables the estimation of pump power in the dependence of the fluid flow and corresponding pressures in the well, as well as on the surface. For the production pump design, a Schlumberger catalogue of electric submersible pump (ESP) is used to estimate, i.e., to size the ESP for the chosen well. For each pump from the catalogue, a capacity at maximum efficiency is listed. Before selecting a pump, two conditions must be fulfilled: the Velocity check and the Operating range check. The calculation selects the pump with the flow at the maximum efficiency which is nearest to the required flow. For the injection pump design, the pumps installed on the existing wells are used from which the proxy curves were made. Based on the fluid and the well parameters, the pump power and head, wellhead injection pressure, and bottomhole injection are calculated for each of the installed pumps used for calculation, and the pump that runs at highest efficiency within the operating range was chosen as the pump which will be installed at the wellhead. For the sedimentary rocks and meta-sedimentary rocks demo site the pump with the same installed power was choosen since these two sites have a similar reservoir pressure, fluid flow and both have been vertical wells, so the pump depth is the same. The production pump in volcanic rocks is set at the depth of 75 m with the power of 11 kW. The production installed in the crystalline rocks demo site has the power of 290 kW at the lower depth, 470 m, due to the higher reservoir pressure. As for the injection flow, for all four demo sites, corresponding to the flow, the same type of injection pump is installed. The corresponding cumulative flow is divided into two streams which flows into two injection pumps, arranged in parallel, each of 130 kW of installed power.

Capital costs for each demo site are shown in the Table VI. Volcanic demo site has the lowest capital cost, which is understandable due to low cost of drilling and completion of production and injection wells. The capital cost production and injection wells and stimulation cost are derived from the [16] and then scaled regarding well depths. It is assumed that the depth of the injection well is the same as the production well depth. The cost of leasing and additional cost is the same at all four demo sites since it is chosen to have the same land use surface. The calculated analysis would have been more accurate by using the real data about the leasing, drilling, stimulation, etc., and similar activities in different geological settings. The plant equipment cost depended on the installed capacity and the 'six-tenth rule' was used to evaluate these costs for each demo site. The latter mentioned costs are the same at all four demo site since the thermal power plant has the same installed heat capacity (Table IX) in all four demo sites. Costs for the pipes are the same for each demo site since the length stays the same in each case. If the specific capital costs are compared, the sedimentary demo site has the highest value, together with the meta-sedimentary demo site (13,675 €/kW). The crystalline rocks demo site has a slightly lower specific capital cost (13,620 €/kW) where the difference is in the lower production pump cost. The volcanic demo site has the lowest specific capital costs (5,216 €/kW) since its well depth is only 560 m with the same installed power.

Table VI. Capital investment costs for each demo site

Parameter	Sedimentay rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Leasing	1,430,000 €	1,430,000 €	1,430,000 €	1,430,000 €
Additional cost	4,095,000 €	4,095,000 €	4,095,000 €	4,095,000 €
Production well cost	11,457,000 €	3,080,361 €	11,457,000 €	11,457,000 €
Injection well cost	10,309,000 €	2,771,707 €	10,309,000 €	10,309,000 €
Stimulation cost	2,000,000 €	537,725 €	2,000,000 €	2,000,000 €
Instrumentation	28,357 €	28,357 €	28,357 €	28,357 €
Heat exchanger	523,154 €	523,154 €	523,154 €	523,154 €
Heating network	700,916 €	700,916 €	700,916 €	700,916 €
Engineering	99,741 €	99,741 €	99,741 €	99,741 €
Substation	182,859 €	182,859 €	182,859 €	182,859 €
Piping and valves	192,638 €	192,638 €	192,638 €	192,638 €
Production pump	1,223,704 €	46,358 €	1,223,704 €	1,093,136 €
Injection pump	424,000 €	424,000 €	424,000 €	424,000 €
TOTAL	33,090,369 €	14,536,816 €	33,090,369 €	32,959,801 €
Specific cost	13,675 €/kWh	5,216 €/kWh	13,675 €/kWh	13,620 €/kWh

Individual costs associated with operating and maintenance costs for each case are summarized in Table VII. Maintenance costs consist of wellfield maintenance costs and power plant maintenance costs. Maintenance cost in all four demo sites is the same because of the same installed capacity. Labour costs also depend on the installed capacity. Power plant operating costs are directly related with the parasitic load, i.e., with the energy consumption from the production and injection pumps. It can be seen in the Table VII, that volcanic rock demo site has the lowest power plant operating costs, due to low power consumption of the pumps, followed by crystalline rocks demo site that has a slightly lower pump power consumption than sedimentary and meta-sedimentary demo sites.

Table VII. Summary of operating and maintenance costs (O&M) for each demo site

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Maintenance cost	158,101 €/year	158,101 €/year	158,101 €/year	158,101 €/year
Labour	96,290 €/year	96,290 €/year	96,290 €/year	96,290 €/year
Power plant operating cost	0.02106 €/kWh	0.00936 €/kWh	0.02106 €/kWh	0.01899 €/kWh

Financial parameters that were used for the economic analysis are shown in Table VIII. Same financial parameters were used for all modelled and evaluated scenarios.

Table VIII. Financial and economic parameters used in the economic analysis

Parameter	All scenarios
Discount rate	7.06%
Inflation rate	1%
Effective tax rate	30%
Insurances (of installed costs)	1%
Heat selling price	45 €/MWh
Capacity based incentive	50% of production well and stimulation cost

2.3.1.1 Results analysis

In this chapter, the results for each case are presented in Table IX.

Table IX. Results analysis for each demo site for the heat production scenario

Parameter	Sedimentay rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Duration of operational period	30 years	30 years	30 years	30 years
Installed capacity - heat	2,630 kW	2,630 kW	2,630 kW	2,630 kW
Total produced heat	342,418 MWh	342,418 MWh	342,418 MWh	342,418 MWh
Total unsatisfied heat demand	0 MWh	0 MWh	0 MWh	0 MWh
LCOH	313.43 €/MWh	143.65 €/MWh	313.43 €/MWh	306.54 €/MWh
Total avoided CO_2 emissions	81,634 tonnes	164,683 tonnes	77,171 tonnes	99,527 tonnes

All the heat demand can be satisfied by installing the same plant power. Since it is the same power installed, with the power plant availability of 90% during the 30 years of operation, the produced heat is the same at all four sites, as seen in the Figure 16. The total avoided CO_2 emissions are different from site to site, depending on the emission factors of each fossil fuel and fossil fuel mix which are country specific input values.

