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Socio-economic analysis report of repurposing abandoned wells for industrial processes

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D.1.2.1: SOCIO-ECONOMIC ANALYSIS REPORT OF REPURPOSING ABANDONED WELLS FOR INDUSTRIAL PROCESSES

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0. Executive Summary

This report was prepared by the consortium of the project TRANSGEO to provide the deliverable D1.2.1, "Socio-economic analysis report of repurposing abandoned wells for industrial processes." The aim of this document is to analyse the repurposing possibilities of abandoned wells for industrial heating and cooling processes and the conditions required for an economically feasible reuse of existing wells for different industrial applications. This work is a result of the project partners' research into the social and economic factors affecting reuse of abandoned wells in industry, with special attention to heating and the conditions required for an economically feasible reuse of existing wells for different industrial applications. The report reflects the views of the authors.

In general, social and economic aspects of well reuse are strongly location dependent. Therefore, a site-specific socio-economic analysis is required to determine the feasibility of a specific reuse case. Here, the general socio-economic aspects of well reuse for industrial applications are presented. This includes the variety, but also the outline, of the socio-economic situations of the 5 participating countries (Slovenia, Croatia, Germany, Austria, and Hungary) with respect to the potential reuse of abandoned wells for industrial purposes.

The social analysis reflects the general attitude towards well reuse, displays potential benefits and risks to developers and end users, and represents the implementation drivers, including communication strategy, data accessibility, clear process for implementation, and others. Regarding the social aspect, the Aquifer Thermal Energy Storage (ATES), Borehole Thermal Energy Storage (BTES), Deep Borehole Heat Exchanger (DBHE), and Hydrothermal Energy (HE) reuse technologies are seen as established, sustainable, ecological, and renewable options for geothermal redevelopment of abandoned hydrocarbon wells. For the 5th technology, Enhanced Geothermal Systems (EGS), there are minor obstacles connected to the environment and potential seismic events. However, application of EGS, along with HE, provides the maximum output of thermal energy, with ATES, BTES, and DBHE providing lower energy output. Depending on the installed power and resource potential, EGS or HE can produce up to 50 MW_{th}.

The analysis is focused on the demand patterns for heat distribution in the industrial sector and involves repurposing of existing boreholes infrastructure for geothermal energy in a variety of applications, including the food and beverage, pulp and paper, and chemical/petrochemical industries. The non-ferrous metals and machinery and transport industries were added to these primary three targets, with calculations indicating that the higher-capacity geothermal reuse technologies (ATES, EGS, and HE) will be required for effective application in all 5 industries. In general, the lower-capacity technologies (BTES and DBHE) do not have the energy required for industrial application, though it may be possible to use geothermal energy for space heating or to combine multiple wells in a single system which meets the higher temperature and energy needs for most industries. Electricity generation from reused geothermal wells currently plays only a minor role, because it is limited to the presence of an adequate resource and the introduction of appropriate technology for exploitation. As new technologies are developed (e.g. Eavor-Loop), this may change in the future. We outline the possible implementation of known technologies on reused wells, together with the benefits and challenges of applying these technologies.

The analysis included the preparation of an extensive questionnaire, and project members were designated for completing the questionnaire for each country. After collecting data and analysing the obtained information, a summary was made regarding the current social and economic situation in each country, demand patterns, and social and economic aspects for the industrial sector. The economic analysis focuses on determining the minimal required equipment for each technology to supply heat from the underground. Cost estimates are divided into investment cost (well workover, downhole equipment, surface equipment, connection pipelines, etc.) and maintenance and operational cost (services, monitoring, maintenance, etc.).

An estimate was also made of the costs of carrying out workover operations on a well with the aim of converting it to geothermal use via one of the recognized repurposing technologies. We also estimate the costs of surface and downhole equipment (connecting pipelines, heat exchanger, surface installations, submersible pumps, and others) and estimated the annual maintenance cost to show the overall financial effect of the investment plus operational cost.

The overall cost of workover operations varies between countries due to their different economic situations. Therefore, we divided the partner countries into two groups for comparison. In Austria and Germany, the costs of performing a well workover in 2024 would be the lowest for DBHE, BTES, and ATES, with a cost between EUR 400.000 and EUR 630.000. For Hungary, Croatia, and Slovenia, the costs of a well workover for DBHE, BTES, and ATES would be between EUR 230.000 and EUR 355.000. For the more powerful technologies (EGS and HE), the cost in Austria and Germany lies between EUR 915.000 and EUR 3.200.000. In Hungary, Croatia, and Slovenia, we estimate the implementation cost for HE and EGS is between EUR 590.000 and EUR 1.720.000. Of course, costs can be significantly higher depending on the design of the system.

We also investigated the cost of drilling a new well in all partner countries. The overall cost is connected to local conditions such as geology, casing, cementation, reservoir pressure, brine chemistry, gas presence, and others which influence the final well construction, risk mitigation, and precaution measures. The estimated cost for new 2.000 m and 3.000 m wells vary between EUR 2,25 Mio and EUR 8,34 Mio. This cost comparison shows that reusing old wells makes a new geothermal project much more financially feasible than drilling a new well. Thus, financial risk of geothermal development projects may be reduced, and social aspects may also be more positive, if existing well infrastructure can be put to new uses.

The TRANSGEO project (https://www.interreg-central.eu/projects/transgeo/) is co-funded by the European Regional Development Fund through the Interreg Central Europe program. The overall objective of TRANSGEO is to investigate the potential to transform abandoned hydrocarbon wells into new sources of green geothermal energy. To reach this goal, the TRANSGEO team is providing new tools and knowledge to support communities and industries in the energy transition and to break down economic and technical barriers to well reuse.

1. Introduction

Within the TRANSGEO project Work Package 1 (WP1), activity A 1.2., a ˝Socio-Economic analysis of repurposing abandoned wells for industrial processes˝ was conducted. The main goal of this activity was to investigate the public acceptance and evaluate possible options for using geothermal energy from existing hydrocarbon wells, which are not in oil and gas production anymore or where production will cease in the near future. Considering this, several technologies, analysed in TRANSGEO project activity A 1.1 ("Validation of technical approaches for well repurposing"), were identified to be potentially applicable for geothermal energy use in target industries in Central Europe such as paper and chemical production, machinery and transport, and other sectors that require typical geothermal temperatures below ~200°C.

Because of significant diversity among the TRANSGEO project partner countries (Austria, Croatia, Germany, Hungary, and Slovenia), we started our analysis by gathering information to understand the current situation of geothermal energy use in each country. A questionnaire was developed, through which each partner country provided general and specific information focused on demand patterns of different customer groups, economic analysis, social analysis, and other topics connected to using geothermal energy from existing wells. Additionally, an analysis of strengths, weaknesses, opportunities and threats (SWOT analysis, Appendix 6) was done which explored use of geothermal energy from existing wells and our project members' understanding of the current situation. All relevant information obtained has been integrated into this report.

In focusing on reuse of existing wells, we found that in each of the countries, there is a variety of repurposing projects and techniques employed on abandoned wells. Most of these projects have been successfully implemented and are still in operation today. There are five geothermal repurposing technologies which could be used on abandoned oil and gas wells:

- Deep Borehole Heat Exchangers (DBHE)
- Borehole Thermal Energy Storage (BTES)
- Hydrothermal Energy (HE)
- Aquifer Thermal Energy Storage (ATES)
- Enhanced Geothermal System (EGS)

Each of these technologies is shown in Chapter 3 as well as described briefly in the Terminology section at the end of this report.

This analysis covers investigation of the general situation in converting abandoned oil and gas wells into geothermal energy wells to be used by industry. An overview of the target groups which would be potentially interested in implementing such systems was created. The social aspects of the use of abandoned wells and their acceptability in the local environment are presented. We show potential outcomes from the different reuse methods implemented to existing abandoned wells and the overall costs of the intervention. The economic factors considered include initial redevelopment project investment costs, yearly operational costs, and abandonment costs as well as produced energy per year, price per kWh at which the energy can be sold, and the estimated lifetime of operation.

2. Demand patterns, applicability, and target groups

2.1. Demand patterns

By investigating the overall energy use in different sectors in the five partner countries, we discovered that most of the energy is consumed by the following 3 sectors:

- Industry
- Transport
- Private households

These three sectors consume 84-90% of the overall energy used in the 5 TRANSGEO partner countries. Service and agriculture sectors represent 10–16% of consumption. Details are shown in Table 1. Represented data are the starting point for understanding the current energy market and identifying the potential contribution that geothermal energy can make to the sectors which need energy (Federal Ministry Republic of Austria on Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2023; Hungarian Central Statistical Office, 2022; Ministry of the Economy and Sustainable Development (Croatia), 2022; Republika Slovenija, 2022; Statistisches Bundesamt Deutschland, 2024).

	AUSTRIA		GERMANY		HUNGARY		CROATIA		SLOVENIA	
	TWh	%	TWh	%	TWh	%	TWh	%	TWh	%
Industry	84,7	28,8	699,0	29,0	55,0	25,2	13,1	16,9	15,0	26,6
Transport	95,3	32,4	653,0	27,0	56,9	26,0	25,9	33,2	21,8	38,6
Private sector (households)	79,9	27,1	670,0	27,0	74,7	34,2	26,4	33,9	13,8	24,3
% of overall consumption		88,3		83,0		85,4		84,0		89,5
Service sector	28,3	9,6	385,0	16,0	24,2	11,1	9,4	12,1	4,4	7,8
Agricultural sector	6,1	2,1	24,0	1,0	7,8	3,6	3,1	3,9	1,6	2,7
% of overall consumption		11,7		17,0		14,6		16,0		10,5

Table 1. Energy consumption (including heat and electricity) by sector in the TRANSGEO partner countries (Federal Ministry Republic of Austria on Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2023; Hungarian Central Statistical Office, 2022; Ministry of the Economy and Sustainable Development (Croatia), 2022; Republika Slovenija, 2022; Statistisches Bundesamt Deutschland, 2024).

The primary “customer” groups for heat energy supply from reused abandoned wells are represented by industry, agriculture, and municipalities (service and private sector). These three sectors represent 60-70% of the energy demand in each of the partner countries. The reuse of abandoned wells is most appropriate to cover base load energy needs. A breakdown of annual heating demand in the industrial sector in the European Union is shown in Figure 1.

In Figure 1 we see that the heat used in industrial processes represents 74% of all energy required in the industrial sector (as of 2017). Only 9% of this industrial heat is renewable. Demand for heat below 150 C represents 30% of 85 EJ, meaning that 25,5 EJ of the industrial heat demand in the European Union can be supplied by temperatures which can be reached by geothermal (reuse) technologies in Central Europe.

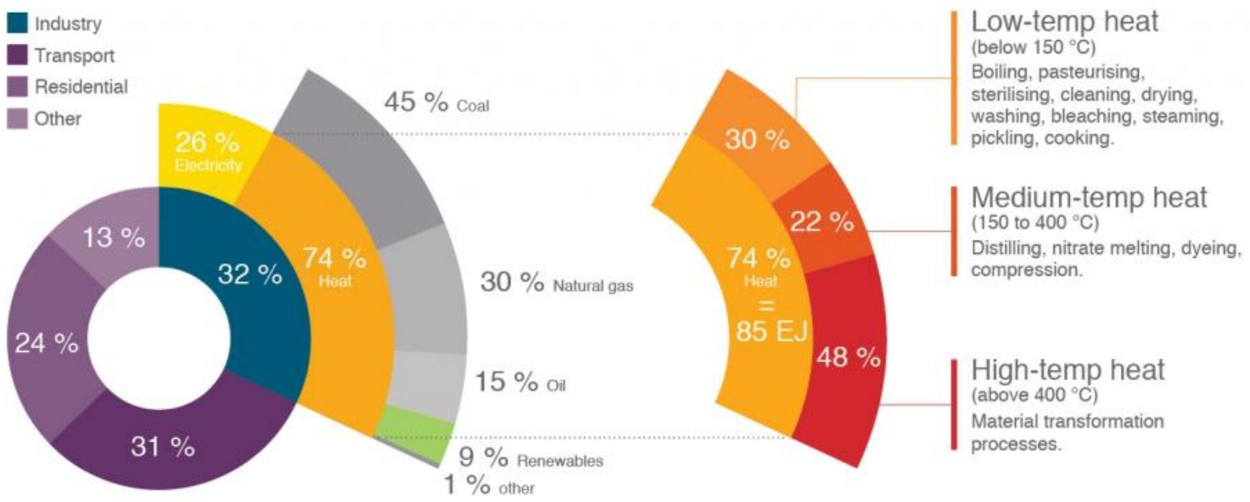


Figure 1. Heat demand in industry, based on IEA statistics and calculations by IRENA (Philibert, 2017).

In the next section we focus on the industrial sector, which represents 17-29 % of the total energy demand in the five partner countries (13 to 699 TWh per year). The potential reuse of abandoned wells for agricultural and municipal applications is analysed in separate documents (TRANSGEO project Deliverables D 1.2.2 and D 1.2.3[1]).

2.2. Applicability

2.2.1. General

The reuse of abandoned oil and gas wells could have significant potential in the near future because there are thousands of wells which are left behind after exploitation and which could be potentially re-used, with the proper technology and knowledge, for geothermal or other purposes. One of the sectors which could benefit from redevelopment of those abandoned wells is the industrial sector because of the following:

- The heat demand of the industrial sector is significant, up to 30% of the national demand.
- Industrial heat is needed on a 24/7 basis and varies in temperature and load depending on the type of industry.
- Some industrial facilities already use geothermal energy for space heating, using shallow wells extracting heat through shallow aquifer (open) systems or borehole heat exchangers (closed) system applications.
- Compared to municipal heat demand, locations where industry is developed are often closer to abandoned oil and gas fields. The majority of hydrocarbon wells are located in rural, agricultural areas.
- Different industries require different amounts of energy and different temperatures. Process heat can be quite high and is likely out of range for the investigated geothermal reuse technologies, but low and medium temperature applications are more common and offer potential widespread heat demand for well reuse.
- Heating and cooling of the industrial infrastructure is an option for reuse technologies, in case waste heat from the process is not used for heating.
- Industrial applications often have waste heat which may be stored in ATES or BTES systems.

[1] Available at https://www.interreg-central.eu/projects/transgeo/?tab=outputs

2.2.2. Ongoing projects

Geothermal energy projects exist in all 5 partner countries, as follows:

- Germany: 1 BTES research project, 1 EGS research site, 3 DBHE projects, 2 ATES projects, and 34 HE projects (Bundesverband Geothermie, 2024) (none to date in the industrial sector)
- Austria: 1 ATES project and 12 HE projects (none in the industrial sector)
- Hungary: more than 1000 HE projects, with more than 50 of them in the industrial sector
- Croatia: 4-5 HE projects (none in the industrial sector)
- Slovenia: 1 DBHE project and 2 HE projects (none in the industrial sector)

As can be seen from the list above, Hungary leads the TRANSGEO partner countries in using geothermal for industrial applications, focusing on the HE technology. The reason for the lack of application in other countries and of other technologies could be the lack of information, awareness, and economic potential compared to other available technologies on the market. Therefore, it is important to present the potential benefits and opportunities for using geothermal energy in industry where such application would be applicable and economically justified. Most development of geothermal projects is connected to newly drilled wells, but existing data from nearby abandoned wells are almost always used to reduce the prospecting risks. Accordingly, there is a large opportunity to raise awareness of the existence and potential of repurposing abandoned wells for geothermal energy exploitation with reduced technical and financial risk by implementing current technologies and using available data (Appendices 1-5, Questionnaires from partner countries).

2.2.3. Energy potential

Considering installed capacities (or annual energy production of storage projects) from existing operational projects, we can assume the following capacities/yearly energy outputs for reuse of abandoned deep wells:

- DBHE: 0,05–0,5 MW_{th} (e.g., Bundesverband Geothermie, 2024)
- BTES: 0,05–0,5 MW_{th}
- ATES: 0,5-20 MW_{th}, (Fleuchaus et al., 2018)
- HE: 10-50 MW_{th} (e.g., Bundesverband Geothermie, 2024)
- EGS: 1-5 MW_{e} or 10-50 MW_{th}

These numbers are promising regarding potential energy outcomes or “gain” from already existing infrastructure, which is no longer in use and could be again productive by repurposing. However, the installed capacity and storage potential of the closed systems (DBHE and BTES) is more than an order of magnitude lower compared to open systems (HE, EGS, and ATES) which have much higher energy and heat potential.

2.3. Societal willingness to implement geothermal energy solutions

Similar to municipal application, the willingness to implement geothermal energy solutions in industry is determined by location and the economic feasibility of the project. Although municipalities have motivation to carry out such projects due to environmental or social benefit, industry is more focused on economics. In general, there is a visible expansion in geothermal sector development; geothermal energy is being actively developed in all partner countries and some projects are already exploring the reuse of existing wells and relevant technical modification options. The most important aspect of well reuse is the economic feasibility of reusing existing well infrastructure and equipment, versus building conventional hydrothermal systems with new wells, which costs substantially more (see Section 4.6). Without financial incentives, implementation of geothermal solutions or changing the existing heat supply is challenging and connected to:

- High initial investment cost and the payback period,
- The legal situation of well use and ownership of wells,
- Energy potential, which depends on the local geology, which determines which type of technology can be applied (closed vs. open systems),
- Reliability and sustainability of the system, considering that some reuse projects have had short lifetimes, and
- Environmental risk assessment.

Currently, the most promising sectors for the use of local geothermal sources are municipal district heating systems and agriculture, which are examples of applications receiving increased interest, as geothermal aligns effectively with their energy needs and sustainability goals. In addition to providing base load energy, technologies are available which can optimise geothermal systems to cover peak loads, so that they are sustainable and can meet the entire energy needs of individual users. System design with customer energy needs at the forefront is the key to effective implementation of geothermal solutions and, thus, social acceptance.

Using geothermal heating applications in industry has similar exploration risk and high upfront investment, thus avoidance of potential failure or insufficient energy yield can bring significant benefits to a company investing in such resources, as long as the risks are mitigated and well-managed. Therefore, it is necessary to highlight and present to the decision-makers examples of good practices and to familiarize the interested audience with possible risks and mitigation options. With this kind of approach, oil and gas well reuse projects can be more effectively implemented in the industrial sector.

Increasingly, society expects the industrial sector to use clean energy and the best available technology if they intend to operate in regions which are sensitive to environmental protection. To promote societal acceptance of geothermal development in abandoned wells, it is crucial to raise awareness and to increase the knowledge of the technologies available and the multiple benefits, including:

- Replacing fossil fuels with renewable energy sources,
- Reduction of CO_2 emissions,
- Security and independence of the geothermal energy supply, and
- Reuse of existing infrastructure without major new environmental impacts.

2.4. Target groups in industry

The process heat needs for a variety of industrial processes are shown in Table 2. Represented are industries which need minimum and maximum temperatures from 80 to 240 °C. According to the table, the DBHE, BTES and ATES reuse technologies have limited applicability. Remaining are HE and EGS, which need relatively high outputs to be considered potential options in industrial processes within the listed sectors.

Industrial process	Use	Heat-carrying form	Temperature
Food	Rinse	Air	80-150 °C
	Concentrate	Steam	130–190 °C
	Drying	Steam (air)	130–240 °C
Plastic	Initiation	Steam	130–150 °C
	Rapid Separation	Steam	150 °C
	Extrusion	Steam	150 °C
	Drying	Steam (air)	180 °C
	Blend	Steam	150 °C
Glass	Flatten	Air	110–150 °C
	Dry fibers	Air	130–180 °C
Chemical industry	Heating dipping	Steam (air)	150–180 °C
	Drying	Steam (air)	150–180 °C
Paper-making	Kraft bleaching	Steam	150–180 °C
	Drying	Steam	150 °C
Woodworking	Drying in cellar	Air	80–120 °C
	Preparation of plywood	Steam	120–180 °C
	Hot-pressed fiberboard	Steam	200 °C
Synthetic rubber	Initiation	Steam	130 °C
	Monomer recovery	Steam	130 °C
	Drying	Steam (air)	130 °C
Textile industry	Rinse	Water	80–100 °C
	Handle	Steam	80–130 °C
	Drying	Steam (air)	80–140 °C
Road construction	Melting asphalt	Steam	120–180 °C
Tobacco industry	Silk making	Steam	150–200 °C

Table 2. Heat demand in select industrial processes (Yan et al., 2022).

