DELIVERABLE D6.12 SUMMARY OF GÖTTINGEN SITE OPTIMIZATION FOR INTEGRATION OF GEOTHERMAL RESOURCES IN THE ENERGY SUPPLY

WP6: DEMONSTRATION OF ELECTRICITY AND THERMAL POWER GENERATION

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PUBLIC SUMMARY

This public deliverable D6.12 was prepared in the framework of the MEET project and aims at presenting the concept of heat and cold supply system for the Göttingen University campus based on utilization of deep, medium deep and shallow geothermal energy. Considering the stepwise planned renovation of campus' buildings and complete reconstruction of the University Medical Center, the concept is supposed to fit well to sustainable development of the campus. One of the key components of the concept – Enhanced Geothermal System (EGS) – is discussed, its potential risks are identified, and prevention measures are suggested. Additionally, Gantt chart for potential development of EGS for Göttingen demo site is proposed. The following progress of the Göttingen demo site development depends on public acceptance and support, research well financing (including public funding schemes) and future results being derived from the exploratory drilling and stimulation.

1 EXECUTIVE SUMMARY

The following document entitled “Summary of Göttingen site optimization for integration of geothermal resources in the energy supply” is a Deliverable of Work Package 6 “Demonstration of electricity and thermal power generation” of the MEET project.

The MEET project (Multidisciplinary and multi-context demonstration of Enhanced Geothermal Systems exploration and Exploitation Techniques and potentials) aims at developing EGS techniques in a variety of geological settings across Europe at a competitive cost and involves, in total, 16 partners from five different European countries. The Göttingen campus is a demo site of the project for one of the four representative geological settings for EGS (“Variscan folded and thrusted metasediments overprinted by younger extensional tectonics” as part of Work Package 5: Variscan Geothermal Reservoirs: Granitic and Metamorphic Rocks).

The study (Romanov and Leiss, 2021) supplements this report with the key findings:

- the parameters of brine should be at least 40 l/s and 140 °C for a feasible EGS in the reference case;
- government subsidies, proximity to the campus, temperature drawdown and drilling costs can significantly influence profitability;
- up to 18100 t CO_2/y can be potentially saved.

1.1 DESCRIPTION OF THE DELIVERABLE CONTENT AND PURPOSE

The goals of this deliverable are to consider the possibility of developing Enhanced Geothermal System at the Göttingen demo site, to analyze associated risks and to propose a concept for heat and cold supply of the Göttingen University campus based on the utilization of deep, medium deep, and shallow geothermal energy in order to reduce CO_2 emissions of existing fossil fuel-based district heating and cooling (DHC) system. The deliverable is supposed to present to the decision-makers within the University one of the potential concepts for sustainable development of the campus area and some recommendations for future implementation.
The content of this deliverable includes materials and results of pursuing the aforementioned goals.

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

Development of geothermal systems is usually considered only for one of the target depths: either deep, or medium, or shallow one. A new concept of integrated exploration and utilization of geothermal energy at different depth levels is proposed. If realized, the concept is supposed to replace a part (or the whole) of the heat and cold generation from the existing fossil fuel-based heat and cold supply system of the Göttingen University campus in the future, thus mitigating greenhouse gas emissions of the campus.

1.3 CORRECTIVE ACTION (IF RELEVANT)

N/A

1.4 IPR ISSUES (IF RELEVANT)

N/A

2 DELIVERABLE REPORT

2.1 INTRODUCTION

The campus of the Georg-August-University (UGOE), the University Medical Centre (UMG) and other institutions such as the Max-Planck-Society are located in the central and in the northern parts of Göttingen (Germany), within a radius of about 2 km (Figure 1). The MEET Project is focused on analyzing potential of EGS in different representative geological settings of Variscan granitic and metasedimentary rocks within Europe and integrating such EGS in energy systems (Trullenque *et al.*, 2018; Dalmais *et al.*, 2019), and the Göttingen University campus is one of the four demo sites of the project which is supposed to investigate a possibility of developing an EGS in deformed metasedimentary rocks of Göttingen (Leiss and Wagner, 2019). This can make the Göttingen demo site a real laboratory for expanding knowledge in this area and serving as a representative case study for other places with similar geological settings in Europe (Work Package 7).

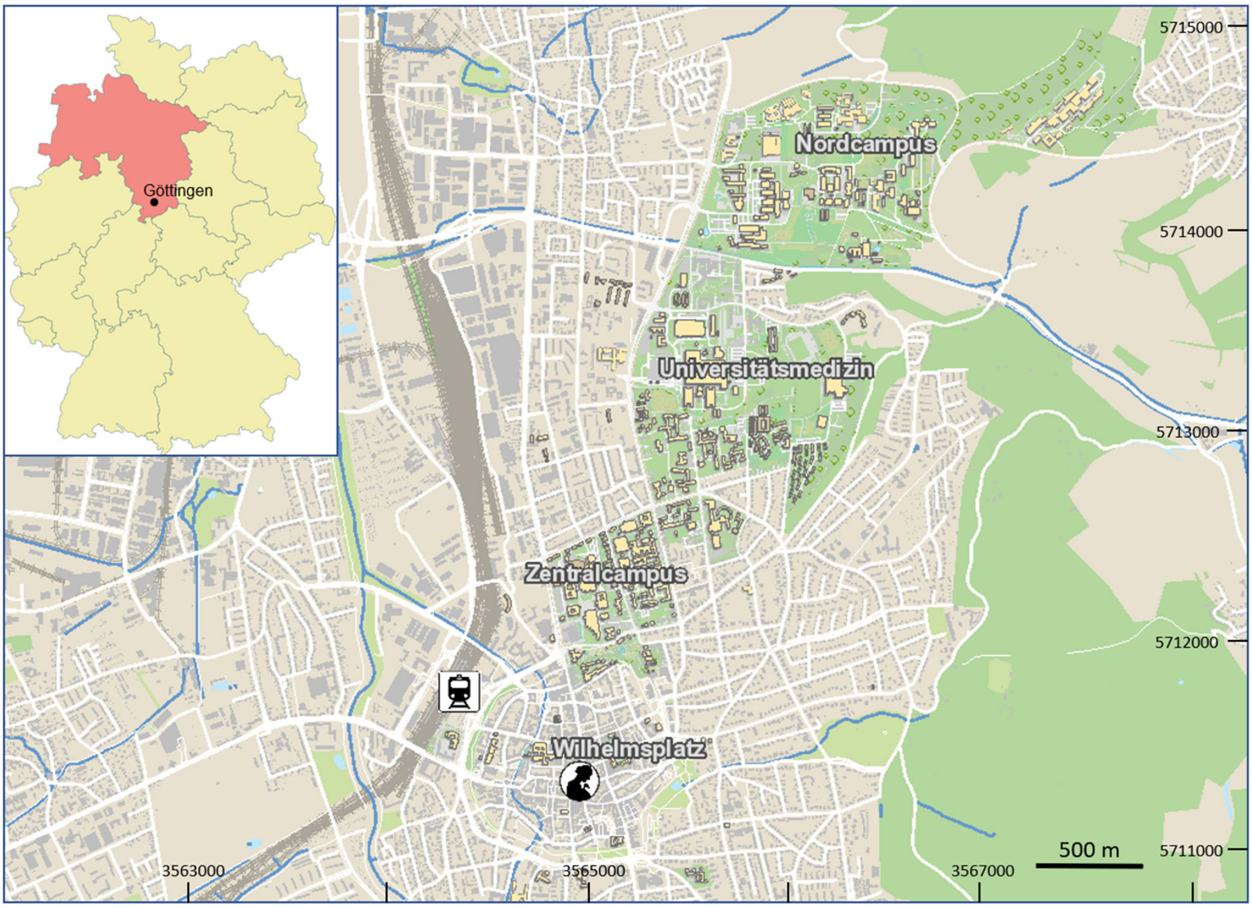

Figure 1. Location of Göttingen in the south of Lower Saxony state (orange) within Germany and the city centre of Göttingen (Wilhelmsplatz), the central campus (Zentralcampus), the area of the University Medical Center (Universtiätsmedizin) and the northern campus (Nordcampus).
Sources of the maps:
wiki.erepublik.com/index.php/[File:Region-Lower_Saxony_and_Bremen.png];File:Region-Lower_Saxony_and_Bremen.png and www.geodata.uni-goettingen.de/Lageplan/?lang=en.

2.1.1 Geological setting

Although the data on geological setting of Göttingen is quite limited, the initial study (Leiss *et al.*, 2011) and following seismic survey (Leiss *et al.*, 2021) validated that the upper several thousand meters of the subsurface of Göttingen are built up of three main units shown in Figure 2, which can be used for exploitation of geothermal energy:

- Variscan basement (3000-5000 m depth, above 90 °C: deep geothermal system for district heating and absorption district cooling system of the campus).
- Zechstein successions or the overlying sandstone layers (500-1300 m depth, 25-40 °C: medium deep geothermal system as an underground seasonal thermal energy storage).
- uppermost layers of water-saturated quaternary alluvial sediments and sedimentary Mesozoic units as e.g. karstified Mesozoic carbonates (8-15 °C; shallow geothermal systems for heating and cooling purposes).

Additional information on the geological setting of Göttingen can be found in the studies (Leiss *et al.*, 2021; Leiss, Romanov and Wagner, 2021).

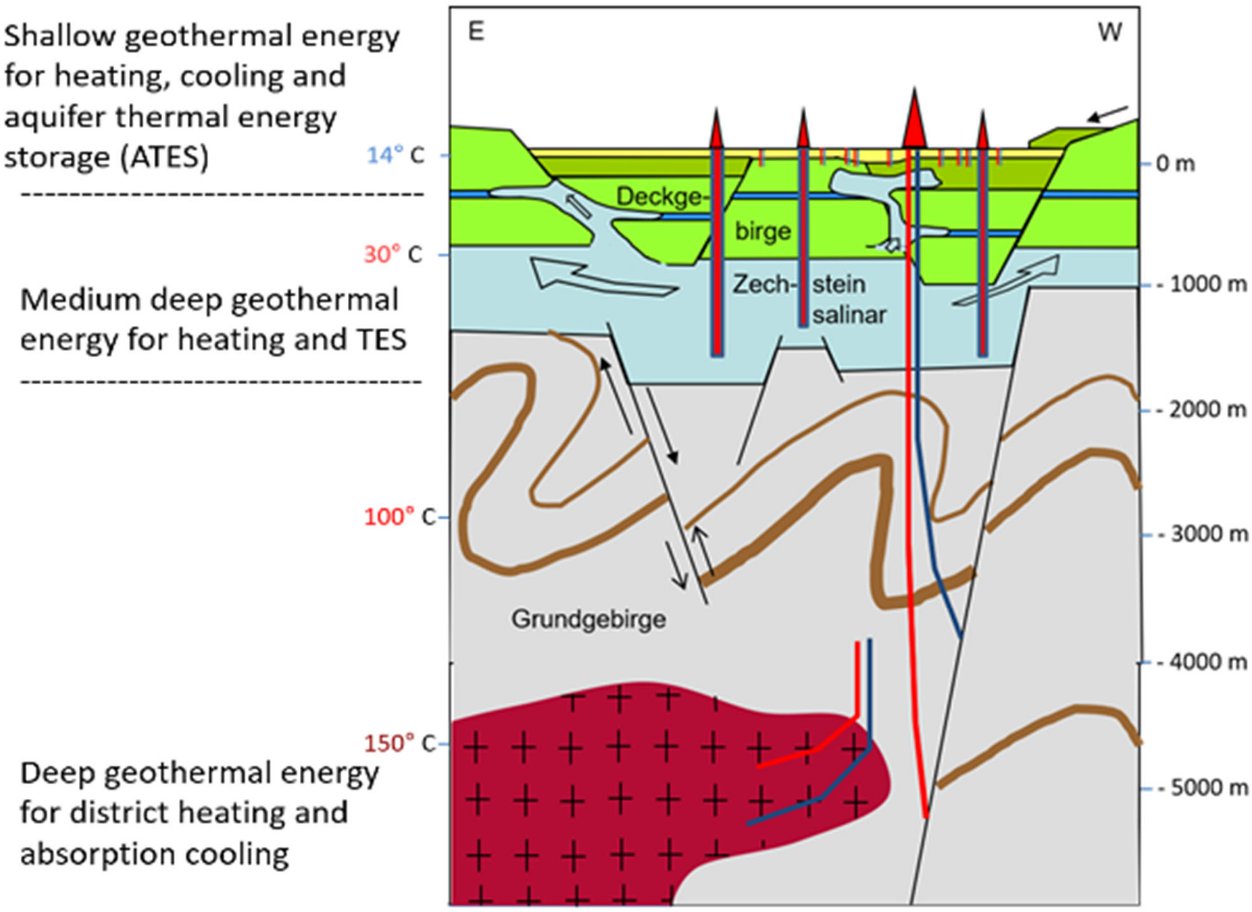

Figure 2. Göttingen subsurface structure illustrating the different potential geothermal target horizons (after Leiss *et al.*, 2011).

2.1.2 Description of current energy system

Figure 3 summarizes the main components of the existing district heating and cooling system of the campus. Electricity, heat, steam and cold are needed for operation of the UGOE and UMG buildings. Energy is produced either on site or provided by external suppliers, in both case based on fossil fuels. Natural gas consumption of the combined heat and power (CHP) plant is about 358 GWh/a, which is shown in the Sankey diagram (Figure 4).

The lifetime of a gas turbine (manufactured in 1997) at the CHP plant is coming to an end. Moreover, the renovation of the old low energy-efficient buildings, mainly of the University medical center on the campus, is planned, which will take the next 15-20 years, and initial constructions have already begun. These factors create important prerequisites for potential switching to renewable energy sources and making UGOE and UMG deliberate on the future concept of their energy supply.