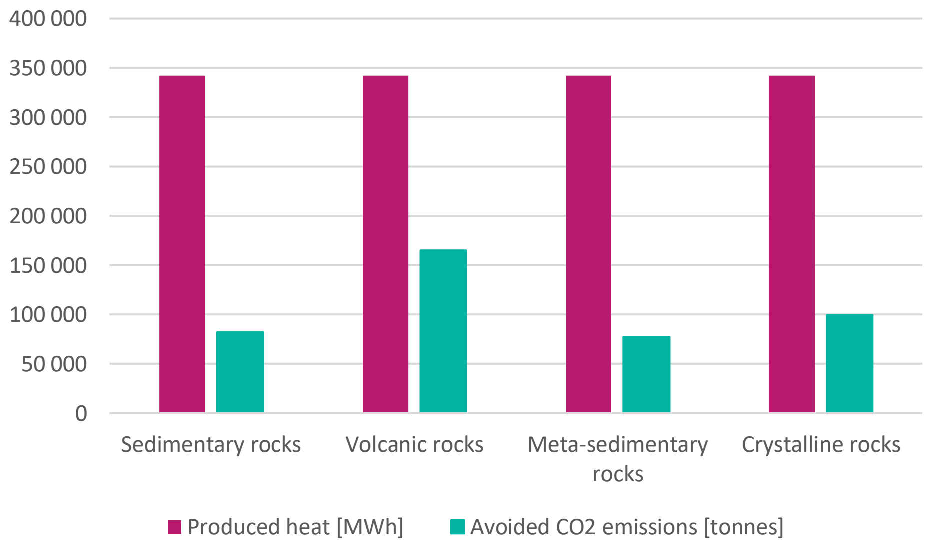

Figure 16. Total lifetime produced heat and avoided CO_2 emissions for each demo site

The results of LCOH calculations for each analysed demo site are shown in Figure 17. For the comparison, the average cost of heat from natural gas is shown [17]. It can be observed that all demo sites have higher LCOH than the mentioned average cost from natural gas boilers, except Grásteinn, being the closest to the gas price with smallest difference in value of LCOH and gas price. This can be explained with the low capital cost for wells drilling and achieving the same wellhead temperatures with lower depths, i.e., producing the same heat quantities with much lower well depth and at the same fluid rate. It can be concluded that performing the only heat production scenario at the volcanic site could be market competitive project and energy source in comparison with the natural gas prices should the gas prices rise or the technology price decrease. The LCOH is, as expected, the lowest in the volcanic case, due to the low capital investment cost and the same production quantity as in the rest of the demo sites. Higher LCOH has the crystalline rocks site because of the lower production pump cost. The highest LCOH have the sedimentary and meta-sedimentary demo sites.

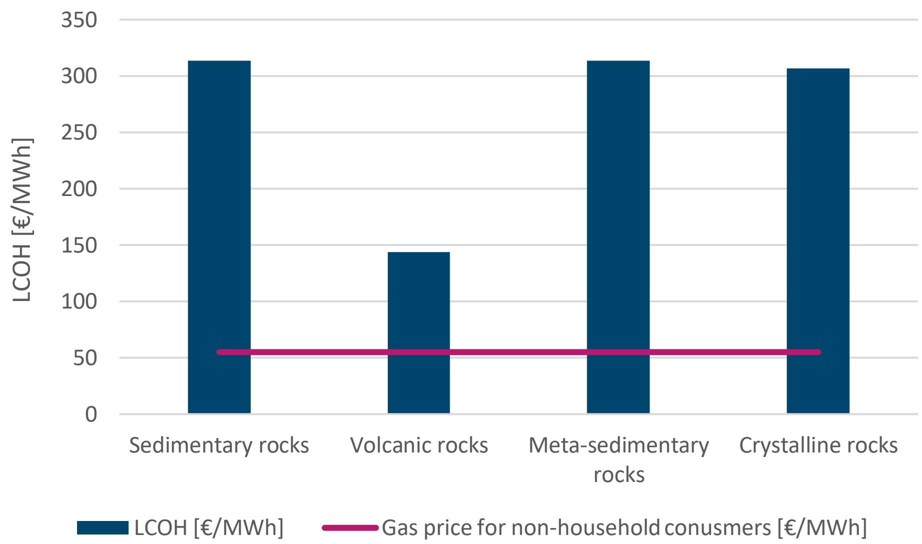

Figure 17. LCOH for each demo site in comparison with average cost of heat from natural gas boilers [18]

MCDM was conducted to evaluate each demo site separately. The results of MCDM analysis were received with the corresponding weighted factors and are shown in Figure 18 where the highest grade was calculated for the sedimentary, followed by the volcanic, and then the crystalline and meta-sedimentary rocks sites. Since all the sites have similar technological and economic background, predominant factors were mostly from the geological group, as well as support schemes and environmental factors. It can be concluded that the most feasible heat production scenario when putting the most emphasis on the geological setting criteria, followed by economic criteria, according to the MCDM analysis was the scenario at the sedimentary site, due to its high values of permeability and porosity, followed by volcanic with a slightly lower grade for injection temperature criterion which is being graded with sub-criterions like reinjection temperature, injection pressure, well spacing, and scaling and corrosion hazard. The sub-criterion scaling and corrosion hazard was marked as “not present” in the sedimentary demo site, opposite than in volcanic demo site. When the scaling and corrosion problems are present, which directly influences the final grade in MCDM analysis.

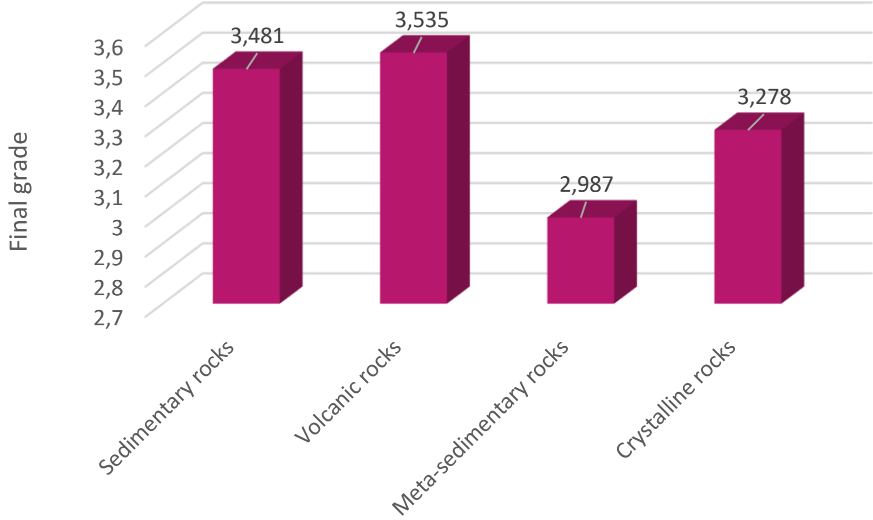

Figure 18. Result of MCDM analysis for each of demo site

2.3.2 Only electricity production scenario

In this scenario the electricity production from different geological setting was analysed. To bring the geological features to the fore, the flow rate, reinjection temperature, yearly temperature drawdown, distance to the power grid, power plan availability, and month of maintenance are kept the same for each demos site. Additionally, the same approach as in only heat production scenario was applied and for the sites to be comparable, the same well depth (both production and injection wells) is targeted, except in the volcanic setting where the production well is expected to be at lower depth due to the higher geothermal gradient. So, when equalizing the sites according to the depth is not possible, the equalizing based on the wellhead temperature is applied.

The electricity production is based on an Organic Rankin Cycle (ORC) unit. The ORC unit is foreseen to be installed close to the production well and is modelled according to the data from ENOGIA presented and thoroughly described in [19]. Namely, the ORC unit in DMS-TOUGE was modelled based on the significant number of discrete operational points of ORC power plant that was precalculated from their models. With known geothermal mass flow rate and wellhead temperature following parameters are necessary in order to evaluate the ORC power plant production: Delta T – the difference of inlet and outlet temperature on primary loop of the heat exchanger, ETA_{ORC} – ORC power plant efficiency as the function of geothermal brine wellhead temperature and Delta T, F_{COOL} – ORC power plant efficiency correction factor that takes into account different temperatures of ORC cycle coolant as function of geothermal brine wellhead temperature and Delta T. This ORC module was thoroughly described in [8]. It should be noted that this module is best fitted for the ORC cycle coolant temperature values in the range from 0 – 40°C, for Delta T values in range from 0 – 40°C, and for geothermal brine wellhead temperature values in range from 80 – 120°C. For wellhead temperatures above this value the same approach was applied, however this part of the module was modelled based on the real operational data from the Soultz-sous-Forêts power plant.

