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Evaluation of the geothermal energy potential of Switzerland- a techno-economic approach

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ABSTRACT

This research evaluates the geothermal energy potential in Switzerland focusing on different geothermal systems (hydrothermal, EGS, AGS) and purposes (heat or electricity). The evaluation utilises subsurface properties, expected costs for the infrastructure and drilling, and demand for the generated heat or power. A techno-economic model is developed to assess the feasibility of utilising geothermal resources for energy generation, with a specific focus on economic viability as the most critical factor. The results are presented through potential maps, highlighting favourable locations for a geothermal system. The maps aim to simplify the site search process, reducing costs associated with preliminary work for geothermal projects. The research considers three different temperature scenarios for heat (60 °C and 100 °C) and electricity purposes (150 °C). The results show that the Molasse Basin is a favourable region for hydrothermal systems, while the Jura region presents a potential for EGS projects.

1. GEOTHERMAL ENERGY IN SWITZERLAND

The use of geothermal energy in Switzerland is currently limited to the extraction of thermal energy for heating and cooling purposes or balneology (EnergieSchweiz and AG, 2017). Borehole heat exchangers with heat pumps are by far the predominant applications in Switzerland. The only large-scale geothermal district heating plant is located in Riehen near Basel. Case studies from neighbouring Germany indicate that the geology of the pre-Alpine Mo- lasse basin and the Upper Rhine trench is well-suited for geothermal energy extraction, including electricity generation. (Eyerer et al., 2017).

To achieve the defined net zero target, Switzerland must also use geothermal energy for its power supply. The ambitious goal for Switzerland is to produce 4.4 TWh geothermal electric power by 2050, which would cover 7% of the electricity consumption in Switzerland (EnergieSchweiz and AG, 2017).

The map in Figure 1 illustrates the operational deep geothermal plants in Switzerland, along with the ongoing and former deep geothermal projects in the country. The projects and plants in the map are classified into the following plant types: Deep geothermal probes, hydrothermal, petrothermal systems (synonymous with EGS) and High- Temperature Aquifer Storage (HT-ATES).

Out of a total of 15 hydrothermal projects, only three are in operation - Riehen (for district heating), Schaffhausen (for agriculture), and Vaud (for thermal bath heating).

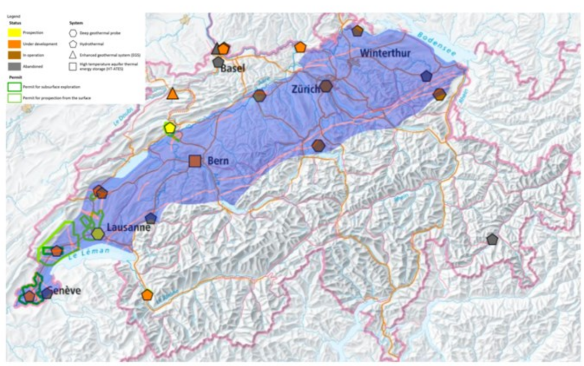


Figure 1: Deep Geothermal Projects in Switzerland with the Molasse basin highlighted in blue (Swisstopo, 2023a).

The majority of deep geothermal projects are concentrated within the Molasse Basin shown in Figure 1 by the blue colour or above in the Jura region (Swisstopo, 2023a). The two main complications of planning deep geothermal plants are the limited knowledge about the subsurface and the high initial investment costs. When realising a hy- hydrothermal project the greatest financial risk is related to the forecast of the flow rate and the permeability of the reservoir rather than the temperature (Link and Zingg, 2017).

2. GOAL AND MOTIVATION

The main goal of this work is to evaluate the geothermal energy potential in Switzerland with a high degree of detail and highlight favourable spots for the different geothermal systems (hydrothermal, EGS, AGS) and purposes (heat or electricity). This evaluation is based on subsurface properties and expected costs to guide future operators to successfully place their first exploration in a favourable location. To achieve this goal, available geological and geophysical data, information about the costs of a project, and the demand for the generated heat or power are evaluated for all of Switzerland. The focus is intentionally on the economic viability of a project given its status as the most constraining factor. A potential map is drawn, showing the respective favourable locations for each system (hydrothermal, EGS, and AGS), which developers could use to identify future project sites.

To separate the different purposes and applications of geothermal energy, three different target temperatures are determined: 60 °C, 100 °C, and 150 °C. The temperature values selected for analysis were chosen based on existing isotherms for the Molasse basin, which describe the respective depth of these temperatures in the subsurface (Swisstopo, 2022a). The lower temperatures of 60 °C and 100 °C can be used for heat and district heating applications, while the 150 °C temperature can be utilised for both electricity generation and heating purposes.

Geothermal systems with fluid temperatures between 95 °C and 150 °C have a low energy density, resulting in limited energy conversion efficiency. Binary cycle power plants, utilising a low-boiling-temperature fluid heated via a heat exchanger, can produce electricity via the organic Rankine cycle (ORC) and typically have efficiencies ranging from 10 to 20% (Chamorro and Mondejar, 2022). Reservoir temperatures of 100 °C or less in the reservoir are insufficient for electricity production.

This paper does not further explore the 100 °C case for electricity, as it employs a techno-economic approach and considers the associated high risk of potential losses. This paper follows the workflow of Brasnett (2022), who pursued similar goals for the province of Alberta in western Canada for his master's degree at the University of Calgary (Brasnett, 2022).

3. METHODOLOGY AND RESULTS

The research is carried out using the geographic information system ArcGIS Pro. The template for the grid for Switzerland was taken from the "Federal Office of Topography" page. The orthophoto mosaic "SWISSIMAGE 10 cm" is a composition of digital colour aerial images over the whole country. It has a ground resolution of 10 to 25 cm and divides Switzerland into about 42'700 tiles of 1 km x 1 km (Swisstopo, 2020).

Temperature plays a key role in the feasibility and effectiveness of geothermal systems. The ability to access and utilise a specific temperature range is of utmost importance, as it directly influences the efficiency of power generation and heat extraction processes.

In the Northern part of Switzerland, extensive investigations have been conducted by Nagra (Swiss National Cooperative for the Disposal of Radioactive Waste) to explore the sub-surface in relation to finding the most suitable site for deep storage of nuclear waste and therefore more information exists about the subsurface temperature. For the southern part, only individual deep wells with temperature and depth information are available, especially for some of the valleys (Swisstopo, 2023b).

The temperature map is interpolated from these two datasets. Due to the low density of data in southern Switzerland, there is greater uncertainty in the resulting isotherms.

3.1 NPV (Net Present Value)

Net Present Value is a financial metric used to evaluate the profitability of an investment or project in the future. It consists of summing the discounting future cash inflows and outflows resulting from project operation with a certain discount rate r over the lifetime n of the project (Zizlavsky ́, 2014).

Lifetime costs and lifetime revenues were estimated in Swiss Francs (CHF) for each grid cell of the cost and revenue layers. Both the costs and the revenues are summarised in the net present value in equation 1 to give an overall statement of the rentability and therefore the feasibility of a project:

$$NPV = \sum_{i}^{n} \frac{AnnualRevenue_i}{(1+r)^i} - InitialCosts \qquad (1)$$

A geothermal project lifetime is assumed to be 30 years but is heavily dependent on the permeability of the reservoir, the production rate, the distance between the two wells, and geothermal heat flux (Smit, 2014). The discount rate reflects the time value of money and the risk associated with an investment, where a higher discount rate indicates higher risk or a greater opportunity cost. This rate is considered to be 7.5% for Switzerland as a part of the Organisation for Economic Co-operation and Development (OECD) (IRENA, 2020).

3.2 Project costs

3.2.1 Surface Infrastructure: Roads

One factor that complicates the construction of wells and the power plant is the slope of the terrain. Therefore, a global layer with the terrain slope in degrees was downloaded from the Living Atlas and integrated into ArcGIS Pro (ESRI, 2023a). The global layer was extracted for Switzerland and the mean was obtained for every 1 km x 1 km- Raster.

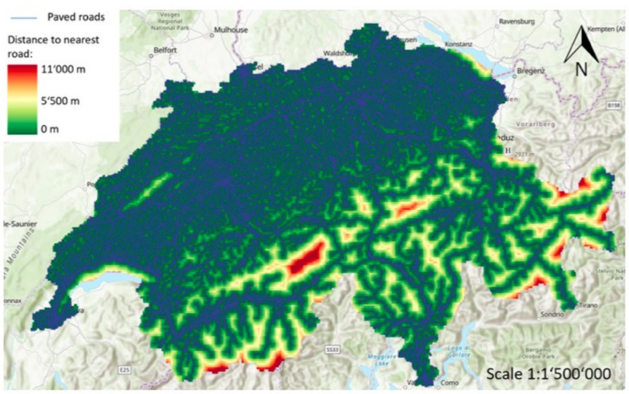
Assumptions are made that an 80% slope gradient, which represents approximately 40 degrees, can multiply the costs for a road by 5. This assumption is made based on a model for more accurate estimations in road costs, established on terrain surface properties (Stuckelberger et al., 2006).

This cost assumption for road costs was adopted for the other infrastructure elements as the pipelines and transmission lines and the facility construction costs. All these costs were multiplied by a factor of (1 + slopeindegree/10).