Based on the test reference year data from the weather service (Deutscher Wetterdienst, 2020) and internal documents from the University, an expected heat load profile of the campus after its reconstruction including the heat demand for the existing buildings[1], for the new (to-be-built) buildings, and for the absorption cooling machines was compiled in Figure 5. The design peak heat load of the to-be-built buildings and the remaining existing buildings is estimated at 32.6 and 23.2 MW_{th}, respectively, while the heat load of absorption chillers reaches up to 10.7 MW_{th} in summer. The heat demand of those consumers is 110.8, 78.8 and 19.9 GWh_{th}/a, respectively (Romanov and Leiss, 2021). A part (or the whole) of those demands can be covered by renewables and, particularly, geothermal energy.

Additional information on the technical background and the energy system of the campus can be found in the works (Leiss *et al.*, 2021; Leiss, Romanov and Wagner, 2021).

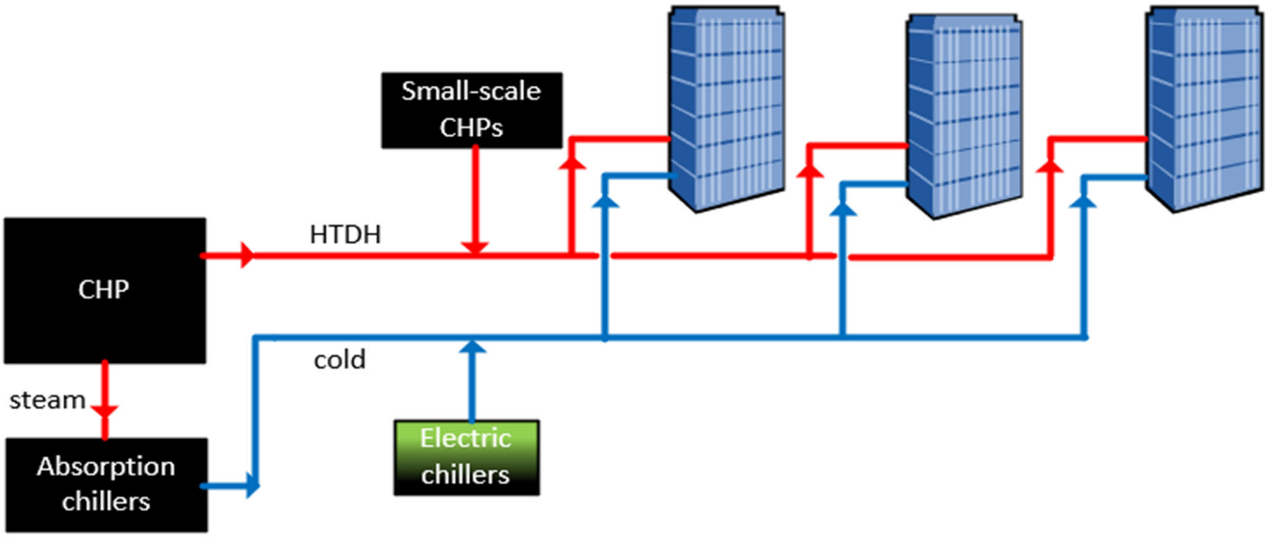

Figure 3. Existing district heating and cooling system of the campus in 2020 (Leiss *et al.*, 2021)**. Note: HTDH – high temperature district heating; CHP – combined heat and power plant; return lines are not shown.**

[1] A part of the existing buildings is planned to be deconstructed, and only remaining buildings are meant here.

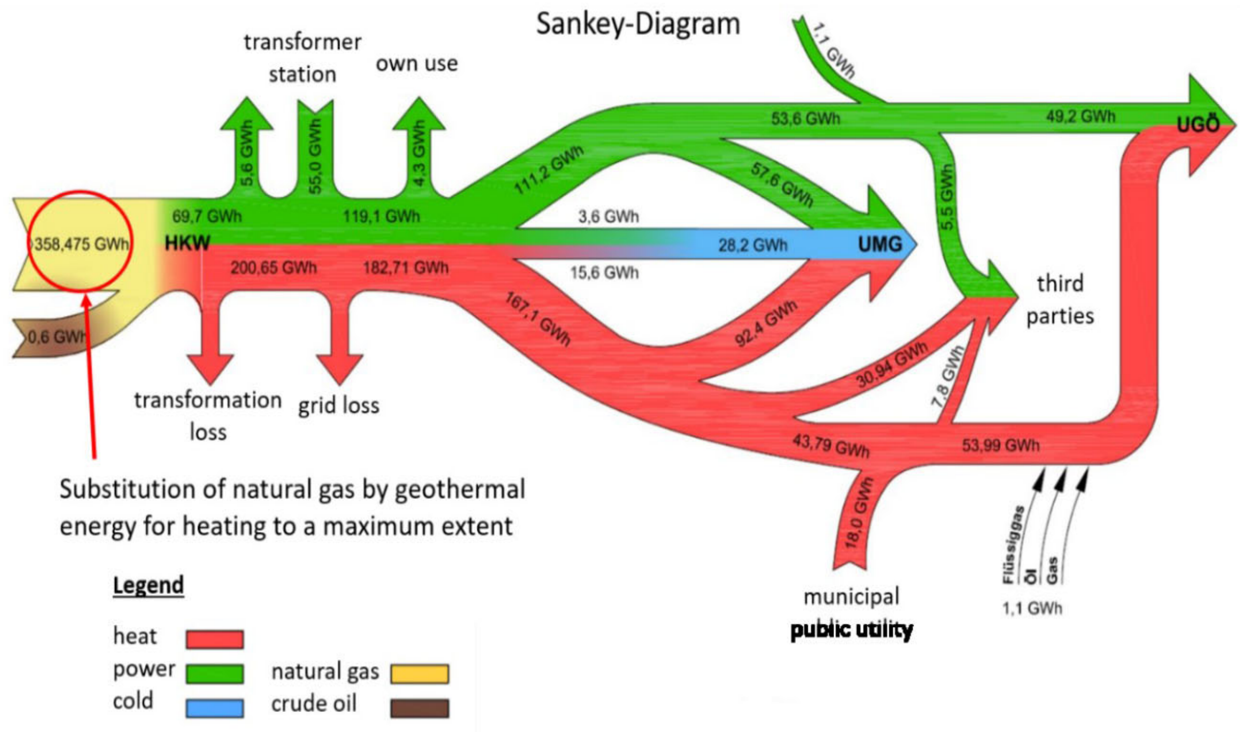

Figure 4. Energy balance of the Göttingen University campus in 2018 (*Energiebericht 2018. Annual report*, 2019; Leiss, Romanov and Wagner, 2021)**.**

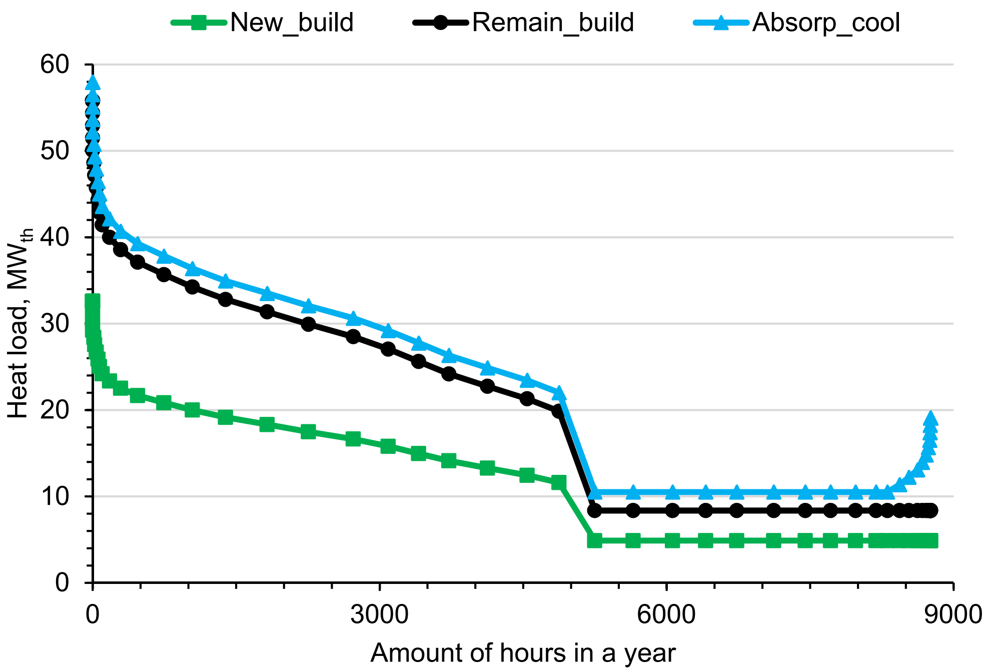

Figure 5. Expected heat load duration curve after reconstruction of the campus (including to-be-built buildings, remaining existing buildings, and heat for absorption cooling).
Note: absorption cooling is constant throughout the year, except for summer peak.

2.1.3 CO_2 emissions of the campus

Based on the numbers from Figure 4 and considering natural gas and electricity mix emission factors equal to 202 t CO_2/GWh and 397 t CO_2/GWh$_{el}$ (Juhrich, 2016; Buck *et al.*, 2020), respectively, emissions of the campus and specific emissions for 2018 were evaluated (Table 1). Coefficient of performance of boilers was assumed to be 0.9. Natural gas consumption needed for generating different products of CHP plant was distributed proportionally among them. For external power grid, German electricity mix was considered, and for external district heating – specific emissions of hot water production of the campus. As seen in Table 1, total emissions of the generating facilities of the campus are 72400 t/y. In addition to that, external power grid and external district heating are responsible for 21800 t/y and 4800 t/a, respectively. In total, the emissions reach almost 100000 t/y. In Table 2 distribution of the CO_2 emissions among UMG, UGOE and third parties is presented. The values were obtained with the help of specific emissions from Table 1.

Table 1. CO_2 emissions from different energy supply options of the campus in 2018.

Parameter	CHP plant			Boilers		Total	External power grid	External district heating
	Power	Steam	Hot water	Steam	Hot water		German mix	Hot water
Production, GWh/y	69.700	63.919	50.808	22.361	63.563	__	55	19.1
Natural gas consumption, GWh/y	99.397	91.153	72.456	24.845	70.625	**358.5**	__	__
CO_2 emissions, t/y	20074	18409	14633	5018	14263	**72398**	**21835**	**4826**
Specific CO_2 emissions from supply options, t/GWh	288.01	288.01	288.01	224.40	224.40	__	*397*	*252.66*[2]
Specific CO_2 emissions related to products, t/GWh	**336.08**[3]	**271.52**[4]	**252.66**[5]	**271.52**	**252.66**	__	__	__

[2] The value is assumed to be equal to specific emissions of hot water production of the campus.
[3] The value is weighted average of the specific emissions from the CHP plant and electricity mix.
[4,5] The value is weighted average of the specific emissions from the CHP plant and boilers.

Table 2. CO_2 emissions by different consumers of the campus in 2018.

Parameter	UMG					UGOE		3rd parties	
	Power	Power for cooling	Steam	Steam for cooling	Hot water	Power	Hot water	Power	Hot water
Consumption (with losses), GWh/a	62.52	3.91	69.28	16.99	31.38	53.40	58.81	5.97	42.20
CO_2 emissions, t/a	21045	1315	18812	4614	7927	17976	14860	2010	10663

2.2 TRANSITION FROM FOSSIL FUELS TO GEOTHERMAL ENERGY

Even though the current share of deep geothermal energy in German electricity and heat mix is very low (BMWi, 2019), deep geothermal energy is estimated to be an enormous source of renewable energy of non-intermittent nature (Chamorro *et al.*, 2014; Jain, Vogt and Clauser, 2015; Lu, 2018). That is why many studies currently focus on the development and exploitation of Enhanced Geothermal Systems (EGS) and overcoming of related issues and risks (Dalmais *et al.*, 2019; Garapati *et al.*, 2019; Olaf Gustafson *et al.*, 2019; Ragnarsson, Óladóttir and Hauksdóttir et al., 2021).

Many researchers consider EGS for generating electricity (Organic Rankine Cycle or Kalina Cycle) or combined generation of heat and power (Moya, Aldás and Kaparaju, 2018; Van Erdeweghe *et al.*, 2018, 2019; Meng *et al.*, 2020). However, for the University campus, it is preferable to use deep geothermal energy only for covering the heat demand due to the following reasons:

(1) It is unlikely that heat production of the local deep geothermal reservoir will exceed the heat demand of the campus, so extra geothermal heat capacity is not expected for an additional ORC installation. In case of a very high heat production, an ORC installation can always be realized at a later stage;

(2) Low efficiency of binary cycles (usually about 10%) makes electricity production from geothermal energy less attractive in comparison with other renewables. Thus, the electric demand can be met by various other renewable energy sources like solar, wind energy or biomass, which are being developed quite quickly – all renewables in total already surpassed the share of fossil fuels in Germany in 2019 (Fraunhofer ISE, 2020). Moreover, in contrast to heat, electricity can be easily transmitted from distant external sources.

As for local electricity generation, photovoltaic (PV) modules can be installed on the roofs and facades of the to-be-built UMG buildings, for example. According to the report (Wirth, 2021), average annual irradiance in Germany is 1088 kWh/m^2/y; nominal efficiency of PV modules is about 20%; performance ratio of a PV plant is about 85%; and efficiency of PV inverters is 98%. Taking these data into account, average specific electric yield of a PV plant in Germany is 181 kWh/m^2/y. Then assuming that 90000 m^2 of roof and façade area will be available in result of renovation and refurbishment of the UMG buildings, annual electricity generation from the PV plants can be 16.3 GWh/y, which is about 25% of UMG's total electric demand (Table 2).

However, this value can be achieved only in combination with effective electricity storage systems enabling to cope with solar intermittency.