In Figures 19, 20, 21 and 22, monthly average outside air temperature for the each site is shown. The air temperature, i.e., air serves as a coolant for the ORC unit and therefore influences the thermal efficiency of the ORC unit.

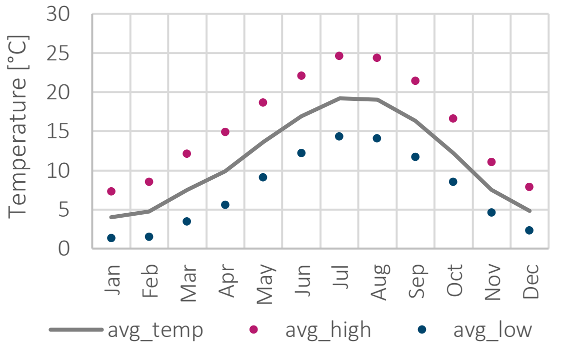

Figure 19. Monthly average outside air temperatures for sedimentary rocks site

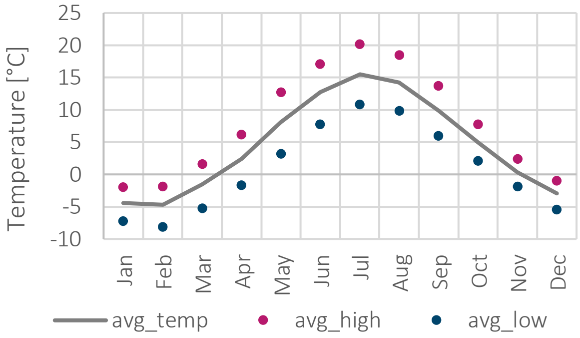

Figure 20. Monthly average outside air temperatures for volcanic rocks site

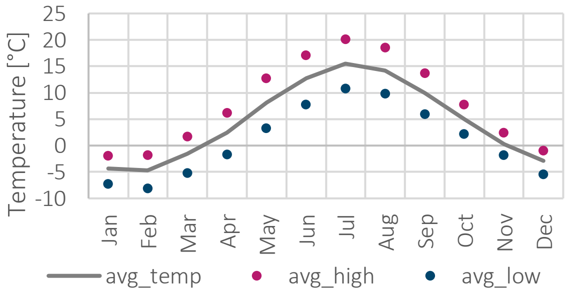

Figure 21. Monthly average outside air temperatures for meta-sedimentary rocks site

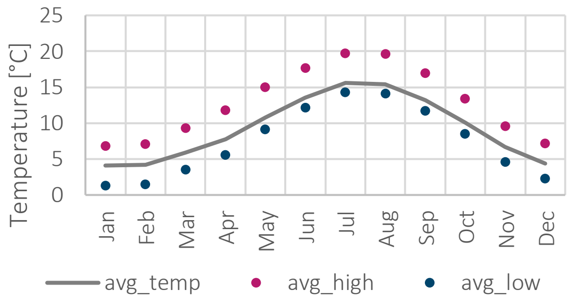

Figure 22. Monthly average outside air temperatures for crystalline rocks site

The main input parameters for each demonstration site which represents each geological setting are shown in Table X. The depth of the injection well is the same as the depth of the production well.

Table X. Main input parameters for each demo site

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Usage	electricity production	electricity production	electricity production	electricity production
Flow rate (total)	0.03 m^3/s	0.03 m^3/s	0.03 m^3/s	0.03 m^3/s
Depth of production wells	5,000 m	560 m	5,000 m	5,000 m
Wellhead temperature	140°C	140°C	134.10°C	175°C
Reinjection temperature	70°C	70°C	70°C	70°C
Temperature drawdown	0.3 %	0.3 %	0.3 %	0.3 %
Distance to the power grid	3,000 m	3,000 m	3,000 m	3,000 m
Power plant availability	90%	90%	90%	90%
Month of maintenance	July	July	July	July

In Table XI the main data about the production and injection pumps are shown. The pumps used in the only electricity production scenario are modelled in the same way as in the only heat production scenario. The costs are calculated using the 'six-tenth rule'.

Table XI. Input data about the production and injection pumps for each demo site

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
ESP power	350 kW	11 kW	350 kW	290 kW
ESP depth	550 m	75 m	550 m	470 m
ESP cost	1,223,704 €	46,358 €	1,223,704 €	1,093,136 €
Injection pump power	130 kW	130 kW	130 kW	130 kW
Injection pump cost	424,000 €	424,000 €	424,000 €	424,000 €

Capital investment costs for each demo site are shown in Table XII. The volcanic demo site has the lowest total capital investment costs (in €) since the drilling and stimulation costs amount around 50% of total capital costs, which is significantly lower than in the case of other demo sites where these costs amount for 70% of total capital costs. This is explained by the fact that volcanic demo site has the lowest well depth where the targeted temperature was reached. As in the only heat production scenario, the leasing and additional costs are equal for all demo sites since it is foreseen and standardized that the land use is equal for all sites. The calculated analysis would have been more accurate by using the real data about the leasing, drilling, stimulation, etc., and similar activities in different geological settings. However, since such detailed data was not available the standardized value was used for all sites. The plant equipment cost depended on the installed capacity and the 'six tenth rule' was used to evaluate these costs for each demo site. If the specific capital costs are compared, the highest value has the sedimentary site (34,113 €/kW), followed by the meta-sedimentary rocks site (27,123 €/kW), volcanic site (14,099 €/kW), and crystalline site with lowest (13,592 €/kW). Such variation comes from differences in installed capacity.

Table XII. Capital investment costs for each demo site

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Leasing	1,430,000 €	1,430,000 €	1,430,000 €	1,430,000 €
Additional cost	4,095,000 €	4,095,000 €	4,095,000 €	4,095,000 €
Production well cost	11,457,000 €	3,080,361 €	11,457,000 €	11,457,000 €
Injection well cost	10,309,000 €	2,771,707 €	10,309,000 €	10,309,000 €
Stimulation cost	2,000,000 €	537,725 €	2,000,000 €	2,000,000 €
ORC unit	677,371 €	702,617 €	777,284 €	1,173,791 €
Cold loop ancillaries	81,284 €	84,314 €	93,274 €	140,855 €
Dry cooler	135,474 €	140,523 €	155,456 €	234,758 €
Container housing	169,342 €	175,654 €	194,321 €	293,447 €
Start-up commissioning	50,802 €	52,696 €	58,296 €	88,034 €
Production pump	1,223,704 €	46,358 €	1,223,704 €	1,093,136 €
Injection pump	424,000 €	424,000 €	424,000 €	424,000 €
TOTAL	33,090,369 €	14,536,816 €	33,090,369 €	32,959,801 €
Specific cost	34,113 €/kWh	14,099 €/kWh	27,123 €/kWh	13,592 €/kWh

Individual costs associated with operating and maintenance costs (O&M) for each demo site are summarized in Table XIII. O&M costs consist of power plant maintenance cost, wellfield maintenance cost, labour cost, and power plant operating cost. The power plant maintenance cost depends on the installed capacity of the ORC power plant and the 'six tenth rule' was used to obtain those costs. Well field maintenance cost is depth dependent. Only for volcanic demo site these costs are smaller since the depth of the well is 560 m. Labour costs also depend on the plant installed capacity and the 'six tenth rule' was used to calculate them for each site. Power plant operating costs are directly related to the production and injection pumps power, i.e., their consumption. The higher the amount of covered self-consumption of those pumps the lower the operating costs.