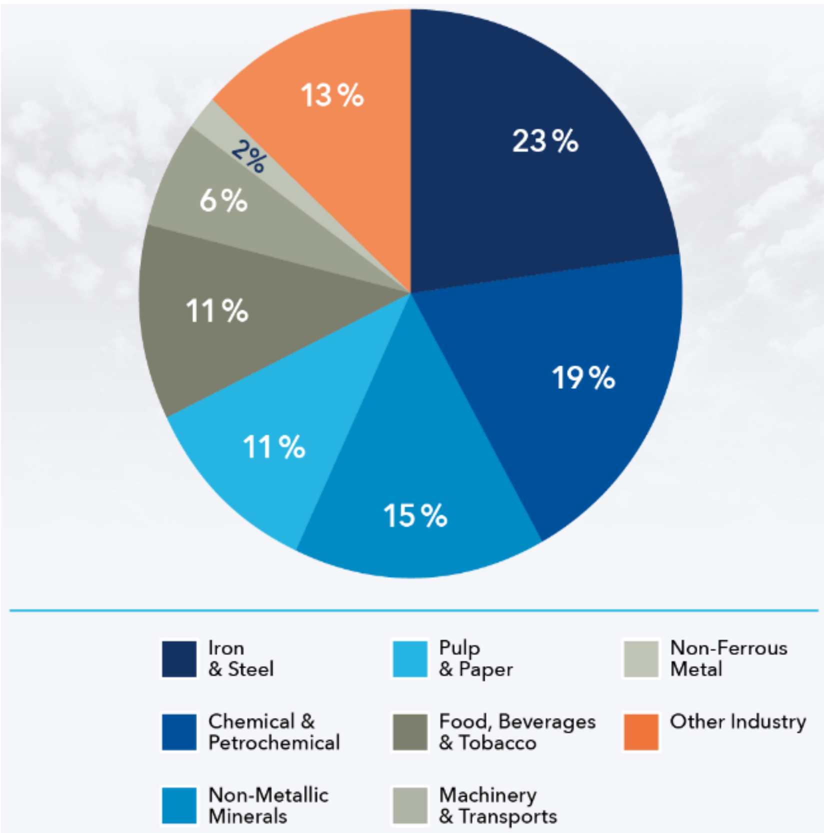


Figure 2. EU28 industrial heat consumption, by sector (TrustEE, 2017).

Figure 2 shows the main industrial sectors. As seen in Figure 3, most of the process heat demand in EU28 industry is above 500°C, for the iron and steel, chemical and petrochemical, and non-metallic minerals industries. The pulp and paper, and food, beverages and tobacco industries mostly use heat at low temperatures (TrustEE, 2017). To provide process heat below 100°C, the likely prospective industrial sectors are:

- Food, Beverages and Tobacco
- Chemical and Petrochemical
- Machinery and Transport
- Non-Ferrous Metal

For temperatures up to 200°C, the most prospective industrial sectors are:

- Pulp and Paper
- Food, Beverages and Tobacco
- Machinery and Transport

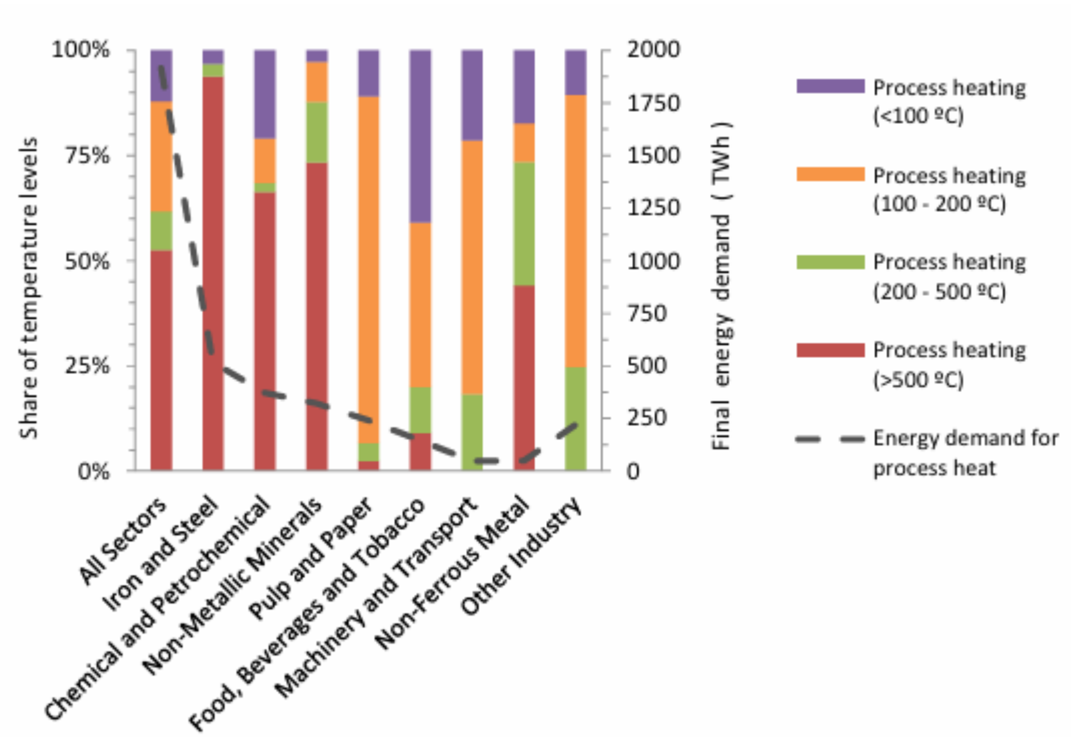


Figure 3. Final energy demand for process heat and share of temperature levels by industrial sector for EU28 (TrustEE, 2017).

There are two main configurations of energy systems used in industry: systems that only generate heat and plants for combined heat and power production (CHP). Figure 4 presents a flow diagram for the possible energy production systems usually applied in industrial facilities.

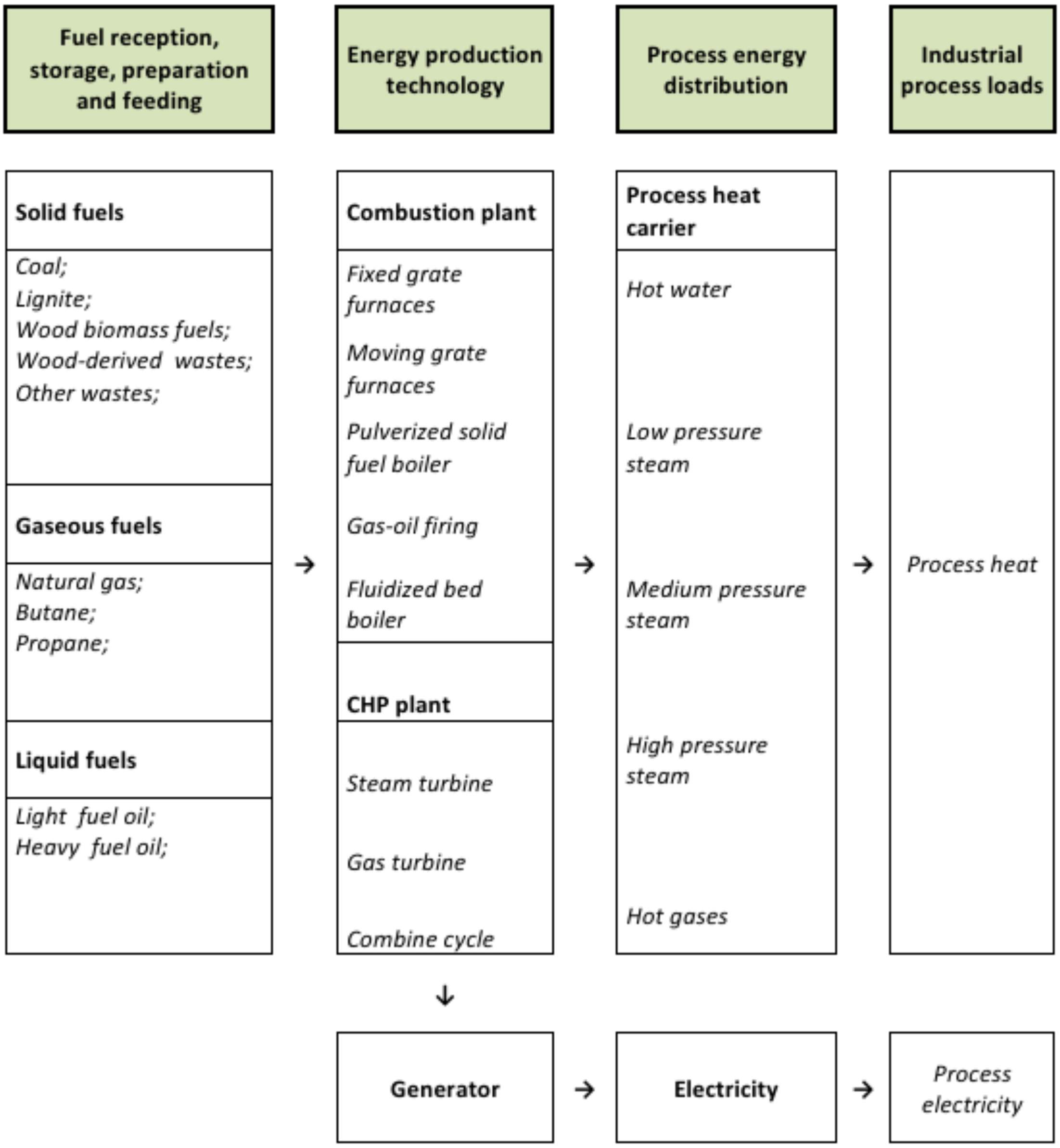


Figure 4. Schematic heat production system layouts usually applied in industrial facilities (TrustEE, 2017).

Different installations have different energy production system layouts that mainly depend on the production size, fuel accessibility, process heat loads, and age of the installation. One of the most important parameters to evaluate a given energy production system or to compare energy production systems is the efficiency of energy conversion. The most widely used combustion systems applied in industry have a fuel conversion efficiency above 0.5 and combustion boilers can achieve efficiencies of 0.95. In CHP (combined heat and power) technology, the overall fuel conversion efficiency depends on the electrical energy output, on the usable heat output, and on the thermal losses within the system. An example of a CHP plant optimized for heat production integrates a combustion boiler for steam production and a back-pressure steam turbine for power generation. This system presents a fuel efficiency of 0.8 where usable heat energy output is 60% and power output is 20%. Table 3 gives reference values for fuel conversion efficiencies of different energy production systems and the corresponding fraction of power and usable heat output. The temperature for each production system is also indicated.

Energy production system	Usable heat energy output (%)	Electrical energy output (%)	Total energy output (fuel efficiency)
Heat production: heating boiler for space heating (70 ºC)	90	0	0.90
Electricity generation: combined cycle technology (200ºC)	0	55	0.55
Industrial CHP plant: steam boiler + back pressure steam turbine (200ºC)	60	20	0.80
Industrial CHP plant: combined cycle with steam tapping (200ºC)	12	50	0.62
Industrial CHP plant: gas turbine with recovery steam boiler (200ºC)	48	32	0.80
Industrial CHP plant: gas turbine with recovery steam boiler and back pressure steam turbine (200ºC)	45	35	0.80
Small-scale CHP plant: gas engine with heat-exchanger (200ºC)	55	35	0.80

Table 3. Energy outputs for typical industrial heat production systems (TrustEE, 2017).

Within the industrial sector, the biggest energy consumers in the EU in 2020 were the chemical and petrochemical industry (2.121 Petajoules (PJ), or 22% of the total final industrial energy consumption), the non-metallic minerals industry (1.372 PJ or 14%), and the paper, pulp and printing industry (1.326 PJ or 14%). The only other sector consuming more than 10% of the total was the food, beverages, and tobacco industry (1.147 PJ or 12%) (Eurostat, 2022).

2.4.1. Food and Beverages

The food and drink manufacturing industry is a major part of the EU economy with a turnover of €1.089 billion in 2014 and employing 4.25 million people. It is the largest manufacturing sector in the EU by turnover (14.9%) and employment (15%) (FoodDrink Europe, 2016). The industry therefore has an important role to play in Europe's objectives to secure a smart and sustainable economy. Its input into environmental targets and development is equally vital. Five countries - Germany, France, Italy, Spain, and the UK - account for 66% of the turnover for EU25 in 2016 (TrustEE, 2017).

The food and drink industry is a highly diversified sector with many companies of different sizes. 99% of food and drink companies are SMEs (small and medium-sized enterprises). These SMEs generate almost 50% of the food and drink industry turnover and value added and provide two thirds of the employment of the sector. The food and drink industry accounts for more than 285 000 SMEs. With such a high number of members, the industry is less capable of adapting innovative technologies quickly.

Food SMEs typically have limited financial resources and do not have the financial strength required by banks for on-balance-sheet financing for energy efficiency and renewable energy solution projects (TrustEE, 2017). In the food and drink industry thermal energy is mostly used for cleaning and disinfection, washing, pasteurization, sterilization, sanitation, blanching, drying, and concentration/ evaporation.

The basic heat production system in the food and drink industry is a boiler with a fossil fuel (natural gas, diesel, light fuel oil) combustion burner. Natural gas and fuel oil are the most convenient fuels. However, a few food and drink installations in the EU still burn solid fuels such as coal. In some cases, biomass and biogas produced from residual biowaste or wastewater are also used as fuel *(TrustEE, 2017)*.

Reuse technologies like HE and EGS would be potentially applicable to meet the needs for heat energy of this sector. Nevertheless, the small size of many of the sector's members is important because SMEs likely face difficulties in making investments which are large in relation to outcome and their actual needs.

2.4.2. Pulp and Paper

Europe is the world's second largest producer of pulp, paper, and board. The role of this industry is important, with Europe accounting for a quarter of total global production in 2013. For the countries of the Confederation of European Paper Industries (CEPI), total pulp production in 2014 was around 36.5 billion tonnes, and paper and board production was over 90 billion tonnes (Figure 5).

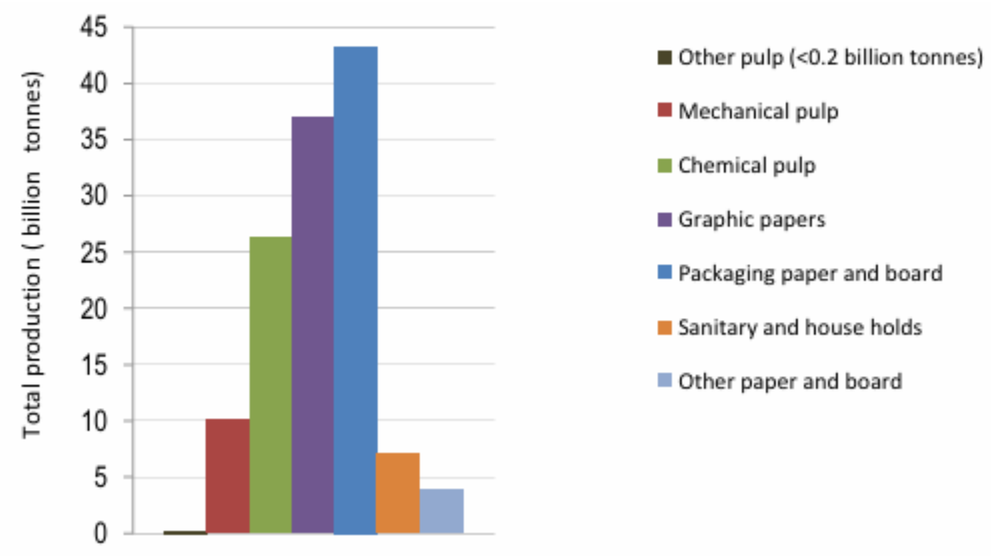


Figure 5. Production contribution by grade for CEPI countries (TrustEE, 2017).

Paper is an energy-intensive industry. In Europe, it is the fourth largest industrial consumer of energy, using 11.5% of the total final energy for industry in 2014 (around 31.7 Mtoe), representing 3% of the total final EU28 energy consumption (Eurostat, 2016). In the pulp and paper industry, it is common to have energy production systems that use a mix of fuels in co-combustion of biomass, mill residues, and fossil fuels. There are two main configurations for the energy systems used in the sector: production of heat alone and combined heat and power production (CHP). Therefore, it would be possible to meet some of this heat demand with geothermal energy from HE and EGS reuse technologies.

2.4.3. Chemicals and Petrochemicals

The largest low and medium temperature industrial energy consumer is chemicals and petrochemicals. In 2020, the sector accounted for 26% of final energy consumption, which makes it the third largest energy end-user in the EU, after transport and households. Energy use is essential in the sector primarily for industrial processes but also for non-process-related purposes, such as space heating, cooling, and lighting.

Data from 2020 show that electricity and natural gas accounted for nearly two-thirds of final energy consumption in the EU's chemicals and petrochemicals sector (33% and 32%, respectively; Figure 6) (Eurostat, 2022). Breakdown by energy product also shows the sector's dependence on fossil fuels. Natural gas, oil and petroleum products, solid fossil fuels, and non-renewable waste combined accounted for more than half of the final energy consumption in the industry in 2020. Since 2022, REPowerEU attempted to address this strong reliance on fossil fuels in European industry, by introducing measures calling for a transformation of industrial processes to replace gas, oil, and coal with renewable electricity and fossil-free hydrogen (Eurostat, 2022).

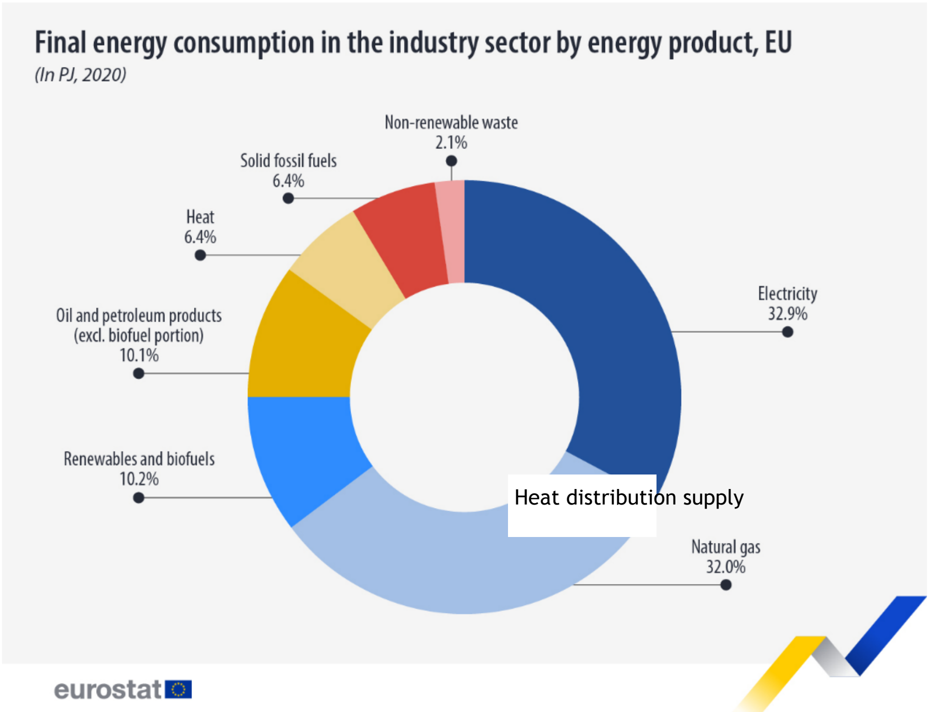


Figure 6. Energy consumption in the chemical and petrochemical industry sector 2022 (Eurostat, 2022).