The construction of roads for geothermal projects involves designing and building a transportation network that provides reliable access to project sites. These roads not only connect the project site to existing transportation routes but also serve as a conduit for the delivery of infrastructure components. T

he swissTLMRegio Transportation road network (Swis- stopo, 2022c) contains all roads and paths of Switzerland. The non-paved roads, which also include hiking trails and similar paths, were excluded from the dataset as they are not suitable for accommodating the transportation needs associated with the geothermal system. The width of the roads was not included in the attribute table of the data set, which could otherwise have led to a second selection process. The following map in Figure 2 shows the nearest distance to every paved road for each cell in the 1km x 1km grid using the "Euclidean Distance"- tool. The spatial Analyst-tool from ArcGIS Pro calculates the distance from each cell in a raster to the nearest source cell, measuring the distance in a straight line between the cell centres (ESRI, 2023b).

Figure 3 shows the number of costs added to build the missing roads for each cell in the 1 km x 1 km grid for Switzerland.



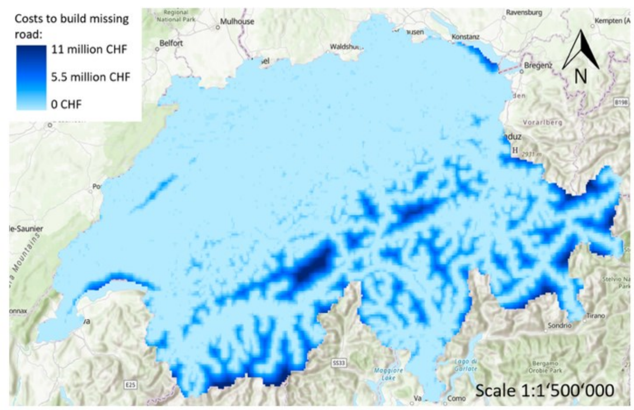


Figure 2 (left): Distance to the nearest road for each cell in the 1 x 1 km grid for Switzerland. Figure 3 (right): Costs to build the missing roads for each cell in the 1 x 1 km grid for Switzerland

3.2.2 Direct Use Heat: Pipelines

The transport of the extracted heat leads to the need for additional infrastructure and thus to additional costs. The cost calculation considers the heating demand in Switzer- land and the costs for heating pipeline installation.

Insulated pipes are rarely used for heat transport purposes in Switzerland due to their expense. This means that normal pipes are used, but a fixed heat loss must be included.

For the heat demand map, the buildings in Switzerland were downloaded from Swisstopo, 2022b. The residential density was then calculated using the "Kernel Density" tool in ArcGIS.

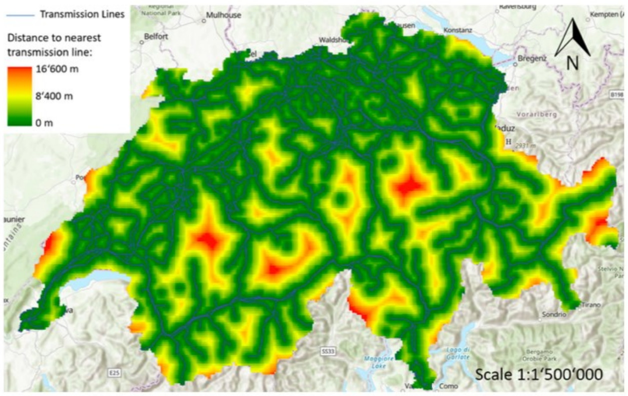
According to the information sheet of the Central Agricultural Commodity Marketing and Energy Network (C.A.R.M.E.N), the costs for medium-sized heating networks are between 200 and 400 C per metre of pipe laid for Germany. Given the higher cost environment in Switzer- land and the expectation of implementing a medium to large system, an assumed value of 500 CHF/m is adopted (C.A.R.M.E.N, 2013).

3.2.3 Surface Infrastructure: Transmission Lines

Swissgrid is the national grid company and is responsible for the secure operation and monitoring of the Swiss trans-mission grid. From the costs of recent transmission line projects the assumed mean of overhead power line construction costs per kilometre would be 2.92

million Swiss francs. Construction costs depend on the total space crossed. Important factors are topography and subsurface composition, but also potential natural hazards and natural obstacles that require different routes for the power lines (Swissgrid, 2019).

The existing transmission lines in Switzerland were extracted from the global dataset ”Global Transmission Net- work” by Rachel Fox (2020). With the ”Euclidean Distance”-Tool in ArcGIS the nearest distance to a trans-mission line was calculated for every of the approximately 47’000 grid points. Figure 4 shows this distance. The red colour highlights the locations in Switzerland with the largest distance to an existing transmission line. In Figure 5 the mean cost per kilometre for transmission lines was added for each grid cell.



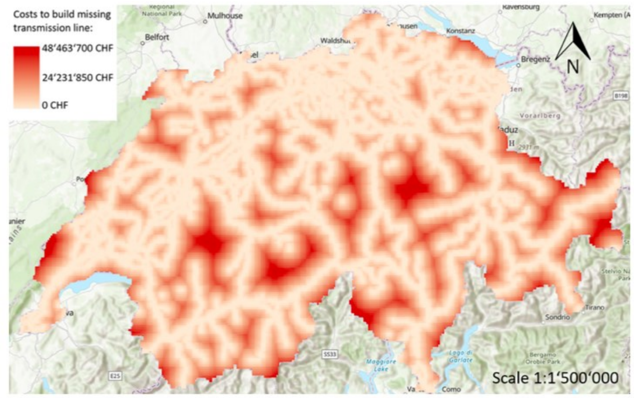


Figure 4 (left): Distance to the nearest transmission line for each cell in the 1 km x 1 km grid for Switzerland. Figure 5 (right): Costs to build the missing transmission line for each cell in the 1km x 1km grid for Switzerland

3.2.4 Drilling costs

Two primary pieces of information define the drilling costs to a certain temperature at the subsurface: the necessary borehole depth to the wanted temperature and the drilled material. To simplify, the latter is subdivided into sedimentary or crystalline.

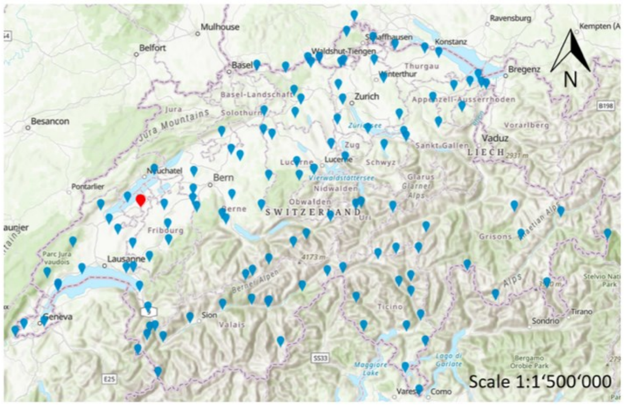
Deep wells are nowadays drilled using conventional rotary drilling methods. These methods involve a complex rig that rotates a string of drill pipes to create the borehole. While this works well in soft rocks, it becomes challenging in harder, crystalline rocks. In the softer rocks, the penetration rates are reaching up to 30m/hr compared to drilling speeds of 1-7m/hr for the crystalline rock or even lower due to the need for frequent bit replacement (Wang et al., 2017). Recent work has shown significant improvements in drilling rates in igneous rock, however, a conservative estimate was used in this work.

A comprehensive depth map delineating the initiation of crystalline formation does not exist. In the Molasse basin, the solution was to create as many virtual wells as possible with the GeoMol viewer and extract the BMes (Basis Mesozoic) values, which mark the basis of the Mesozoic.

Data from deep wells (Swisstopo, 2023b) was utilised for areas outside the Molasse basin, while a depth factor of 0 was assigned to account for the distance from the surface to the basement in regions where the crystalline formation is exposed at the surface. These areas were identified by a lithological map of Switzerland called ”Groups of rocks”. The map classifies the subsurface material into unconsolidated rocks, sedimentary rocks and crystalline rocks (Swisstopo, 2006).

Finally, a sediment cover was added to the Rhone valley, which in turn was derived from a Swisstopo filter ” Thickness model of unconsolidated deposits” (Swisstopo, 2021).

Figure 6 shows all locations used to extrapolate the necessary borehole depth from the surface to reach the crystalline. The extrapolation was done with the ”Empirical Bayesian Kriging”-Tool in ArcGIS and is shown in Figure 7.



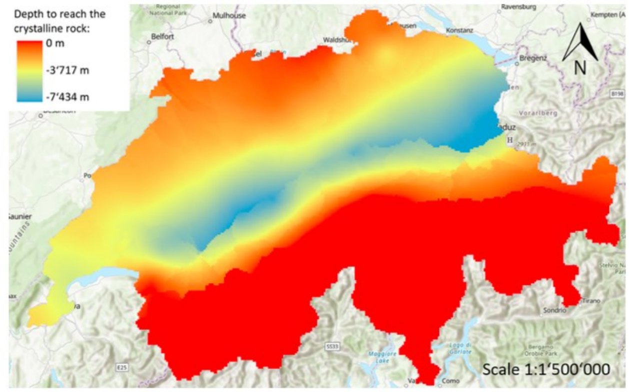


Figure 6 (left): Data points to estimate the depth of the crystalline rock. The red pin marks the location of the virtual borehole. Figure 7 (right): Extrapolation of the depth to the crystalline rock made in ArcGIS Pro with the "Empirical Bayesian Kriging"- tool.

Drilling costs differ for crystalline or sedimentary rocks. To calculate the final drilling costs at each grid point, the drilling depth in ArcGIS was divided into metres of sediment and metres of crystalline for all three temperatures.