Table XIII. Summarized operational and maintenance costs (O&M) for each demo site

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Power plant maintenance cost	214,245 €/year	222,100 €/year	245,850 €/year	389,785 €/year
Well field maintenance cost	200,000 €/year	53,770 €/year	200,000 €/year	200,000 €/year
Labour	142,830 €/year	148,070 €/year	163,900 €/year	259,857 €/year
Power plant operating cost	0.0258 €/kWh	0.0328 €/kWh	0.0412 €/kWh	0.0224 €/kWh

Financial and economic parameters that were used for the economic analysis are shown in Table XIV. Same financial parameters were used for all demo sites.

Table XIV. Financial and economic input parameters used in the economic analysis

Parameter	All scenarios
Discount rate	7.06%
Inflation rate	1%
Effective tax rate	30%
Insurances (of installed costs)	1%
Electricity selling price	100 €/MWh
Capacity based incentive	50% of production well and stimulation cost

2.3.2.1 Results analysis

The results for each demo site are presented in Table XV. For all modelled sites the total parasitic load of production facility can be covered by the energy production at site and the remaining net produced energy can be sold. four . As expected, the crystalline demo site yields highest installed capacity since the wellhead temperature is the highest (175°C) at the depth of 5,000 m (Figure 23). As it can be seen in Figure 23 total avoided CO_2 emissions do not depend only on the total produced amount of electricity but also on the replaced fossil fuel mix and emissions factors of each replaced fossil fuel, and both these parameters are country specific. Therefore, the avoided CO_2 emissions output parameter should be taken with slight precaution, having in mind that this changes with the geographic location of evaluated site.

Table XV. Analysis results for each demo site for the only electricity production scenario

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Installed electricity capacity	970 kW	1,031 kW	1,220 kW	2,425 kW
Total produced electricity	174,003 MWh	184,977 MWh	199,522 MWh	394,956 MWh
LCOE	593.57 €/MWh	351.51 €/MWh	619.35 €/MWh	168.25 €/MWh
Total avoided CO_2 emissions	104,058 tonnes	126,799 tonnes	95,913 tonnes	190,625 tonnes

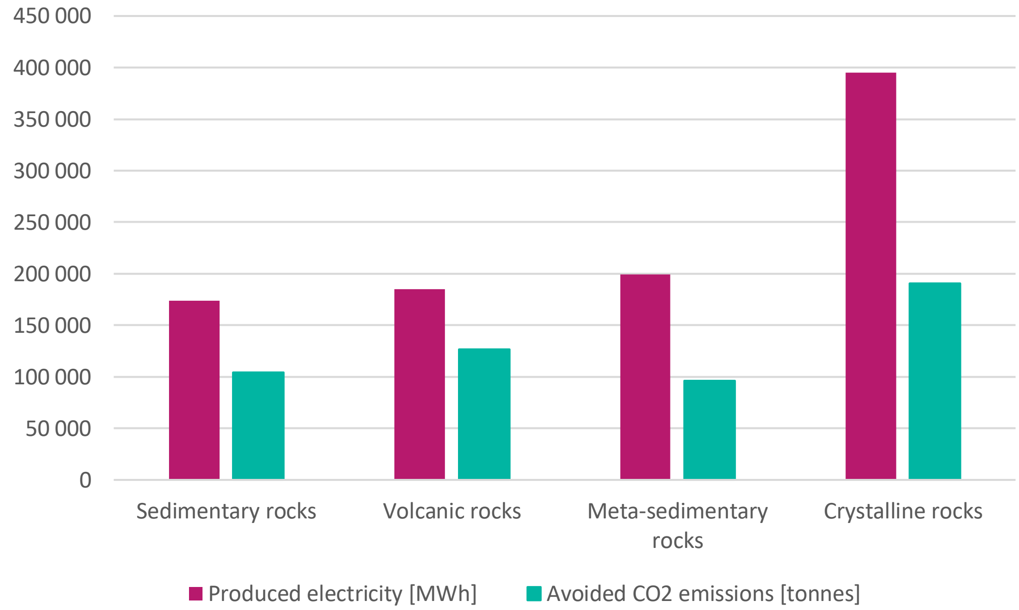

Figure 23. Total lifetime produced electricity and avoided CO_2 emissions for each demo site

The results of LCOE calculations for each analysed demo site are shown in Figure 24. For comparison the average electricity wholesale price in selected countries[1] in the European Union (EU) from September 2020 to September 2021 (78.4 €/MWh), and average electricity wholesale price in selected countries in the EU from September 2021 (142.03 €/MWh) are also plotted. As it can be observed all demo sites showed much higher LCOE compared to those average wholesale electricity prices, except crystalline demo site. This can be explained by the fact that the crystalline demo site had the highest wellhead temperature which enables highest production rates and consequently highest revenues from selling produced electricity. Namely, capital investment costs are similar for sedimentary, meta-sedimentary, and crystalline however, the maximum possible produced amount of electricity for sedimentary and meta-sedimentary demo site is much lower for those sites as it is seen in Figure 23. Furthermore, the volcanic site has higher LCOH than crystalline site although the capital investment costs are approximately 60%

[1] Selected countries include Ireland, Italy, Greece, Hungary, Germany, France, and Norway

lower. However, the installed capacity of the ORC at volcanic site is 50% smaller than in crystalline which consequently yields much lower incomes.

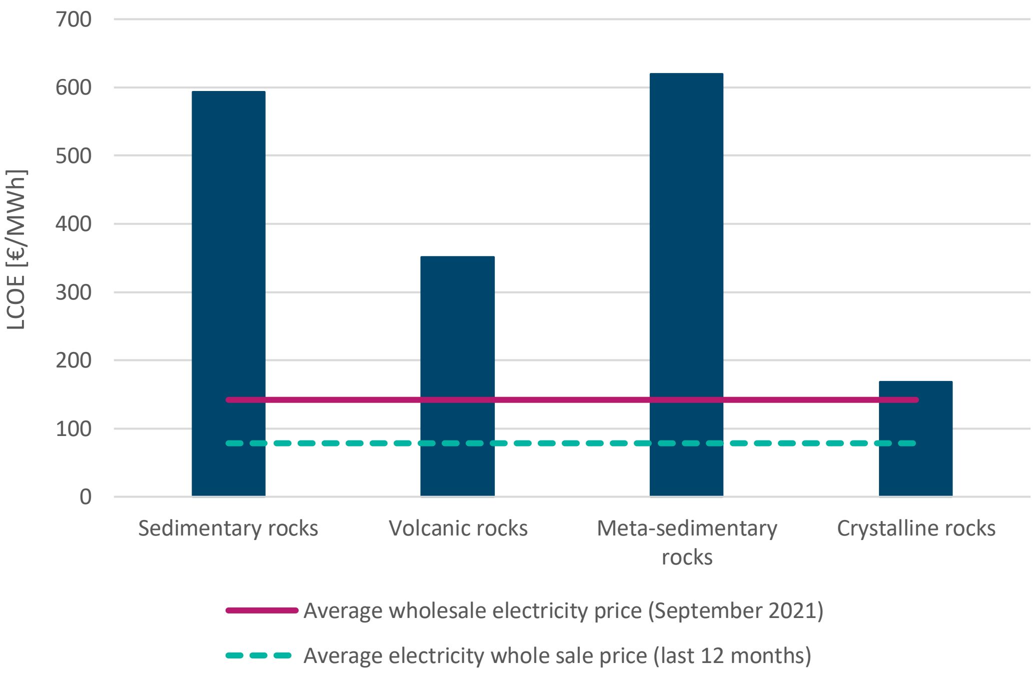

Figure 24. LCOE for each demo site in comparison with average wholesale electricity price in September 2021 and last 12 months (September 2020 - September 2021) (source: [18])