The chemical and petrochemical industry has been strongly dependent on natural gas. The manufacturing of chemicals and chemical products used 630 PJ (34% of the total final energy consumption for this sector) of natural gas in 2020, including the manufacture of basic pharmaceutical products and pharmaceutical preparations which consumed 52 PJ (Eurostat, 2022). Electricity was the second most important energy product for both sectors in 2020. Because of the very small percentage of renewable energy contribution (10,2 %) to the overall energy mix, a consideration of the introduction of reuse technologies HE and EGS seems reasonable. Several factors would need to be considered:

- Load and capacity
- Inlet and outlet temperature
- Proximity of the well to the demand
- Integration into the existing system

EU27 Renewable energy consumption in the chemical industry sector more than doubled in the last 20 years (CEFIC, 2023), mostly by using biofuels, solar, and heat pumps. Addition of geothermal energy could lead to a further increase by introducing reuse technologies to meet demand.

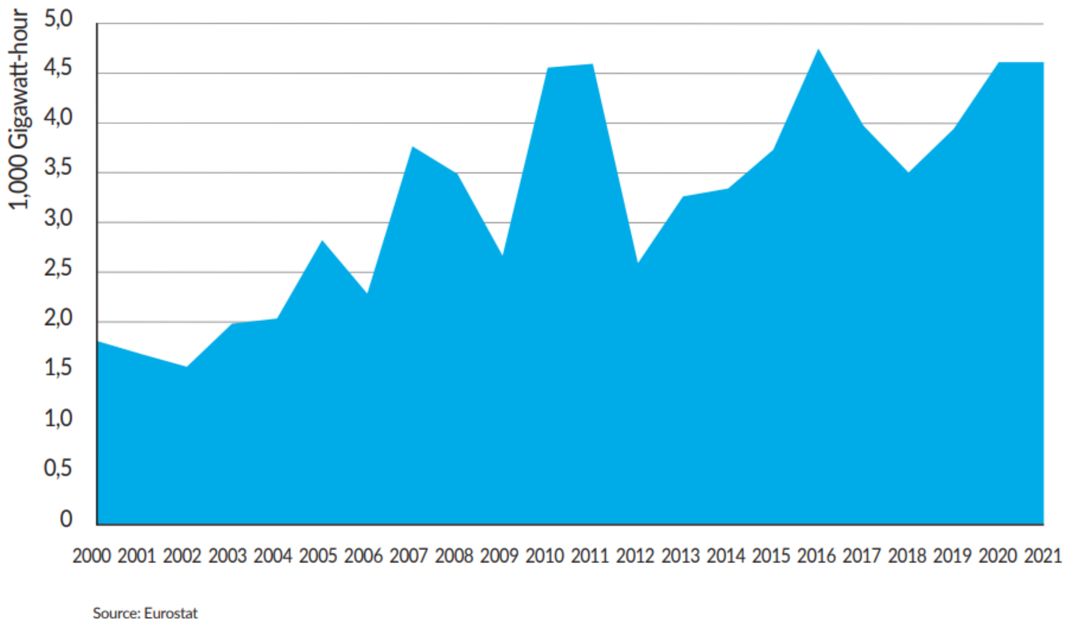


Figure 7. Renewable energy consumption in the EU 27 chemical industry (CEFIC, 2023).

3. Social analysis

3.1. General attitude regarding well reuse

In general, reuse of abandoned wells was an uncommon topic in all partner countries until recently. Neither the possibility of using abandoned oil and gas wells, nor the possible reuse technologies, were widely known. For this reason, the awareness of a potential local energy supply from existing well infrastructure for geothermal energy should be enhanced by wider promotion of the potential benefits and capabilities of such systems. One of the major benefits would be energy independence, which will play a significant role in the near future, due to the global uncertainty and unreliability of supply chains of energy products in connection with high prices. The use of underground heat through repurposing abandoned wells can be a significant local resource. There are tens of thousands of wells which are no longer in use, and at least some of them could be repurposed into local thermal energy producers (Appendices 1-5, questionnaires from partner countries).

Until recently, reuse of abandoned wells was limited to investors who identified the potential of reuse technologies and could access the wells for redevelopment. Such trail-blazing projects have been challenging, partly due to lack of knowledge and experience but also to economic challenges and permitting barriers that slow progress, and have thus required a significant effort to achieve the desired result. Accordingly, from the TRANSGEO analysis (Appendices 1-5, questionnaires from partner countries), we have identified several points which would benefit from clarification and improvement to enhance the public attitude toward well reuse, including increased data availability, clear implementation procedures, transparent legal frameworks, and guidance in obtaining permits and licenses.

3.2. Potential benefits and risks to end users

The potential benefits and risks of well reuse are influenced by numerous factors. To simplify, we identify four aspects for analysis:

- Technical considerations
- Social factors
- Economic factors
- Legislation and legal procedures

Technical benefits and risks: The technical benefits and risks mainly correspond to geological properties of the sub-surface such as thermal gradient, permeable zones, diameter of the well, well proximity to demand, and others. On the other hand, there are risks connected to well integrity, reserves of the resource, limited heat flow, injection limitations, and others. The technical aspects need to be reviewed and analysed by professionals for each field: geological, mining, mechanical, chemical, and energy engineering.

Compared to drilling new wells, the two largest benefits of reuse are the reduced geological risk (since the subsurface is already known at the location of the existing well) and the reduced technical effort (as the well has already been drilled). On the other hand, depending on the well's age and condition, well reuse may have an increased risk associated with well integrity as the wells can be very old and were designed for a different purpose.

Social benefits and risks: For social benefits, in the case that the heat source is present and accessible through deep wells, the local end users can experience significant benefit. Having a heat and energy source locally available provides energy independence with reliable supply. Use of existing infrastructure also plays a significant role: if old wells are available and in usable condition, drilling a new well is not required, preventing significant construction interventions and local disturbance. This avoidance of new construction in a community is one of the major benefits of well reuse. The risks connected to the social aspects are related to potential pollution in case of leakage or integrity issues. Nevertheless, these can be mitigated with proper maintenance and risk management. A final aspect is the fear of induced seismicity, which may occur especially in association with hydraulic stimulation treatments to develop EGS applications. However, this risk is very site-dependent and can largely be mitigated by risk assessment and mitigation procedures such as traffic light systems.

Compared to drilling new wells, reuse has a significant sustainability benefit of reusing existing infrastructure and providing green, local, and reliable energy to rural areas which can attract industries to areas where geothermal energy may not otherwise be developed due to the higher cost of drilling new wells.

Economic benefits and risks: Economic benefits and risks are associated with the particular technical situation, social conditions in the community, and legal procedures, including permitting. All aspects of a geothermal development have to fit together to have an economically feasible project, considering all potential details from the point of view of a potential investor. Major economic benefits accrue when the project is successful and the reused wells perform at or beyond design expectations. Heat or electricity can be supplied to the industrial end users, improving the competitive advantage of the region where the investment is done, potentially lowering energy prices, reducing environmental impact, and promoting the use of renewable energy sources. On the other hand, there are also significant risks in the case that the performance of the reuse technology provides heat or electricity on a smaller scale than anticipated.

Compared to drilling new wells, the costs of reuse are typically lower, especially as the high upfront investments for drilling new wells with high geological risk are significantly reduced. The risks are (1) longer heat transport lines may be required to connect the existing, often remote wells, to the nearest consumers, (2) the heat output (income) for closed systems is relatively limited compared to the costs, which may still be significant, and (3) the lifetime of the wells is limited (reducing income) or the wells need more maintenance (increasing costs).

Legislation and legal procedures: Legislation and legal procedures also play a significant role in development of geothermal projects with existing oil and gas wells. These are connected to claiming the concession over the abandoned well for further use, inheriting pollution from former well use, and other legal issues. The legislation and legal procedures of well reuse are complex, especially when a transfer of ownership is required. In addition, new standards may be in place that cannot be met by older boreholes (for example, cement barriers are required to protect groundwater in Germany). More details regarding legislation and legal procedures are available in TRANSGEO Deliverable 3.1.1[2], which focuses on legal and policy considerations in all the TRANSGEO partner countries.

Below, we present each geothermal well reuse technology, pointing out specific benefits and challenges. Table 4 outlines the benefits and challenges common to all 5 reuse technologies.

BENEFITS OF WELL REUSE	CHALLENGES OF WELL REUSE
Energy independence	Well integrity issues
Local heat or energy supply	Scaling and injection issues
Pollution reduction	Potentially long distance to heat consumer
Reduction of CO_2 emissions	Uncertainty of old data
Less expensive than drilling new well	
Low geological risk	
Improved sustainability of existing infrastructure	

Table 4. Benefits and challenges of well reuse, common to all 5 geothermal reuse technologies (ATES, BTES, DBHE, EGS, and HE).

All listed benefits are common to a conventional geothermal system and are also applicable for reuse. The primary benefit is the lower cost, since no new drilling is needed, making projects more feasible for small industrial enterprises. The major challenge is the distance to the heat consumer, as the wells are often not close to industrial areas.

Understanding and mitigating the potential risks represents the key to success for implementation of reuse technologies on abandoned wells. An important aspect is full availability of reliable and up-to-date data on the well, its history, and the local geology. These data usually exist for old wells and can be accessed through the original well owner/operator or the local government office that manages boreholes, though sometimes they can be missing, or owners are not willing to share.

Below, the benefits and challenges of using each of the 5 geothermal reuse technologies are highlighted in Figures 8 to 12.

[2] Available at https://www.interreg-central.eu/projects/transgeo/?tab=outputs

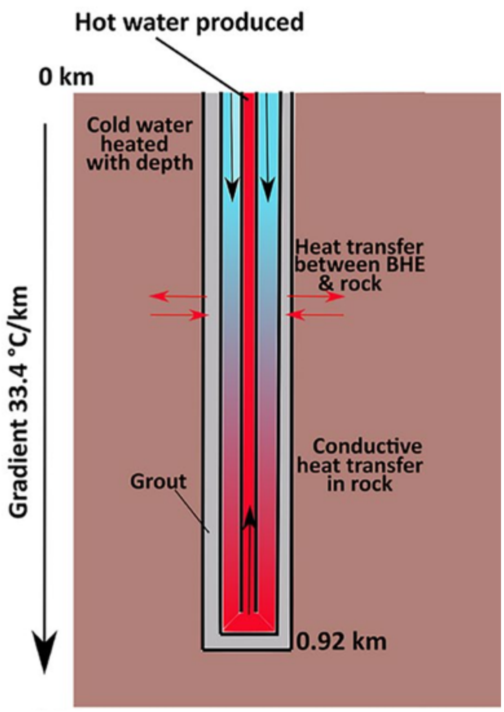
<table>
<tr><th>Deep Borehole Heat Exchanger (DBHE)</th><td rowspan="3">
</td></tr>
<tr><td>BENEFITS
Easy to implement, as no special downhole equipment is needed.
Easy maintenance and control during operation.
Wide range of applicability.
Reliable and controlled flow rate.
Can be installed in dry or unsuccessful boreholes without extensive interventions.
Relatively inexpensive, compared to other methods.
Can be used in deep wells without aquifers.
Fewer environmental considerations and regulations than open systems.</td></tr>
<tr><td>CHALLENGES
Limited thermal power compared to open geothermal systems, because heat is transferred only by conduction from the reservoir to the working fluid inside the well, thus heat transfer is low.
Integrity issues due to leakage of production tubing.</td></tr>
</table>

Figure 8. Benefits and challenges of using a Deep Borehole Heat Exchanger (DBHE) (Brown et al., 2023).

Taking an example of a 2000 m DBHE, Zhang et al. (2022) found the optimum check valve operation condition to be at depth of 900 m with an inlet temperature of 50°C. Working temperatures of 40°C to 50°C are more attainable and practical for both cooling and heating compared to 85°C-90°C inlet temperatures used for other systems (Schulte et al., 2016), thus DBHE at mid-depths (less than 1 km) may be preferentially used for projects with lower temperature requirements.

A large-scale DBHE array heating project, iHarbour, located in Shaanxi, China at the new campus of Xi'an Jiaotong University, selected DBHEs as the main method for space heating, to pursue low-carbon emissions on campus. The university has more than 20,000 students and consists of 52 buildings, including a research centre, student dormitory, and cafeteria, which equate to a total heating area of 1.59 million m^2. The entire pilot project, completed in 2019 (and still in stable operation), consists of ninety-one 2500 m deep DBHEs separated into 6 groups with an auxiliary natural gas boiler, producing a combined heating capacity of up to 75.69 MW for the university community (Kolo et al., 2024).

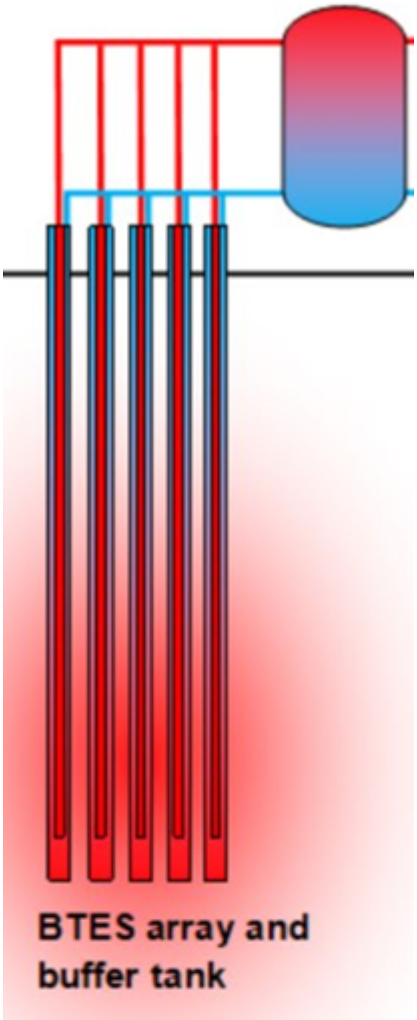
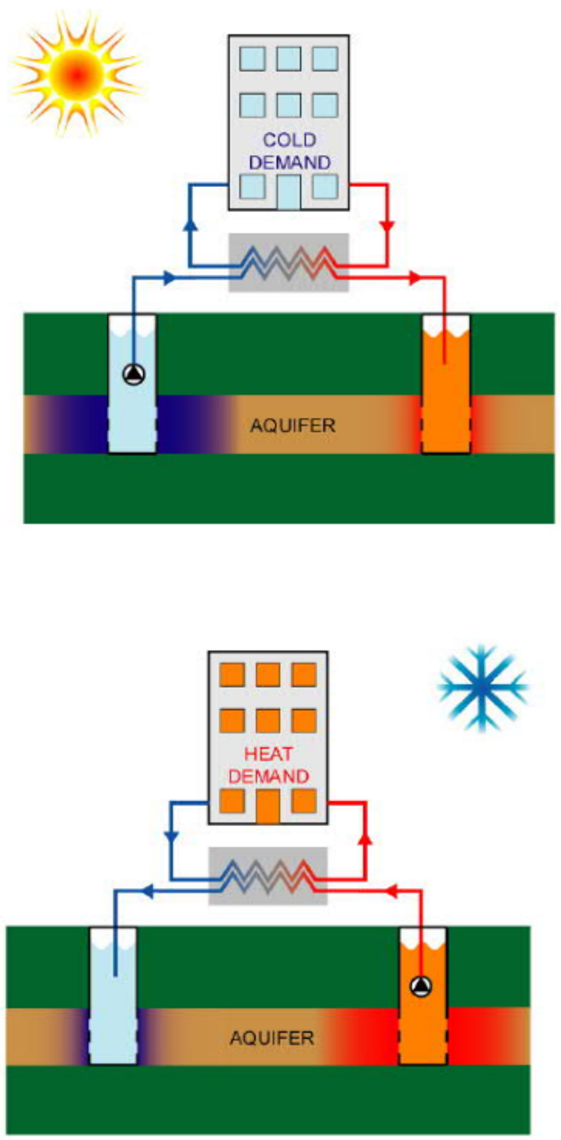
Borehole Thermal Energy Storage (BTES)	
BENEFITS Allows excess energy to be stored in the ground during off-peak times and retrieved when needed, improving energy efficiency. Easy to implement, as no special downhole equipment is needed. Easy maintenance and control during operation. Supports energy grid stability by providing stored energy during peak demand periods. Can scale up by using arrays of boreholes functioning together. Can store heat and excess heat in deep wells without aquifers. Fewer environmental considerations and regulations than open systems.	
CHALLENGES Stores only a relatively small amount of heat, as heat transfer between the carrier fluid and the hot rock mass only occurs through conduction. Usually, multiple wells close to each other are needed to improve the efficiency of the system. Optimal spacing is critical to maximize efficiency of the system. Limited to small scale industrial applications (unless large BTES arrays are installed), and the excess heat source and the heat consumer must be nearby to avoid costly heat transportation lines.	

Figure 9. Benefits and challenges of using a Borehole Thermal Energy Storage (BTES) system (Kolo et al., 2024).

BTES installations require fewer environmental considerations than Aquifer Thermal Energy Storage (ATES) systems, since they do not interact directly with the groundwater, and they have lower initial costs compared to long-term tank and pit thermal energy storage and thus have been widely accepted as a solution. The BTES technology has positive environmental and economic aspects, and it can support district heating and cooling (DHC) networks. For a storage capacity in the range of 100-1000 MWh, BTES has the lowest energy-specific costs compared to other solutions, averaging between 1000 and 2000 EUR/MWh. BTES can provide up to 96% efficiency and can have as little as a 17-year payback period

(Sadeghi et al., 2024), making BTES systems economically feasible. BTES are typically arrays of shallow wells as opposed to single or few deep wells.

<table>
<tr><td>Aquifer Thermal Energy Storage (ATES)</td><td rowspan="3">
</td></tr>
<tr><td>BENEFITS

Large amounts of energy can be stored.

ATES systems are well-suited for large scale heating and cooling applications with an industrial heat source and/or heat consumer.</td></tr>
<tr><td>CHALLENGES

Existence of suitable aquifers with high permeability, manageable water chemistry, and sufficient volume.

Scaling and/or bacteria may form, clogging filter zones.

Compliance with water management and environmental regulations can be complex for ATES projects due to their typical relatively shallow depth and the potential proximity to drinking water aquifers.</td></tr>
</table>

Figure 10. Benefits and challenges of using Aquifer Thermal Energy Storage (ATES) (Drijver et al., 2003).

ATES is particularly suited to provide heating and cooling for large-scale industrial applications. Compared to conventional technologies, ATES systems can achieve energy savings between 40% and 70% and CO_2 savings of up to several thousand tons per year. Capital costs decline with increasing installed capacity, averaging 200.000 € for small systems and 2 Mio. € for large applications. The typical payback time is 2–10 years. Worldwide, there are currently more than 2800 ATES systems in operation, abstracting more than 2.5 TWh of heating and cooling per year. Most of these (99%) are low-temperature systems (LT-ATES) with storage temperatures of $< 25\ ^{\circ}C$. 85% of all systems are in the Netherlands, and a further 10% are found in Sweden, Denmark, and Belgium (Fleuchaus et al., 2018).

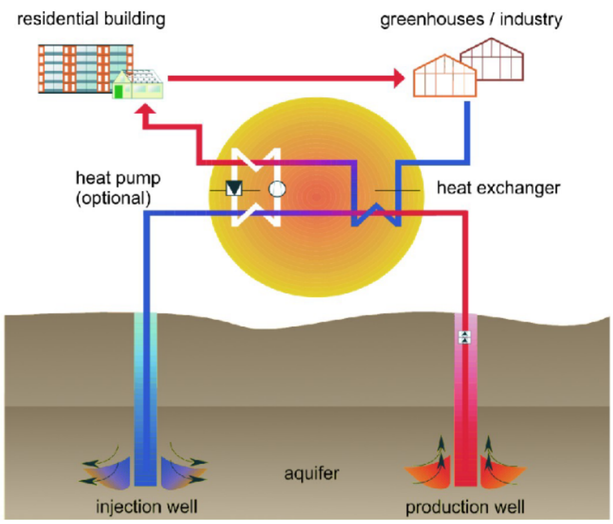
Hydrothermal Energy (HE)	
BENEFITS Well-established technology with predictable and reliable operation. Constant flow and temperature. Reliable baseload energy for grid stability.	
CHALLENGES Requires a high permeability reservoir. Scale and sand challenges. Filtration and reinjection of used thermal water.	

Figure 11. Benefits and challenges of using Hydrothermal Energy (HE) (Agemar et al., 2014).