For the case of the 100 °C the initial assessment involved comparing the required borehole depth of 100 °C with the depth to reach the crystalline formation. In cases where the borehole depth surpassed the depth to the crystalline, the drilling procedure involved penetrating both sedimentary layers and the crystalline basement, excluding regions within the Alps where the crystalline formation is directly exposed at the surface. Conversely, if the borehole depth fell short of the depth to the crystalline, the drilling process solely targeted the sedimentary layers until reaching the desired point. In Figure 8 this "sediment only"- sector is represented by the green colour.

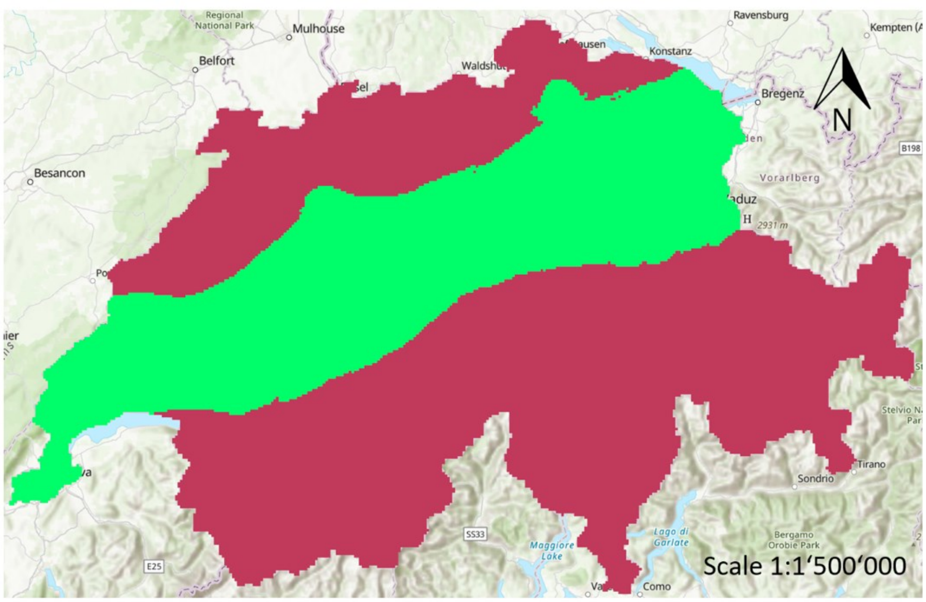
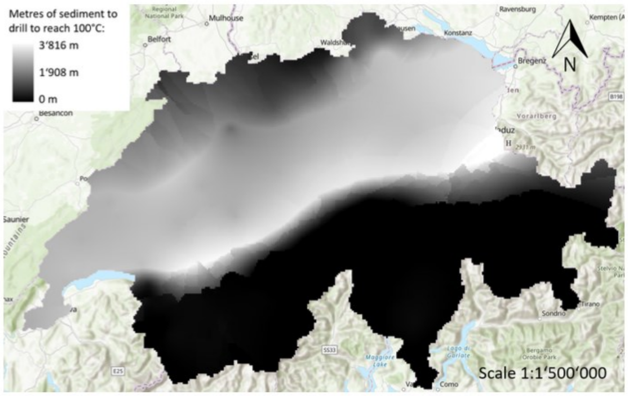


Figure 8: The green area symbolises that the necessary borehole depth to reach 100 °C lies in a smaller distance from the surface than the depth of the crystalline (no crystalline has to be drilled). In red areas, the crystalline is reached before the 100 °C is reached.

As expected the area of the "sediment only"- piece becomes smaller as the desired temperature rises. Following the division, the number of drilling metres required in sediment and crystalline formations can be calculated. Figure 9 il- lustrates the number of meters in sediment, while Figure 10 shows the number of meters drilled through crystalline.



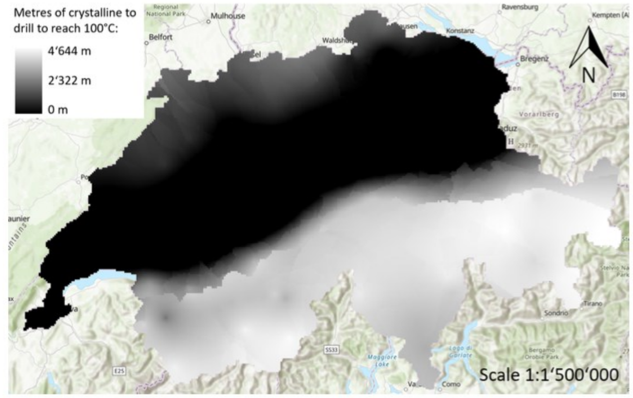


Figure 9 (left): Metres to drill into the sediment to reach a temperature of 100 °C. Figure 10 (right): Metres to drill into the crystalline to reach a temperature of 100 °C.

The paper of Mallants et al., 2021 gives an overview of drilling into sediment costs compared to drilling into hard rock (granite) costs. The costs include mobilisation and de-mobilisation of the rig, the cost of the drill bits, drilling fluid, fuel, casing, and cementing as well as the cost of engineers and site supervisors. These values are representing large diameter boreholes of 0.76 m. It is assumed that normally the boreholes for geothermal drilling are slightly smaller and therefore the values are rounded down (Serpen and Korkmaz Basel, 2015). The last column in Table 1 corresponds to the value used per metre of drilled material to calculate the final drilling costs for Switzerland.

Table 1: Activities and costs for drilling a deep large-diameter borehole, adapted from Mallants et al., 2021

	Sediment	**Crystalline**
Costs for a 3km borehole [CHF]	14'077'946	19'950'264
Costs per metre [CHF/m]	4'693	6'650
Assumed costs for smaller diameter [CHF]	4'000	6'000

3.2.5 Reservoir Stimulation

Stimulation of geothermal reservoirs is needed if the permeability, e.g. fluid pathways is not sufficient for a commercial operation of the wells and power plant. There are three different techniques for stimulating reservoirs: hydraulic stimulation with pressurised water, chemical stimulation and thermal stimulation.

Most of the time, in EGS, the stimulation of the crystalline rock is necessary and carried out using hydraulic stimulation. There are two different scenarios, either the rock is completely impermeable before stimulation and new fractures are created through stimulation or low permeable fractures exist and the stimulation creates new permeability through shearing existing fractures (Li et al., 2022).

In an analysis of EGS Development Scenarios for District Heating and Cooling at the Gottingen University Campus in Germany from Romanov and Leiss, 2021, the costs for the stimulation of crystalline rock are predicted to be 2 million euros per well. Taking into account the purchasing power parities and the resulting price relations between Germany and Switzerland leads to costs of CHF 3 million per well for hydraulic stimulation of crystalline rock (BFS, 2015).

Hydraulic stimulation is not only used in EGS. It can also increase the permeability of reservoirs in hydrothermal systems by increasing or initiating secondary porosity and flow pathways. Especially in deep reservoirs with a depth of up to 5 km, the permeability of the rocks is generally not sufficient for the required flow rates to achieve sufficient productivity (Huenges et al., 2004).

3.2.6 Cost Summary

Costs are summarized in the following Table 2 as used in this analysis.

Table 2: All the assumed costs for the analysis and its source

	Baseline value (Reference)
Roads	975 CHF/m x Distance to nearest road in m (Daibau, 2023)
Pipelines	non-insulated pipelines 500 CHF/m (C.A.R.M.E.N, 2013)
Transmission lines	2'920CHF/m x Distance to nearest transmission line (Swissgrid, 2019)
Electricity equipment	3'500$/kW x Electrical output (dependent on flow rate) (Brasnett, 2022)
Facility construction and land purchase	5 Million CHF (Beckers and McCabe, 2019)
Operational expenses and maintenance	10% out of Capital Expenses – > 500'000 CHF/year (personal communication Roman Shor)
Drilling	4'000 CHF/m for sediment and 6'000 CHF/m for crystalline (Mallants et al., 2021)
Reservoir stimulation	3 Million CHF/well (Romanov and Leiss, 2021)

4. RESULTS

4.1 60 °C temperature aim

The generated 60 °C isotherm map in Figure 11 represents an initial preliminary result, indicating the depth at which a temperature of 60 °C is reached throughout the entire country. Temperature is a binding factor, and the depth at which this temperature is attained significantly impacts drilling costs.

The map clearly indicates that in the northern half of Switzerland, the 60 °C isotherm is closer to the surface compared to the southern part covered by the Alps. In the southern region, there are two main areas where the desired temperature is found at shallower depths on average. These areas are the valley in the canton of Valais and the southern part of Ticino.

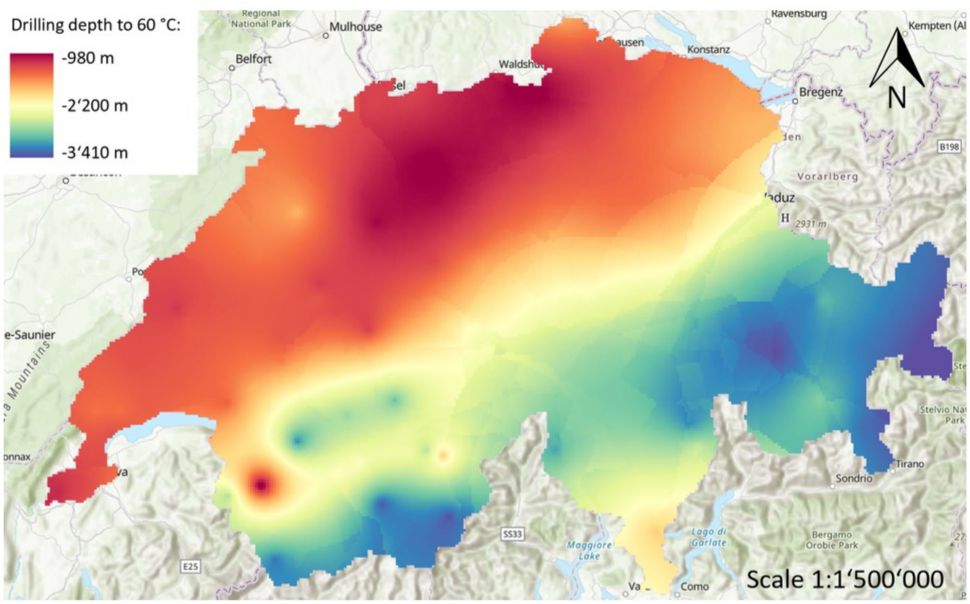


Figure 11: Necessary drilling depth to reach a temperature of 60 °C.