Additionally, the MCDM analysis was done for all demo sites regarding only electricity production. The results of MCDM analysis were calculated with the corresponding weighted factors (Figure 13) and are shown in Figure 25 where the highest grade was calculated for the volcanic, followed by the sedimentary site, and then the crystalline and meta-sedimentary rocks demo site. Since all the scenarios have similar technological and economic background, with slight difference for volcanic site, predominant factors were mostly from the geological group of factors, as well as support schemes and environmental factors. It can be concluded that the most favourable electricity production scenario, according to the MCDM analysis was the scenario at the volcanic site, due to its high values of permeability and porosity, followed by sedimentary site. This comes from the fact that sedimentary site has slightly lower grade for capital costs criterion since sedimentary had the highest specific capital investment costs in €/kW (Table XII). As can be seen from the final results the reservoir temperature, which is the highest at crystalline site did not have such big influence in final grade, because all other sites had also quite high temperatures. Meta-sedimentary rocks site did not only had the worst evaluation of permeability and porosity factors, but also because of country specific emission factors and fossil fuel mix, it had the lowest grade for the environment related avoided CO_2 emissions criteria.

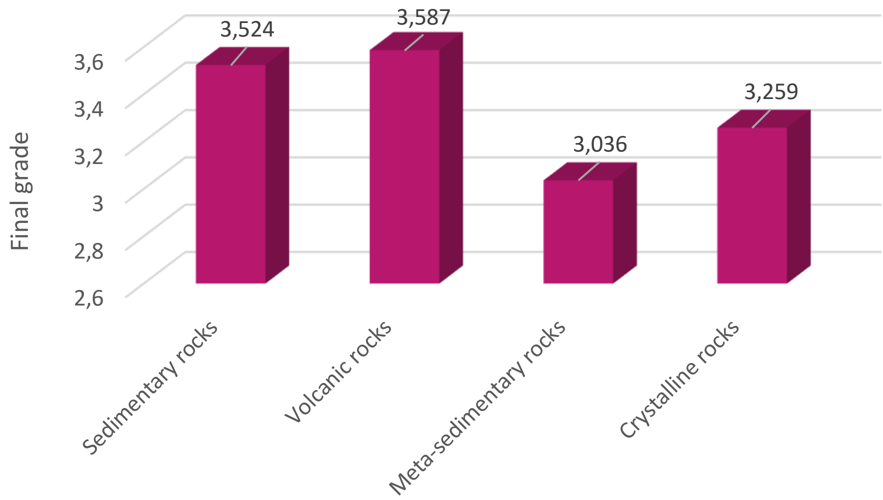

Figure 25. Final grades for each demo site obtained with MCDM analysis

2.3.3 Combined heat and power scenario

In this scenario the combined heat and electricity production from different geological setting was analysed. In other words, heating production is upscaled with additional ORC unit for electricity production or electricity production is upscaled with exploiting the remaining heat from the electricity production. The depth of the injection well is the same as the depth of the production well.

Table XVI. Main input parameters for each geological setting demo site

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Usage	Greenhouse heating + ORC unit	Greenhouse heating + ORC unit	Greenhouse heating + ORC unit	Greenhouse heating + ORC unit
Flow rate (total)	0.03 m^3/s	0.03 m^3/s	0.03 m^3/s	0.03 m^3/s
Depth of production wells	5,000 m	560 m	5,000 m	5,000 m
Wellhead temperature	140°C	140°C	134,10°C	175°C
Reinjection temperature	70°C	70°C	70°C	70°C
Temperature drawdown	0.3 %	0.3 %	0.3 %	0.3 %
Distance to the heating network	1,000 m	1,000 m	1,000 m	1,000 m
Distance to power grid	3,000 m	3,000 m	3,000 m	3,000 m
Power plant availability	90%	90%	90%	90%
Month of maintenance	July	July	July	July

To bring the geological features to the fore, the flow rate, reinjection temperature, yearly temperature drawdown, distance to the power grid, power plan availability, and month of maintenance are kept the same for each demos site. Additionally, the same approach as in only heat production scenario and only electricity production scenario was applied and for the sites to be comparable, the same well depth (both production and injection wells) is targeted, except in the volcanic setting where the production well is expected to be at lower depth due to the higher geothermal gradient. So, when equalizing the sites according to the depth is not possible, the equalizing based on the wellhead temperature is applied.

The main input parameters for each demonstration site which represents each geological setting are shown in Table XVI.

In Table XVII the main data about the production and injection pumps are shown. The pumps used in the CHP scenario are modelled in the same way as in the only heat production scenario. The costs are calculated using the ‘six tenth rule’.

Table XVII. Input data about the production and injection pumps for each demo site

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
ESP power	350 kW	11 kW	350 kW	290 kW
ESP depth	550 m	75 m	550 m	470 m
ESP cost	1,223,704 €	46,358 €	1,223,704 €	1,093,136 €
Injection pump power	130 kW	130 kW	130 kW	130 kW
Injection pump cost	424,000 €	424,000 €	424,000 €	424,000 €

Capital investment costs for each demo site are shown in Table XVIII. The volcanic demo site has the lowest total capital investment costs (in €) since the drilling and stimulation costs amount around 50% of total capital costs, which is significantly lower than in the case of other demo sites where these costs amount for 70% of total capital costs. This is explained by the fact that volcanic demo site has the lowest well depth where the targeted temperature was reached. As in the only heat production scenario, the leasing and additional costs are equal for all demo sites since it is foreseen and standardized that the land use is equal for all sites. The calculated analysis would have been more accurate by using the real data about the leasing, drilling, stimulation, etc., and similar activities in different geological settings. However, since such detailed data was not available the standardized value was used for all sites. The plant equipment cost depended on the installed capacity and the ‘six-tenth rule’ was used to evaluate these costs for each demo site. When capital investment is expressed in €/kW, the highest capital cost has the sedimentary site (9,508 €/kW), followed by the meta-sedimentary (9,450 €/kW), crystalline site (8,065 €/kW), and volcanic site with lowest (4,096 €/kW). Such variation comes from differences in installed capacity for sedimentary, meta-sedimentary, and crystalline rocks sites and total investment costs which are around 60% lower for the volcanic site.