Additionally, considering only direct heat use without producing electricity presents more flexibility for EGS development since the required supply temperature can be lower. Moreover, geothermal energy is one of the examples of low potential energy sources which should be used to cover low temperature (potential) demand (Hepbasli, 2012). District heating usually requires such low-exergy sources, but the campus is currently provided with high-exergy fossil fuels only. In order to save valuable fossil fuel resources and reduce carbon dioxide emissions, district heating should be supplied by low temperature (low potential) sources.

Uncertainty of the geological conditions is one of the main constraining factors for developing EGS. In the study (Olaf Gustafson *et al.*, 2019), direct use of deep geothermal energy for district heating of an American university was considered. The idea of cascaded use of geothermal energy (serial connection of consumers) was considered and 20% of the campus needs (5.5 MW_{th}) can be met. In addition, some approaches for reducing the risks of EGS projects were presented: to define the range of potential flows and temperatures of the brine; to lower the injection temperature as much as possible; to evaluate the heat demand using real-time data; to incorporate hot water storage; to integrate energy efficient buildings, cascading use and heat pumps into geothermal system. All of these measures are also applicable to the Göttingen demo site.

In Germany, the questions of exploration of EGS in the area of Dresden were considered in (Förster, Förster and Krentz, 2018). Authors pay attention to several factors leading to uncertainties in temperature prediction during the exploration of the reservoir: geology, rock thermal properties, mantle and surface heat flow. For coping with the uncertainties, a temperature model was developed (including parameters such as thermal conductivity and radiogenic heat production). However, validation of the model requires real data from deep boreholes. For the Göttingen demo site, an exploration well is also necessary to reduce subsurface uncertainties and develop an EGS concept.

As deep geothermal energy will most likely not be able to cover the total heat demand of the campus at the lowest marginal cost, the system will probably also rely on natural gas boilers or CHP plants in the nearest future with the perspective of gradually shifting to 100% of energy supply from renewables. Similar approach was investigated in the work (Sun *et al.*, 2019), where the authors focused on hybrid system exploiting gas boilers, geothermal energy with absorption heat pumps and absorption heat exchangers. In summary, the authors claim that the hybrid system allows for 54%-savings of natural gas consumption, which is partly achievable due to absorption heat exchangers lowering the return temperature from consumers to 25 °C. So, absorption heat exchangers can be installed at consumer’s side instead of traditional heat exchangers in order to increase the efficiency of the system. In order to minimize the use of peak boilers during a day, a heat storage should be installed to smooth daily demand peaks. Financial and environmental benefits of such approach were shown in another study (Kyriakis and Younger, 2016).

Similar feasibility study – transition from a fossil fuel-based DHC system to a geothermal one for a University campus with natural gas boilers as boosters – was performed in the study (Garapati *et al.*, 2019). This work shows that the contribution of geothermal energy to such hybrid system turned out to be not more than 12%. Authors suggest that the reason is that the campus uses steam for heating and cooling purposes, and replacing steam with hot water may improve the performance of geothermal part of the system. That is also the case for UMG, as it currently uses steam for absorption cooling. However, the transformation from steam to hot water absorption chillers might be considered by UMG in the nearest future, which will enable a higher share of geothermal energy in the energy balance of UMG.

Other studies (DeLovato *et al.*, 2019; Li *et al.*, 2020) review different applications of solar and geothermal energies. One of such applications is solar-geothermal hybrid power plant where solar collectors are used to boost the temperature level of a heat carrier after geothermal heat exchanger. This solution might be taken into account for the campus in case the heat generation from the geothermal wells is not enough. Another synergetic effect of coupling solar and geothermal energy might come from underground thermal energy storage (UTES) for storing excessive solar energy in summer, e.g. by medium deep borehole thermal energy storage (Welsch *et al.*, 2018). Additionally, an UTES can be used for storing waste heat of the campus.

Another paper (Schüppler, Fleuchaus and Blum, 2019) shows a possibility of shallow geothermal aquifer exploitation for heat and cold supply of a hospital in Karlsruhe (Germany). In comparison with the currently used technologies for the hospital (district heating and compression chillers), the shallow aquifer system is paid back in 3 years and abates 600 t CO_2 annually. Similar aquifer system for a hospital in Belgium is estimated to be paid back after 8 years (Vanhoudt *et al.*, 2011). These results show the feasibility of this technical solution, therefore it can be also taken into account for the UMG hospital.

2.3 EGS FOR GÖTTINGEN DEMO SITE

The development of an EGS project from the early stages of exploration to operating facilities might take from 5 to 7 years (Stefánsson, 2002; Pan *et al.*, 2019). In order to make planning of the geothermal system construction clear and coherent with the planning of the reconstruction of the campus' buildings, the Gantt chart for potential EGS development in Göttingen is proposed in Table 3.

The red color in the table shows the investment decision gates. There are three investment phases: the research well (to be converted to production well later on), the injection well, and the surface infrastructure. The most important phase of the project is the first one, when the research well drilling is financed, the research work is done, and it will be clear what outcome can be achieved. In case of a complete failure of the EGS project, insurance schemes should be provided for investors to cover their losses (*GEORISK: Providing financial de-risking schemes for geothermal*, 2020).

Although financing is an essential part of implementing the activities from Table 3, social acceptance is also one of the factors worth mentioning with regard to the launch of an EGS project since it may slow down the development of a geothermal project significantly or to cancel it completely (Kunze and Hertel, 2017). In the work (Knoblauch and Trutnevyte, 2018), it was shown that an EGS plant in a close proximity to consumers is a more advantageous solution. Such scenario is impossible without strong support of public, which is also needed for the Göttingen demo site. Own studies on the acceptance of deep geothermal energy in the public of Göttingen started in 2015 with a seismic campaign within the city area (Schmidt, 2016).

Table 3. Gantt chart for potential development of EGS for Göttingen demo site.

Activity	Year						
	0	1	2	3	4	5	6
Feasibility study							
Permitting and public survey							
Research well financing							
Research well drilling							
Research work							
Stimulation tests							
Injection well financing							
Injection well drilling							
Transformation: research well -> production well							
Stimulation tests							
Surface infrastructure financing							
Surface infrastructure construction							
Start-up and commissioning							
Start of operation							

The consumers at the campus currently require a heat carrier of 70/50 °C (supply/return) in the secondary circuit, so the minimum wellhead temperature of the brine from an EGS system should be 80 °C in order to satisfy that. But considering potential reservoir cooling effect (temperature drawdown), 80 °C might be not enough in the long term.

If the existing district heating network of the campus is to be used for an EGS, velocities in the pipelines should be considered. Current design supply and return temperatures in the network (primary circuit) are 120/60 °C. Potential achievable temperature difference for the brine from an EGS is likely to be lower which might cause higher velocities in the existing network, hence issues like larger pressure drop, larger electricity consumption by pumps, water hammer effects.

Heat exchangers in substations should be also adjusted to different supply and return temperatures in the primary circuit. If acceptable or achievable temperature difference from an EGS is lower, then the heat exchangers will need higher heat exchange surface, which means additional heat exchange plates in the existing heat exchangers or, in the worst case, new heat exchangers (Romanov, Pelda and Holler, 2020).

On the other hand, the EGS system might supply new buildings (e.g. the medical center) with higher insulation standards and lower temperature requirements by means of a new low temperature district heating (LTDH) network in case of a high temperature drawdown, or high velocities in the existing network and insufficient pump power, or insufficient heat exchange surface.

It can be concluded that a successful surface equipment and infrastructure design requires a good analysis of building needs and available resources, with assumptions and uncertainties clearly communicated between all involved parties: geologists, engineers, contractors, building managers.

2.4 EGS RISK ANALYSIS

The development of an EGS is, in general, a challenging task in view of geological, technical and financial risks. At the Göttingen demo site, it is even more challenging and risky because of poorly known geological setting. In order to cope with that, risk analysis was carried out with the help of the tool developed by GEORISK project (*Georisk Tool*, 2021). The tool presents multiple potential risks which should be evaluated with regard to likelihood and potential damage. The results of the evaluation are presented in Figure 6, Figure 7 and Figure 8. Readers are referred to online version of the risk register (*Georisk Tool*, 2021) for description of IDs of different risks.

Among managerial and socio-economic risks, “lack of financing for the next phases” (B-2) was identified as the most significant one.
The most serious operational and geological risks are “flow rate lower than expected” (D-1), “temperature degrades too quickly” (D-4), “target formation is missing in the well” (D-9), “target formation has no/insufficient fluid for commercial production” (D-10), “excessive scaling in the geothermal loop” (D-12), “excessive corrosion in the geothermal loop” (D-13) and “hydraulic connectivity between wells is insufficient for commercial use” (D-15).

The most serious drilling-related risks are “induced seismicity” (F-3) and “technical failure/difficulties during drilling” (E-5). The prevention measures for the aforementioned risks were taken from the Georisk Tool and are listed in Table 4.

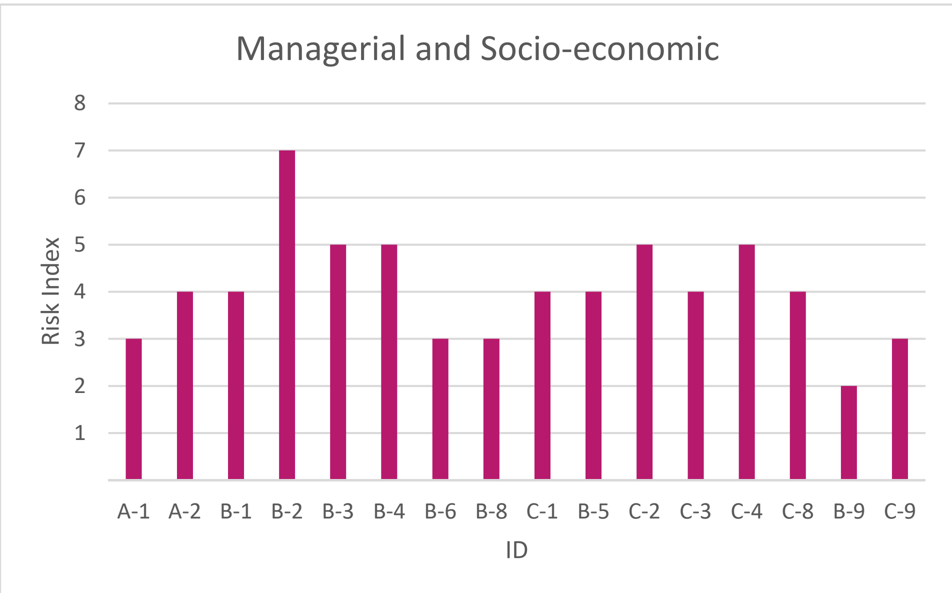

Figure 6. Evaluation of managerial and socio-economic risks (ID, see Table 4)

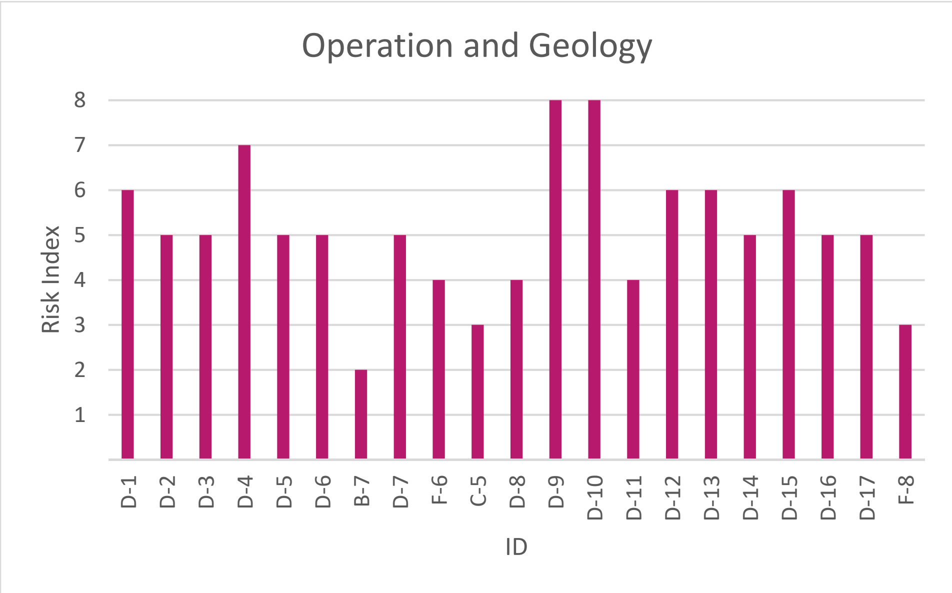

Figure 7. Evaluation of risks related to operation and geology (ID, see Table 4)

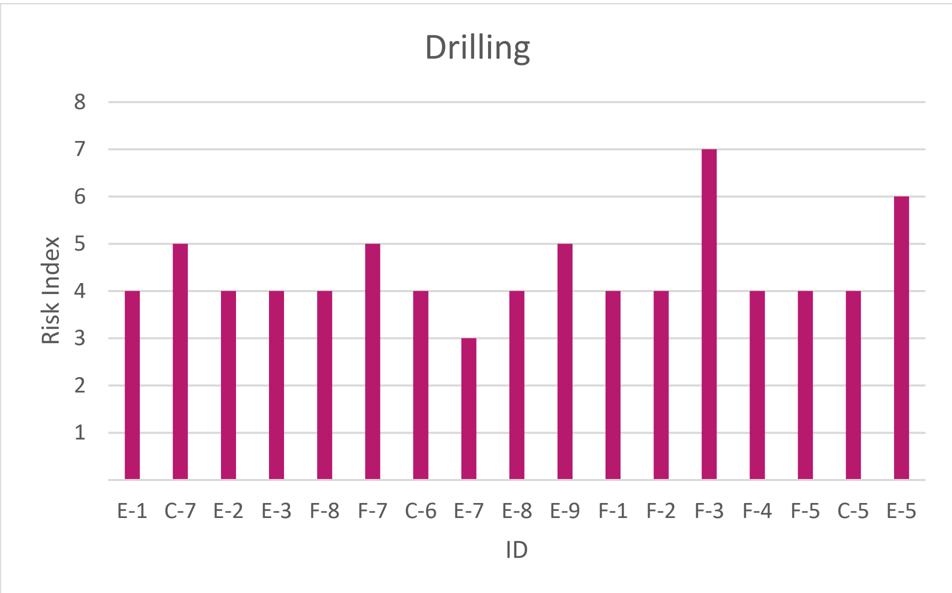

Figure 8. Evaluation of drilling risks (ID, see Table 4)

Table 4. Prevention measures (*Georisk Tool*, 2021).