Drilling costs for the depth of 60 °C as the desired temperature are shown in Figure 12. They are calculated with separate prices for drilling into sediment and crystalline. The results show a hard cut between the Northern and Southern parts of Switzerland. In the north, the expected drilling costs do not exceed 10 million Swiss francs at any location, while in the south the costs reach up to 20.5 million CHF.

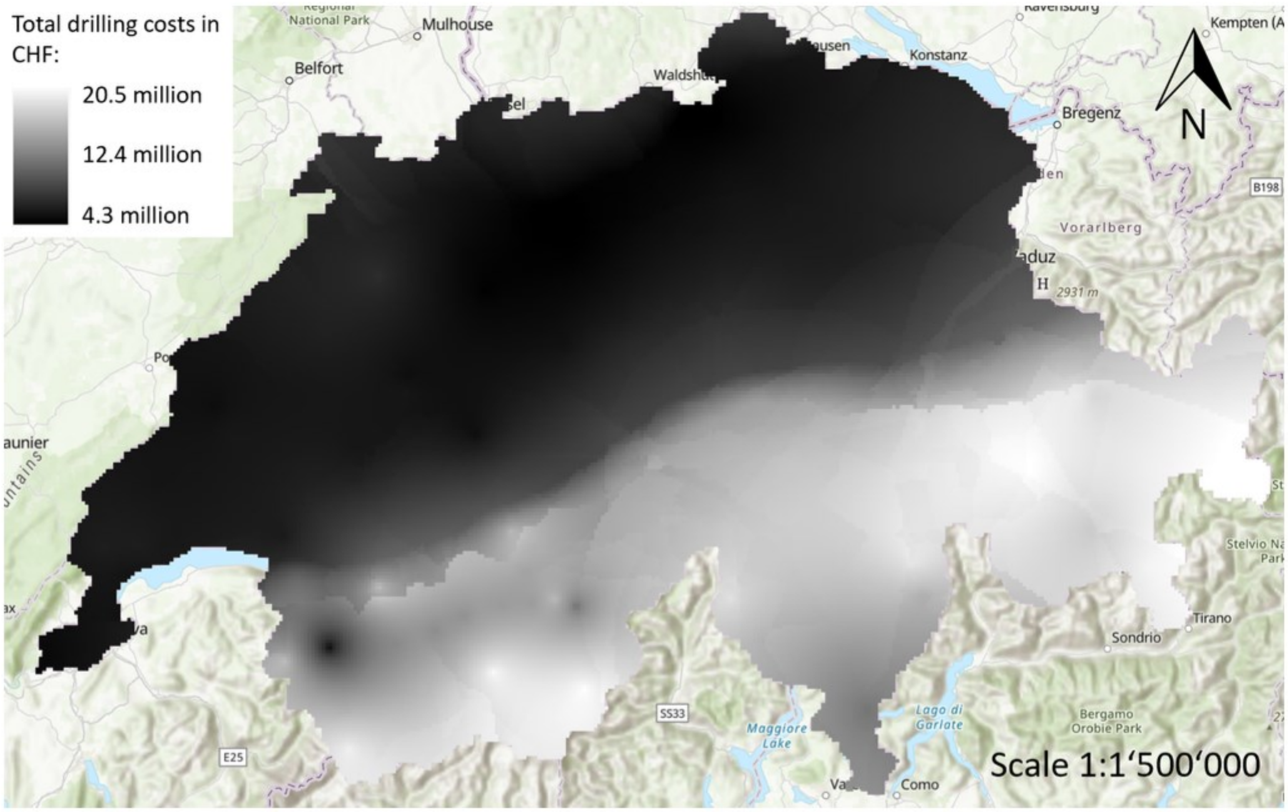


Figure 12: Map of the total drilling costs for the 60 °C temperature.

The 60 °C case is used for heating only. Due to the trans-port of the warm water in uninsulated pipes, a temperature loss per kilometre in the range of 2.0-5.0 °C/kilometre is expected (Chiasson, 2016). This means that the location of the heat demand should be chosen reasonably close to the geothermal system. In the 60 °C case, the distance was set to a limit of 7 km to ensure that a minimum temperature of 25 °C reaches the end user. This minimum temperature is also required for the agriculture and aquaculture industry, where temperatures with values of 25 °C to 90 °C are needed. Space heating typically necessitates higher temperatures ranging from 50 °C to 100 °C. Conversely, cooling and industrial processing typically demand temperatures exceeding 100 °C (Lund and Toth, 2021).

This limitation eliminates remote areas as a location for a lower-temperature geothermal system. The costs for a geothermal system extracting hot water at a temperature of 60 degrees are calculated by inserting all generated parameters into the total cost formula for every part of Switzerland. Figure 13 shows all the possible areas for a geothermal system extracting 60 °C warm water for heating purposes and its final costs.

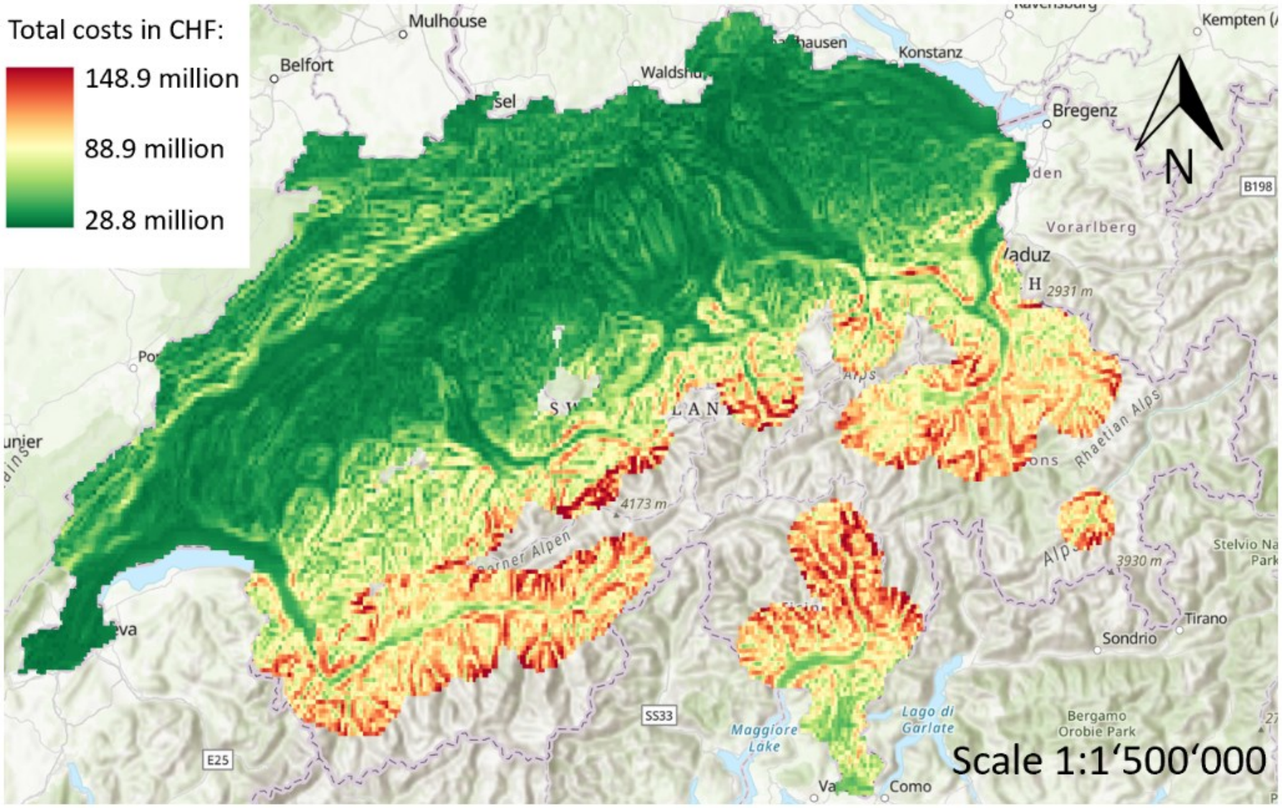


Figure 13: Map of the total costs for the 60 °C temperature extracted for the limit of 6 km pipeline to the areas with high heat demand.

The most lucrative sections to build a geothermal system are clearly visible in the Northern part of Switzerland including the Western parts with the cantons of Vaud and Geneva. Furthermore, the Southern part of Ticino and the Rhone Valley are displayed in light purple and blue colours, indicating that these areas also have the potential as suitable sites for geothermal energy extraction.