The application of the HE procedure to the geologic setting in the Hannover-Celle area (Germany) shows that geothermal projects are economically viable. Prognosis for the geothermal power in the reference case is 5.5 MW; the total power of the coupled system is approximately 15.7 MW. The annual heat supply of the coupled system for the load structure amounts to approximately 41 GW per year, corresponding to an annual revenue of 3.3 million Euros for the total system at a heat price of 8 cents/kWh. The 50% reduction in full load hours (from the reference state of 6000 to 3000 load hours) leads to a geothermal system without coupling, i.e., a system supplying approximately 16.5 GWh heat at a power of 5.5 MW (Schlagermann et al., 2024).

The economic viability of HE systems is shown by dozens of projects in Germany and hundreds in Hungary. Hydrothermal Energy projects and systems producing tens of MWth are a mature technology developed many times in Central Europe. HE systems have proven economic models, and their high energy output make HE suitable for industrial use. The application is limited to locations with permeable reservoirs, which is especially relevant for Hungary, where hundreds of HE geothermal wells are in production.

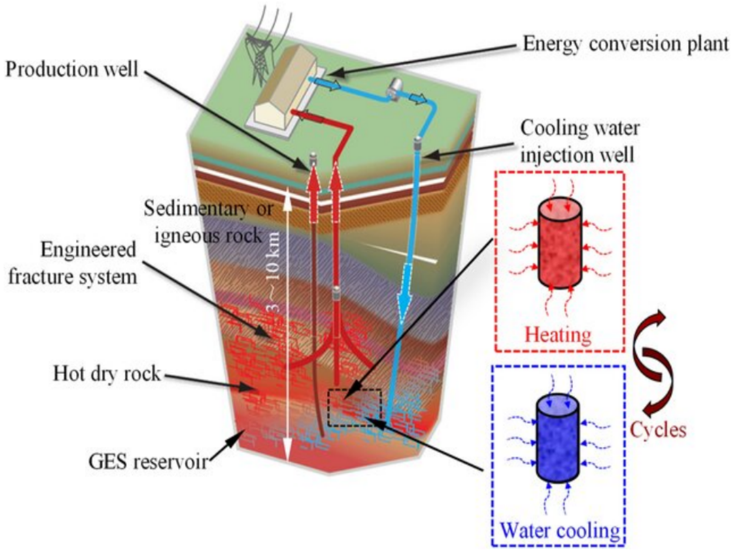
<table>
<tr><td>Enhanced Geothermal Systems (EGS)</td><td rowspan="3"></td></tr>
<tr><td>BENEFITS
Unlocks geothermal energy potential in impermeable reservoirs or regions with low-permeability basement geology.
Potential to provide large amounts of geothermal power where proper heat source is available and accessible.</td></tr>
<tr><td>CHALLENGES
Potential induced seismicity.
Public acceptance due to “Fracking.”
Technology still in the research and development phase.
Drilling deep wells in hard rock formations can be expensive and technically challenging.</td></tr>
</table>

Figure 12. Benefits and challenges of using Enhanced Geothermal Systems (EGS) (Yin et al., 2021).

The energy reserves in the upper 10 km of the earth's crust are approximately 1.3×10^{27} Joules, which could supply global energy use for millions of years. The exploitable geothermal potential could reach up to 1200 GWe, based on an optimistic estimated probability of 70%. In 2050, there could be more than 70 GW_e from EGS, based on an estimated probability of 85%. Since EGS wells are typically several kilometers deep, the potential economic impact of reusing an old well, versus drilling a new deep well, is large. Additionally, existing wells may be used for seismic monitoring close to the reservoir. For production, EGS is not as mature as the other technologies, and further development is required to reach these values (Lu, 2018).

3.3. Drivers for implementation

Overall, the 5 geothermal well reuse technologies on which TRANSGEO focuses are not known to the wider public. For this reason, promotion and awareness of the potential for reuse of existing borehole infrastructure will play an important role in implementation of these projects. During the process of gathering information, we identified several aspects which need more attention to accelerate well reuse. The important drivers for moving forward are as follows:

- Effective communication strategy targeting user communities, supplying initial information on the potential for well reuse.
- Improved data access, requiring data on old wells to be made publicly available.
- Clear process of applications for legal approval to reuse an old well, including the possibility of testing the well prior to the final implementation decision.
- Transparent legal situation, where the rights and responsibilities of the previous and new owners are clear, and individually designed contracts are possible for transferring ownership of an old well.
- Effective European Union and national grant schemes for reuse.

By establishing a framework that includes the points above, the reuse of abandoned wells could contribute to achieving the goals in the "green" transition and help to:

- Replace fossil fuels with renewable energy sources,
- Increase the self-sufficient supply of heating and cooling,
- Reduce CO_2 emissions, and
- Represent competitive advantage through promotion of sustainable energy use.

4. Economic analysis

4.1. Well status

When considering reuse of old wells, there are different situations that should be investigated in advance to evaluate potential reuse. Below, we present different possibilities for three well statuses that are potentially suitable for further investigation and reuse (Table 5).

The well status is very important for the economic evaluation. Implementation costs of reuse technologies are heavily influenced by the well status, because there are significant differences between interventions on wells that are active, shut-in, or abandoned (shut-in is the ideal status, requiring the least effort for redevelopment). Workover and new drilling operations also depend on the production medium and the age of the borehole. Therefore, data collection and a good record of the well's history are key to have an understanding of initial conditions. The basic situations that distinguish the status of a well are described in more detail below.

	Status		
	Active	Shut-in (temporarily abandoned)	Abandoned (permanent)
Casing	Production casing (Intermediate casing) Surface casing	Production casing (Intermediate casing) Surface casing	Production casing (Intermediate casing) Surface casing
Downhole equipment	Production pipes Packer Sand control equipment	Production pipes Mechanical plugs	No equipment
Cementation	Potentially partial cementation of unused zones	Potentially partial cementation of unused zones	One or multiple cement plugs, or cemented up to the surface
Wellhead	Production wellhead	Production wellhead 1 - 2 master valves	No wellhead

Table 5. Potential well statuses.

4.1.1. Active well

An active well represents a mining object for exploitation of underground fluids such as oil, gas, and brine. The fluids are transferred from the reservoir layers to the surface through the production equipment, which consists of several parts (downhole pump, production pipes, packer, safety valves, sand control, etc.). Figure 13 shows a typical active well with downhole production equipment.

Intervention on an active well can be simple or challenging, depending on the production fluid, reservoir pressure, integrity status, well age, etc.

The benefits of reusing an active well are that the well location is known and can be accessed easily, and no additional work is needed to start an investigation and apply the proper reuse technology.

Risks of reusing an active well are connected to potential exposure to elevated reservoir pressure as well as potential integrity issues and aggressive fluids that may damage equipment, be difficult to manage, or be dangerous for well technicians. It is therefore necessary to assess these risks and to develop a plan for the closure of depleted extraction zones.

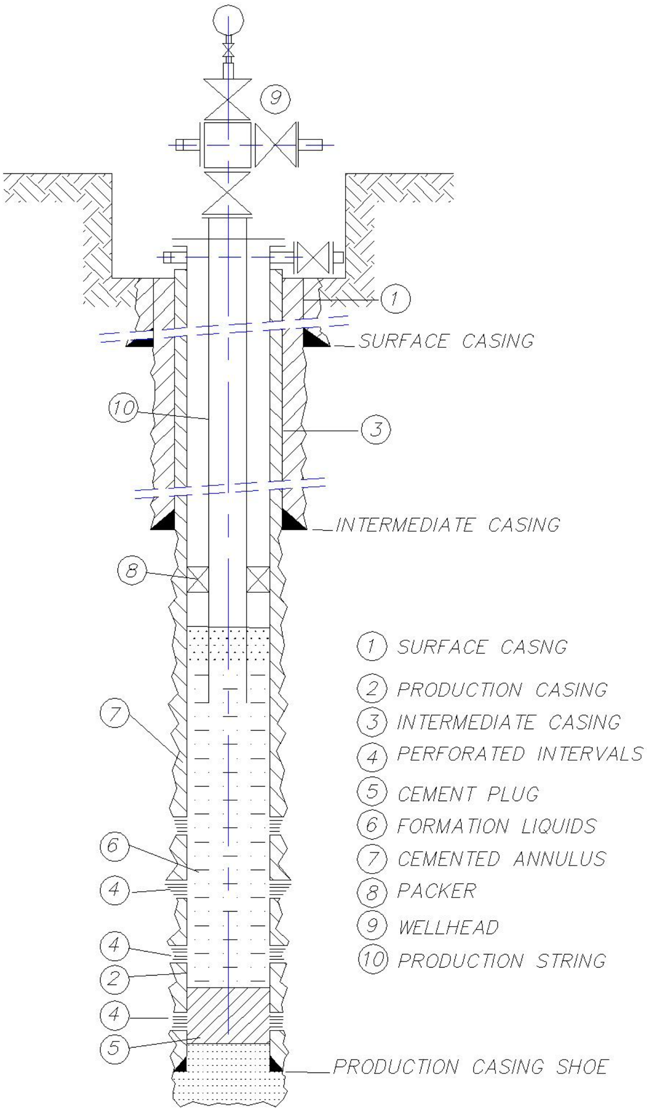


Figure 13. Typical configuration of an active well.

4.1.2. Shut-in well (temporarily abandoned)

A shut-in well represents a mining object which serves a monitoring purpose or is waiting to be abandoned. Usually, the production layers should be closed and isolated with mechanical plugs and cement if the well is waiting for abandonment. In case the well is used for monitoring, the connection to the produced reservoir is still intact, which means that the connection to fluids such as oil, gas, and formation water remains. Mostly, shut-in wells are safe and easy to access, and they may still have some downhole equipment in place (production pipes, mechanical plugs, etc.). Figure 14 shows a typical shut-in well with downhole equipment.

Intervention on a shut-in well is even more straight-forward than with an active well. Production reservoirs are likely sealed, the well integrity has been checked, and the well is usually waiting to be abandoned. Thus, shut-in wells are ideal targets for geothermal reuse.

The benefits of using a shut-in well are that the location is known and can be accessed easily, and no additional work is needed to start the investigation and apply the proper reuse technology. Risks of reusing a non-abandoned well are connected to potential reservoir pressure exposure, potential integrity issues, and aggressive fluids. Therefore, it is necessary to evaluate those risks.

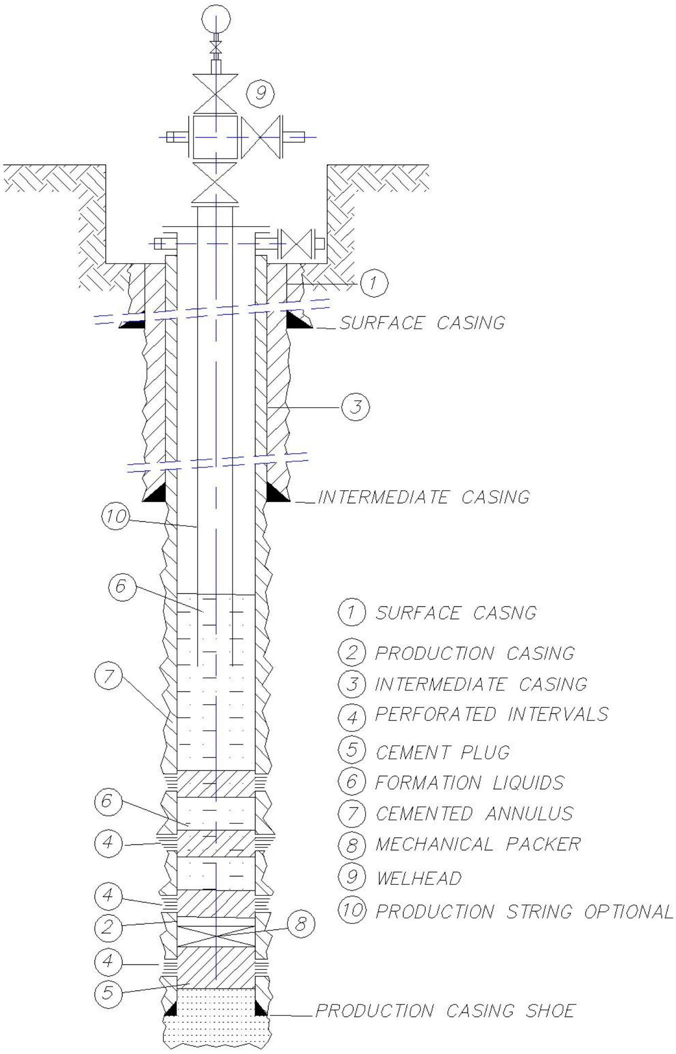


Figure 14. Typical configuration of a shut-in well.

4.1.3. Abandoned well (permanent)

An abandoned well represents a mining object which no longer exists on the surface and has been recultivated completely. The production layers are sealed with cement (and also usually mechanical plugs). The well can be either cemented up to the surface, or cement bridges may be set (with or without plugs). All casings are usually cemented and pressure tested, the well head is cut off, and the casing is sealed with a welded steel plate for each annulus and the last intermediate and/or production casing. There is no connection to the reservoir which was producing during operation. No downhole and surface equipment is present in the well, and the soil is recultivated. Figure 15 shows a typical abandoned well without any downhole equipment.

Intervention on an abandoned well is the most difficult, because the well has been closed. Production reservoirs have been sealed, integrity was checked, and the well has been abandoned, plugged, and sealed. The well is usually not visible from the surface as the soil has been recultivated.

Restrictions regarding implementation are no access road, no rig platform, and no wellhead. Construction work will likely be needed before any intervention, and there may be safety risks in case the abandoned well was not properly secured prior to abandonment, including potential formation pressure exposure, in case of leaks.

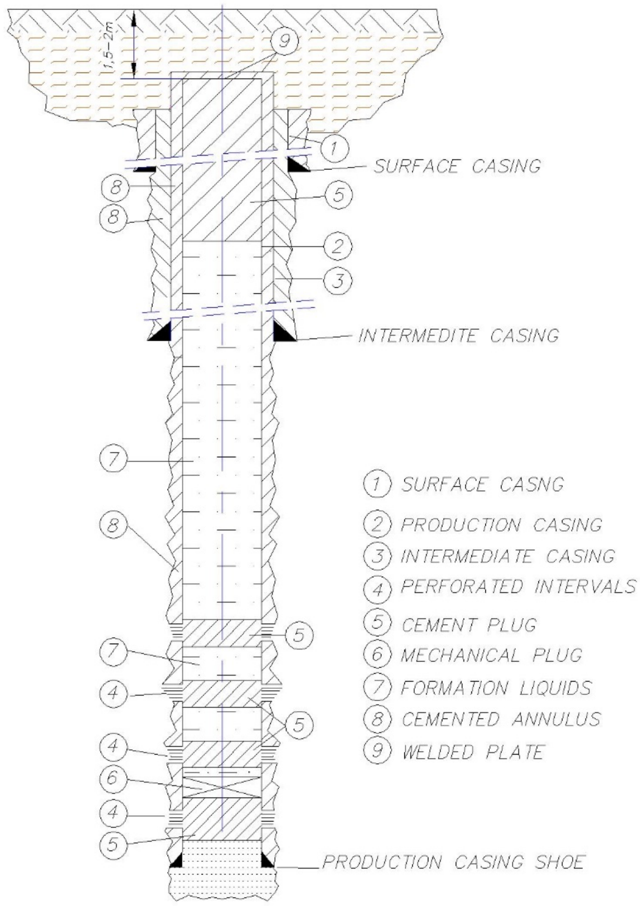


Figure 15. Typical configuration of a permanently abandoned well.

4.2. Footprint

Depending on the technology used in an active, shut-in, or abandoned well, a specified area of land will be occupied during the production lifetime. Usually, the area varies and is connected to the project needs, design, and relevant legislation. The area occupied depends on the applied technology, as different technologies require different surface equipment which covers a certain area around the well.

Regarding the applicable technologies, DBHE, BTES, and ATES usually only require a few square metres around the well, because the technologies are relatively simple and not demanding of surface space. Therefore, we assume a well location footprint of 1-6 m^2/well. Though some HE systems can be small (under 10 m^2), the application of HE and EGS generally requires more area, so we assume that these technologies cover a well location footprint of 60 to 900 m^2/well, depending on the prescribed safety measures to be considered. When a drill rig is needed for well interventions, typical areas of geothermal drilling sites are between 2.000 m^2 and 12.000 m^2.

The footprint for implementation is usually not a big challenge in a rural environment because land is available. Accordingly, the implementation is usually not restricted due to area required and accessibility for the machinery needed.

4.3. Well proximity to demand

Besides the well status and its current technical condition, an additional important aspect is the well location. Proximity to demand is an important factor, as a well that is far from the place where the heat would be needed may not be useful. Considering potential heat supply, we divide the reuse technologies into two groups related to potential energy recovery and energy distribution distance. Taking into account the different expected energy outputs of the 5 different reuse technologies, we distinguish:

- Short-distance distribution technologies that should be limited to a few hundred meters
    - DBHE, BTES, and ATES
- Long-distance distribution technologies which may supply heat over several kilometers
    - HE and EGS

The distinction between short and long distance depends on the expected wellhead temperatures and achievable flow rates. For the short-distance distribution technologies, we assume lower temperatures and more wells connected to supply the energy (especially in BTES systems which usually have many wells). In the case of long distances, HE and EGS technologies require at least 2 wells (a producer and injector pair) so that the system forms a geothermal well doublet. Heat transfer through pipelines was assessed by Röder et al. (2021), which describes the correlation between investment costs and capacity and thermal losses versus capacity (Figure 16).

For the example of a diameter nominal (DN) value DN 125 pipeline, the investment cost is 390 Euro/m and the capacity for transferring thermal power is 2100 kW, compared to a DN 150 pipeline which costs 500 Euro/m and has a capacity of transferring 4000 kW. Thermal losses for a DN 125 pipeline are around 30 W/m and are approximately 33 W/m for a DN 150 pipeline. This highlights that a bigger pipeline (DN 150) has a higher capacity for transferring heat while, at the same time, thermal losses are almost the same (Röder et al., 2021).

For industrial applications, it may be possible to develop industries near existing reused hydrocarbon wells, which could significantly reduce costs. This would increase the commercial output and lead to higher income and new jobs in rural areas.

4.4. Implementation cost of applying a geothermal extraction technology

For all reuse technologies and all project scales, there is a minimum of required equipment for production and distribution of heat which includes:

- Wells - production, plus possibly injection
- Hot/cold buffer tanks
- Transfer pump
- Electric submersible pumps (ESP)
- Heat exchanger
- Heat pump

- Filtration/cleaning of the water prior to injection/re-injection
- Pipes, fittings, valves, system control, and other equipment

Figure 17 shows the typical configuration for this equipment and how it relates to the connection flange from the wellhead.

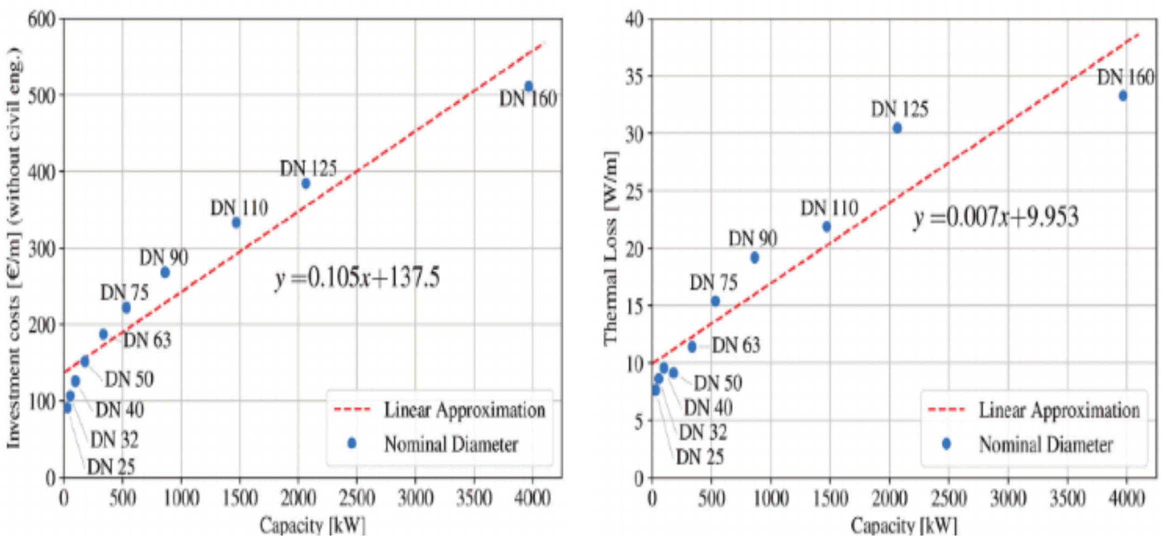


Figure 16. Correlation between investment costs, thermal losses, and capacity (Röder et al., 2021).