Table XVIII. Capital investment costs for each demo site

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Leasing	1,430,000 €	1,430,000 €	1,430,000 €	1,430,000 €
Additional cost	4,095,000 €	4,095,000 €	4,095,000 €	4,095,000 €
Production well cost	11,457,000 €	3,080,361 €	11,457,000 €	11,457,000 €
Injection well cost	10,309,000 €	2,771,707 €	10,309,000 €	10,309,000 €
Stimulation cost	2,000,000 €	537,725 €	2,000,000 €	2,000,000 €
ORC unit	623,559 €	656,200 €	621,343 €	869,269 €
Cold loop ancillaries	74,827 €	78,744 €	74,561 €	104,312 €
Dry cooler	124,711 €	131,240 €	124,268 €	173,853 €
Container housing	155,889 €	164,050 €	155,335 €	217,317 €
Start-up commissioning	46,766 €	49,215 €	46,600 €	65,195 €
Instrumentation	17,679 €	17,679 €	17,679 €	17,679 €
Heat exchanger	326,164 €	326,164 €	326,164 €	326,164 €
Heating network	436,991 €	436,991 €	190,211 €	190,211 €
Engineering	62,184 €	62,184 €	62,184 €	62,184 €
Substation	114,005 €	114,005 €	114,005 €	114,005 €
Piping and valves	120,101 €	120,101 €	120,101 €	120,101 €
Production pump	1,223,704 €	46,358 €	1,223,704 €	1,093,136 €
Injection pump	424,000 €	424,000 €	424,000 €	424,000 €
TOTAL	33,041,580	14,541,724 €	32,791,155 €	33,068,426 €
Specific cost	9,508 €/kW	4,096 €/kW	9,450 €/kW	8,065 €/kW

Individual costs associated with operating and maintenance costs (O&M) for each demo site are summarized in Table XIX.

Table XIX. Summarized operational and maintenance costs (O&M) for each demo site

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Power plant maintenance cost	215,974 €/year	218,448 €/year	215,806 €/year	234,596 €/year
Well field maintenance cost	200,000 €/year	53,770 €/year	200,000 €/year	200,000 €/year
Labour	102,756 €/year	102,756 €/year	102,756 €/year	102,756 €/year
Power plant operating cost	0.0135 €/kWh	0.0058 €/kWh	0.0136 €/kWh	0.0109 €/kWh

O&M costs consist of power plant maintenance cost, wellfield maintenance cost, labour cost, and power plant operating cost. The power plant maintenance cost depends on the installed capacity of the ORC power plant and heating plant, and the 'six tenth rule' was used to obtain those costs. Well field maintenance cost is depth dependent. Only for

Grásteinn site these costs are smaller since the depth of the well is 560 m. Labour costs also depend on the plant installed capacity and the ‘six tenth rule’ was used to calculate them for each site. Power plant operating costs are directly related to the production and injection pumps power, i.e. their consumption. The higher the amount of covered self-consumption of those pumps the lower the operating costs. Financial and economic parameters that were used for the economic analysis are shown in Table XX. Same financial parameters were used for all demo sites.

Table XX. Financial and economic input parameters

Parameter	All scenarios
Discount rate	7.06%
Inflation rate	1%
Effective tax rate	30%
Insurances (of installed costs)	1%
Heat selling price	45 €/MWh
Electricity selling price	100 €/MWh
Capacity based incentive	50% of production well and stimulation cost

2.3.3.1 Results analysis

The results of conducted analysis are shown in the Table XXI. It can be concluded that all four cases are feasible in terms of technology since in all modelled scenarios the heat needs can be satisfied. i.e., there is no unsatisfied heat demand. In the first three sites, a parallel configuration mode is used with the temperature difference in the ORC of 60°C to manage to satisfy all heat demand, except in the last site, where it is decided to implement series configuration mode since it yields higher installed electricity capacity while satisfying the heat demand. As for the electricity production, series configuration in crystalline rocks demo site yielded greater installed ORC capacity and consequently higher electricity production quantities, followed by volcanic, sedimentary, and meta-sedimentary rocks demo site that have similar installed power. Higher wellhead temperature at crystalline site, enables longer exploitation and keeping the temperature difference of ORC, since the reinjection temperature is the same for all demo sites. Also, in series configuration, the fluid flow stays the same and it does not divide according to the heat demand. Such technological settings enable greater production of electricity. The avoided CO_2 emissions are directly dependant on produced energy, emission factor and share of each fossil fuel in fossil fuel mix which are country specific parameters. The meta-sedimentary site has the highest avoided CO_2 emissions, despite not having the highest energy quantities produced, and situated in Belgium, which has 70% of coal in its heat and power production with the high emission factor for coal (2,090 g/kWh). The comparison of produced energy and avoided CO_2 emissions can be seen in Figure 26.

Table XXI. Analysis results for each case of combined heat and power scenario

Parameter	Sedimentary rocks	Volcanic rocks	Crystalline rocks	Meta-sedimentary rocks
Installed capacity - heat	2,630 kW	2,630 kW	2,630 kW	2,630 kW
Total produced heat	342,418 MWh	342,418 MWh	342,418 MWh	342,418 MWh
Total unsatisfied heat demand	0 MWh	0 MWh	0 MWh	0 MWh
Installed capacity - electricity	845 kW	920 kW	840 kW	1,470 kW
Configuration	Parallel	Parallel	Parallel	Series
Total produced electricity	182,927 MWh	203,219 MWh	177,988 MWh	248,887 MWh
LCOH	261.38 €/MWh	-30.52 €/MWh	321.77 €/MWh	250.62 €/MWh
LCOE	287.87 €/MWh	-92.21 €/MWh	403.2 €/MWh	292.79 €/MWh
Total avoided CO_2 emissions	255,543 tonnes	291,402 tonnes	823,230 tonnes	245,872 tonnes

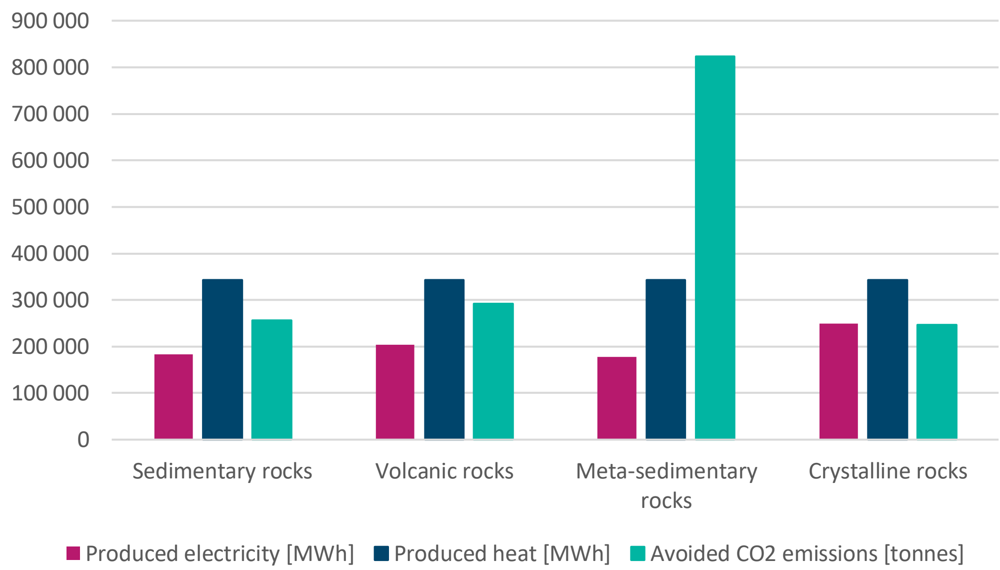

Figure 26. Total lifetime produced electricity, produced heat, and avoided CO_2 emissions for each demo site

The results of LCOE and LCOH calculations for each analysed demo site are shown in Figure 27 and Figure 28. The sedimentary, meta-sedimentary, and crystalline sites have positive LCOE higher than the average wholesale electricity price (both from September 2021 and in the last 12 months). Based on the aforesaid, it can be concluded that these scenarios are not market competitive with the other sources of energy, such as natural gas. The LCOE values of volcanic can be explained with the low capital investment costs and high revenues from selling heat. It can be concluded that performing the combined heat and power scenario at volcanic site will be profitable during the operational phase. The meta-sedimentary site has the highest LCOE which is the result of lowest installed capacity and one of the highest capital costs among the sites, followed by crystalline rocks site and sedimentary site. The value of LCOH is lowest for the volcanic site since the revenues from selling the electricity exceed the capital investment costs, and thus making the development of geothermal project and energy exploitation at the mentioned site competitive with other energy source such as natural gas. The remaining three sites have much higher LCOH value, with meta-sedimentary site having the greatest LCOH, followed by sedimentary and crystalline rocks demo site. The high values of LCOH are explained with high capital investment costs and small amount of produced energy and the lack of incentives.