The terrain slope has an undeniable impact on the costs seen in the structure of the cost map in Figure 13. The flatter a location, the more advantageous it is cost-wise for constructing a geothermal facility and its associated components. In addition to the Midland region, the valleys are therefore prominently emphasised as favourable areas for geothermal energy in the final cost map.

4.2 100 °C temperature aim

Figure 14 shows the isotherm map for the temperature of a 100 °C. The map reveals that the target temperature of interest initially emerges at a depth of 1'600 meters below the surface within the dark red region. In contrast, the area where the temperature is found deepest in the earth's interior is observed in the east of Switzerland, where such temperatures can be found at depths of up to 4'500 metres.

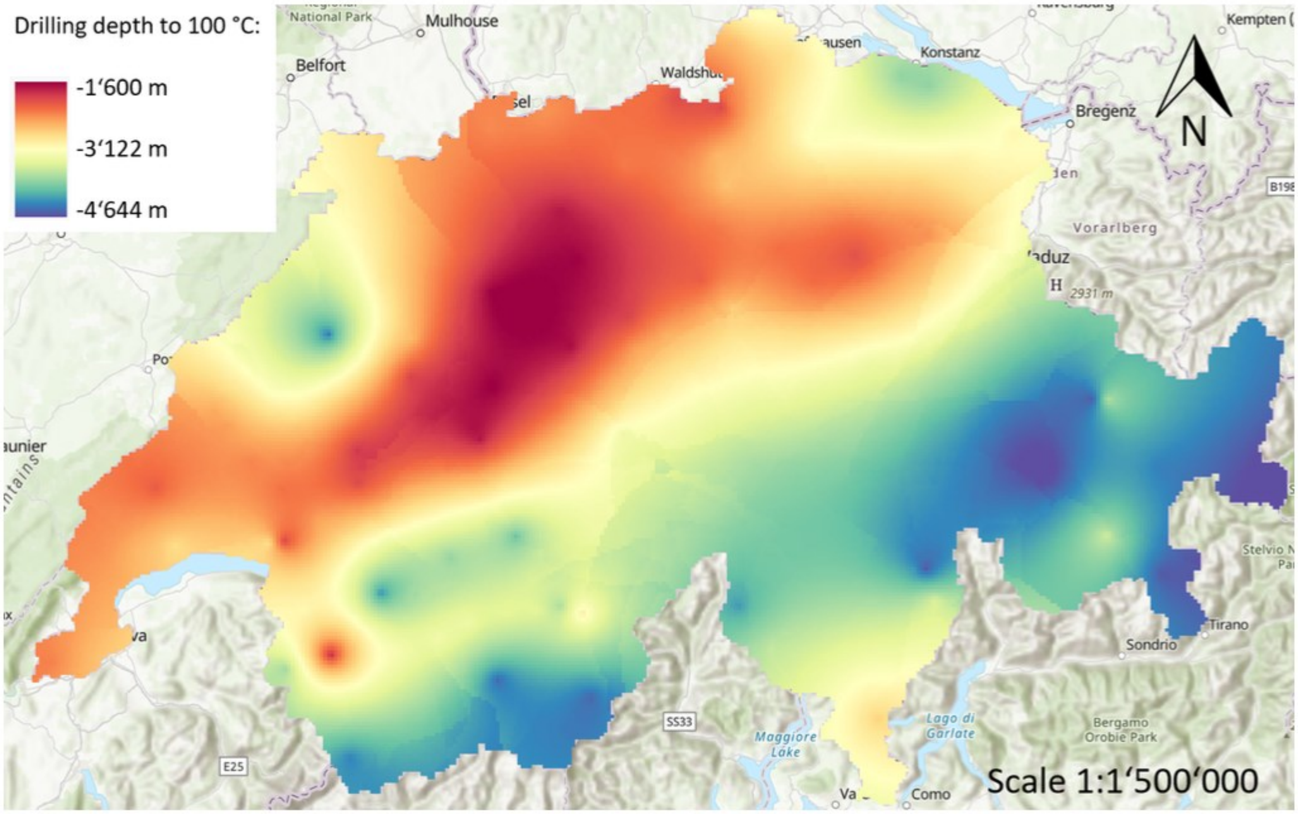


Figure 14: Necessary drilling depth to reach a temperature of 100 °C

In Figure 15 the total drilling costs to reach a temperature of 100 °C for every location in Switzerland are shown. The costs exhibit an inverse relationship with the crystalline drilling thickness required to reach the desired temperature as drilling through crystalline is more expensive than sediment.

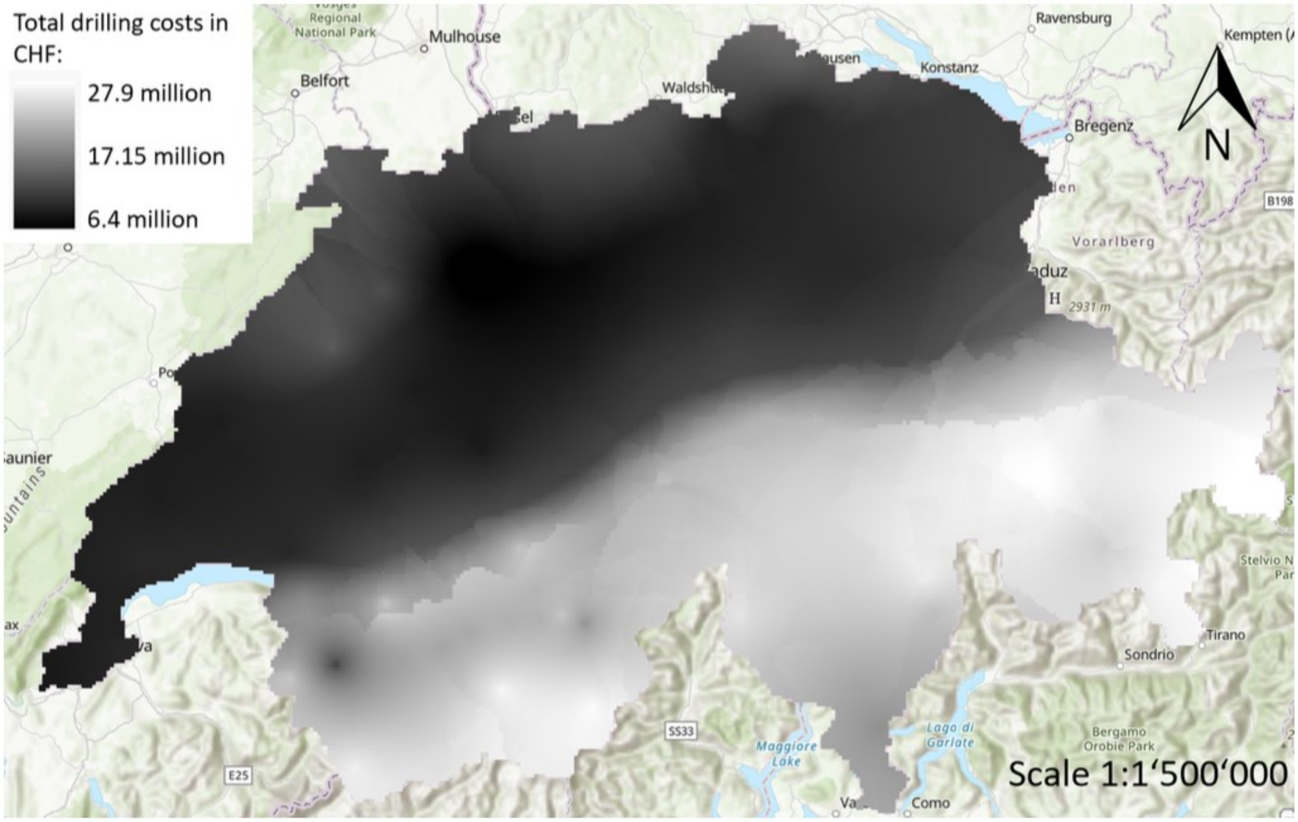


Figure 15: Map of the total drilling costs for the 100 °C temperature.

The final costs have been created with the same formula as in the 60 °C case. The only parameter that changes the two cases is the costs of drilling, which are analogously higher. The limitation distance due to the heat loss was set to 15 km. If the heating demand area is further away, the temperature can drop below 25 °C in the worst-case scenario and the water can no longer be used for agricultural and aqua-cultural uses (Lund and Toth, 2021).

The extracted final cost map is shown in Figure 16. It is not remarkably different from the 60 °C case and highlights the same productive areas. The total expenditure in these areas is generally in the range of 4-5 million CHF more expensive because of the deeper drilling and also of the bigger volume where crystalline has to be drilled for reaching a 100 °C.