ID	Description	Prevention measures
B-2	Lack of financing for the next phases	- Thorough feasibility study including risks (thorough cost management and business plan); - Thorough analysis of funding opportunities; - Valorize CO_2 abatements;
D-1	Flow rate lower than expected (reservoir)	- Implement best practices for well and completion design, in consistence with reservoir targeted; - Investigation ahead of project to characterize the reservoir hydraulic parameters; - Investigate secondary geological target and /or chemical stimulation;
D-4	Temperature degrades too quickly	- Thorough reservoir management plan (e.g. thermal fluid re-injection); - Select suitable production rates;
D-9	Target formation is missing in the well (unexpected geology, insufficient exploration)	- Additional investigation early in the project to provide accurate interpretation of expected geology and information on the target reservoir (e.g. geophysical methods);
D-10	Target formation has no/insufficient fluid for commercial production	- Accurate collection an interpretation of expected geology for securing information on the target reservoir;
D-12	Excessive scaling in the geothermal loop	- Perform adequate evaluation of scaling potential; - Use of inhibitors to prevent scaling and adapted flowrates; - Injection of nitrogen in surface iron conduit to avoid air going into the geothermal loop and precipitation phenomena;
D-13	Excessive corrosion in the geothermal loop	- Perform adequate evaluation of corrosion potential; - Apply corrosion resistant alloys; - Injection of nitrogen in surface iron conduit to avoid air going into the geothermal loop and precipitation phenomena;
D-15	Hydraulic connectivity between wells is insufficient for commercial use	- Thorough well testing; - Thorough reservoir planning;
F-3	Induced seismicity (above sensitivity level)	- Detailed geological and seismotectonic studies to identify faults capable of generating damaging earthquakes; - Operational protocols jointly defined by operators and public regulators (e.g. traffic light system); - Avoid high re-injection pressure/rate, balanced injection/production; - Proper design and operation of reinjection wells;

Table 4. Continuation.

ID	Description	Prevention measures
E-5	Technical failure/difficulties during drilling (due to any additional causes that were not mentioned)	- Exploitation of the equipment according to the manual; - Accurate collection and interpretation of expected geology and their features for securing information on the forecasted drilling difficulties; - Doing new surface geophysical measurements for the better understanding of expected geology and their features for securing information on the forecasted drilling difficulties; - Careful selection of subcontractors and careful contracting, including their insurances;

2.5 CONCEPT FOR DISTRICT HEATING AND COOLING OF THE CAMPUS

Geological setting in Göttingen makes it possible to utilize geothermal energy from different depth levels (deep, medium deep and shallow) instead of focusing on just one particular horizon. In combination with biomass boilers, absorption and electric chillers, and heat pumps, the new district heating and cooling system of the campus can be more sustainable and environmentally friendly. The concept of such system is presented in Figure 9. It points out that the core aspects of energy transition are system thinking and comprehensive approach which are relevant not only in local conditions of Göttingen, but also on European and global level.

The preliminary plan of the University includes construction of new energy efficient buildings, a new low temperature district heating network (LTDH) and a replacement of the steam absorption chillers by hot water absorption chillers. This plan facilitates the implementation of the concept in Figure 9. Nevertheless, for a comprehensive approach, additional components (or modules) can be integrated in the planning of the University:
- utilization of deep geothermal energy for the base heat load of the campus instead of existing fossil fuel-based solutions;
- utilization of biomass boilers (or CHP plants) instead of small-scale fossil fuel-based CHP plants as back-up supply units;
- green electricity from power generating companies for heat pumps and electric chillers;
- utilization of waste heat of the campus with the help of seasonal thermal energy storage in the medium deep geothermal horizon and heat pumps;
- utilization of shallow geothermal energy for direct cooling and supplying LTDH via heat pumps;
- intelligent control and optimization;
- waste management system, e.g. conversion of the food waste from the canteen into bioenergy (Ma *et al.*, 2018);
- utilization of sustainable and energy-efficient materials for the campus renovation.

Following these suggestions, the University campus might be able to have green and sustainable energy supply in the next 15-20 years. Taking into account such prolonged period of the renovation and transition, cutting edge technologies should be preferred and a modularized approach meaning that different parts (modules) of the concept in Figure 9 can be implemented step by step according to the progress of the buildings' renovation. The benefits of such approach are schedule time flexibility, reduction of the risks associated with EGS development and allocation of capital expenditures per many years instead of immediate high investments.

However, long lifetime of the project can hardly be attractive for private investors, therefore it will be difficult to initiate the project without financial support from the government.

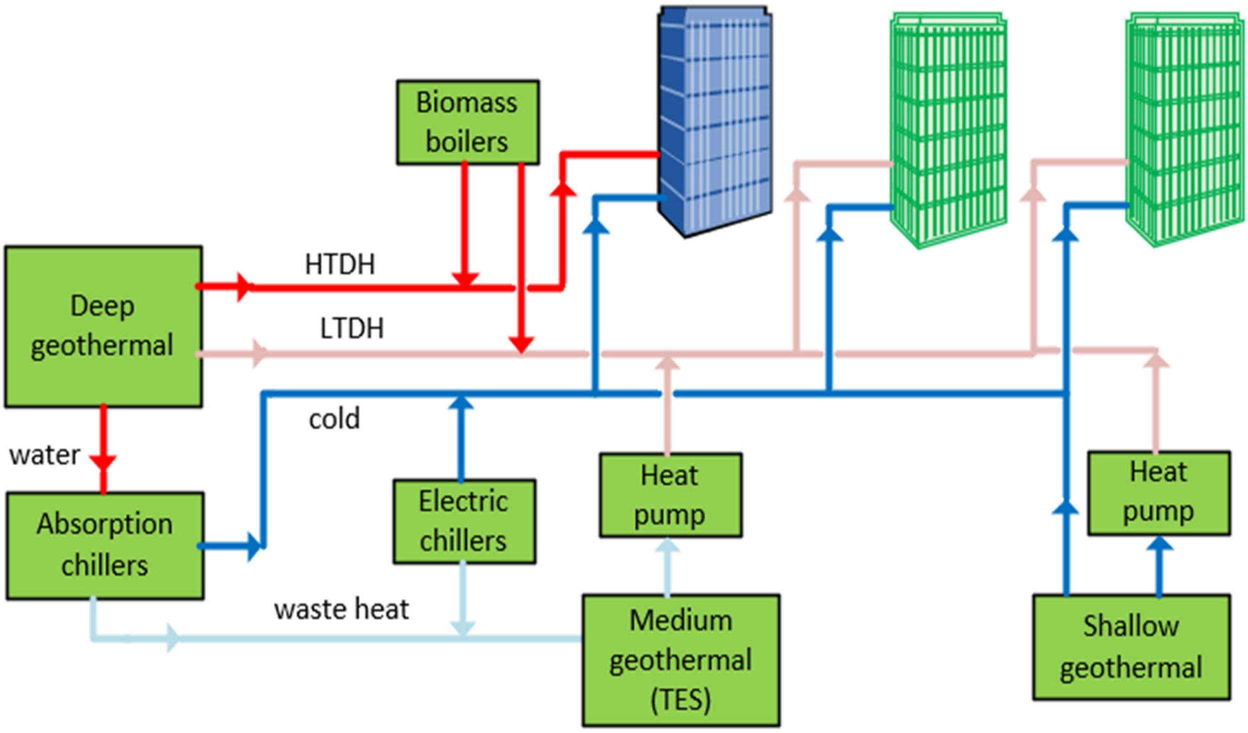

Figure 9. Suggested district heating and cooling system of the campus for the future (Leiss *et al.*, 2021)**.**
Note: HTDH – high temperature district heating; LTDH – low temperature district heating; TES – thermal energy storage; return lines are not shown.

2.6 CONCLUSIONS AND OUTLOOK

The results demonstrate that geothermal energy can be only one component in a transition concept from a fossil fuel-based to a renewable energy-based heat and cold supply. An important, efficient and necessary key element in such transition concept is the primary energy saving in all buildings (Agemar, Suchi and Moeck, 2018). In the case of the University campus development, this can be achieved e.g. with the new UMG buildings and the energetic refurbishment of existing buildings, which, after being completed, eventually define the CO_2 emissions of the campus in 2050.

The proposed heat and cold supply concept including deep, medium deep and shallow geothermal energy is a perspective direction of the Göttingen University campus development taking into account planned renovation of the campus' buildings during the next 15-20 years. The concept can significantly contribute to decarbonization of the campus.

The existing surface infrastructure can be partially exploited for the concept, and new infrastructure and facilities can be built in a sustainable and modular way. Such a modular system is supposed to allow a continuous, step-by-step adaptation of the buildings' renovation progress to the geothermal exploration and exploitation results. Thus, harmonized, hand in hand subsurface-related exploitation and a surface-related infrastructure development should be aimed at. However, this requires intensive cooperation between all stakeholders as well as elaboration of converging processes related to the timelines of the different planning and financing teams.

One of the key components of the concept – Enhanced Geothermal System (EGS) – is quite risky, challenging and uncertain because of very little explored geothermal reservoir and geological setting. That is why potential risks were identified, prevention measures were suggested, and the plan of potential development of EGS in a form of Gantt chart was presented in this deliverable.

The results of the previous study (Romanov and Leiss, 2021) show that an EGS for the district heating and cooling system of the Göttingen University campus can be profitable under some conditions and scenarios (e.g. flow rate and wellhead temperature of brine equal to 40 l/s and 140 °C, respectively) while providing an opportunity to abate up to 18100 t CO_2 annually.

Nevertheless, the whole concept as well as its EGS part require further additional research (particularly, with the help of the research well) in order to overcome different geological, technical, economical, administrative, and societal barriers and challenges. The following progress of the Göttingen demo site development depends on public acceptance and support, research well financing (including public funding schemes) and future results being derived from the exploratory drilling and stimulation.

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Appendix A

Submitted article: Analysis of Enhanced Geothermal System development scenarios for district heating and cooling of the Göttingen University campus.

geosciences

MDPI

Article

Analysis of Enhanced Geothermal System development scenarios for district heating and cooling of the Göttingen University campus

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Abstract: Huge energy potential of Enhanced Geothermal Systems (EGS) makes them perspective sources of non-intermittent renewable energy for future. This paper focuses on potential scenarios of EGS development in a poorly known geological setting – Variscan basement – for district heating and cooling of the Göttingen University campus. On average, the considered single EGS doublet can cover about 20% of the heat demand and 6% of the cooling demand of the campus. Levelized cost of heat (LCOH), net present value (NPV) and CO_2 abatement cost were evaluated with the help of a spreadsheet-based model. In result, the majority of scenarios of the reference case are currently not profitable. Based on the analysis, EGS heat output should be at least 11 MW_{th} (brine flow rate is 40 l/s and wellhead temperature is 140 °C) for potentially profitable project. However, sensitivity analysis presented some conditions that yield better results. Among the most influential parameters on the outcome are subsidies for research well, proximity to the campus, temperature drawdown and drilling costs. Support of the government, public acceptance and effective cooperation between all stakeholders were identified as the key prerequisites for launching EGS project in Göttingen, which can save up to 18100 t CO_2 (34%) annually.

Keywords: deep geothermal energy; EGS; Variscan basement; district heating and cooling; economic indicators; CO_2 abatement cost; sensitivity analysis.

1. Introduction

According to the report by the German Federal Ministry for Economic Affairs and Energy [1], the share of geothermal energy in the renewable-based electricity generation in Germany in 2019 was just 0.1%. Analogous value for heat generation is 8.9%. While 8.2% are related to shallow geothermal energy, which is usually used for local, decentralized low temperature applications in urban areas [2], deep geothermal energy accounts for only 0.7%. At the same time deep geothermal energy is potentially an enormous source of renewable energy of non-intermittent nature that has low land and water requirements and significant CO_2 sequestration potential [3,4]. Other positive and negative sustainability issues of geothermal energy are reviewed in Ref. [5].

Enhanced (or engineered) Geothermal System[1] (EGS) is a technology implying artificial enhancements of rock permeabilities, e. g. by creation of new or by opening and/or widening of preexisting fractures in rocks, to extract geothermal energy from depths of 3-5 km where sufficient natural permeability is low or absent [6]. In paper [7], authors developed a subsurface model for evaluating maximum electric output from an EGS in dependence on brine flow rate and the distance between the wells. The authors estimated that 13450 EGS plants can be built in crystalline areas in Germany providing 474 GW$_{el}$ (4155 TWh$_{el}$). At the same time, the technical potential of EGS in Europe was assessed at 6560 GW$_{el}$ [8], which is significant amount of renewable energy. That is why various research groups currently focus on the development and exploitation of EGS and overcoming of related geological, technical, economic, ecological and social issues and risks [9–14].

As of now, the technology is not mature enough, and there are just a few successful R&D or commercial EGS projects, e.g. [15,16]. Most of them have been realized in igneous and sedimentary rocks and have reservoir temperatures less than 165 °C and flow rates less than 40 l/s [17]. However, there are some exceptions, e.g. the geothermal heat plant in Rittershoffen producing more than 70 l/s of brine with temperature of 170 °C [18].