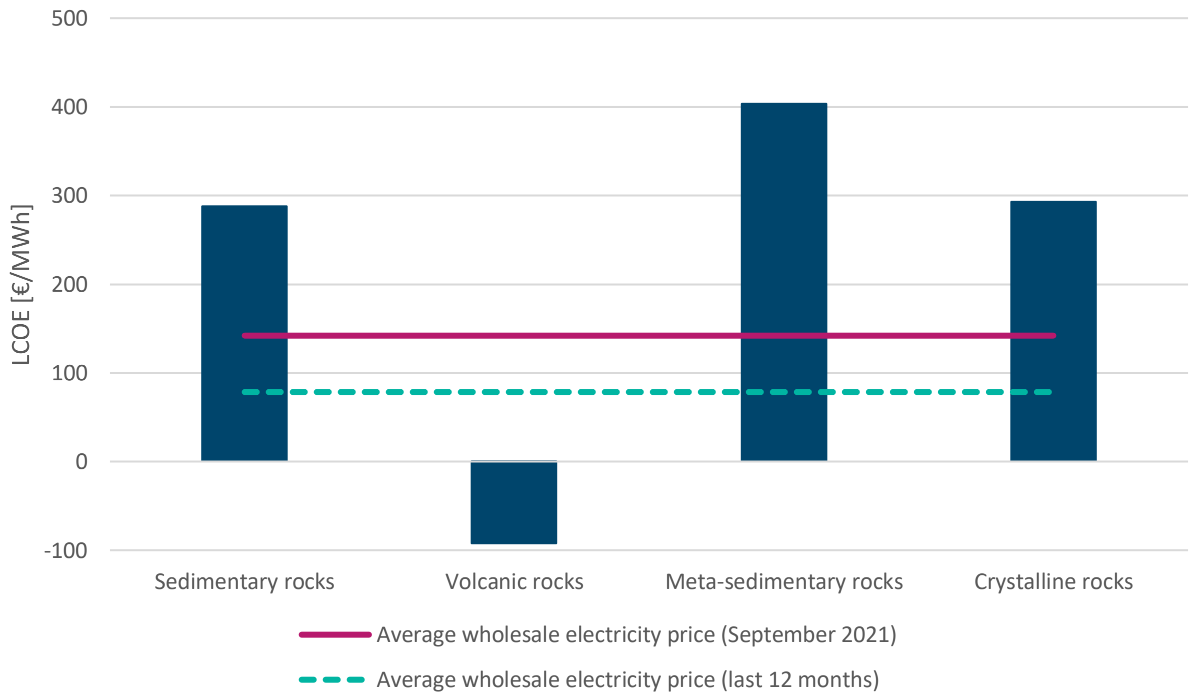

Figure 27. LCOE for each demo site in comparison with average wholesale electricity price in September 2021 and last 12 months (September 2020 - September 2021) [18]

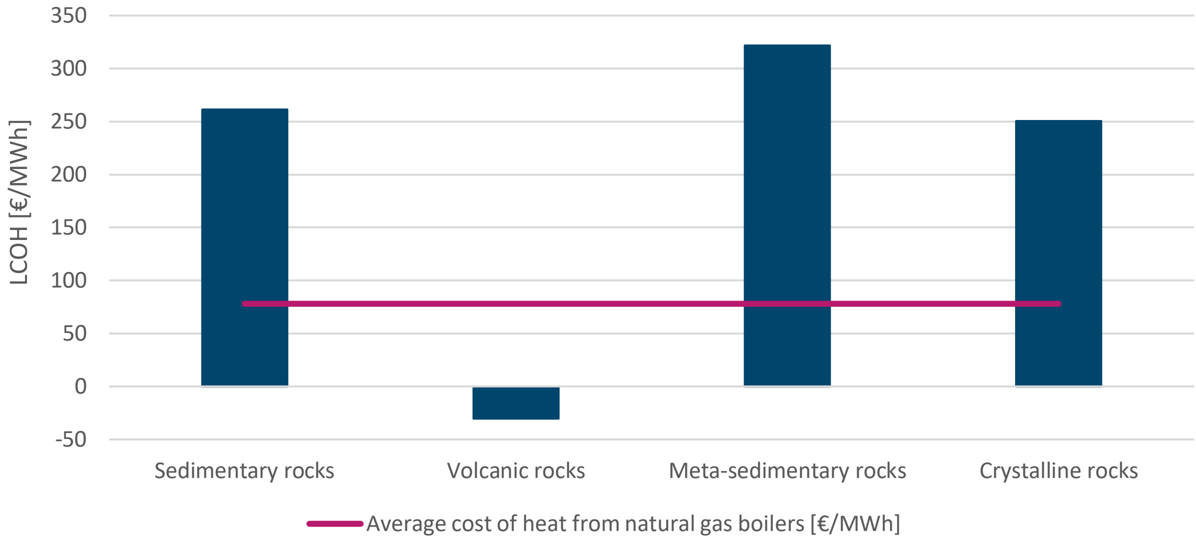

Figure 28. LCOH for each demo site in comparison with average cost of heat from natural gas boilers [17]

Additionally, the MCDM analysis was performed for all demo sites regarding only electricity production. The results of MCDM analysis were calculated with the corresponding weighted factors (Figure 13) and are shown in Figure 29 where the highest grade was calculated for the volcanic site, followed by the sedimentary site, and then the crystalline and meta-sedimentary sites. Since all the scenarios have similar technological and investment costs, with slight difference for volcanic site, predominant factors were mostly from the geological and economic group of factors. It can be concluded that the most feasible CHP scenario, according to the MCDM analysis was the scenario at the volcanic site, due to its high values of permeability and porosity, followed by sedimentary site. This comes from the fact that sedimentary site has slightly lower grade for capital costs criterion since sedimentary had the highest capital investment costs in €/kW (Table XII). Additionally, volcanic site is the only analysed site that could have discounted payback period lower than the project lifetime. Furthermore, since both LCOE and LCOH for volcanic have negative values, it means that the revenues from secondary product (either heat or electricity is primary product of the CHP plant) are higher that the investment and operational costs which leads to the highest grade for this criterion. As it can be seen from the final results the reservoir temperature, which is the highest at crystalline site did not have such big influence in final grade, because all other sites had also quite high temperatures. Meta-sedimentary site did not only had the worst evaluation of permeability and porosity factors, but also lower wellhead temperature than crystalline rocks site, and consequently lower global efficiency of the power plant which led to the lowest final grade of meta-sedimentary site.