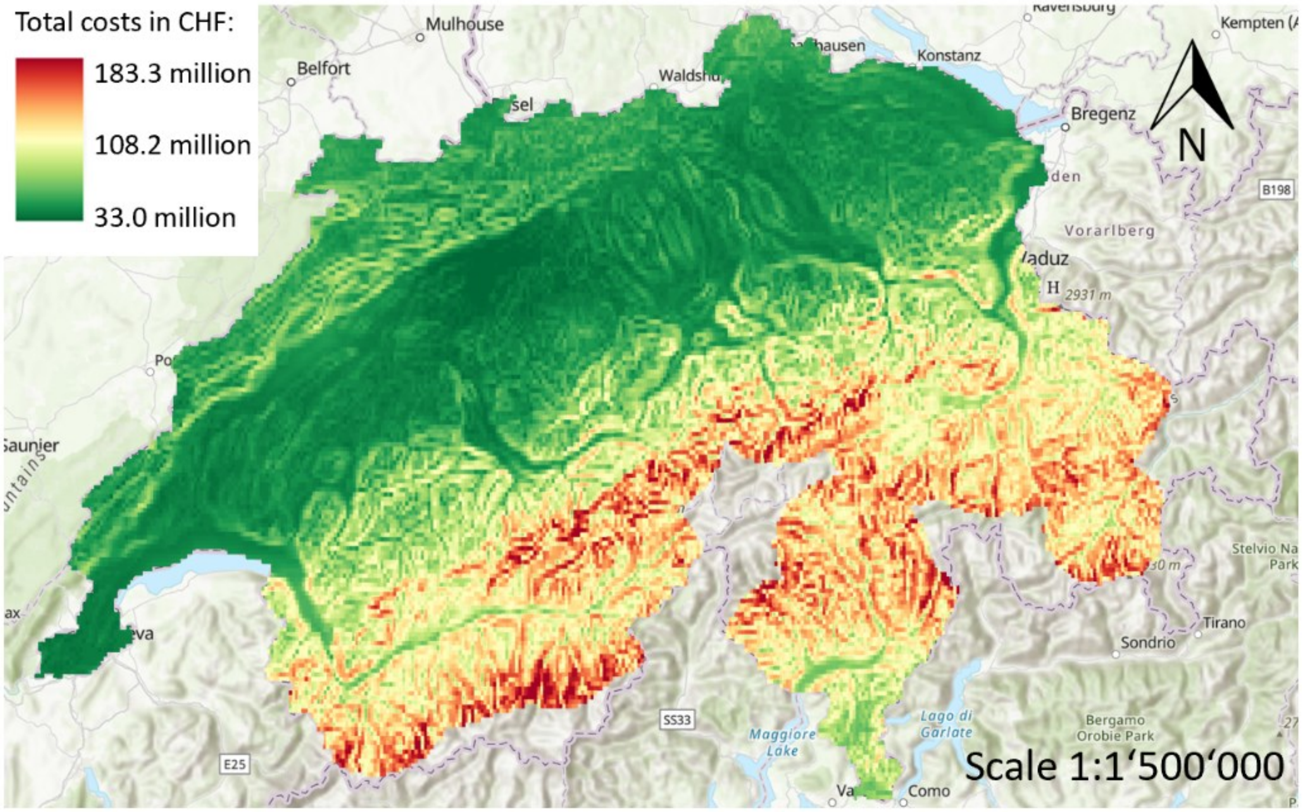


Figure 16: Map of the total costs for the 100 °C temperature extracted for the limited 15 km from areas with high heat demand.

Due to the higher limit, there are more potential areas to build a geothermal system. However, building in these areas also means that more heat is lost.

4.3 150 °C temperature aim

Figure 17 shows the temperature isotherm for the last of the three cases, i.e. a temperature of 150 °C. Because of the decrease in the temperature gradient in Figure ??, this temperature lies at an even greater depth than assumed with a uniform gradient. The 150 °C first occurs at a depth of 3’760 metres and is located in the same area as for the 100 °C. The location of the deepest occurrence also remains unchanged.

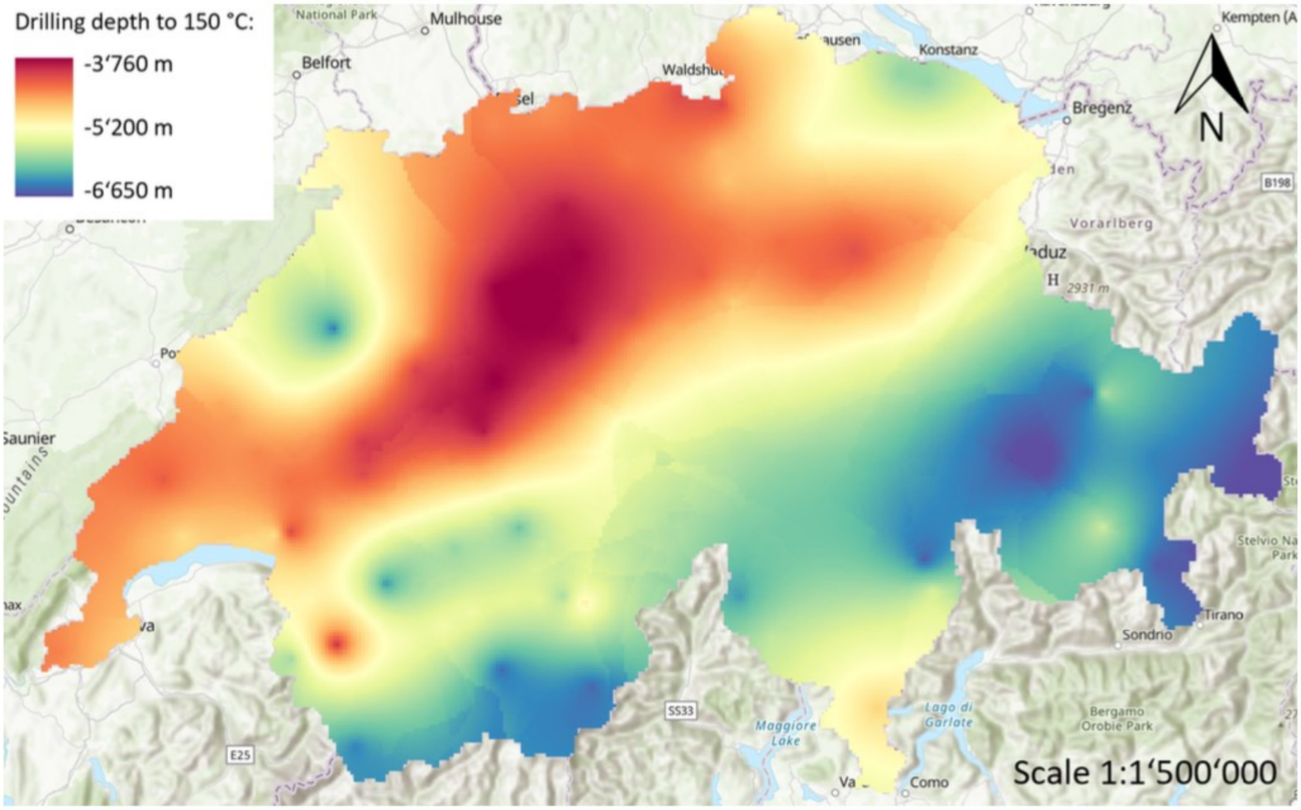


Figure 17: Necessary drilling depth to reach a temperature of 150 °C.

Drilling costs for the 150 °C case are shown in Figure 18. The drilling costs are disproportionately lower in places where only sediment was drilled. On the contrary, they reach costs of almost 40 million CHF in places where only crystalline drilling was carried out.

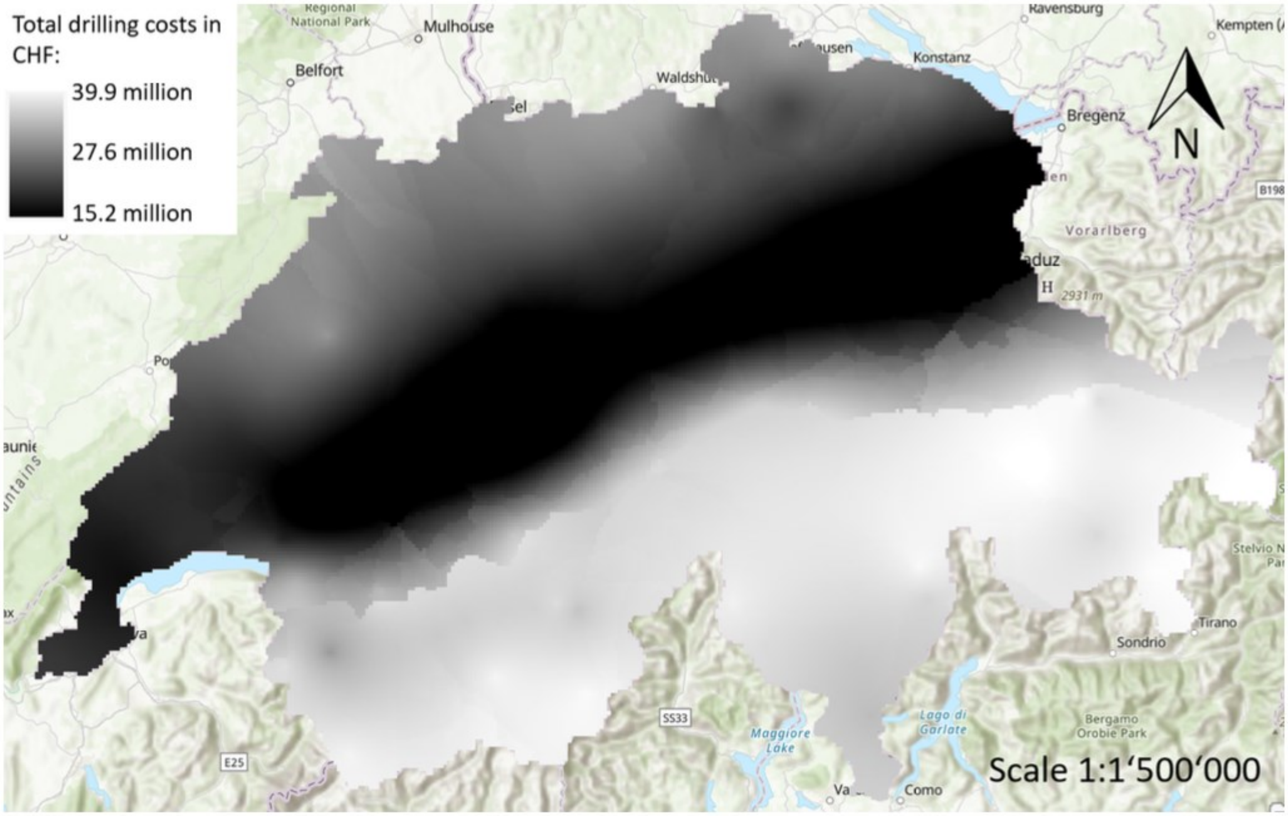


Figure 18: Map of the total drilling costs for the 150 °C temperature.