Many research works related to EGS focus on electricity generation or combined generation of heat and power via Organic Rankine Cycle (ORC) or Kalina cycle [19–21]. In the work [22], multiple-criteria decision making (MCDM) for EGS and decision-making tool were presented, and the authors used the tool to calculate levelized cost of electricity (LCOE) and perform a sensitivity analysis. Levelized costs of electricity generated from EGS were acquired and analyzed in other works as well [23–26]. The values of LCOE for solar-geothermal plants in Northern Chile were estimated in Ref. [27]. In the work [28], Monte Carlo simulations were used to assess LCOE of a double-flash geothermal plant, and the values were compared with gas prices. The investments in the plant are more attractive if natural gas prices are higher. Two software packages EURONAT and GEOPHIRES were used in Ref. [29] for economic studies, and the authors concluded that EGS facilities are not likely to be competitive with either renewable on non-renewable energy sources by 2030. Nevertheless, the latest studies and reports by different organizations [30–33] have shown that LCOE of renewables, including geothermal energy, is already competitive or even lower than LCOE of fossil fuel-based alternatives. The findings of the work [34] show that 4600 GW$_{el}$ of EGS with LCOE less than 50 €/MWh$_{el}$ can be installed worldwide by 2050.

While renewable energy sources met 42.1% of German gross electricity consumption in 2019, the share of renewables in final energy consumption in heating/cooling sector was just 14.7%. And final energy consumption was 576 TWh$_{el}$ and 1218 TWh$_{th}$, respectively [1]. It can be observed that German energy transition (Energiewende) focuses much more on electricity sector than on heating and cooling one. Additionally, electricity (e.g. from distant wind farms) can be transmitted on long distances easier than heat. That is why this work considers EGS as a locally available energy source to cover base load for heat and cold supply rather than for electricity supply. The latter can be met by various other renewable energy sources like solar, wind energy or biomass.

In the work [35], the authors also used the tool GEOPHIRES to estimate LCOE and levelized cost of heat (LCOH) for different technology readiness levels of EGS. The estimated value of LCOH for today's technology is about 42 €/MWh$_{th}$. In the work [36], LCOH for a doublet in the West Netherlands Basin with production rate of 200 m^3/h was estimated at around 30 €/MWh$_{th}$. The cost of geothermal heat for oil sands extraction in Northern Alberta (Canada) was estimated at up to 38 €/MWh$_{th}$ [37]. Economic analysis made for a university in the USA showed that low-potential geothermal reservoir at 3-km depth assisted by a heat pump can supply the University's district heating system having LCOH about 20 €/MWh$_{th}$ [38]. Perspective development of CO_2 storage technologies is CO_2-EGS which utilizes CO_2 as the circulating heat exchange fluid or the working fluid.

[1] also referred to as Hot Dry Rock (HDR) in some works

For potential cogeneration CO_2-EGS in the Central Poland, the calculations showed that LCOH varies from 25 to 45 €/MWh$_{th}$ [39].

The existing literature gives quite good overview of economic indicators of electricity and heat generation from EGS. Meanwhile, the majority of LCOH values found in different works show quite promising and optimistic economic picture when considering that current average costs of heat from oil and gas boilers in German households are 65-75 €/MWh$_{th}$ [40] and from natural gas CHP – 74 €/MWh$_{th}$ [41]. That means that energy transition from fossils to renewables by exploiting EGS in Germany might be quite attractive. However, this work focuses on the EGS exploration of metasedimentary sequences of the Variscan fold- and thrust belt which has been poorly investigated yet. That is why one of the goals of this work is to perform an economic and ecological analysis of different potential scenarios on the preliminary stage of EGS development for district heating and cooling of the Göttingen University campus. Such analysis is necessary because of many geological uncertainties of EGS exploration in Variscan geological setting, and it is supposed to show the minimum required output parameters of a successful EGS project, which will be a target for subsurface investigation and modelling. Another goal is to show potential investors and stakeholders the range of possible outcomes of EGS development and define which factors are the most important for the outcome and to which of them to pay increased attention when developing EGS systems.

2. Background

The campus of the Georg-August-University (UGOE) and University Medical Centre (UMG)[2] takes large area in the center and in the north of the city of Göttingen. Being a demo site of the EU Horizon 2020 project MEET (Multidisciplinary and multi-context demonstration of EGS exploration and Exploitation Techniques and potentials [42,43]), the University has a good chance to commit itself to renewable energy utilization, and particularly, to geothermal energy by developing an EGS concept in deformed metasedimentary rocks. In the best case scenario, Göttingen demo site can become a real laboratory for exploring and expanding the knowledge about EGS in Variscan basement and serving as a representative case study for other places with similar geological setting in Europe.

2.1 Geological setting

The geological setting in Göttingen and its vicinity is quite poorly investigated since there are only a few exploration wells with maximum depth of 1500 m in the surrounding area. This indicates that exploration of geothermal energy potential in Göttingen is currently at very early stage. However, some progress has been made in 2015, when a seismic campaign with two profiles crossing the campus area at an exploration depth of 1500 m could validate that the upper several thousand meters of the subsurface of Göttingen are built up of three main units [44]:

- the lowermost unit (below 1500 m) represents low-grade metamorphic basement mainly consisting of Devonian and Carboniferous metasedimentary and -volcanic successions (greywackes, slates, quartzites, cherts, diabase) that have been folded and thrusted during the Variscan Orogeny in the late Carboniferous;
- Permian sedimentary sequence (several hundred meters of thickness) on top of the basement unit. It starts with either no or only locally deposited metavolcanics or sandstones of the Rotliegend as well as sequences of rock salt, potash salt, anhydrite, dolomite and clay-dominated layers of the Zechstein age;
- the uppermost major unit comprises the sedimentary cover (500 to 800 m of thickness) mainly made up mainly of sandstones, clay rocks and limestones of Triassic age (Buntsandstein, Muschelkalk and Keuper).

[2] both UGOE and UMG referred to as "the University" further on

The whole sequence is overprinted tectonically by the north-south striking Leinetal Graben structure which developed during Mesozoic to Cenozoic times. It is still not clear whether the faults continue into the Variscan basement or they are decoupled mechanically by the Zechstein successions and possibly located elsewhere. Within the Leinetal Graben structure, Quaternary alluvial and wind-carried sediments form an additional unit of minor thickness but of importance regarding the utilization of shallow geothermal systems.

2.2 Technical background

The campus' main energy supplier is a combined heat and power (CHP) plant which includes a gas turbine and several steam and hot water boilers. The existing high-temperature district heating (HTDH) network (13 km of pipelines) delivers heat from the plant to the consumers of the campus. Apart from electricity and heat for district heating, the UMG also needs steam and cold. The latter is produced by both absorption cooling (base load) and vapor compression machines (peak load). Currently, total natural gas consumption of the CHP plant and boilers for producing electricity (partly for cold), hot water (district heating) and steam (partly for cold) for the campus is about 358 GWh/a [45] and corresponding CO_2 emissions are about 72000 t/a. Additional indirect emissions result from an external power grid and external district heating for the campus (about 22000 and 5000 t/a, respectively).

The complete renewal of most of the UMG buildings within the next 15 years and the soon-expected end of the gas turbine lifetime put a question to the UGOE and the UMG on what their energy supply system should consist of in the future. The plans of the University involve the construction of not only new buildings but also a low-temperature district heating (LTDH) network. Although it is not exactly clear at the moment at which level of temperatures the LTDH network will operate, design supply and return temperatures in the network for this work are assumed to be 70 °C and 40 °C, respectively. This level of temperatures correlates with Ref. [46,47]. Additionally, steam absorption cooling machines are going to be replaced with low-temperature ones supplied by hot water with the minimum temperature of 70 °C. Although these measures are good prerequisites for utilization of geothermal energy at different depths and for energy transition at the campus, other additional measures can be also considered [48] including an integrated energy concept and energy efficient construction of new and refurbishment of old buildings of the campus. The latter aspect is one of the key elements of a successful energy transition and CO_2 neutrality until 2050 [49].

2.3 Initial data and scenarios

Since there are no geological and geophysical well data and no reliable numerical reservoir model yet, several probable scenarios for brine flow rate and wellhead temperature were considered. The values vary from 10 to 50 l/s with a step of 10 l/s and from 90 to 140 °C with a step of 10 °C, respectively. Higher flow rates and temperatures can hardly be expected in this Variscan geological setting. Density and specific heat capacity of the brine were derived from dependencies provided in Ref. [50]. Average geothermal gradient was considered to be a standard value for Europe, which is 30 °C/km [51]. Several other uncertain parameters were composed in the reference case and two cases for sensitivity analysis: unfavorable and favorable deviations, which are presented in Table 1. The values of CO_2 tax equal to 55-65 €/t correspond to the ones set by the German Government and starting from 2026 [52]. Since CO_2 taxes in Sweden and Switzerland are already much higher [53], 100 €/t was also considered as additional favorable scenario in this work. Parameter "Subsidy for production well" includes 50% or 80% (both favorable deviations) subsidy for drilling and stimulation of the research well (to be transformed in production well later on).

The EGS system in Göttingen is supposed to represent a doublet (one production and one injection well). The research (production) well depth was assumed to be 5000 m since it is not known at what depth the most suitable conditions can be found. Only after a first research well is drilled, it will be clear at what depth an EGS could be developed with the highest efficiency. Thus, the depth of the second well (injection) is a variable, and it is defined by the considered temperature scenarios and the geothermal gradient.

For different scenarios "Distance to the campus", heat losses in the pipelines and specific electricity consumption for pumping the heat carrier from the site to the campus were assumed based on Ref. [54] and shown in Table 2.

Table 1. Parameters for the reference case and two cases with parameters for sensitivity analysis.

Case	L [km]	C_{drill} [%]	$OPEX$ [%]	d_n [%]	S_{gov} [%]	C_{carb} [€/t]	β [%]	τ [years]	T_{draw} [%/year]	T_{inj} [°C]
Unfavorable deviation	10	130	130	9.1	___	___	15	8	2	70
Reference case	5	100	100	7.0	0	55	10	6	1	60
Favorable deviation	0.5	85	85	6.0	50 80	65 100	5	4	0.5	55

L – distance to the campus; C_{drill} – cost of drilling; $OPEX$ – operational expenditures; d_n – nominal discount rate; S_{gov} – subsidy for research (production) well; C_{carb} – CO_2 tax; β – brine salinity; τ – construction time; T_{draw} – temperature drawdown; T_{inj} – injection temperature.

Table 2. Heat losses and specific electricity consumption for different distances to the campus [54].

L [km]	q_{hl} [%]	e_{spec} [kW_{el}/MW_{th}]
0.5	5	5
5	10	7.5
10	15	10

L – distance to the campus; q_{hl} – heat losses in the pipelines; e_{spec} – specific electricity consumption for pumping.

Usually, it takes from 5 to 7 years to develop a deep geothermal project from the early stages of exploration to operating facilities [55,56]. In order to make planning of the geothermal system construction clear and coherent with the planning of the reconstruction of the campus' buildings, the Gantt chart for potential EGS development in Göttingen is proposed in Table 3. There are also the reference case, unfavorable deviation and favorable deviation in the chart. Parameter "Construction time" from Table 1 correlates with the parameter "Start of operation" from Table 3.

For investors, important milestones in the chart are marked with darker color, which means moments when investments for the project are needed. The investments can be split up on three parts: research well (on average 45%), the second well (on average 37%), and surface infrastructure (on average 18%). The decisive part of the whole project is the first one, when the research well drilling is financed, the research work is done, and it will be clear what outcome can be achieved. In case of geologically unsuitable and unpromising conditions leading to a failure of the project, the first part of the investments is lost and the other two parts make no further sense for investors. This shows that EGS projects can be quite risky and not very attractive for investors. However, there are initiatives and projects aiming at establishing financial instruments for insurance of deep geothermal projects [57] which might be able to attract investors.

Table 3. Gantt chart for potential development of EGS for Göttingen demo site. Solid squares – favorable deviation; squares with horizontal stripes – reference case; squares with vertical stripes – unfavorable deviation.

Activity	**Year**								
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Research well financing (~ 45%)									
Research well drilling									
Research work									
Stimulation tests									
Injection well financing (~ 37%)									
Injection well drilling									
Transformation of the well: research -> production									
Stimulation tests									
Surface infrastructure financing (~ 18%)									
Surface infrastructure construction									
Start-up and commissioning									
Start of operation									

3. Materials and Methods

Based on the test reference year data from the German weather service [58] and internal documents from the University, a future heat load profile of the campus including the heat demand for the new (to-be-built) buildings, for the remaining existing buildings, and for the absorption cooling machines was compiled. The assumption was made that potential EGS supplies the new buildings as a first priority, then the remaining existing buildings, and, in the last turn, the absorption chillers. The calculations of the total EGS heat generation were done considering the limitation that the injection temperature is at least 5 °C higher than the return temperature from a consumer and not lower than noted in Table 1.

The main focus of the methodology is calculation of LCOH, net present value (NPV), and CO_2 abatement cost for the campus for different scenarios described in section 2.3. These parameters are one of the main indicators for potential investors and stakeholders to make a decision with regard to an EGS project. A spreadsheet-based model, which is explained below, was developed for evaluating those parameters.

Capital expenditures (CAPEX) include the following components:

$$CAPEX = C_{drill} + C_{stimul} + C_{pipes} + C_{land} + C_{manage} + C_{equip} \quad (1)$$

where:

C_{drill} – cost of drilling. Dependencies of drilling costs from depth were acquired from several sources [59–63], and the average values were taken for the calculations.

C_{stimul} – cost of hydraulic stimulation; assumed to be 2 M€/well.