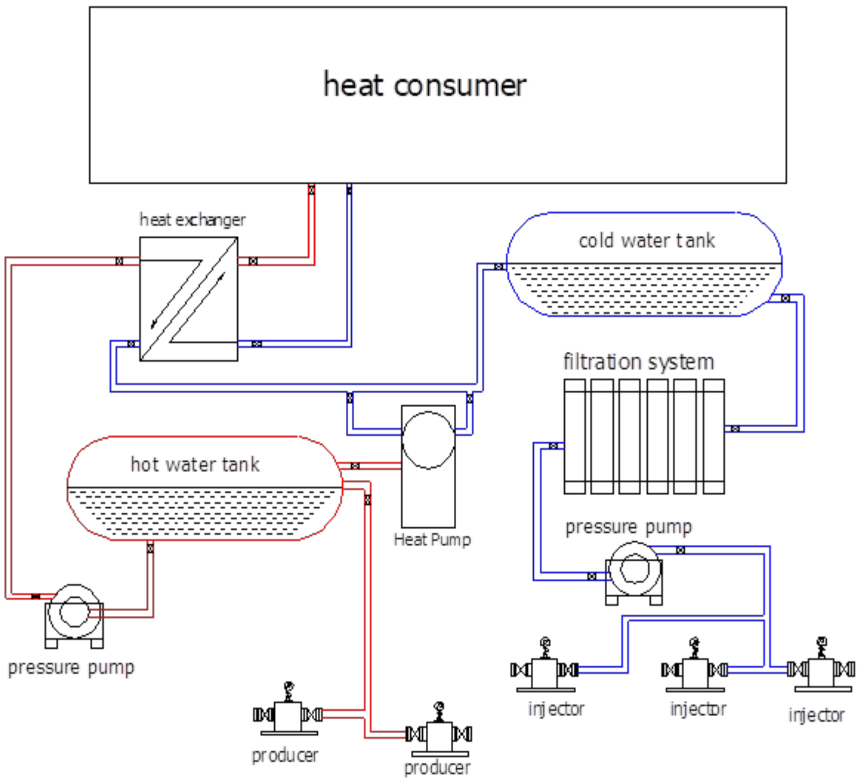


Figure 17. Typical surface equipment installation. Heat consumers may be from industry, municipalities, or agriculture.

4.5. Estimated workover costs for applying a geothermal extraction or storage technology

The overall costs of implementing one of the possible technologies for geothermal heat production, heat storage, and/or electricity production from a hydrocarbon well vary depending on the overall depth of the well, its location, country, and other factors. To provide a generic case, however, we have summarised expected investment costs and the outcome in Tables 6 and 7. Based on typical configurations and depths, we have made the assumption that the workover operation for technologies DBHE and BTES is performed on one 2.000 m deep well, and ATES includes a workover on two 1.000 m deep wells. HE is performed on two 2.000 m deep wells, and for EGS, the workover is on two 3.000 m wells. The workover, services, and material costs are estimated according to the current market prices in the partner countries in 2023/2024 and thus may be a minimum cost for future years. The actual costs will vary depending on the well location, status of the well, well depth, downhole equipment, the actual type of implementation (e.g., steel vs. PE piping in the DBHE technology, or single EGS stimulation of a long open-hole section vs. multi-stage stimulation from a cemented horizontal liner) and other details of a specific well (Appendices 1-5, questionnaires from partner countries).

TECHNOLOGY	AUSTRIA / GERMANY			TOTAL COST BY TECHNOLOGY
	Workover	Services	Material	
DBHE (1 x 2000 m)	330.000 - 350.000 €	45.000 - 50.000 €	150.000 - 160.000 €	**525.000 - 560.000 €**
BTES (1 x 2000 m)	330.000 - 350.000 €	45.000 - 50.000 €	150.000 - 160.000 €	**525.000 - 560.000 €**
ATES (2 x 1000 m)	240.000 - 260.000 €	45.000 - 50.000 €	50.000 - 60.000 €	**335.000 - 370.000 €**
HE (2 x 2000 m)	510.000 - 550.000 €	55.000 - 65.000 €	50.000 - 60.000 €	**615.000 - 675.000 €**
EGS (2 x 3000 m)	2.000.000 - 2.100.000 €	120.000 - 150.000 €	100.000 - 120.000 €	**2.220.000 - 2.370.000 €**

Table 6. Investment costs for workover intervention for DBHE, BTES, ATES, HE, and EGS technologies according to the market prices in 2023/2024 in Austria and Germany (Appendices 1-5, questionnaires from partner countries).

TECHNOLOGY	HUNGARY / CROATIA / SLOVENIA			TOTAL COST BY TECHNOLOGY
	Workover	Services	Material	
DBHE (1 x 2000 m)	180.000 - 200.000 €	20.000 - 30.000 €	70.000 - 80.000 €	**270.000 - 310.000 €**
BTES (1 x 2000 m)	180.000 - 200.000 €	20.000 - 30.000 €	70.000 - 80.000 €	**270.000 - 310.000 €**
ATES (2 x 1000 m)	135.000 - 145.000 €	20.000 - 30.000 €	30.000 - 40.000 €	**185.000 - 215.000 €**
HE (2 x 2000 m)	320.000 - 350.000 €	30.000 - 40.000 €	30.000 - 40.000 €	**380.000 - 430.000 €**
EGS (2 x 3000 m)	860.000 - 900.000 €	90.000 - 100.000 €	90.000 - 110.000 €	**1.040.000 - 1.110.000 €**

Table 7. Investment costs for workover intervention for DBHE, BTES, ATES, HE, and EGS technologies according to the market prices in 2023/2024 in Hungary, Croatia, and Slovenia (Appendices 1-5, questionnaires from partner countries).

4.5.1. Estimated costs for required surface equipment installation

Surface equipment for the use of heat energy from wells is standardised, and its components do not differ significantly depending on the technology of heat extraction from wells. However, it is necessary to consider the parameters that influence the size and design of surface installations required for utilizing thermal energy from wells. Temperature, flow rate, water quality, and heat/cool demand are important factors for designing the surface equipment. Corrosion and scaling of the casing and other equipment can be a challenge depending on the chemistry of the geothermal fluid, the operational parameters (temperature and pressure changes in the system), and the installed technical equipment (e.g., electrochemical reactions between chemical components in the geothermal brine and the steel casing, which has previously been protected from reservoir fluids by a hydrocarbon production string in the well). In many instances, undesired chemical reactions can be avoided by suitable system design (maintaining pressure and temperature changes in certain ranges), deploying inhibitors, and by other technical measures. Heating networks are usually not affected by this as a heat exchanger (plate or tube bundle heat exchanger) is usually used to transfer the heat of the produced geothermal fluid to the working fluid in the district heating network, thus the geothermal fluid from the subsurface does not circulate freely in the heating network itself (Ryan, 1981; Lund, 1998).

The primary components of most low-temperature direct-use systems include surface installations such as circulation pumps, transmission and distribution pipelines, peak load or backup plants, and a heat exchanger. Fluid disposal is either on the surface or the subsurface (re-injection). When the geothermal water temperature is below 50°C, heat pumps are often used to meet higher temperature demands (Lund, 1998).

The required equipment for production includes:

Downhole pumps and production string

Unless the well in an open geothermal system is artesian or a closed geothermal system operates based on density-driven convection (thermosiphon effect), downhole pumps are needed in open loop systems. Surface pumps are needed in closed-loop systems. The two most common types are electrical submersible pumps (ESPs) and line shaft pumps. A line shaft pump system (Figure 18, left) consists of a multi-stage downhole centrifugal pump, a surface mounted motor, and a long drive-shaft assembly extending from the motor to the pump. Most line shaft pumps are enclosed, with the shaft rotating within a lubrication column which is centred in the production tubing. This assembly allows the bearings to be lubricated by oil, as hot water may not provide adequate lubrication. A variable-speed drive set just below the motor on the surface can be used to regulate the flow instead of turning the pump on and off. An electrical submersible pump system (Figure 18, right) consists of a multi-stage downhole centrifugal pump, a downhole motor, a seal section (also called protector) between the pump and the motor, and an electric cable extending from the motor to the surface electricity supply (Lund, 1998).

Surface installation for distribution

Transmission pipelines carry fluids from the wellhead to either a site of application (e.g., heat exchanger) or a gas-water separator. Thermal expansion of pipelines heated rapidly from ambient to geothermal fluid temperatures causes stress that must be accommodated by carefully designed engineering solutions. The cost of transmission pipelines and distribution networks in direct-use projects is significant. This is especially true when the geothermal resources are located at a great distance from the site of use. Supply and distribution systems can consist of either a single-pipe or a two-pipe system. The single-pipe is a once-through system where the fluid is disposed of after use. This can only be used if no re-injection is required and if the produced fluid can be distributed directly within the district heating system without a heat exchanger in between. In a two-pipe system, the fluid is recirculated, so the fluid and residual heat are conserved. A two-pipe system must be used if it is necessary to prevent mixing between supplied hot water and returned cold water. Two-pipe distribution systems typically cost 20-30% more than single-pipe systems. At flowing conditions, the temperature loss in insulated pipelines is in the range of 0.1 to 1°C/km. In uninsulated lines, the loss is 2 to 5°C/km for flows of 5 to 15 L/s for a diameter of 150 mm (Figure 19) (Lund, 1998).

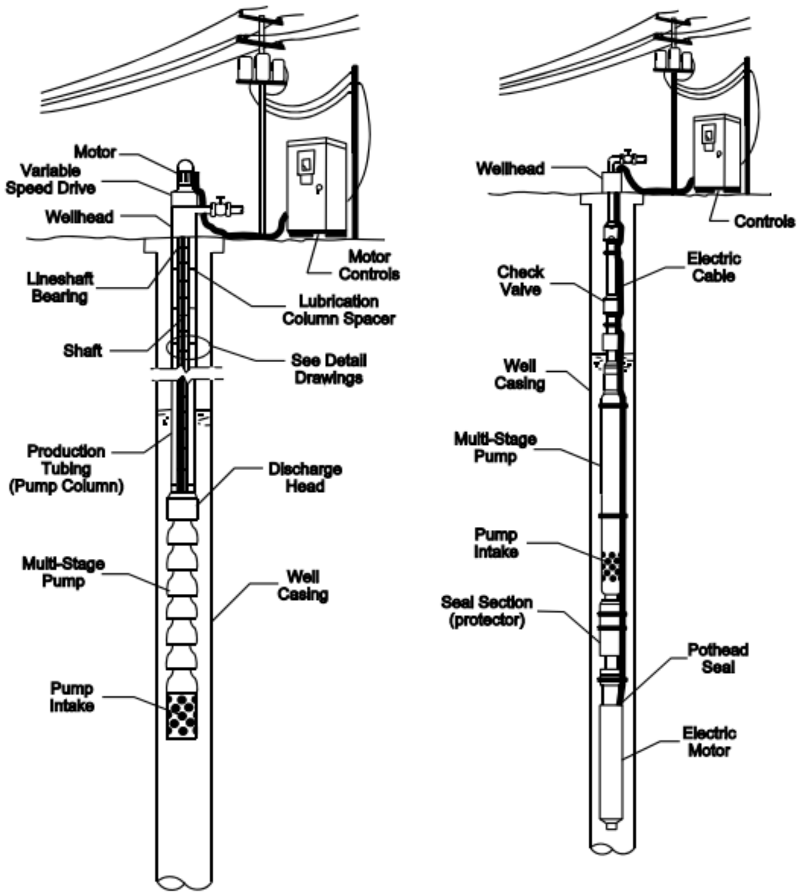


Figure 18. Downhole pump systems: line shaft pump (left) and electrical submersible pump (right) (Lund, 1998).

Heat exchanger

The principal heat exchanger types used in geothermal systems are plate heat exchangers and tube bundle heat-exchangers. Plate heat exchangers consist of a series of plates with gaskets held in a frame by clamping rods (Figure 20). The counter-current flow and high turbulence achieved in plate heat exchangers provide efficient thermal exchange. Usually, they are made of stainless steel, though titanium can be used when the fluids are especially corrosive. Plate heat exchangers are commonly used in geothermal heating applications worldwide (Lund, 1998).

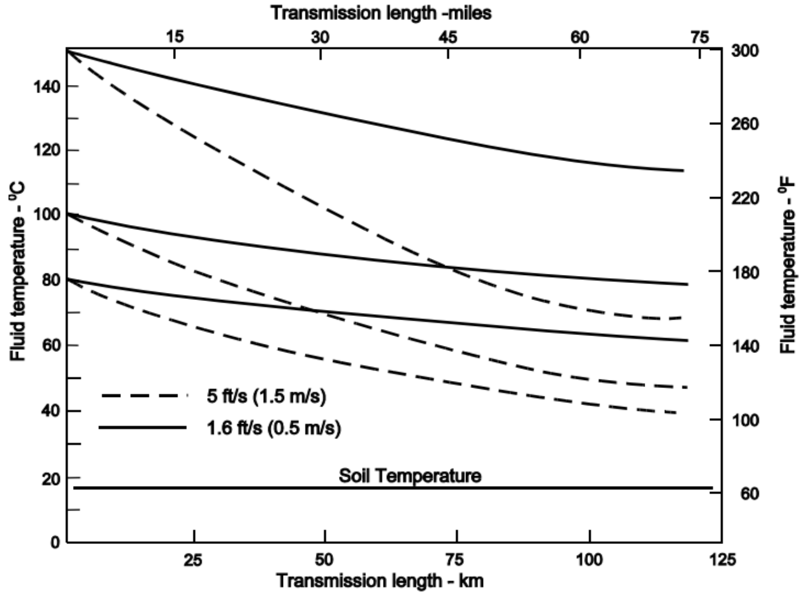


Figure 19. Temperature drop in a hot-water transmission line (Lund, 1998).

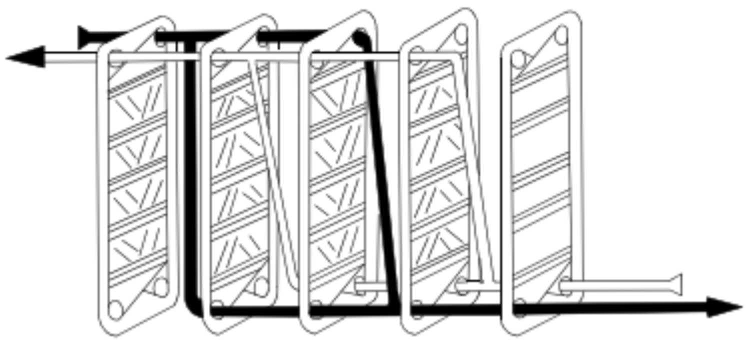


Figure 20. Plate heat exchanger (Lund, 1998).

Metering

It is important to have a reliable system which monitors and measures all critical parameters such as fluid temperature, pressure of the reservoir, volumetric flow rate, potential scale formation, and physical characteristics of underground structures (Lund, 1998).

Overall costs for implementing surface equipment vary depending on the overall flow rates and temperatures, location, country, etc. Summaries of the investment cost and the outcome are presented in Tables 8 and 9, assuming that the minimal required equipment consists of surface/downhole equipment, piping installation, heat exchanger, and a metering system. The investment costs are estimated according to the current market prices in 2023/2024. The actual cost will vary depending on the well location, status of the well, well depth, downhole equipment, and other specific factors (Appendices 1-5, questionnaires from partner countries).

In the current analysis, we determined that the heat transfer distance is an important factor in DBHE, BTES, and ATES technologies. Due to the relatively low output temperatures and/or installed capacity, it is recommended to place such systems near the end users. Therefore, we evaluated a transfer distance of 50 m as appropriate. With this short distance, we try to eliminate the impact on the losses of efficiency of the technology on surface installations.

Meanwhile, for HE technology a heat transfer distance of 1000 m was used, and a distance of 2000 m was used for EGS. The HE and EGS methods usually operate at relatively higher temperatures and flow rates, so effective heat transfer is possible over a greater distance compared to other technologies. In estimating the cost of implementation, we focused on critical parts such as surface and downhole equipment, connecting pipelines, heat exchangers, and measuring equipment used to monitor the systems. In Tables 8 and 9, cost estimates are given, though the exact cost will depend on the individual case and actual implementation concept.

TECHNOLOGY	AUSTRIA / GERMANY				TOTAL COST BY TECHNOLOGY
	Surface/ Downhole pumps	**Piping installation**	**Heat exchanger**	**Metering system**	
DBHE (distance 50 m)	10.000 - 15.000 €	15.000 - 20.000 €	15.000 - 20.000 €	10.000 - 15.000 €	**50.000 - 70.000 €**
BTES (distance 50 m)	10.000 - 15.000 €	15.000 - 20.000 €	15.000 - 20.000 €	10.000 - 15.000 €	**50.000 - 70.000 €**
ATES (distance 50 m)	25.000 - 30.000 €	15.000 - 20.000 €	15.000 - 20.000 €	10.000 - 15.000 €	**65.000 - 85.000 €**
HE (distance 1000 m)	50.000 - 60.000 €	200.000 - 250.000 €	60.000 - 150.000 €	50.000 - 60.000 €	**360.000 - 520.000 €**
EGS (distance 2000 m)	180.000 - 220.000 €	400.000 - 500.000 €	150.000 - 500.000 €	60.000 - 80.000 €	**790.000 - 1.300.000 €**

Table 8. Investment cost for surface equipment required for DBHE, BTES, ATES, HE, and EGS technologies according to the market prices in 2023/2024 in Austria and Germany (Appendices 1-5, questionnaires from partner countries). The values are estimated.

TECHNOLOGY	HUNGARY / CROATIA / SLOVENIA				TOTAL COST BY TECHNOLOGY
	Surface/ Downhole pumps	**Piping installation**	**Heat exchanger**	**Metering system**	
DBHE (distance 50 m)	3.000 - 5.000 €	10.000 - 15.000 €	10.000 - 15.000 €	7.000 - 10.000 €	**30.000 - 45.000 €**
BTES (distance 50 m)	3.000 - 5.000 €	10.000 - 15.000 €	10.000 - 15.000 €	7.000 - 10.000 €	**30.000 - 45.000 €**
ATES (distance 50 m)	15.000 - 20.000 €	10.000 - 15.000 €	10.000 - 15.000 €	7.000 - 10.000 €	**42.000 - 60.000 €**
HE (distance 1000 m)	20.000 - 30.000 €	160.000 - 190.000 €	60.000 - 150.000 €	30.000 - 40.000 €	**270.000 - 410.000 €**
EGS (distance 2000 m)	120.000 - 160.000 €	320.000 - 380.000 €	150.000 - 500.000 €	50.000 - 70.000 €	**640.000 - 1.110.000 €**

Table 9. Investment costs for surface equipment required for DBHE, BTES, ATES, HE, and EGS technologies according to the market prices in 2023/2024 in Hungary, Croatia, and Slovenia (Appendices 1-5, questionnaires from partner countries). The values are estimated.