In Figure 19 the final cost map for the 150 °C case is shown. This map was generated using the cost composition formula for the applicable case.

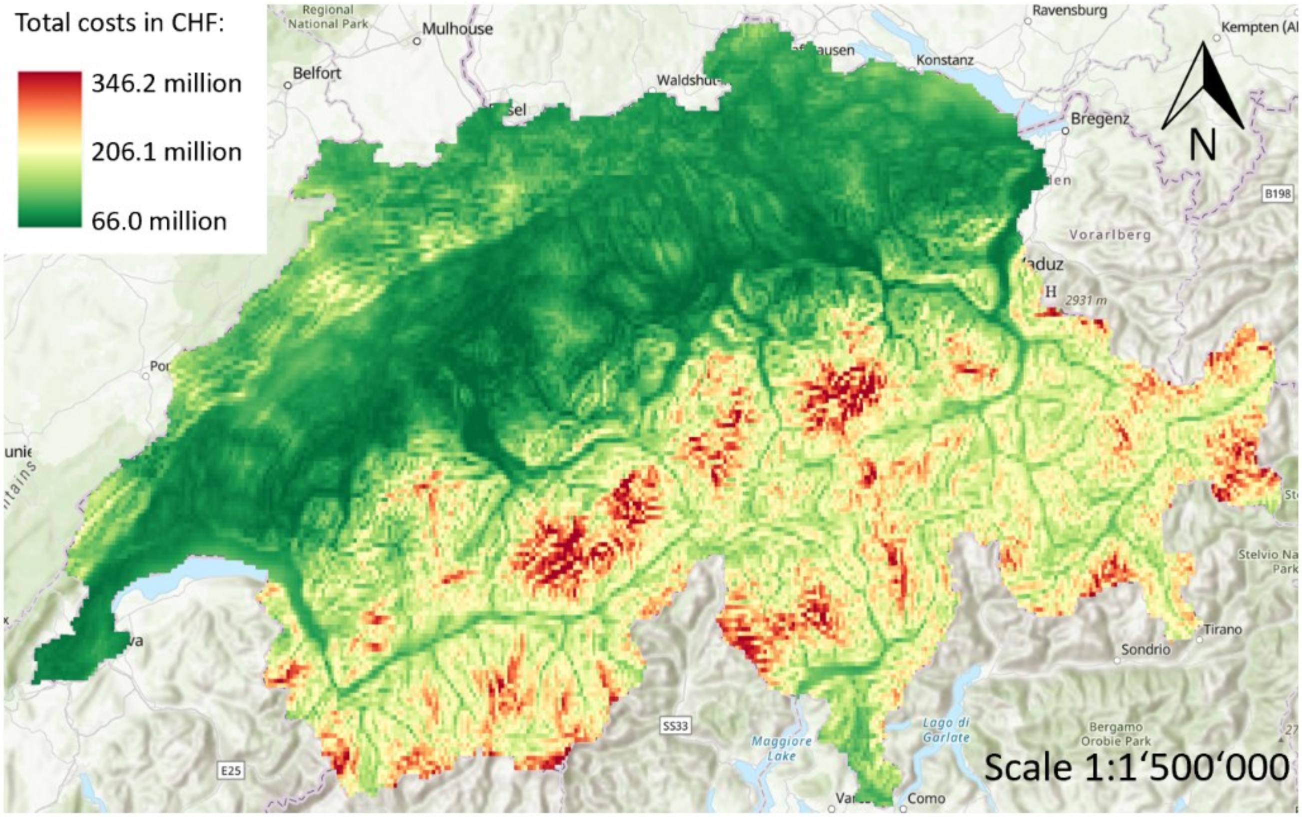


Figure 19: Map of the total costs for the 150 °C temperature.

4.4 Overview of favourable locations

The purpose of Figure 20 is to provide a comprehensive overview of the most suitable geothermal system for different locations. These areas may overlap and the map is not intended to be a firm and definite solution.

The dashed blue line in the figure represents the area where temperatures of 150 °C are found in the sediment, limiting the potential for electricity generation from hydrothermal systems to this region. The regions filled in blue within this area indicate the most economically viable locations. Similarly, for warm extraction from hydrothermal systems, the yellow dashed area indicates regions where temperatures of 60 °C exist in the sediment. The areas filled in yellow highlight the most cost-efficient locations for this purpose.

Regarding EGS and AGS, areas were selected where the crystalline layer is not excessively deep. The red areas for AGS were primarily chosen in regions with an elevated seismic risk, as EGS should be avoided in such areas to prevent induced earthquakes.

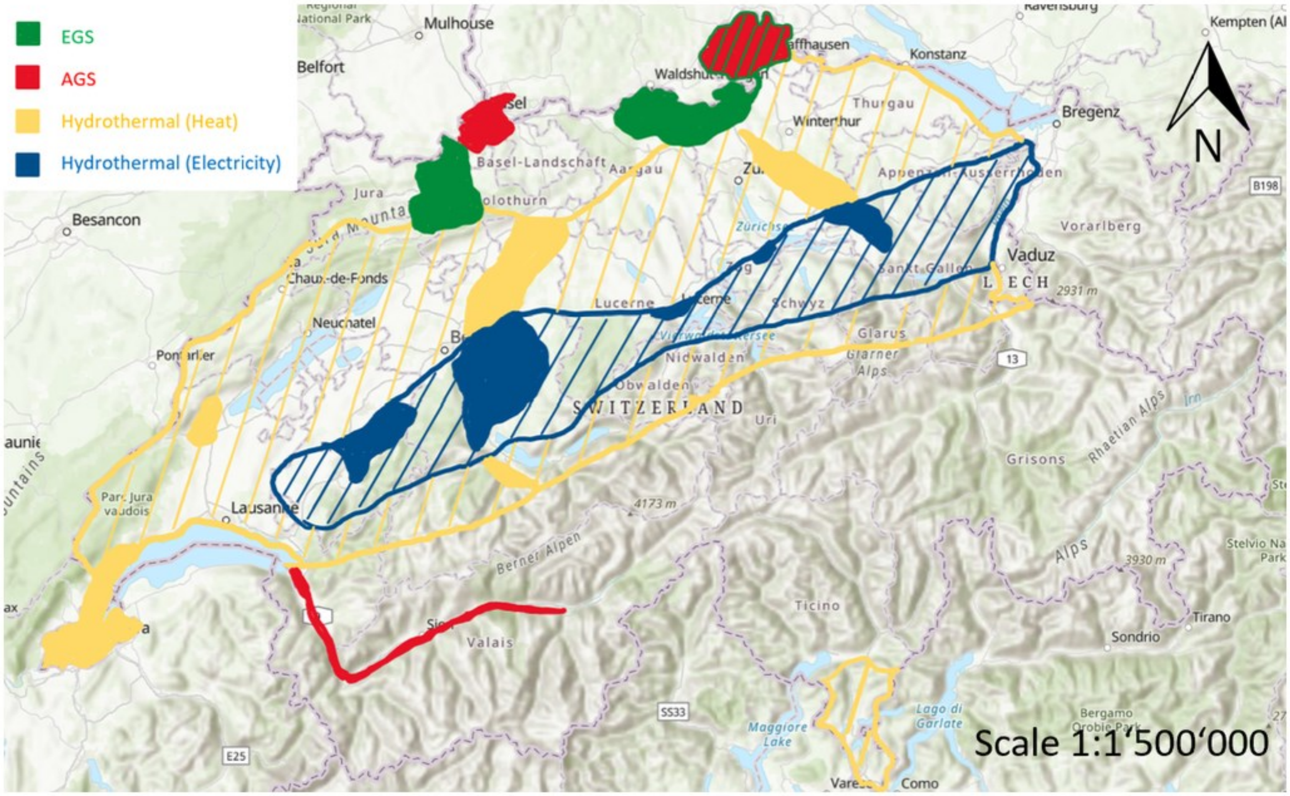


Figure 20: Favourable locations according to the different systems: Hydrothermal (for heat or electricity), EGS and AGS

This site selection process excluded lakes and considered suitable systems based on seismicity. However, further evaluation is required to assess whether the identified favourable locations are situated within nature reserves or protected areas, as well as the availability of free land and sufficient space for establishing a geothermal plant.