C_{pipes} – cost of the main pipelines from the site to the campus (distribution pipelines are already a part of the existing HTDH network and not included here; and the cost of the planned distribution LTDH network is also not included); derived from the work [64].

C_{land} – cost of land; specific value was assumed to be 37.5 €/m^2 [62]. Land requirement is 5000 m^2/MW [65]. For the scenario "0.5 km from the campus", this cost is zero since the University already owns the land.
C_{manage} – cost of project management, cost of campaigning for public acceptance and other costs [62,66].
C_{equip} – cost of equipment (pumps, heat exchangers, piping valves, auxiliaries), which can be calculated as follows:

$$C_{equip} = C_{sub\_pumps} + C_{pumps} + C_{HEX} + C_{valves} \quad (2)$$

C_{sub_pumps} – cost of submersible pumps; derived from Ref. [67] using Producer Price Index (PPI) equal to 1.6 [68][3]. The pumps are to be replaced every 5 years.
C_{pumps} – cost of circulation pumps for district heating network. The values were obtained from price lists of manufacturers.
C_{HEX} – cost of surface heat exchangers; average specific cost is 0.009 M€/MW$_{th}$ [59].
C_{valves} – cost of piping valves and auxiliaries; assumed to be 25% of the equipment cost.

Operational expenditures (OPEX) include the following components:

$$OPEX = C_{el\_pump} + C_{labor} + C_{mainten} + C_{insur} \quad (3)$$

where:
C_{el_pump} – annual cost of electricity for pumping. Submersible pumps' electricity consumption was assumed to be 10% of the total heat production from EGS [65,69]. For the circulation pumps in the district heating network, specific values from Table 2 were used. Electricity price for non-households in Germany in 2020 was 178 €/MWh$_{el}$ [70].
C_{labor} – annual cost of labor [62].
$C_{mainten}$ – annual cost of maintenance and repair [62].
C_{insur} – annual cost of insurance and legal assistance [62].

LCOH was calculated according to the Ref. [71]:

$$LCOH = \frac{\sum_{j=0}^{L}(CAPEX_j + OPEX_j) \cdot (1 + d_n)^{-j}}{\sum_{j=S}^{L} Q_{egs_j} \cdot (1 + d_n)^{-j}} \quad (4)$$

where $CAPEX_j$ – capital expenditures from year 0 to S; $OPEX_j$ – annual operational expenditures from year S to L; S – year of the operation start; L – total project lifetime; Q_{egs_j} – annual amount of heat delivered from the EGS to the campus (from year S to L) considering heat losses derived from Table 2; d_n – nominal discount rate [72], which can be calculated by formula (5):

$$d_n = (1 + d_r) \cdot (1 + e) - 1 \quad (5)$$

where d_r – real discount rate; e = 0.015 – annual average inflation rate [70].

Operational lifetime was defined by temperature drawdown: operation ends when wellhead temperature reaches the value of 10 °C higher than injection temperature. Otherwise, operational lifetime was considered to be 30 years.

NPV was calculated according to formula (6):

$$NPV = \sum_{j=0}^{L} \frac{-CAPEX_j - OPEX_j + Q_{egs_j} \cdot C_{heat}}{(1 + d_n)^j} \quad (6)$$

where C_{heat} = 89 €/MWh$_{th}$ – prognosed heat tariff (price) for the University from fossil-fuel based system taking into account the CO_2 tax in Germany equal to 55 €/t from the

[3] exchange rate: 1 USD = 0.85 EUR (November 2020)

year of 2026 [52]. For the favorable deviations of CO_2 tax in Table 1, heat tariff is 91 and 100 €/MWh$_{th}$, respectively.

CO_2 abatement cost was calculated according to formula (7):

$$AC = \frac{-NPV}{\sum_{j=S}^{L} CO2_j^{sav}} \quad (7)$$

where $CO2_j^{sav}$ – annual CO_2 savings during operation from year S to L considering electricity mix and natural gas emission factors equal to 397 and 202 t CO_2/GWh , respectively [73,74]. Positive values of AC show how much money is required to avoid one ton of CO_2 emission, while negative values show that the process is economically profitable.

4. Results

4.1 Heat demand of the campus and potential heat supply from EGS

Figure 1 illustrates future heat load of the campus when its reconstruction is finished. The design heat load of the to-be-built buildings and the remaining existing buildings is estimated at 32.6 and 23.2 MW$_{th}$, respectively, while the heat load of absorption chillers reaches up to 10.7 MW$_{th}$ in summer. Thus, the influence of the to-be-built buildings on future heat and cold supply of the campus will be quite high. The heat demand of the campus in summer is, in many scenarios, lower than potential heat production. That is why practically achievable EGS heat generation is lower than potential one. Red dashed line in Figure 1 shows the estimated maximum geothermal output, and in this case, the load factor is 88%, while other values of the output lead to higher load factors. The average distribution of geothermal energy between the heat demand of the to-be-built buildings, remaining existing buildings, and absorption cooling machines is 91%, 7%, and 2%, respectively.

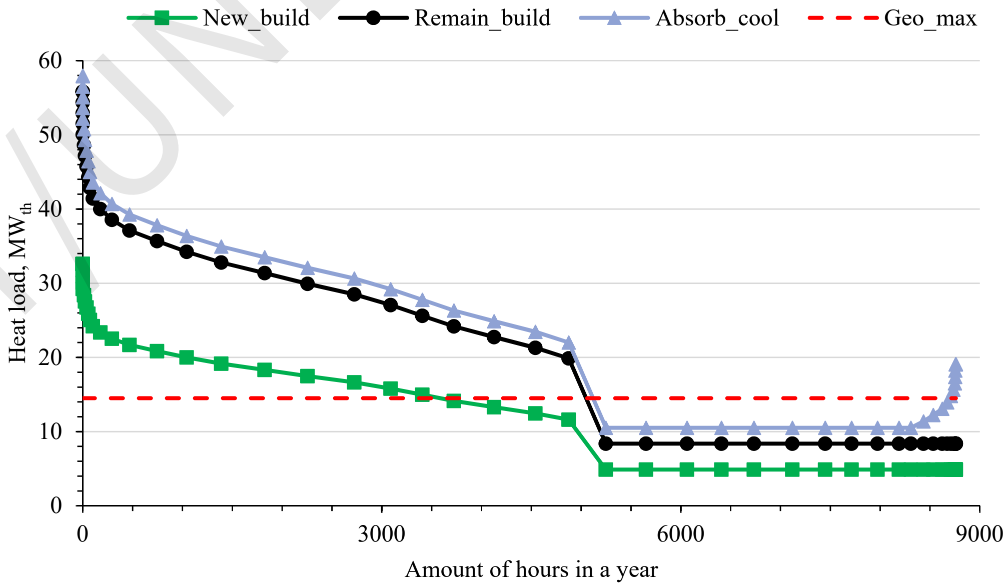

Figure 1. Future heat load of the campus (including to-be-built buildings, remaining existing buildings, and heat for absorption cooling) in comparison with the estimated maximum geothermal output.

In Figure 2, lifetime-average EGS heat generation (without heat losses in the network) and design EGS heat output for the reference case are shown depending on brine flow rate and wellhead temperature. The heat generation can vary from 7.6 to 86.0 GWh$_{th}$/a, while the heat output – from 1.1 to 14.5 MW$_{th}$. Table 4 displays how much heat demand of different consumers of the campus can be potentially covered by an EGS. On average, the values amount to 30.8%, 5.0%, and 6.1% of the heat demand of new buildings, remaining existing buildings, and absorption chillers, respectively. Existing heat and cold supply sources of the campus, which are supposed to cover the remaining demand, and back-up options were not considered in this study. Additionally, CO_2 emissions from the fossil-fuel based heating and cooling system of the campus[4] are shown in Table 4. Thus, from 3.6 to 41.1% of CO_2 emissions can be theoretically saved if the EGS causes no greenhouse gases emissions during operation.

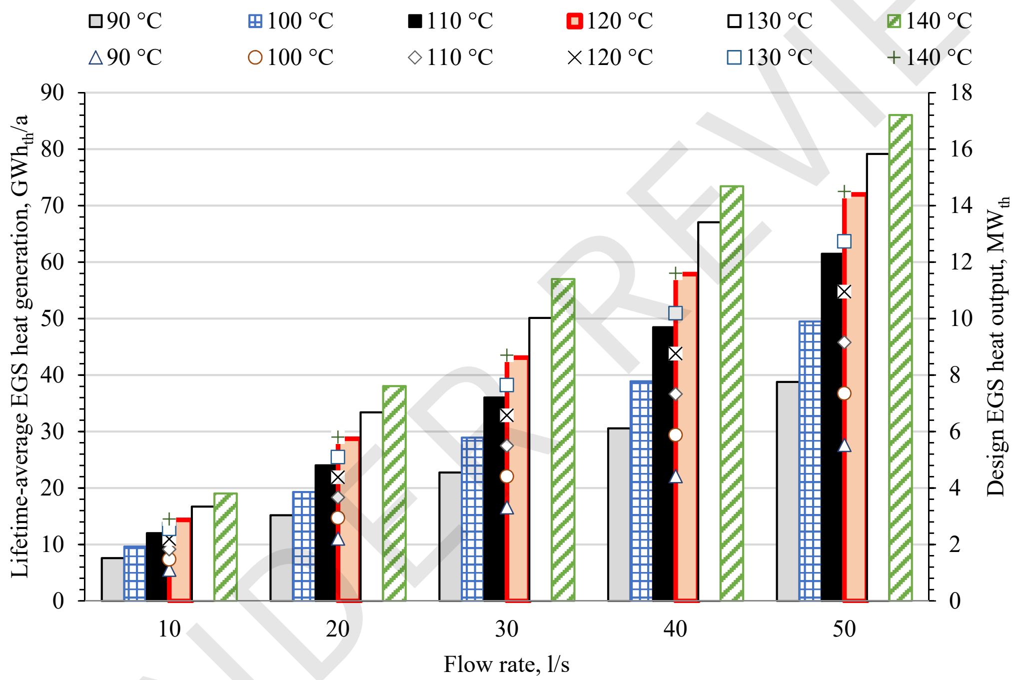

Figure 2. Lifetime-average EGS heat generation (columns) and design EGS heat output (symbols) for the reference case.

Table 4. Lifetime-average potential heat supply from EGS as a share of heat demand of different consumers and CO_2 emissions of future fossil-fuel based heating and cooling system.

Application	Type of heat consumer	Heat demand (100%) [GWh_{th}/a]	CO_2 emissions from fossil-fuel system [t/a]	Potential heat supply from EGS		
				Minimum [%]	Average [%]	Maximum [%]
Heating	New buildings	110.8	27991	6.8	30.8	60.6
	Remaining buildings	78.8	19920	0.0	5.0	15.3
	Buildings total	189.6	47910	4.0	20.1	41.8
Cooling	Absorption chillers	19.9	5029	0.0	6.1	34.0
H & C	Total	209.5	52939	3.6	18.8	41.1

4.2 Economic and ecological results

Capital expenditures for the reference scenario and for 5 km and 10 km scenarios are shown in Figure 3. Costs of drilling and stimulation of two wells represent from 56 to 86% of CAPEX, and the next costly items are the costs of pipelines and the cost of project management. It is worth noting that components "Land", "Pipes_5km", and "Pipes_10km" are applicable only for 5 km and 10 km scenarios. Since drilling-related costs form the biggest part of the CAPEX, the components of CAPEX are shown in the chart only in

[4] the specific CO_2 emissions are 252.7 g/kWh_{th}

dependence to the wellhead temperature, which is directly related to the drilling depth, and the influence of fluid flow rate on the total CAPEX is relatively small. In the same chart, specific CAPEX for different flow rates in the reference case are shown. The smallest values are for the highest considered flow rate (50 l/s); they vary from 5.8 to 2.9 k€/kW$_{th}$ for the temperatures from 90 to 140 °C. At the same time, the values for 10 l/s vary from 26.1 to 12.3 k€/kW$_{th}$.

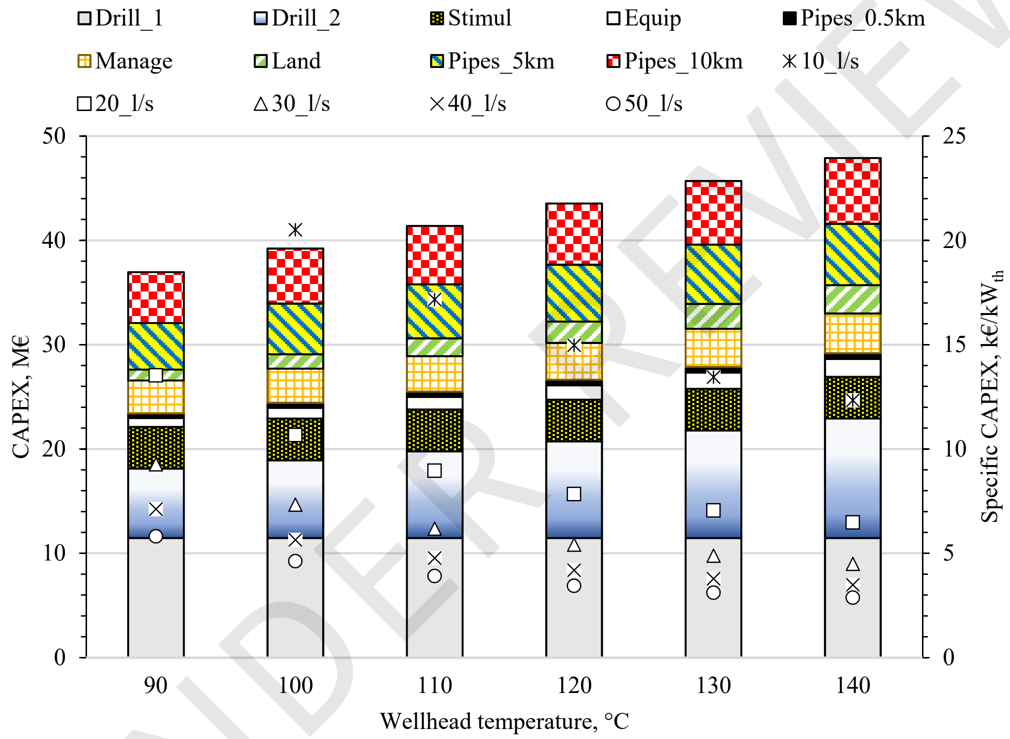

Figure 3. Components of CAPEX for different wellhead temperatures (columns) and specific CAPEX for different flow rates under the reference case conditions (symbols).
Note: the value of specific CAPEX for 10 l/s under 90 °C is 26.1 k€/kW$_{th}$.