4.5.2. Energy saving potential and self-sustainability

Table 10 compares the energy output from our 5 target geothermal reuse technologies with the potential industrial applications discussed previously in the report. The following realistic combinations of demand and supply are identified:

- Food, beverage, or tobacco production could be supplied with ATES, HE, and EGS applications
- Chemical and petrochemical production could be supplied with HE and EGS applications
- Machinery production and transport could be supplied with ATES, HE and EGS applications
- Non-ferrous metal production could be supplied with HE and EGS applications
- Pulp and paper production could be supplied with ATES, HE, and EGS applications

	Energy output (heat)	Food, beverages, and tobacco	Chemical and petro-chemical	Machinery and transport	Non-ferrous metal	Pulp and paper
DBHE	0,05 - 0,5 MW_{th}	0,5 - 50 MWth	5 - 50 MWth	5 - 50 MWth	5 - 50 MWth	0,5 - 50 MWth
BTES	0,05 - 0,5 MW_{th}					
ATES	0,5 - 20 MW_{th}					
HE	5 - 50 MW_{th}					
EGS	5 - 50 MW_{th}					

Table 10. Comparison of energy outputs and needs in industry (Yan et al., 2022; TrustEE 2017).

4.6. Complete cost estimates for each technology

Here we present the overall estimated investment cost required for the different well reuse technologies for heat extraction. The focus is on presenting information on workover cost on a shut-in or active well, setting up minimal required surface infrastructure by reuse technology, and estimating annual operational and maintenance cost. The presented values correspond to the current market prices (2023/24) gathered in partner countries for each individual task.

DBHE and BTES

- Investment cost for workover (1 well) and surface installation is estimated to be
  - Austria and Germany: 575.000-630.000 EUR
  - Croatia, Hungary, and Slovenia: 300.000-355.000 EUR

- Maintenance and Operation for a 20-30 year operation is estimated to be
  - Austria and Germany: 200.000-300.000 EUR
  - Croatia, Hungary, and Slovenia: 100.000-150.000 EUR

With a thermal power of 0,05 to 0,5 MW_{th} and an annual operating time of 8.760 working hours (365 days), this results in a yearly produced energy of 438-4.380 MWh. With a price of 150 EUR/MWh, the annual income from the obtained energy would be between 65.700 and 657.000 EUR.

ATES

- Investment cost for workover (2 wells) and surface installation is estimated to be
  - Austria and Germany: 400.000-455.000 EUR,
  - Croatia, Hungary, and Slovenia: 227.000-275.000 EUR

- Maintenance and Operation for a 20-30 year operation is estimated to be
  - Austria and Germany: 400.000-600.000 EUR
  - Croatia, Hungary, and Slovenia: 200.000-300.000 EUR

With an energy output of 0,5 to 20 MW_{th} and an annual operating cycle of 7.200 working hours (300 days), the production would range between 3.600 and 144.000 MWh/year. If the price per MWh is 150 EUR, the annual income from the obtained energy hence lies between 540.000 and 21.600.000 EUR.

HE

- Investment cost for workover (2 wells) and surface installation is estimated to be
  - Austria and Germany: 975.000-1.195.000 EUR,
  - Croatia, Hungary, and Slovenia: 650.000-840.000 EUR

- Maintenance and Operation for a 20-30 year operation is estimated to be
  - Austria and Germany: 1.000.000-1.500.000 EUR
  - Croatia, Hungary, and Slovenia: 600.000-900.000 EUR

With a thermal power of 5 to 50 MW_{th} and an operating cycle of 7.200 working hours (300 days), production would be between 36.000-360.000 MWh MWh/year. If the price per MWh is assumed to be 150 EUR, the annual income from the obtained energy would be between 5.400.000 and 54.000.000 EUR.

EGS

- Investment cost for workover (2 wells) and surface installation is estimated to be
  - Austria and Germany: 3.010.000-3.670.000 EUR,
  - Croatia, Hungary, and Slovenia: 1.680.000-2.220.000 EUR

- Maintenance and Operation for a 20-30 year operation is estimated to be
  - Austria and Germany: 1.800.000-2.700.000 EUR
  - Croatia, Hungary, and Slovenia: 1.000.000-1.500.000 EUR

With an electric power of 1-5 MW_e and an operating cycle of 7.200 working hours (300 days), a production range between 7.200 and 36.000 MWh/year would result. If the price per MWh is assumed to be 150 EUR, the annual income from the obtained energy would be between 1.080.000 and 5.400.000 EUR. For electricity production, a binary power plant (in addition to the heat exchanger) would be required, which adds significant costs.

With a thermal power of 5 to 50 MW_{th} and an operating cycle of 7.200 working hours (300 days), production would be between 36.000 and 360.000 MWh/year. If the price per MWh is assumed to be 150 EUR, the annual income from the obtained energy would be between 5.400.000 and 54.000.000 EUR.

NOTE: The economic evaluation is assuming reuse of shut-in wells, where access to the location is provided, partial rehabilitation and isolation of the production layers was carried out, and integrity has been confirmed to be acceptable. If another type of well (active or abandoned) will be reused, the cost of the intervention must be adjusted according to the specific situation. The cost estimates above were taken from the current market conditions (2023/24) in the partner countries.

An important factor for comparison is the price of a new well, which in general will add a significant cost to the project but also fluctuates depending on the location, depth and geology of the deposit, current drilling demand, and the country. For comparison with reusing an existing well, we estimate the approximate price of one deep new well with depths of 2.000 m and 3.000 m:

1. Well depth of 2.000 m
    a. Austria and Germany: 3.650.000-4.380.000 EUR
    b. Croatia, Hungary, and Slovenia: 2.250.000-2.700.000 EUR

2. Well depth of 3.000 m
    a. Austria and Germany: 6.950.000-8.340.000 EUR
    b. Croatia, Hungary, and Slovenia: 3.780.000-4.536.000 EUR

This comparison clearly shows that reuse of wells is significantly more economical than drilling a new well, if an appropriate existing well can be identified and used.

5. Current status and suggestions for action

Based on the review of the socio-economic situation of well reuse for industrial applications in the TRANSGEO partner countries, there exists growing potential for cost-effective development of new geothermal resources from hydrocarbon wells. The economic and social situation for a specific well development project is strongly site- and application dependent, but many of the existing wells in Central Europe are located in rural environments without nearby industrial users. We found that there is a lack of awareness and knowledge regarding the possibilities, potential benefits, and potential risks of reusing existing wells for geothermal energy production or energy storage. The majority of the industrial sector already has a working energy supply chain which is hard to update and offer new ideas and possibilities. However, industries will be required, or will desire, to transform their heat supply in the coming years and use a reliable green heat source. Some facilities already use shallow geothermal energy for space heating or cooling. Usually those interventions correspond with management awareness and market shifts or subsidies to steer the changes in energy supply.

The analysis did not show major obstacles to reuse, and multiple reuse projects in each of the five countries already demonstrate that such projects are technically, legally, and economically feasible. The main challenges identified in our analysis are related to data availability and the condition of the well. None of the partner countries have precisely defined procedures or guidelines for establishing the reuse of wells after their initial purpose has been completed. This is likely connected to the limited number of such reuse projects to date, though this is changing.

The social analysis revealed suitable possibilities for the use of existing wells for new purposes. In principle, users do not have concerns with well reuse, because the geothermal reuse implementation and permanent equipment cover only a relatively small area (depending on the technology) and do not represent a disturbance to nearby life in communities. It is likely that well repurposing projects are expected to receive most support in former and current mining areas and hydrocarbon production areas because residents are accustomed to these types of interventions and facilities. The industrial sector's use of geothermal energy is fairly undeveloped and has much opportunity for expansion.

Regarding economic sustainability, our analysis reveals that it is usually significantly more cost-effective to use existing wells in comparison to drilling new wells, though well reuse is not always possible and thus the cost depends heavily on the particular situation.

To determine the financial reality of well reuse, it is important to consider the condition of the well prior to intervention. In case the well is abandoned and the well location recultivated, it requires significant effort and expense to use it again. The easiest types of wells to reuse are shut-in or active suspended wells; these have quite a beneficial situation for reuse. In these cases, the reuse must fit into the abandonment time plan for these wells. Abandoned oil and gas fields are often located near villages with limited industry. Therefore using existing wells would be a reasonable consideration for attracting investments in the industrial sector in rural areas. The majority of applications in industry use HE technology. Even though DBHE, BTES, and ATES have high reliability and lower investment than the higher-capacity HE and EGS technologies, the applicability of these lower-capacity technologies for industrial use can be challenging, because of lower output temperatures and heating capacity.

HE and EGS would be more suitable for industrial processes which require temperatures between 80°C and 200°C. However, to encourage changes in the energy supply chain requires engineering expertise, confidence, and leaders to demonstrate successful development. Usually, industrial processes are compact and designed for conventional energy supplies such as fossil fuels, biomass, or wood. Nevertheless, the source and reliability of geothermal reuse projects combined with economic factors and environmental benefits is a very attractive option for the transformation of industrial heating applications, provided one or more usable wells are available.

As seen by this report, there are innovative ways that all 5 reuse technologies could be used for industry and other potential customer groups such as agriculture and municipalities. As evidenced by the increasing interest and activity related to well reuse, it is apparent that repurposing existing hydrocarbon wells for new geothermal energy production is an application that is growing in Europe and can be facilitated in the TRANSGEO partner countries by our project.

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7. Terminology

Active (or producing) well	A well that is currently in use, producing fluids (gas, oil, or water).
Inactive (shut-in) or temporarily abandoned well	A well where production, injection, disposal, or workover operations have ceased, but permanent abandonment has not taken place. Inactive wells should be classified as either shut-in or temporarily abandoned. Shut-in status should begin 90 days after operations stop, and temporarily abandoned status should commence after temporary abandonment operations have been completed (downhole lift equipment and tubing have been removed, and a bridge plug has been set). An inactive or temporarily abandoned well can be more easily put back in production than a permanently abandoned well.
Permanently abandoned (or liquidated, suspended, or decommissioned) well	A well is permanently closed off when no viable hydrocarbons are discovered or it is depleted and no longer capable of producing profitably. The well is permanently plugged downhole, producing subsurface formations have been isolated and permanently plugged, and the well has been permanently decommissioned. The wellhead is usually cut off and the land surface reclaimed.

Reuse, repurpose	Repurposing is the process by which a well with one use is transformed or redeployed with an alternative use. In this case, hydrocarbon wells may be used for other purposes, e.g. water production or geothermal energy.
Workover	A workover is any operation done on, within, or through the wellbore after the initial completion. Although proper drilling, cementing, and completion practices minimize the need, virtually every well will need several workovers during its lifetime to satisfactorily fulfill its purpose. Workovers may be required for one or more of the following reasons: unsatisfactory production or injection rates, supplemental recovery project requirements, regulatory requirements, competitive drainage, reservoir data gathering, lease requirements, or abandonments. Workover can include artificial lift installation, acid stimulation, scale and paraffin removal, hydraulic fracturing, sand control, etc.
ATES	**Aquifer Thermal Energy Storage** In ATES, heat is stored in a subsurface aquifer when it is available in excess (usually summer), and it is retrieved when it is needed (winter). Crucial parameters for success are appropriate thermal conductivity and heat capacity, hydraulic conductivity, and storage capacity of the aquifer. ATES facilities can be used either in shallow unconfined or in deep confined aquifers. Deep confined aquifers are often preferred because the regional groundwater flow is usually low or negligible (which prevents loss of the hot stored water), the heat loss is reduced due to the depth, and the initial temperature regime is higher due to the natural geothermal gradient. ATES systems in shallow unconfined aquifers are less expensive for well installation and monitoring, but groundwater horizons must be protected from potential impacts of heat storage.
DBHE	**Deep Borehole Heat Exchanger** A Borehole Heat Exchanger (BHE) is a device to extract geothermal heat from rocks without production of water or other formation fluids. It is a heat exchanger installed inside a borehole, circulating heat-carrying fluid down and up. The fluid does not interact directly with the rocks or water in the borehole but is restricted to flow only inside pipes inside the borehole, so heat is transferred by conduction. BHE's can be shallow or deep. Deep Borehole Heat Exchangers (DBHE) can reach rocks of higher temperatures and thus can supply more energy than shallow BHEs. DBHEs are often installed in dry unsuccessful boreholes.
BTES	**Borehole Thermal Energy Storage** Similar to ATES systems, BTES installations store heat in the underground, but instead of open communication with the aquifer as in ATES, BTES systems store and retrieve heat to and from the

	subsurface by means of Borehole Heat Exchangers (BHEs). BTES is recommended for small to moderate energy needs where groundwater is scarce or hydrogeological conditions are unfavorable for pumping water. To avoid subsurface water movement and thus loss of the stored heat, groundwater flow should be minimal. The energy production capacity of BTES is lower than ATES but is compensated by easier design and installation. BTES arrays often contain many BHE's for scaling up the energy production.
EGS	**Enhanced Geothermal System** EGS can be used to describe any geothermal system that has been engineered by technological means to improve permeability or fluid mass flow. EGS is often used in settings where a well has been drilled and does not produce fluid as expected. Enhanced flow can be accomplished by creation of fractures in impermeable or low-permeability rock (through, for example, injection of water to pressurise the subsurface or selective dissolution of rock), thus allowing fluid to flow more freely and energy to be produced in areas where production was previously not possible or was not economical.
HE	**Hydrothermal Energy** HE is electricity or heat energy produced from hydrothermal heat, which is the thermal energy stored in hot water and steam within the Earth's crust, usually associated with volcanic activity or geothermally active areas. In a geothermal power plant, this heat can be converted into usable energy. In the case of electricity production (which, for HE, is more common than production of heat), hydrothermal heat is used to produce steam, which drives turbines connected to electricity generators.

Appendix 1 - Questionnaire Austria

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Country	Austria
Contact	Doris.Rupprecht@geosphere.at; Monika.Hoelzel@geosphere.at

1. General status: Are there a geothermal project in your country currently going on? What is the acceptability of such projects by users and the local community? Please provide a short description.

In the following section only projects with a depth > 300 m needing at least one borehole are described. E.g. projects, like tunnel drainage waters are not covered.

HE Vienna Basin (approval stage)

Deep geothermal plant in Vienna (Aspern) with maximal power of 200 MW operated by joint venture of OMV and Wien Energie (deep). Approval procedures are currently pending. Drilling is scheduled to start towards the end of 2024 and the plant should go into operation in 2027.
https://www.ots.at/presseaussendung/OTS_20231106_OTS0061/fuer-klimaneutrale-fernwaerme-wien-energie-und-omv-gruenden-joint-venture-fuer-tiefengeothermie

The project is based on former studies like GeoTief (https://www.geotiefwien.at/) and a positive well test of an existing former gas well (Aderklaa 97; newspaper article in german: https://m.noen.at/gaenserndorf/bezirk-gaenserndorf-sitzt-der-bezirk-auf-heisswasser-schatz-bezirk-gaenserndorf-geothermie-heisswasser-omv-bohrloecher-fernwaerme-print-344343810) in 2022.

ATES Vienna (feasibility study)

Feasibility study of an ATES in the Vienna Basin with an energy capacity of 10 GWth and temperatures of 40 °C: The project will be based on either new wells or reuse of existing wells. Duration is from 2021 to 2024.

The study integrates the geological, technical and economic perspective, with the integration options into district heating networks, additionally with an evaluation of the socio-economic and regulatory framework conditions for future ATES applications in Vienna/Austria.

Public perception

The acceptability depends on projects size, operators and stakeholders. Generally spoken we would assume the attitude towards geothermal energy as positive.
In Vienna a 3D seismic was measured within the city boundaries by OMV and Wien Energie for HC purposes and geothermal projects (see above project deep). They managed to finish the campaign without any opposition.

For the small reuse project Prottes T 11 (2009-2011) the reaction of the public was positive. See press release (in German) in Chapter D.1 of this questionnaire.
The GSA team has found that in measurement campaigns, individuals can often jeopardise the implementation of projects by opposing them, e.g. blocking geoelectric measurements on their property.

Public awareness
Still, the level of awareness towards the use of geothermal energy is rather low in Austria. Hence, the share of geothermal heat production (direct use and heat-pump supplied) in the heat production heat is estimated around 1.6%.)
https://europeangeothermalcongress.eu/wp-content/uploads/2019/07/CUR-01-Austria.pdf

2. Do some geothermal projects include repurposed old wells? If yes, what is the user experience and acceptability of the local environment where it is implemented? Please provide a short description.

Deep Borehole Heat Exchanger

Prottes T 11: Reuse of an oil producing well in the Vienna Basin (Weinviertel). The well was drilled in 1974 with a total depth of 2980. The used interval for DBHE equipment was 0 - 2243 m with a bottom hole temperature of 83°C. Before re-completion a pressure test for well integrity was undertaken. The project was running from 2009 – 2011 and operated by OMV AG. The heat customer was the municipality of Prottes, where a sports hall was heated. Project report (in German): https://www.klimafonds.gv.at/wp-content/uploads/sites/16/BGR0262011EE_Geothermie.pdf

Neukirchen a.d. Vöckla (Mühlleiten-002): Reuse of an uneconomic gas well in the Molasse Basin, started in 2012 and is shut-in recently. The well was drilled in with a total depth of 2850 m with a temperature of 105 °C. Operator is RAG Austria and the heat is delivered 1 km pipeline to Bioenergie Neukirchen for communal heating.

Press release (in german):
https://www.ots.at/presseaussendung/OTS_20120503_OTS0111/einzigartiges-regionales-energie-projekt-aus-einer-kombination-von-erdwaerme-und-biomasse-fuer-neukirchen-ad-voeckla-eroeffnet

There were no issues with the acceptability. For both projects a municipality was the heat consumer of the installations.

3. Are there any reuse projects implemented or in the planning phase? Please indicate the name and a short description, if possible.

DBHE: Muehlleiten (shut-in), Molasse Basin (Upper Austria), ATES: feasibility study with existing or new infrastructure, Vienna Basin (Lower Austria). For details see answers 1 and 2.

4. Is there a promotion of potential reuse of wells in your country? Do investors/state/others show interest in well reuse? If so, please provide a short description.

There is nearly no promotion of this kind of geothermal energy. Only within the (scientific) community the topic is sometimes mentioned but it is integrated into the “geothermal roadmap” of Austria (in german: https://nachhaltigwirtschaften.at/resources/nw_pdf/BMK_Geothermie_Roadmap.pdf)

B. Demand patterns for different customer group

Data in this section concerns the knowledge about energy consumption, willingness on changing the current energy source, suitability of geothermal energy regarding the current energy supply chain, …

1. What is the general energy demand of industry, agriculture, and municipalities in your country? Please describe each customer group.

2022	Demand - Consumption		
	Petajoule	**TWh**	**%**
Producing sector	305	84,7	28,8
Transport	343,1	95,3	32,4
Service sector	101,8	28,3	9,6
Private sector (households)	287,6	79,9	27,1
Agricultural sector	22	6,1	2,1
All energy consumers	1059,5	294,3	100

In terms of final energy consumption, electricity is the second most important energy source after oil products, followed by gas and biogenic energy sources. Transport is the most important energy demand sector, accounting for almost a third of total final energy demand, followed by the manufacturing sector and private households, which account for almost 29 percent and just over 27 percent respectively.

Energy - References

Federal Ministry Republic of Austria on Climate Action, Environment, Energy, Mobility, Innovation and Technology https://www.bmk.gv.at/themen/energie/publikationen/zahlen.html

Statistics Austria https://www.statistik.at/en/statistics/energy-and-environment/energy/energy-balances

Description Economy

In 2021, around 358,600 companies in the market-oriented economy were SMEs, representing 99.6 percent of all domestic companies in the market-oriented economy.

Around 87 per cent of SMEs were micro-enterprises with fewer than ten employees. This size category also includes one-person companies (i.e. companies with a single employee), which accounted for around 41 per cent of all companies in 2021. Around eleven percent of SMEs were classified as small businesses (ten to 49 employees) and two per cent as medium-sized businesses (50 to 249 employees).