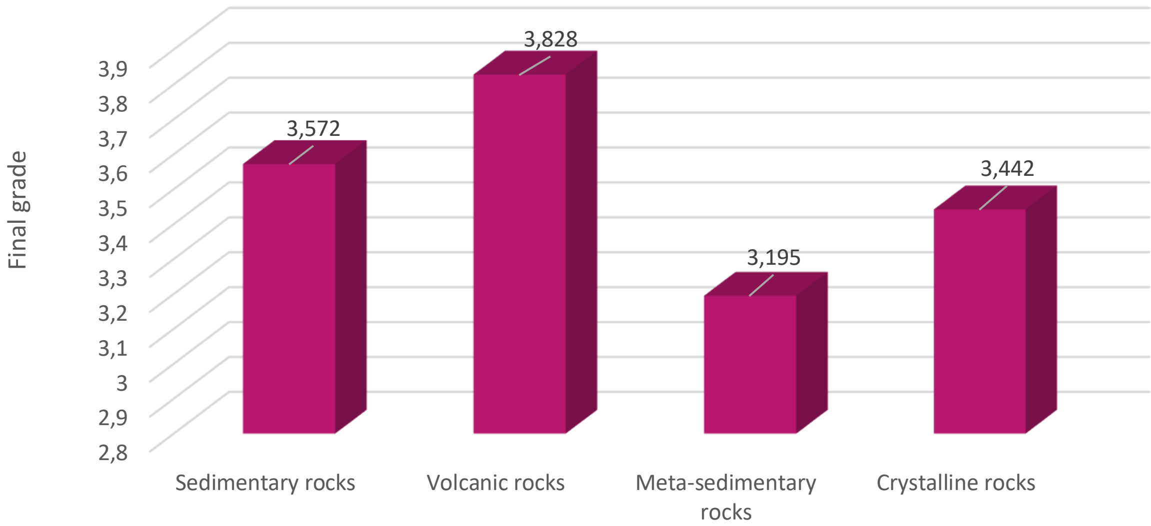

Figure 29. Final grades for each demo site obtained with MCDM analysis

3 CONCLUSION

In the Deliverable 7.2, a site-specific analysis of various EGS demonstration sites in different geological conditions was caried out. The analyses were made by using the decision-making support tool developed within the MEET project which enables the investor with different background and level of expertise to conduct comparative analysis of different geothermal energy usage at chosen geothermal site, taking into account various influencing factors. The main input parameters for sedimentary rocks, volcanic rocks, crystalline rocks, and meta-sedimentary rocks were taken from the demo sites within the MEET H2020, that is, the Cazaux site, Grásteinn site, UDDGP site, and Havelange site. Three scenarios have been conducted based on the different end-usage: only heat production scenario, electricity production scenario, and combined heat and power production scenario. After obtaining all performance and economic results, the multi-criteria decision-making analysis (MCDM) was done, which is an additional feature of the DMS-TOUGE. The MCDM as a subprocess of the DMS-TOUGE enables a comprehensive understanding of the interaction between economic, geological, social, environmental, and technical uncertainties. Namely, the MCDM feature enables investors with different background and point-of-view to evaluate geothermal projects (with emphasis on EGS). However, this evaluation is directly influenced by preferences of the decision-maker and consequently can vary noticeably. Namely, the decision-maker creates the preferable ranking of determined influencing criteria by giving more importance to specific criteria. This is obtained with the usage of Analytic hierarchy process (AHP) method. Namely, decision makers are more reluctant to make gut decisions based of feelings and hunches, and instead prefer to use analytic and quantitative tools, and base and analyse their decisions on a solid ground. The AHP method allows decision-makers to put emphasis, i.e., more importance to specific criteria, therefore this method is selected as suitable for the purpose of this Deliverable. Namely, it can be used to somehow consider different geological setting and belonging main characteristics into account which highly influence the outcome of decision related to the potential investment.
For the comparison of each site in every end-usage, the boundary condition were needed to be set, where it is decided that the first layer of equalizing would be the well depth, due to the majority of input data were from the cost, and the second layer of equalizing would be the temperature, when there is not possible or economic to reach the same depth in a certain reservoir rocks. Regarding the heat production scenario, with the given input parameters and conditions, all four sites were able to deliver the heat demand, having the same installed capacities. The lowest LCOH had the volcanic rock site the low production and injection well depth, i.e., the related costs, where the targeted temperature is reached at the lower depths. After conducting the AHP analysis, the volcanic rock site resulted in having the highest final grade, since the rest of the sites have the similar technological and economic background, predominant factors were mostly from geological group, i.e., high permeability and porosity values. The additional value for the final grade brought the sub-criterion for the scaling and corrosion since it was not present on the chosen volcanic site.
Regarding the electricity only scenario, with the same flow, different wellhead temperature and the locations, which influences the air temperature (coolant), the highest installed

capacity had the meta-sedimentary rock site, and consequently the highest total produced electricity. The production quantities directly influenced the LCOE, which was the lowest of all four sites, followed by the LCOE from the volcanic rock site. After conducting the AHP analysis, the volcanic rock site resulted in having the highest final grade, since the rest of the sites have the similar technological and economic background, predominant factors were mostly from geological group, i.e., high permeability and porosity values. It can also be concluded that the meta-sedimentary site, having the highest wellhead temperature, did not have such a big influence in the final grade, because all other sites had high temperature, and greater values of permeability and porosity then meta-sedimentary site.

Regarding the combined heat and power scenario, all four sites were able to deliver the head demand, having the same installed capacity for heat production, while the installed capacity for electricity production differentiated, with meta-sedimentary rock site having the highest installed power while performed in series configuration. The lowest LCOE and LCOH hade the volcanic site, having the negative values of LCOE and LCOH. These values can be justified with the revenues from heat or electricity (secondary product) being grater then the investment and operational costs. The highest values of LCOE and LCOH had the crystalline rocks site due to its high investment and operational cost and lowest electricity installed capacity. After conducting the AHP analysis, the volcanic rock site resulted in having the highest final grade, since the rest of the sites have the similar technological and economic background, predominant factors were mostly from geological group, i.e., high permeability and porosity values. In addition, it is the only site that could have discounted payback period lower than the project lifetime. It can be seen from the final results the reservoir temperature, which is the highest at crystalline site did not have such big influence in final grade, because all other sites had also quite high temperatures. Meta-sedimentary site did not only have the worst evaluation of permeability and porosity factors, but also lower wellhead temperature than crystalline rocks site, and consequently lower global efficiency of the power plant which led to the lowest final grade of Havelange meta-sedimentary site.

The biggest constraint of the conducted analysis was the lack of needed data where the conduced analysis would result in more credible results if there were any real existing data. For most of the sites and the corresponding data, i.e., missing data, the advice, and instructions from experts involved were to follow analogue site, take values from the literature, or take the reference values for the asked data. So, by following the given instructions, the authenticity and credibility of the site are lost.

Also, to get meaningful results, the boundary conditions should be the same, in presented case the depth is the reference value, since most data that were delivered were for the costs, so it was the chosen approach. The second condition was the temperature since there is no sense in drilling the 5,000 m deep well in the volcanic rock in. The reason for choosing the temperature as the second boundary condition was the lack of the data about the geothermal gradient for some of the reference sites. That resulted in different temperatures and depths for a specific demo site. From the available data, the reference sites are different, but when it comes to approximating some value due to the lack of data, the difference between them is decreasing. Because of it, the same operating parameters are taken in the analysis, to emphasize the geological settings. Consequentially, the drilling costs in different geological settings are not the same, but since, in general, the data about the drilling costs are confidential, there was other way than to approximate the cost with the gathered data about the cost. Taking it all into account, it can be concluded that there is more space for the upgrading of the conducted analysis using the developed tools with gathering more input data which are from real site or credible enough to replicate different geological setting.

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