In Figure 4, temperature- and flow rate-average structure of operational costs and average annualized capital costs for the reference case are compared with each other. Annualized capital costs were obtained with the help of annuity factor [75], but such approach was used only in this part of the work to allow for the comparison in Figure 4. It can be noted that electricity costs for pumping represent the biggest part of the OPEX.

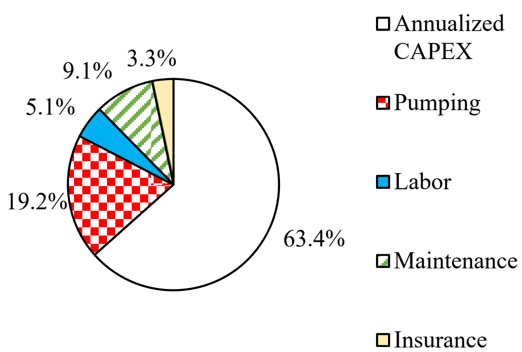

Figure 4. Average structure of operational costs and average annualized capital costs for the reference case.

The results of LCOH and NPV calculations for the reference case are shown in Figure 5. For illustrative comparison, prognosed heat tariff for the campus (89 €/MWh$_{th}$) from fossil-fuel based system under CO_2 tax equal to 55 €/t and hypothetic heat tariff (100 €/MWh$_{th}$ if CO_2 tax is 100 €/t) are also plotted in the chart. LCOH varies from 80 to 525 €/MWh$_{th}$ for the highest and lowest parameters of brine, respectively. It is clear that the majority of the scenarios of the reference case have worse LCOH than the prognosed fossil fuel-based heat tariff. The exceptions are the few scenarios with brine temperatures of 120 °C or higher and brine flow rates equal to 50 l/s and the scenario with parameters 140 °C and 40 l/s. Although the scenarios with high temperatures and flow rates are considered in this work, their practical accomplishment in Variscan geological setting is doubtful, especially when it comes to quite high flow rate such as 40-50 l/s. A bit more realistic flow rate is 30 l/s, for which high temperature scenarios result in LCOH about 111 and 104 €/MWh$_{th}$, i.e. relatively close to the prognosed heat tariff and might be even profitable under some favorable conditions. Scenarios with flow rates less than 30 l/s are far from being economically feasible.

As for the NPV values, they vary from -27.1 to 6.6 M€ for the lowest and highest parameters of brine, respectively. Most of the calculated values are below zero, except for the same high temperature and high flow rate scenarios as in the LCOH part. In general, the values of NPV show similar trends to LCOH. When looking at NPV values, the scenarios with the flow rate of 30 l/s and high temperatures seem to be not so optimistic since the highest achievable NPV for such scenarios is -7.5 M€, which can be improved under favorable conditions though.

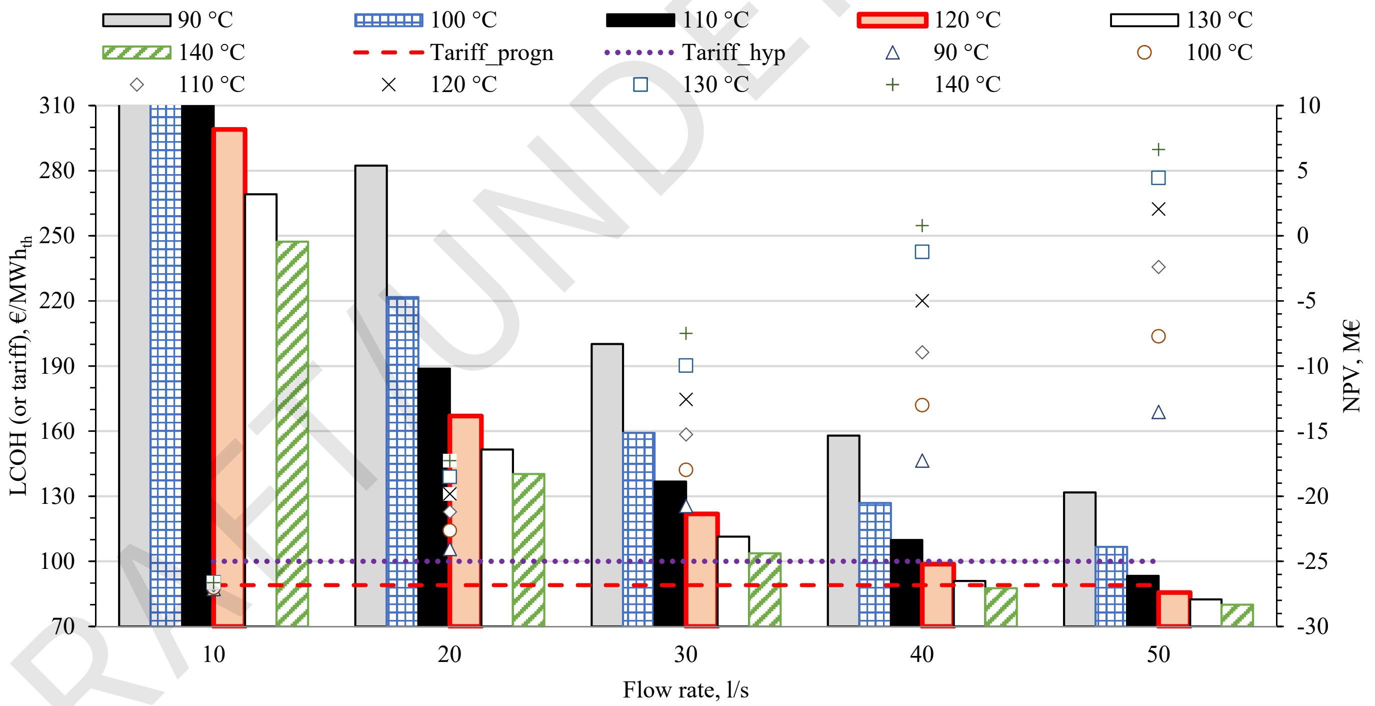

Figure 5. LCOH (columns), prognosed heat tariff for the campus (dashed line), hypothetic heat tariff for the campus if CO_2 tax is 100 €/t (dotted line), and NPV (symbols) for the reference case.
Note: the values of LCOH for 90 °C, 100 °C and 110 °C under 10 l/s are 525, 406 and 342 €/MWh$_{th}$, respectively.

Even though many scenarios are not economically beneficial, their ecological effect is an important factor to consider. CO_2 abatement cost and lifetime-average operational CO_2 savings for the reference case are presented in Figure 6. The CO_2 savings vary from 1600 to 18100 t/a (3-34% of the emissions from the fossil-fuel based heat supply system of the remaining existing buildings, new buildings and absorption chillers) and the CO_2 abatement costs – from -12 to 655 €/t. The highest parameters of the brine yield the best results, as it was demonstrated for LCOH and NPV. The high-temperature scenarios with the brine flow rates of 30 l/s show quite acceptable CO_2 abatement costs, which range from 21 to 31 €/t.

Average specific value of CO_2 emissions resulting from the operation of a potential geothermal plant in Göttingen is 42.4 g/kWh$_{th}$. In the work [16], life cycle assessment for currently operating direct-use geothermal plant Rittershoffen in France was performed, which indicated that specific CO_2 emissions are 7.0-9.2 g/kWh$_{th}$. However, it should be noted that nuclear power-dominated French electricity mix is 9 times less carbon-intensive than the German one (44 g/kWh$_{th}$ vs 397 g/kWh$_{th}$) [73], which explains the difference.

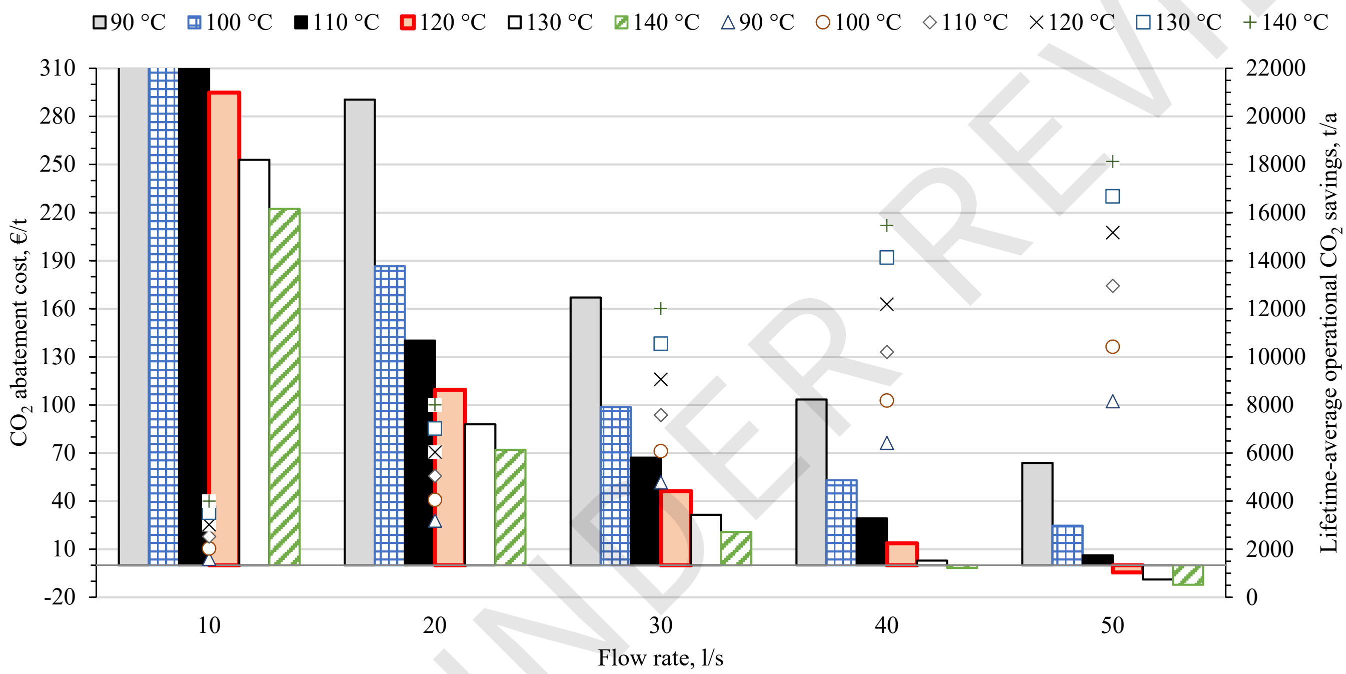

Figure 6. CO_2 abatement cost (columns) and lifetime-average CO_2 operational savings (symbols) for the reference case. Note: the values of CO_2 abatement cost for 90, 100 and 110 °C under 10 l/s are 655, 445 and 355 €/t, respectively.

4.3 Sensitivity analysis

In order to cope with uncertainty of the parameters and to get better understanding of potential deviations from the obtained results of the reference case, sensitivity analysis was carried out. The temperature-averaged results of LCOH sensitivity analysis for the parameters from Table 1 are shown in Figure 7.

Increasing temperature drawdown from 1%/year to 2%/year leads to the biggest increase of LCOH (24-18% for the flow rates from 10 to 50 l/s, respectively). The other significant factor leading to increase of LCOH by 16-20% is 30%-increase of nominal discount rate. Additional parameters worth noting are 10 °C-increase of injection temperature, 10 km-distance from the field to the campus and 30%-increase of drilling costs contributing 13-21%, 17-18% and 13-18% to the increase of LCOH, respectively. Less important parameters are OPEX, construction time (or the year of operation start) and brine salinity.

The most important parameter leading to decrease of LCOH is the research well subsidy of 50 or 80%, which allows to achieve 13-18% or 21-29% of LCOH reduction, respectively. Decreasing the distance from 5 km to 0.5 km has also a large effect (15-18%) on LCOH decrease. The remaining considered parameters are of less importance and contribute not more than 10% to LCOH decrease each.

It can be noted that, in general, factors influencing LCOH have less effect on higher flow rate scenarios which can be explained by larger amount of produced heat by EGS, thus smoothing the fluctuations. The exceptions are "Distance" and "OPEX" parameters showing the opposite trend since they are both proportionally and strongly related to the amount of produced heat.

The temperature-averaged results of NPV sensitivity analysis for the parameters from Table 1 are presented in Figure 8.