Description - References

Federal Ministry Republic of Austria for Labour and Economy

https://www.bmaw.gv.at/Services/Zahlen-Daten-Fakten/KMU-in-%C3%96sterreich.html

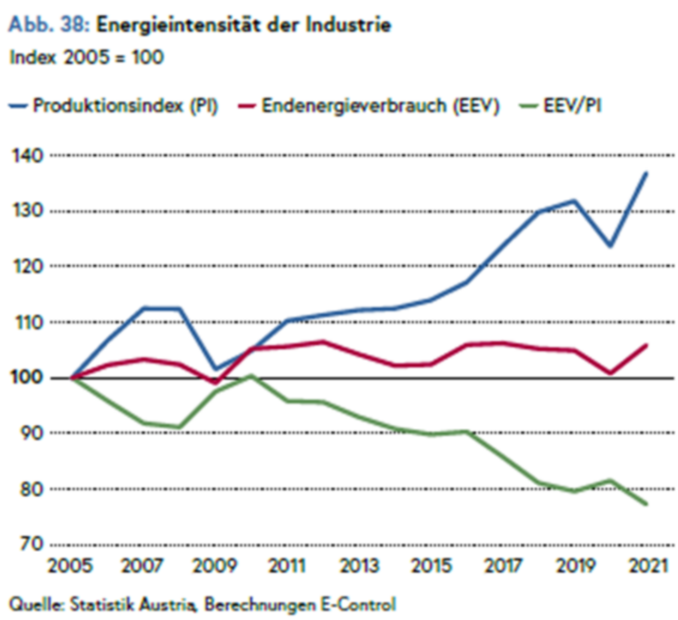
Industry

Final energy consumption in industry is mainly determined by production volumes (activity), the distribution of the various economic products (structure), the outside temperatures (weather conditions) and energy efficiency (energy intensity).

In the period 2014 to 2021, production increased by a total of 21.6%, whereby economic sectors with a lower energy intensity have grown more strongly and thus offset final energy consumption compensated by 9.8%.

The higher number of heating degree days, which an indicator of the frequency of low outdoor temperatures, would increase final energy consumption by 2.4%, whereby room heating is mainly affected by low outside temperatures, the energy intensity across all industrial sectors has improved by 10.7%, even if final energy consumption has risen by 3.6% from 2014 to 2021.

Energy Intensity of the industrial sector



Blue line: Production Index (PI)

Red line: Energy consumption (EEV)

Green Line: Coefficient EEV/PI

With a share of almost 29% of the final energy consumption industry alongside space heating and transport, industry is a major energy consumption sector. In particular, the energy-intensive industry, which in Austria accounts for around two thirds of the final energy consumption of the manufacturing sector influences the final energy consumption.

Agriculture

Federal Ministry of Agriculture, Forestry, Regions and Water Management https://info.bml.gv.at/en/

The Austrian agricultural sector is very small structured based on family farms, which account for 93 % of all farms and are the backbone of Austria's agriculture and forestry (source: Austria's 2020 Farm Structure Survey).

6,500 EMPLOYEES

Around 6,500 people are employed in the agricultural technology sector.

154,953 AGRICULTURAL AND FORESTRY ENTERPRISES

In Austria's small-scale agricultural and forestry sector, there are around 155,000 enterprises.

21.9% PERCENTAGE OF ORGANIC ENTERPRISES

21.9% of the enterprises in Austria carry out organic farming.

13.84 BILLION EUROS IN EXPORTS

The export volume of agriculture was EUR 13.84 billion in 2021.

Agricultural technology - Key data 2021	
Companies	33
Staff	approx. 6.500
Revenues	EUR 3.200 million
Export	EUR 1.900 million

Source: Association of Metaltechnology Industries

Total agricultural foreign trade 2021	
Exports	EUR 13.84 billion (+8.5 %)
Imports	EUR 13.88 billion (+8.8 %)

Source: Statistics Austria, AMA-Marketing

Structure of agricultural holdings 2020	
Number of agriculture and forestry operations	154.953
Number of main holdings	55.875
Number of subsidiary holdings	88.433
Other	10.645
Number of mountain farming operations	54.182
Gross Added Value Austrian agriculture at cost prices (2021)	EUR 3.622 billion
Agriculture and forestry workforce	420.018

2. How many users have experience with using geothermal energy? Which is the preferable technology by end users? Please describe each customer group.

Near-surface geothermal energy, there were around 90,000 installations in 2020, the installed heat output was 1,100 MW and the heat produced was 2,300 GWh. This corresponds to around a 4 % share of the renewable heating market.

Deep geothermal energy, in 2020 there were two electricity generation plants with an installed capacity of 1.2 MW and ten heat generation plants with an installed capacity of 100 MW th , producing 300 GWhth of heat.

Reference: https://www.pwc.at/de/publikationen/pwc-geothermie-in-oesterreich_2023.pdf

Municipalities use geothermal energy for heating and power generation (Styrian Basin, Molasse Basin). A big sector is the use as thermal spa and for balneological applications. These applications are private owned or by municipalities (e.g. Therme Oberlaa Vienna)
Based on these applications a secondary market evolved for the heating of greenhouses (Styrian Basin: Frutura; Molasse: Geinberg)
The end user prefers the cheapest method regarding installation and operation, depending in which place the operation is based.

3. Under which circumstances would current users be willing to change the energy source they are using right now? Would any of the defined customer groups be interested in a local accessible energy source?

Our subjective opinion is that reasons for change energy source are mainly

- operational cost reduction
- independence from imports and variable energy pricing
- environmental issues

4. Would the end user consider geothermal energy usage nevertheless it can cover the base load and they need a backup for peak loads? Is this a major obstacle for the end user's or do they see potential in it?

5. Are there any potential customer groups who would be satisfied only with base load energy supply? If yes, please provide the information regarding user, energy load needed and preferable technology, if applicable.

4/5. Subjective opinion based on experiences from project work. Official (reliable) data could not be found on this topic:

The larger the operator or the greater the energy requirement, the higher (and also more self-evident) the willingness to use an energy mix to cover base and peak load. In the case of deep geothermal energy, it is often assumed that this will only cover the base load (e.g. from experience with large district heating operators). The attitude goes hand in hand with the willingness and understanding to switch to renewable energies.

C. Economic analysis

Data in this section concerns evaluating the economical side of implementation and usage of repurposing technologies in the energy supply chain.

1. What is the optimal transfer distance of energy for recognized reuse methods DBHE, BTES, ATES, HE, EGS? Depending on flow rate and temperature? Please describe each method.

> No official data on this topic found for Austria and no experience concerning different users. At this time of the project very hard to summarise, because depending on variety of parameters and geological setting. Should be one result of Transgeo.

2. What is the cost for implementation of reuse methods DBHE, BTES, ATES, HE, EGS on a well which is active / shut in / abandoned? Please describe each method and each type of well status.

	Status					
	active		shut in		abandoned	
Parts available in the borehole	Casing, production equipment, perforations active, Extras: Packers, Pebble Filter		Casing, perforations closed		no casing, cemented, filled up and re-cultivated	
Knowledge advantage over new well	Reservoir data available: Geological profile, logging, tests, cores, drilling experience, pressure data, temperature, flow rate					
Geothermal method	**Cost of implementation (EUR, end of 2023)**					
DBHE	workover costs, cementing, logging-testing, material costs tubing		workover costs, logging-testing (cementing if leakage test negative), material costs tubing		drilling costs varying with depth, same as new well	2500-3000 Euro per meter
BTES					drilling costs varying with depth, same as new well	2500-3000 Euro per meter
ATES					drilling costs varying with depth, same as new well	2500-3000 Euro per meter

HE	costs for deepening or sidetracking or workover costs, closing HC perforation, logging, perforation of aquifer,injection well		workover costs, logging-testing (cementing if leakage test negative), perforation of aquifer,injection well		drilling costs varying with depth, same as new well	2500-3500 Euro per meter (the 3500 Euros are for higher diameter for production and injection wells)
EGS	workover costs, closing HC perforation, hydraulic fracturing		workover costs, hydraulic fracturing		drilling costs varying with depth, same as new well	2500-3000 Euro per meter

3. What is the cost of surface infrastructure, depending on expected energy supply by each method DBHE, BTES, ATES, HE, EGS? Please describe each method.

Heat pipeline costs: 1500 – 2500 Euro/meter Heat pump 5 MW: 15-20 Mio Euro Reference: https://www.pwc.at/de/publikationen/pwc-geothermie-in-oesterreich_2023.pdf

4. What would be the cost of production equipment for methods DBHE, BTES, ATES, HE, EGS? Well downhole equipment, wellhead, annual maintenance cost, … Please describe each method.

VIT tubing

5. What would be the approximate maintenance cost for each method DBHE, BTES, ATES, HE, EGS on a 5-year production base? Well, surface equipment, piping, valves, …

Information from a DBHE project: 1 well maintenance run per month was ordered by the authority (10 000€ /month) > this number kills every project economy

6. What would be the footprint of the whole installation considering well location, surface facility, piping, etc? Please provide the information for each method DBHE, BTES, ATES, HE, EG

The following description only refers to the surface equipment related to the geothermal method. User surface installations (e.g. green houses, aquaculture, thermal spa) are excluded.

Geothermal method	Surface equipment total (m)	Area in m²	Surface components	Project, Well
DBHE	30,4 x 27,2	825	block heating station (BHKW), control system module (EMSR), Heat Pump Module, Geothermal Module, gas pressure controlling plant (GDRA), pipes	Muehlleiten, ML-002
BTES	-	-	-	-
ATES	-	-	Projecting status	(FFG; ATES Vienna Basin)
HE	174 x 78	ca. 13 572 (not rectangular)	HE power plant, Co2 tanks	Blumau Geothermie, Blumau 3 (?)
EGS	no data for Austria			

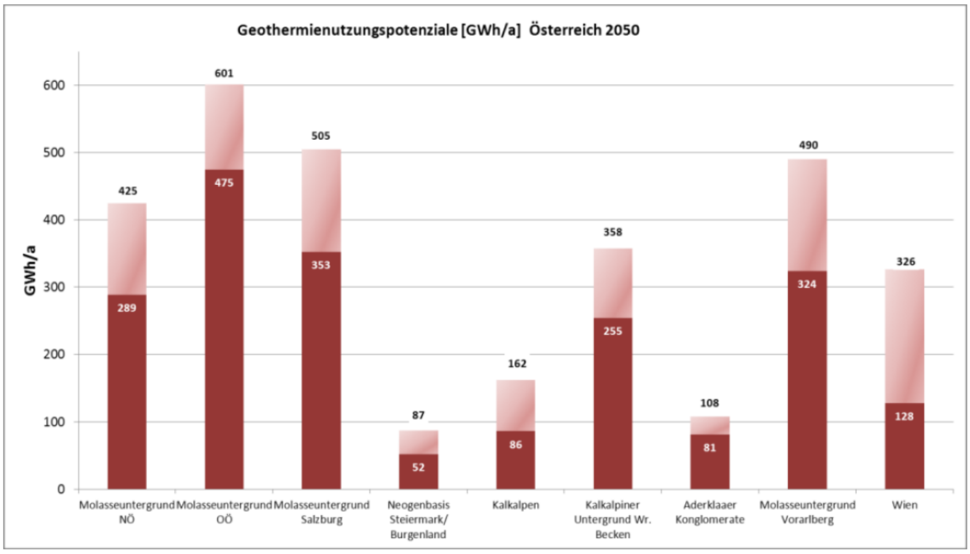
7. How much energy could be produced by each method DBHE, BTES, ATES, HE, EGS in best case scenario and in worst case scenario? Please define the energy in watt (W) for each method.

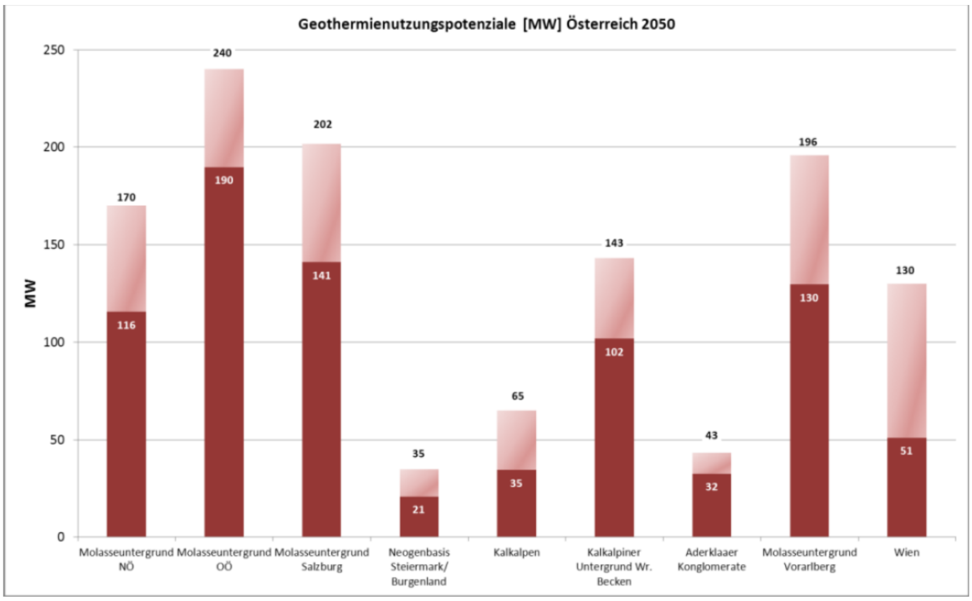
All values are derived from executed or planned projects in Austria.

Geothermal method	**Net Energy productio n (Watt)**			
	Maximum Case	**Geological Unit**	**Minimum Case**	**Geological Unit**
DBHE	400 000 (400 kWh)	Molasse Basin, single well	40 000 (40 kWh)	Vienna Basin, single well
BTES	Can be assumed as unlimited. Geothermal probes, even very deep ones, can be sunk almost anywhere if there are no restrictions like protected areas. It also depends on the intended use, the drilling depth and extraction performance…			
ATES	There is currently no Austrian wide assessment on the impact of ATES on the Austrian heating sector. The final report of the Austrian heat map project lists an excess heat potential from ETS companies of about 10.3 TWh/a, of which 2.6 come from processes with temperatures above 100°C. As high temperature ATES (HT-ATES) is typically used for seasonal storage, (excess heat during summer could be about 50% of this value [assuming equal provision of excess heat during the year and storage of all available excess heat]) resulting in an			

	estimated theoretical potential of ~1TWh (for process > 100°C) when taking storage efficiency into account. A more reasonable number should be available from the ATES Vienna project by the end of 2024.			
HE*	15 000 000 (15 MW)	Styrian Basin; Molasse Basin	1 000 000 (1 MW)	Molasse Basin
EGS	no data available for Austria			

*) ad HE The following figures are summarizing the potential for HE in Austria after Könighofer et al., 2014 (dark red: realistic potential, light red: expanded potential assuming drillings > 6000 m)





8. What are the losses of energy for each method DBHE, BTES, ATES, HE, EGS from the wellhead till the heat exchanger of the end user? Please provide the information in watt (W) for each method.

Would not it be better to assign the energy loss in per cent?

Geothermal method	**Project name**	**Wellhead temp (°C)**	**Total Energy loss (in %; e.g. friction, heatpumps, transport)**	**Energy input (e.g. heat pumps)**	**Energy production (Watt)**	**Consumer (Watt)**
DBHE	Prottes T 11	83	25	25 000	65 000	40 000
	Hirschstetten 5					
	Muehlleiten	105			250 000	data published only with biomass powerplant
BTES						
ATES	ATES efficiency (from storage to injection into DHN) ~ 80-95 % assuming equal injection/production volume.					
HE	Fuerstenfeld/Frutura	124			15 000 000	
	Haag	83			1 000 000	
EGS	no data available for Austria					

All numbers are initial values which could decrease during operation and are based on realised projects in Austria.

9. What are the implementation and production risks for each method DBHE, BTES, ATES, HE, EGS? Please describe the risk for each method.

<table>
<tr><th>Geothermal method</th><th>Technical implementation</th><th>Production</th></tr>
<tr><td>DBHE</td><td>-</td><td>leakage cement (perforations), leakage tubing</td></tr>
<tr><td>BTES</td><td>-</td><td>leakage cement (perforations)</td></tr>
<tr><td>ATES</td><td>Drilling issues, at least 2 wells needed</td><td rowspan="4">Reservoir property changes (e.g. due to mineral growth), flow rate changes, pressure decrease, leaking cement (unused perforations), corrosion issues</td></tr>
<tr><td>HE drilling/sidetracking</td><td>Drilling issues, at least 2 wells needed</td></tr>
<tr><td>HE recompletion</td><td>close old (HC) perforations</td></tr>
<tr><td>EGS</td><td>Hydraulic fracturing</td></tr>
</table>

10. What are measures to mitigate the implementation and production risks for each method DBHE, BTES, ATES, HE, EGS? Please describe the risk for each method.

<table>
<tr><th>Geothermal method</th><th>Major failure sources</th><th>Method to avoid/prevent</th></tr>
<tr><td>DBHE</td><td>Well integrity</td><td>Pressure test, cement bond test</td></tr>
<tr><td>BTES</td><td>Well integrity</td><td>Pressure test, cement bond test</td></tr>
<tr><td rowspan="2">ATES</td><td>Drilling</td><td>Drilling safety</td></tr>
<tr><td>Reservoir presence with good porosity, permeability, temperature and water flow rate</td><td>Well logging, Core Analysis</td></tr>
<tr><td rowspan="5">HE</td><td>Drilling</td><td>Drilling safety</td></tr>
<tr><td>Well testing</td><td>Well testing safety</td></tr>
<tr><td>Reservoir presence with good porosity, permeability, temperature and water flow rate</td><td>Well logging, Core Analysis</td></tr>
<tr><td>Presence of reservoir with certain properties for injection</td><td>Well logging, Core Analysis</td></tr>
<tr><td>Seismic induced earthquake due to injection</td><td>Management of injection flow rates</td></tr>
<tr><td>EGS</td><td>Hydraulic fracturing</td><td>Adequate fracture pressure modelling</td></tr>
</table>

D. Social analysis

Data in this section concerns evaluating the social aspects of implementation and usage of repurposing technologies.

1. What is the general attitude of reusing old wells by reuse methods DBHE, BTES, ATES, HE, EGS on a well which is active / shut in / abandoned? Please describe each method, which would be more acceptable.

As the topic is nearly unknown to the public, a distinction between method or well status needless. See below an example of acceptance in a local newspaper, where this method is presented like an invention.

niederösterreichische DORF STADT erneuerung

BERICHT
Vom Gemeindeenergietag Weinviertel 10.06.2010

Im Mai und Juni fanden auf initiative von LR Dr Stephan Pernkopf in allen Vierteln von NÖ die Energiegemeindetage statt.
Ziel der Aktion ist die Bewusstseinsbildung, Information und Motivation der Bevölkerung klimarelevante Maßnahmen zu setzen . Sowohl im Haushalt als auch bei der Mobilität muss Energie gespart werden In den Gemeinden soll die Energiewende eingeleitet werden – weg von Erdöl und Gas - hin zu erneuerbarer Energie. Laut LR Pernkopf soll bis 2020 in NÖ 50% der Gesamtenergie von Erneuerbaren kommen wie Wind, Biogas, Biomasse, Wasserkraft und Solarenergie. Davor muss jedoch der Verbrauch deutlich gesenkt werden, sonst ist das Ziel nicht zu schaffen. Der Umstieg auf Erneuerbare löst auch einen gewaltigen wirtschaftlichen Impuls aus.

Geothermie Pilotprojekt Prottes

Vormittags hatten Interessierte die Möglichkeit an 3 Exkursionen teilzunehmen.
Eine führte nach Prottes zum Geothermieprojekt der OMV , anschließend stellte Martin Zimmermann in Weikendorf sein Miscanthusprojekt vor (Fernheizwerk mit Elefantengras).

15 Personen besichtigten die Geothermieanlage der OMV in Prottes . Dabei handelt es sich um ein 3 jähriges Forschungsprojekt der OMV zur Ermittlung von technischen Daten und Kosten bei der Gewinnung von Erdwärme aus aufgelassenen Sonden. Pro 100m Tiefe steigt die Temperatur um 3^0C an.
Angezapft wird *Prottes tief 11* – mit 60^0C in etwa 2000m Tiefe, Vorlauftemperatur 40^0C bei Einspeisung ins Heizsystem des Dorfzentrums Prottes . Förderung über Doppelrohr mit Gasisolierung.
Finanziert wird das Projekt vom Future Energy Fund mit ca 1,5Mio Euro .