5. DISCUSSION

The most relevant factor for planning a geothermal power plant is the temperature at depth. In Switzerland, the scarcity of data on temperatures in the subsurface outside the Molasse Basin pushed for a rather bold extrapolation of existing data. This may have led to high errors in certain regions, which cannot be clearly quantified. One way to reduce this error would be to obtain data from non-publicly available data or to calculate the temperature gradients using geologic simulations of different parts of Switzerland. This calculation was carried out uniformly for the whole country. Changing the statistical method can improve the interpolation, but in general, more exploration drilling is needed to generate accurate data. The aim of the temperature extrapolation, in addition to assessing the correct relation between the different regions in Switzerland, was to highlight the Rhone Valley and the flat region of the canton of Ticino, as they are potential areas for geothermal energy development based on existing projects. By incorporating reference points within the valley and its immediate vicinity, an effort was made to ensure a fair representation of these areas that would otherwise be overshadowed by the Alpine terrain during the extrapolation process. The presence of protruding data points on the map indicates the need for a denser data point distribution to achieve a smoother extrapolation. The same applies to the data on the depth of the crystalline rock. Only a few data can be found outside the Molasse basin and therefore the extrapolation made with ArcGIS can only be considered vague.

The subsurface characteristics in Switzerland exhibit a higher level of complexity compared to other countries due to the presence of the Alpine folding, resulting in significant variability across different regions. As a consequence, the predictability of subsurface conditions in Switzerland is not consistent throughout the country. This inherent complexity poses challenges to the reconstruction and understanding of the underground environment, making the acquisition of comprehensive knowledge more difficult. Both of these extrapolated data for the temperature in the subsurface and for the depth of the crystalline bedrock were used to calculate the drilling costs, which make up the largest part of the total costs. The patchy data outside of the Molasse basin is due to sporadic exploratory drilling. Other countries with high resource deposits have been able to accumulate more knowledge about their subsoil and can now make excellent use of this for site selection. In general, the underground of Switzerland at depths below 2000 m has hardly been investigated (EnergieSchweiz and AG, 2017).

Obtaining precise cost estimates for geothermal plant construction was challenging and in the end, all of the costs are rough estimates. Companies such as Schlumberger and Halliburton, who can be involved in the drilling process typically refrain from disclosing project costs.

Also, the cost range associated with geothermal facilities and the additional used infrastructure is extensive, as it is influenced by numerous factors, many of which cannot be comprehensively addressed within the given information. The prices in Switzerland are generally higher compared to most other countries, therefore reference values from countries cannot be directly adopted due to the disparity in prices between Switzerland and those countries. This is a further complication of the estimation of accurate cost amounts. One approach to address this challenge is to export all the raw parameters into a software platform such as Tableau and to give predefined ranges for all the values with it (Tableau, 2023). This enables researchers and practitioners to dynamically adjust and analyse the data, facilitating the exploration and evaluation of different scenarios or hypotheses in a more streamlined manner.

A look at the results clearly shows that the alpine regions, apart from the valleys, are not suitable for a geothermal system. The limited existing infrastructure results in higher costs associated with the installation of road segments and power lines compared to other regions. This is particularly visible in the results where the terrain slope was not taken into account. Added costs because of steeper terrain were originally added to every piece of infrastructure. Construction on steep terrain is more complex and time-consuming, it can include additional measurements and equipment for stability and also makes the access to the construction site more difficult. Adding this amount of costs seems justified. The elongated area in dark green in all of the resulting maps in Figures 13, 16 and 19 represents the area of the Molasse basin where less or no crystalline rock needs to be drilled through for the desired depth. Since drilling is the biggest part of the cost, this area automatically becomes the most profitable area. Intensive research is being carried out into drilling techniques that can penetrate hard rocks more quickly. This would significantly reduce the costs of the geothermal plant or power plant.

In the results obtained for the 60 °C and 100 °C cases, the most favourable locations are slightly shifted towards the Northern part of the Molasse basin. When considering all three temperature maps (Figures 11, 14 and 17), a distinct anomaly area is observed along the borders of the cantons of Solothurn and Berne, where the desired geothermal temperature is found at a shallower depth compared to surrounding areas. Notably, in the 60 °C map, this anomaly appears more northwards than in the other two maps. Consequently, the 60 °C and 100 °C cases exhibit higher profitability due to the specific temperature distribution in these areas.

In the 150 °C case, the temperature anomaly is situated in the same location as in the second case, but the most economically viable sites exhibit a different pattern compared to the other two cases. This discrepancy is attributed to the alignment of costs with transmission lines throughout the entire Molasse basin. The proximity to existing infrastructure in the basin influences the profitability of geothermal projects in the 150°C case.

Overall shown by Figure 20, the Molasse basin looks like a good option for hydrothermal systems. The shell limestone and red sandstone formations within the Malm region are considered to be favourable geological strata for a natural reservoir, which is needed to build a hydrothermal system. The final decision on whether hydrothermal energy is possible is based on the forecast of the flow rate (permeability) rather than the temperature. Unsuccessful projects such as the one in St.Gallen show that these reservoir characteristics can only be fully determined by drilling (Link and Zingg, 2017). The reason for the shutdown of the project in St.Gallen was the combination of insufficient water found, increased earthquake risk as well as a surprising gas flow in the drilled rock strata (St.Gallen, 2018).

Carbonate reservoirs offer the advantage of being amenable to expanding pre-existing interfaces or cavities through acid stimulation techniques, resulting in enhanced productivity and purity of the reservoir. This approach can be considered as a potential measure in situations where the natural reservoir's productivity falls below desired levels, enabling the optimisation of hydrothermal system performance.

The two systems EGS and AGS are installed in the crystalline rocks. Therefore, it makes sense to choose a location where the crystalline rock is not too deep, but still reaches temperatures of 150 degrees to generate electricity. A good solution would be in the Jura region shown in Figure 20, where the topographic profile demonstrates a gradual or moderate slope, indicating a less pronounced incline, or in more southerly parts of Switzerland in a valley.

The Jura region, despite its proximity to the seismically active Basel area, presents a notably low risk of induced seismicity resulting from fracking operations. PartnerRe's findings illustrate a promising area with crystalline formations in the Jura, indicating favourable conditions for the implementation of an Enhanced Geothermal System (EGS) in this region.

Indeed, an active project is underway in the canton of Jura. The Haute-Sorne deep geothermal pilot project has the objective of generating electricity and heat through a geothermal power plant that relies on two approximately 5 km deep boreholes. As a pioneering pilot project, it serves as a technology demonstrator, laying the groundwork for future achievements in various regions across the country (Geo-Energie Jura, 2023).

In the valleys and especially the Rhone Valley an increased temperature is notable. In Lavey-les-Bains, a natural groundwater reservoir in crystalline, fissured rock is extracted and used for balneology. The goal is to soon be able to produce electricity from this natural source ((AGEPP), 2023).

The NPV formula 1 combines project costs and revenues to provide an assessment of overall profitability. To evaluate revenues, it is necessary to have information about the ca- capacity of a system, which is influenced by factors such as fluid flow rate, geological structure, and reservoir characteristics, among others. Due to the inability to differentiate these factors and assuming a constant yield for all systems, this information was omitted in the cost maps. The NPV formula would change the values, but the ratio would remain the same. This means that it is not needed to make comparisons between different locations.

The Swiss electricity prices in the primary supply for households in 2023 rose, in some parts of Switzerland significantly. This results from calculations by the Swiss Federal Electricity Commission (ElCom) based on the tariffs of around 630 Swiss network operators. A typical household pays 26.95 centimes per kilowatt hour (Rp./kWh), averaged over Switzerland (ElCom, 2023).

Higher electricity prices will increase the revenue from electricity generation in geothermal systems. Due to higher electricity prices, the economic viability of geothermal projects improves as the revenue generated from selling electricity at higher rates offsets the operational and maintenance costs associated with the geothermal system. Other factors that can influence the output of geothermal systems, are e.g. the inclusion of the 100 °C case for electricity production through the implementation of more efficient pumps. Additionally, the incorporation of temperatures between the three defined temperature thresholds would also significantly impact the system's output.

6. CONCLUSION

The whole country of Switzerland was investigated on potential areas for geothermal power plant installations. A large set of data was analysed and integrated to give cost estimations for three different geothermal systems (hydrothermal, EGS and AGS). Giving an equal overview of the whole country proved to be difficult because of the sparse data outside the Molasse Basin and because of the heat loss at 60 °C and 100 °C, which automatically leads to areas that cannot be included. The results of the areas outside the Molasse Basin should be considered critically, as the important data such as the temperature and the depth of the crystalline rock were extrapolated for these locations.

An overview of the entire of Switzerland provides a preliminary understanding, especially when knowledge on geothermal energy is limited. However, for a detailed analysis of the potential at a specific location, regional studies must be conducted. These studies can assess the specific geology of a particular region more precisely and reduce potential errors, offering a more accurate evaluation for localised geothermal projects.

Drilling costs make up the biggest amount of the total costs and in the case of electricity generation (150 °C), additional high expenses are incurred for constructing the necessary transmission line components. Hence, it is rational to construct the geothermal system in areas where the depth to the desired temperature is the smallest and where the infrastructure is already well-developed. Regarding the extraction of water at 60 °C, the entire Northern region of Switzerland is deemed suitable based on the drilling depth required for this temperature. The ideal place for the extraction of hot water at 100 °C and 150 °C is located in a more concentrated area near the border between Bern and Solothurn. In this region, the desired temperatures can be reached at shallower depths, minimising additional costs.

Future work can include quantifying revenue from heat and electricity generation and expected thermal energy production based on the different types of systems and temperatures. This would further allow to make a comprehensive statement about the profitability of a geothermal system at a certain location.

For progress in Switzerland, it is crucial to successfully implement the first operational geothermal system for electricity production without any complications, such as induced micro-earthquakes or reduced productivity. Geothermal energy, particularly EGS, would then garner greater acceptance, leading to easier approval of future projects and a faster transition to the construction phase.

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