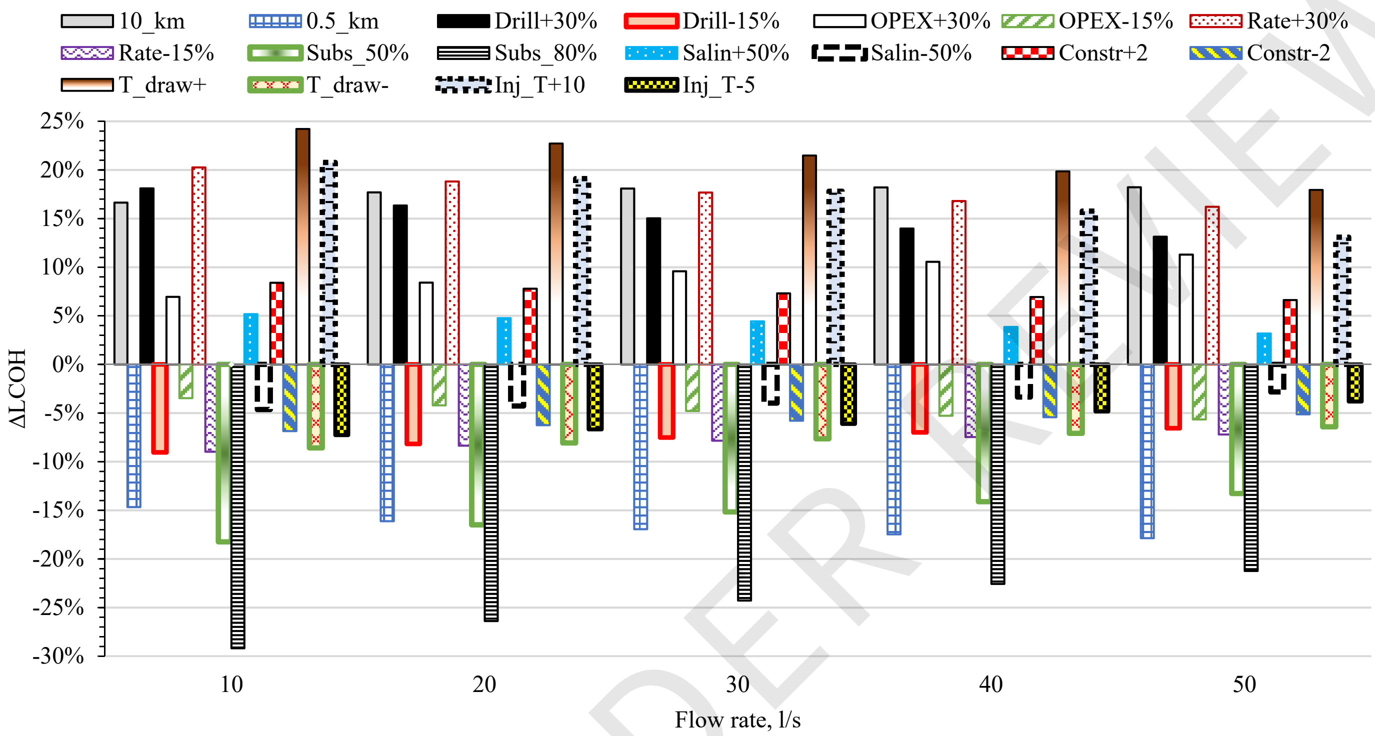

Figure 7. LCOH sensitivity analysis for the parameters from Table 1.

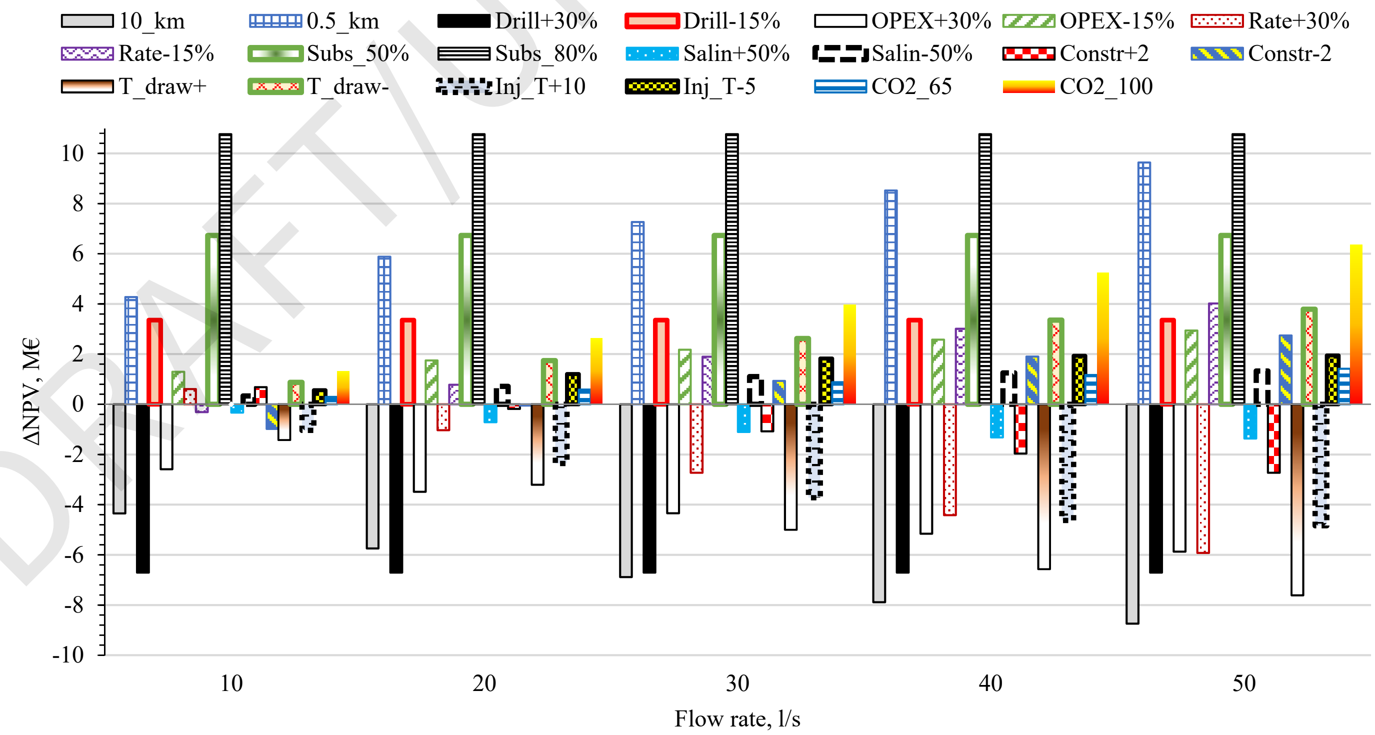

Figure 8. NPV sensitivity analysis for the parameters from Table 1.

Parameters “Distance” and “Drilling cost” are very influential on unfavorable deviations of NPV. If the distance from the field to the campus is increased from 5 to 10 km, NPV decreases by 4.3-8.7 M€ for the scenarios with flow rates from 10 to 50 l/s. Increasing drilling cost by 30% leads to NPV decrease by 6.7 M€. Temperature drawdown is also a parameter worth noting, especially for high flow rates, since it can worsen NPV value by up to 7.6 M€. Other parameters – OPEX, nominal discount rate and injection temperature – have some impact on NPV, and the remaining parameters have relatively minor one.

As for favorable deviation of the parameters, 50 and 80%-subsidy will lead to NPV increase by 6.7 and 10.8 M€, respectively. The possibility to build the geothermal plant just 0.5 km from the campus will result in 4.3-9.6 M€ increase of NPV for the scenarios with flow rates from 10 to 50 l/s. Reducing drilling cost by 15% can improve NPV by 3.4 M€. Potential increase of CO_2 tax up to 100 €/t can lead to 1.3-6.4 M€ increase of NPV. While the influence of temperature drawdown, nominal discount rate and OPEX becomes significant under high flow rates, the other remaining parameters have much less effect.

As seen in Figure 8, the influence of most of the parameters intensifies for higher flow rates. And for low flow rates, e.g. 10 l/s, some parameters barely lead to any change in NPV. Parameters “Construction time” and “Nominal discount rate” show shifting behavior when flow rate increases. For small flow rates, they lead to NPV increase, while NPV decreases for large flow rates. It can be explained by the fact that longer construction time leads to a shift in the schedule for investments (Table 3) which is “beneficial” for low flow rate scenarios because of later discounting of those CAPEX. It simply means that the scenarios are not profitable anyway, but the losses are a bit reduced because the investments were made later. For high flow rates, the situation is opposite since longer construction time delays getting relatively high revenues from the plant operation. Being discounted in later years, those revenues get less value and influence on the overall result leading to decrease of NPV with regard to the reference case. And a similar behavior is true for nominal discount rate.

5. Discussion

Although the results were acquired for the Göttingen demo site, the considered parameters for the calculations and analysis were quite typical. That is why the results can be also applied to an early stage development analysis of other EGS projects in poorly known geological setting for district heating and cooling. But it should be noted that electricity prices in Germany are among the highest in Europe [70], and the district heating prices are above the average level [76]. Therefore, the results will be better for the countries with lower electricity prices and higher heat prices.

Interconnection and interdependence between different parameters were not considered during the sensitivity analysis. For example, large extraction of heat from the geothermal reservoir (high brine flow rate and low injection temperature) might lead to bigger and faster temperature drawdown, and consequently, to much smaller operation lifetime of the project, which puts forward a question of sustainable energy generation from EGS. Additionally, brine salinity and injection temperature are also correlated parameters since injection temperature is limited by scaling and corrosion issues for high-salinity brine. Thus, some parameters from the sensitivity analysis can depend on each other and/or aggregate leading to more complex effects on the final result.

Development of the EGS system in Variscan basement in Göttingen is associated with many uncertainties and risks. Although the risks are not explicitly considered in this work, they should be addressed in future works. One of the biggest uncertainties and risks for any EGS is induced seismicity risk since it affects public acceptance of EGS projects [77] and can completely freeze any further works and lead to the cancellation of a project [78]. Cost-benefit analysis was applied to quantify the trade-off between seismicity risks and proximity to district heating and heat consumers in Ref. [79]. The authors concluded that remote EGS is less favorable even if the seismicity risk is considerably decreased or close to zero. The results of the sensitivity analysis of this work have also shown that proximity of the geothermal plant to the campus significantly improves economic indicators of the project. Nevertheless, it might be quite challenging to drill the wells, conduct hydraulic stimulation tests, and build the plant close to the campus without public acceptance. That is why public acceptance is one of the prerequisites of future successful realization of the EGS project in Göttingen.

One of the obstacles of the project is to correlate and synchronize the University's plans of the campus reconstruction and the development of the EGS plant, which was partially addressed in this study by proposing the Gantt diagram of the EGS development. Nevertheless, effective communication and cooperation between different stakeholders within the University and outside of it is also one of the key prerequisites to launch the project.

The performed analysis has demonstrated that the reference case might be currently not competitive with the existing fossil fuel alternatives. Moreover, such long-term projects are usually not very attractive for private investors. Therefore, the government's support is another necessary prerequisite for the project.

Even if the economic part of the project might happen to be not very promising after the research drilling and hydraulic stimulation tests are done, the importance of its ecological effect is undoubtful. Economic and political measures for CO_2 emissions reduction are likely to become stricter in future which will pave the way for initially commercially unfeasible projects to be supported and implemented. The hypothetic value of the heat tariff depicted in Figure 5 and the values in Figure 8 show that CO_2 tax can be a powerful tool of the government to impact the profitability of EGS projects. On the other hand, other renewable options, which also benefit from high CO_2 tax and can yield better results than EGS due to more mature technological level and undercut the heat tariff, were not considered in this work.

The next important and essential step of the project development is to get research well funding. Additional opportunity of EGS projects in sites with poorly known geological settings, which can be provided by a deep research well, is investigation of shallow and medium layers and their further exploitation, e.g. for underground seasonal thermal energy storages. Such an integrated approach helps not only to increase the overall contribution of geothermal energy, i.e. renewable energy, but also to maximize the public subsidies for a research well, since the research focus is on both deep and medium deep target zones. In Germany, this is crucial when applying for public subsidies because financial support for drilling is preferentially given to the drilling sections defined as not yet investigated target rock units.

6. Conclusions

Geological setting in Göttingen – Variscan basement – is relatively poorly investigated for Enhanced Geothermal Systems exploitation. Nevertheless, there are expectations that geothermal energy will be able to supply district heating and cooling of the Göttingen University campus (a demo site of the MEET project). That is why various scenarios of potential development of EGS for the campus were considered and analyzed in order to deal with different geological, technical and economic uncertainties of the project. On average, the considered single EGS doublet can cover about 20% of the heat demand and 6% of the cooling demand of the campus. For different wellhead temperatures (90-140 °C) and flow rates (10-50 l/s) of brine, the obtained values of LCOH, NPV, and CO_2 abatement cost vary from 80 to 525 €/MWh_{th}, from -27.1 to 6.6 M€, and from -12 to 655 €/t, respectively.

The most influential parameters on LCOH and NPV, which were identified during the sensitivity analysis, are subsidies for research well, distance from the field to the campus, temperature drawdown and drilling costs. These parameters should be primarily dealt with when considering EGS development. CO_2 tax, operational expenditures, injection temperature and nominal discount rate can be also quite influential, especially under high brine flow rates. Other analyzed parameters, namely construction time and brine salinity have significantly less effect on the final result.

For the considered initial conditions in the reference case, it can be concluded that EGS heat output should be at least 11.0 MW_{th} (corresponds to brine flow rate and wellhead temperature 40 l/s and 140 °C, respectively), in order to have more or less economically justified EGS project. If the distance between the field and the campus is 0.5 km, minimum EGS heat output can be 7.2 MW_{th} (30 l/s and 125 °C). In case of 50 and 80%-subsidy, the minimum heat output is 8.1 MW_{th} (30 l/s and 135 °C) and 7.2 MW_{th}, respectively. The abovementioned parameters of brine can serve as a benchmark for geologists, engineers, managers, investors and other involved stakeholders to evaluate the success rate of the project.

Support of the government, public acceptance and effective cooperation between all stakeholders were identified as the key prerequisites for launching EGS project in Göttingen, which can save 1600-18100 t CO_2 annually (3-34% of the emissions from the fossil-fuel based heat supply system of the remaining existing buildings, new buildings and absorption chillers).

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