Insgesamt gibt es etwa 1100 Bohrungen der OMV, von denen pro Jahr ca 15 liquidiert werden.
In Zukunft könnte es durchaus, bei steigenden Energiepreisen und Verknappung der Ressourcen, interessant sein Erdwärme aus tieferen Bohrungen zu nutzen, man braucht jedoch konstante Abnehmer.
Das Projekt stellten seitens der OMV vor: Projektverantwortlicher Ing.Gottfried Heintz , Mitarbeiter DI Gerstner Alex und Projektbetreuer Peter Naderer.

Einspeisung Erdwärme in Heizsystem

Blau - Erdwärmegewinnungssonde Prottes

2. What is the opinion of end users (customer groups industry, agriculture and municipality) regarding the use of old wells? Are there any concerns or restrictions? Please provide description and case studies of good practice if any.

3. What would be the benefits for society regarding the reuse of existing wells for implementation of reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method.

Valid for every method

- use of geothermal energy
- reduction of energy costs
- Save drilling costs
- projects faster
- regional geology already known
- Less emissions
- Supported by public
- Independent of weather
- Reduces the environmental impact of drilling a new well (in terms of required energy input, land use, ...)
- Co2 reduction

Deep Borehole Heat Exchangers (DBHE): Efficient Heating and Cooling: DBHE systems provide efficient heating and cooling for residential, commercial, and industrial buildings, reducing energy consumption and costs. Renewable Energy: DBHE systems can facilitate the adoption of renewable geothermal energy for space conditioning, reducing dependence on fossil fuels. based on TG SWOT
Borehole Thermal Energy Storage (BTES): Seasonal Energy Storage: BTES allows excess energy to be stored in the ground during off-peak times and retrieved when needed, improving energy efficiency. Grid Stabilization: BTES systems can support grid stability by providing stored energy during peak demand periods. based on TG SWOT
Aquifer Thermal Energy Storage (ATES): Large-Scale Heating and Cooling: ATES systems are well-suited for large commercial and industrial heating and cooling applications, reducing energy costs. Sustainable Building Practices: ATES can promote sustainable building practices by using renewable geothermal energy for space conditioning. based on TG SWOT
Hydrothermal Energy (HE): Geothermal Energy Production: HE methods generate renewable electricity from geothermal resources, contributing to a low-carbon energy mix. Reliable Baseload Power: Geothermal power plants provide reliable, baseload electricity, which is essential for grid stability. based on TG SWOT

Enhanced Geothermal Systems (EGS): Expanded Geothermal Resources: EGS has the potential to unlock geothermal resources in regions where traditional geothermal systems are not feasible. Scalable Energy Production: EGS can be scaled up to generate large amounts of geothermal power, contributing to sustainable energy production. based on TG SWOT

4. What would be the risks for society regarding the reuse of existing wells for implementation of reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method.

Borehole Heat Exchangers (DBHE): Well Integrity: Over time, DBHE systems can experience well integrity issues, leading to potential leaks and system inefficiencies Environmental Contamination: Inadequate sealing can result in groundwater contamination, affecting environmental and public health. based on TG SWOT
Borehole Thermal Energy Storage (BTES): Installation Costs: The upfront costs of drilling boreholes and installing infrastructure can be high, potentially affecting project feasibility. Ground Temperature Fluctuations: Seasonal variations in ground temperatures can affect BTES system efficiency. based on TG SWOT
Aquifer Thermal Energy Storage (ATES): Water Quality Concerns: The quality of groundwater in the storage aquifer can be a concern due to potential changes in water chemistry from heat exchange. Regulatory Compliance: Compliance with water management and environmental regulations can be complex for ATES projects. based on TG SWOT
Hydrothermal Energy (HE): Geological Risk: HE projects may encounter geological challenges, like low permeability or rock fractures, limiting energy extraction. Scale Limitations: Not all locations have suitable geothermal resources for large-scale electricity generation. based on TG SWOT

Enhanced Geothermal Systems (EGS): Seismic Risk: Induced seismicity is a concern in EGS, as it involves creating fractures in hot rocks, which can potentially trigger earthquakes. High Drilling Costs: Drilling deep wells in hard rock formations can be expensive and technically challenging. based on TG SWOT

5. What would encourage the potential investors within customer groups (industry, agriculture and municipality) to invest in one of the defined reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method if applicable.

6. Is there any doubt by the local community regarding implementation of reuse methods DBHE, BTES, ATES, HE, EGS because of leak of trust or bad experience in the past? Please describe each method.

For Questions D.1-D.6 ¤ There is very little experience in Austria with the reuse of abandoned wells. Only two installations are known. There is no data available about the perception or acceptance of the systems for any of these installations. Experience from the oil industry shows that in areas where a lot of drilling takes place, the population can react very sensitively to further work in the region. At the same time, knowledge about the use and processing of the deep underground is greater in these areas, which can facilitate communication for reuse for geothermal purposes. In general, the more impact a system can have, the sooner communication with the population needs to take place (see: seismic risk from HE).

For more information on risk, benefits etc. see the summary of the Transgeo SWOT analysis

Appendix 2 - Questionnaire Croatia

A. Author and country

Author	UNIZG-RGNF: Tomislav Kurevija, Marija Macenić, Daria Karasalihović Sedlar, Luka Perković, Ivan Medved, Ivan Smajla
Organisation	UNIZG-RGNF
Country	Croatia
Contact	marija.macenic@rgn.unizg.hr

1. General status: Are there any geothermal projects in your country currently going on? What is the acceptability of such projects by users and the local community? Please provide a short description.

There are several deep geothermal projects in Croatia. For now, these are concentrated on developing the so-called classic geothermal deep reservoirs with geothermal brine production. There are currently 10 geothermal exploitation and 23 exploration licences assigned. Currently, development of these projects in local communities is generally seen as positive. Local communities see advantages of geothermal thermal energy, especially in supplying heat for district heating, where projects are developing near urban areas or for supplying business zones of the cities. There is also support for using geothermal energy in agriculture (greenhouses) as well as in balneology. Cities, such as Bjelovar, Križevci, Karlovac and Sveta Nedjelja, are currently developing such projects and the acceptance of the public is good. The only geothermal power plant in Croatia is also well accepted, as are also newly awarded exploration licences for developing power projects in 5 locations. However, it has to be mentioned that after the earthquakes in Zagreb in March 2020 and Petrinja in December 2020, have brought attention to seismic activity in Croatia. There is some percentage of people who observe any drilling operation, either for hydrocarbon or geothermal exploitation as a potential for increasing the risk for induced seismicity, even though there is no evidence that such an event ever occurred in Croatia.

2. Do some geothermal projects include repurposed old wells? If yes, what is the user experience and acceptability of the local environment where it is implemented? Please provide a short description.

The exploitation field *Velika Ciglena* was developed with the use of exploration well VC-1 and VC-1A, originally drilled and equipped for hydrocarbon exploration and potential exploitation. After discovering the geothermal reservoir additional. Additionally, negative exploratory wells from the late 80's, VC-2 and Ptk-1, were further added to the geothermal field Velika Ciglena and are now used as additional production and injection wells in a setup 2+2. When it comes to exploitation fields for heating purposes, the geothermal field *Ivanić* and geothermal field *Bizovac* are examples where hydrocarbon exploratory wells, or even oil exploitation wells in the case of Ivanić (Iva-2 - previously used for oil exploitation, now added to geothermal field), are used for geothermal exploitation.

The Ivanić field still remains to have wider applicability, however the City is interested to use this potential for district heating, as well as add new potential once the oil field will be out of commission and to use remaining wells. This is also accepted by the public, especially from the environment perspective (there are currently oil production wells within the city premises). The Bizovac geothermal potential is also a positive example, and adds to the development of the town since the geothermal energy is used in balneology in the Bizovac hotel and spa complex.

3. Are there any reuse projects implemented or in the planning phase? Please indicate the name and a short description, if possible.

Lunjkovec-Kutnjak

In the exploration field *Lunjkovec-Kutnjak* there are two existing wells, Lunjkovec-1 (Lun-1) and Kutnjak-1 (Kt-1) drilled in the 1960s and 1970s for the purpose of discovering hydrocarbons. The testing of the wells showed geothermal potential with achieved flow of high temperature water. Measured temperatures at the bottom of the wells ranged between 128 and 144 °C. The exploration licence was given in the bidding round in 2020 to Bukotermal d.o.o., a company owned by the County of Varaždin (85%) and the Municipality of Mali Bukovec (15%). In 2022 and 2023 well testing on both wells were conducted with results of 142°C at 2430 m of reservoir depth. Expected total installed power is around 16 MW with drilling new wells, besides revitalization of existing two. The project is envisioned to develop in a few phases. In the first phase the ORC power plant of 2 MW will use geothermal brine from already existing wells, where Lun-1 and Kt-1 wells are meant to work as a production-injection pair. It is expected that thermal energy for heating in the future development of the project will be around 90 MW.

Babina Greda

On this site old exploratory well Bag-1 from mid 80's was reworked and tested, giving a indication of flow and favourable temperature in range of 120-130°C. Development on this well is planned in a way to perforate deeper horizons which are believed to be very porous and highly permeable, with a brine temperature in a range of 170°C. This well is planned to be part of future geothermal doublet at the site.

Ernestinovo

Out of three existing exploratory wells drilled within the field Ernestinovo in the 1980s, the Ernestinovo -3 well was reworked in order to test the geothermal reservoir. The results are expected in the first quarter of 2024. According to preliminary assessments, it was estimated that the flow and temperature can ensure 10 MWe of power plant capacity.

Merhatovec

Newly awarded exploration field will use some of the existing wells in their respective areas at the moment. The *Merhatovec* will reuse both wells at sites which are equipped with the Christmas tree/wellhead and testing will be carried out. Whether it will remain as a production or an injection well is still unknown and it depends upon flow testing.

Slatina-2

Exploration site Slatina-2 is currently in the testing phase of an old well from mid '80s, PS-5. It is a very deep well with a temperature in brine layers of more than 190°C. Plan is to use this revitalised well in a doublet with one new drilled well in near future for electricity production. Proposed power plant is planned to be ORC with 20 MWe.

4. Is there a promotion of potential reuse of wells in your country? Do investors/state/others show interest in well reuse? If so, please provide a short description.

The promotion of the reuse of wells is for now focused through promotion of the Croatian Hydrocarbon Agency (Associated partner) by awarding geothermal exploration licences in the areas where there are drilled, but not used, wells. The investors have interest in existing wells as the capital costs can be lowered, but also to lower the geological risk of the investment by using obtained data even if the well is not in good condition or is liquidated. It remains up to the investor to decide if the existing well is in good condition and valuable to complete it and reuse it for geothermal brine production.

However, the biggest potential for revitalised wells is present at currently operating exploitation fields of oil and gas with more than thousand of wells currently in operation. On a large number of oil and gas fields, geothermal potential is determined in a form of bottom-type aquifers with a high temperature environment and favourable geology. Most of these fields have reservoir pressure inadequate for eruptive production, so ESP must be imposed on most of the locations.

B. Demand patterns for different customer group

Data in this section concerns the knowledge about energy consumption, willingness on changing the current energy source, suitability of geothermal energy regarding the current energy supply chain, …

1. What is the general energy demand of industry, agriculture, and municipalities in your country? Please describe each customer group.

The energy demand/final consumption in the industry in Croatia was 43,74 PJ in 2021. Distribution by fuel was as follows: a) Coal and coke 7,3 PJ; b) Fuel wood and biomass 2,97 PJ; c) Liquid fuels 1,77 PJ; d) Gaseous fuels 8,97 PJ; e) Electricity 13,36 PJ; f) Steam and hot water 9,38 PJ. Distribution by the industrial sector was as follows: a) Iron and steel industry 2,42 PJ; b) Non-ferrous metals industry 0,93 PJ; c) Non-metallic minerals industry 2,43 PJ; d) Chemical industry 4,98 PJ; e) Construction materials industry 14,10 PJ; f) Pulp and paper industry 2,61 PJ; g) Food industry 6,55 PJ; h) Other manufacturing industries 9,72 PJ.

Total energy demand/final consumption in other sectors in Croatia was 153,53 PJ in 2021. Distribution by fuel was as follows: a) Coal 0,07 PJ; b) Fuel wood and biomass 47,01 PJ; c) Liquid fuels 18,86 PJ; d) Gaseous fuels 32,97 PJ; e) Electricity 44,76 PJ; f) Heat 8,94 PJ; g) Renewables 0,92 PJ. The "other sectors" contains general energy consumption for households, services, agriculture and construction and the distribution was as follows: a) Households 102,25 PJ; b) Services 35,23 PJ; c) Agriculture 10,82 PJ; d) Construction 5,23 PJ.

Currently, district heating systems are present in 13 cities and towns, with heat produced in cogeneration plants in Zagreb, Osijek and Sisak, and the remaining is produced in heating plants, block and boiler houses. The heat is distributed through around 444 km of district heating network (pipelines) to facilities and then to customers. In 2021 around 2,21 TWh of heat was delivered to customers. One system uses geothermal energy for district heating in the municipality of Topusko and is usually referred to as promotion of geothermal heating.

There are two cases of using geothermal for agriculture. The first one is in the vicinity of the city of Sveta Nedjelja, exploitation field Sveta Nedjelja is licensed to produce brine at the flow rate of 25 l/s with wellhead temperature at 65 °C. The geothermal energy is used for heating of the greenhouse where tomato is produced. The second geothermal field is located within the borders of the Bošnjaci municipality. As with the Sv. Nedjelja case, the customer uses the Bošnjaci-1 well for greenhouse heating for growing tomatoes. Bošnjaci-North geothermal field has proved reserves of 10 l/s and installed thermal capacity of 1,4 MW_t.

2. How many users have experience with using geothermal energy? Which is the preferable technology by end users? Please describe each customer group.

When it comes to industry customer groups, the interest is seen only if there is an option to locate the operations in the business zone where geothermal energy is used.

Except for one municipality, users in the district heating system do not have experience in using deep geothermal energy. Only such example is the location Topusko, where natural springs and geothermal brine naturally flowing from deep horizons are captured with shallow wells and directed onto a centralised heating system. However, there are some cities that are in the process of developing projects for heating and/or balneology.

In the customer group of agriculture there are two licence holders using deep geothermal brine for greenhouse heating purposes and are considered to be examples of good practice. There are companies interested in investing in new deep geothermal wells for greenhouses, however this is still in development.

3. Under which circumstances would current users be willing to change the energy source they are using right now? Would any of the defined customer groups be interested in a local accessible energy source?

Most users see the benefits in changing to geothermal in lower costs of heating, which is seen as a good motivator for change, as well as using local energy resources.

As seen from the projects already in development there is an interest in changing the current energy source to geothermal. This is most prominent for the supply of heat via district heating systems or heat pumps with shallow groundwater. There is also interest in agriculture for greenhouse heating purposes.

4. Would the end user consider geothermal energy usage nevertheless it can cover the base load and they need a backup for peak loads? Is this a major obstacle for the end user's or do they see potential in it?

Several such projects are already in the project design phase, where the existing heating system is kept for peak load, while geothermal is considered to cover base load. In such arrangements, geothermal would deliver almost 90% of annual heating needs, although installed power is around 50% compared to natural gas. Current example is the oil field Ivanić-Grad, where studies were made to use direct geothermal heat from brine at temperature of 60-80°C, while leaving existing natural gas boilers as peak load installation. From current experience, users see this as potential to cut energy bills.

5. Are there any potential customer groups who would be satisfied only with base load energy supply? If yes, please provide the information regarding user, energy load needed and preferable technology, if applicable.

Currently, several new geothermal projects are being planned to replace existing fossil fuel district heating in the cities of Velika Gorica, Zaprešić, Sisak, Osijek and Vukovar. Croatian hydrocarbon agency is lead for this project and will invest in drilling of new wells in potential reservoir areas. In case that testing results would be below expectation it is planned to still combine energy from geothermal brine with existing thermal power plants. In this way this would be hybrid district heating where during coldest days of year there would be combined production of energy from geothermal reservoirs and from natural gas/heating oil. This project would still be welcomed by citizens of this area, as reduction in energy cost would still be expected.

C. Economic analysis

Data in this section concerns evaluating the economical side of implementation and usage of repurposing technologies in the energy supply chain.

1. What is the optimal transfer distance of energy for recognized reuse methods DBHE, BTES, ATES, HE, EGS? Depending on flow rate and temperature? Please describe each method.

DBHE, BTES, ATES - If the system is set as a low temperature system with a heat pump (outlet temperature between 15-20°C then the DH system can be very indented with higher distances among each consumer. If there is direct usage of heat energy from well (>35°C) then distances should be nearby well itself (like greenhouses, industrial facility) HE - Since geothermal reservoirs can produce brine at high temperature and flow power plants for production of electricity are constructed at the production wellhead premises. If there is no classic doublet (two inclined wells drilled from the same area on the surface) then the injection well can be at some distance from the production well (usually min. 2-3 km, depending on thickness of reservoir and flow arrangement to provide sufficiently long isothermal production). EGS - Power plant is always constructed at the wellhead premises with two or more inclined wells drilled from the same area on the surface.

2. What is the cost for implementation of reuse methods DBHE, BTES, ATES, HE, EGS on a well which is active / shut in / abandoned? Please describe each method and each type of well status.

Not able to provide the requested data set.

3. What is the cost of surface infrastructure, depending on expected energy supply by each method DBHE, BTES, ATES, HE, EGS? Please describe each method.

Not able to provide the requested data set.

4. What would be the cost of production equipment for methods DBHE, BTES, ATES, HE, EGS? Well downhole equipment, wellhead, annual maintenance cost,... Please describe each method.

Not able to provide the requested data set.

5. What would be the approximate maintenance cost for each method DBHE, BTES, ATES, HE, EGS on a 5-year production base? Well, surface equipment, piping, valves, ...

Not able to provide the requested data set.

6. What would be the footprint of the whole installation considering well location, surface facility, piping, etc? Please provide the information for each method DBHE, BTES, ATES, HE, EGS

Not able to provide the requested data set.

7. How much energy could be produced by each method DBHE, BTES, ATES, HE, EGS in best case scenario and in worst case scenario? Please define the energy in watt (W) for each method.

From current analysis during geothermal potential research there would be following expected thermal/electricity power potential:

1. DBHE - Extensive research was conducted in numerical modelling of Marija Macenić in PhD thesis where deepest wells of 5 km or more could provide around 500 kW - 1000 kW of installed thermal power. However, this technology needs to be connected with a heat pump on the surface to be usable.
2. BTES - This technology is still considered in Croatia, at least not connected with geothermal reservoirs. However, with more geothermal installation available we expect some applications in shallow to mid-depth wells.
3. ATES - This technology is still considered in Croatia, at least not connected with geothermal reservoirs. However, with more geothermal installation available we expect some applications in shallow to mid-depth reservoirs.
4. HE - This is the most prominent method currently, whilst the range of electricity/cogeneration production is ranging between 2-30 MWe per reservoir, while thermal energy ranging from 100 kW - 100 MWt per reservoir.
5. EGS - This is currently not even under consideration in Croatia, due to the high potential of geothermal/hydrothermal reservoirs with production of brine fluid. Still, it is rarely spoken in government energy strategies as a long-term geothermal development method. Also, problems with the ban of fracking gives problems with developing this method. Some research papers by scientists in Croatia give estimation of a few hundred kWe that could be obtained through these superfracture systems in highly conductive base rock formations, or few MW of thermal power at best.

8. What are the losses of energy for each method DBHE, BTES, ATES, HE, EGS from the wellhead till the heat exchanger of the end user? Please provide the information in watt (W) for each method.

This is multiparameter research analysis and complicated to deduce. It depends upon distance of DH system, insulation of pipeline and burial depth. However, there is a general rule that losses of energy are drastically reduced by lowering the distribution temperature of a system. If a system uses a centralised heat pump system, heat losses would be very low compared to delivered energy, no matter of geothermal source type.

9. What are the implementation and production risks for each method DBHE, BTES, ATES, HE, EGS? Please describe the risk for each method.

DBHE - This is the method with lowest implementation and production risk. Since it operates through fundamental thermodynamic laws of heat diffusion equation, it is commonly very predictive by a model. Old wells usually have good temperature measurement data and lithology determination which are crucial input data for DBHE system models. Since completion of DBHE system is identical to completion of oil wells there are no significant risks related to operation failure.

BTES - Very similar to DBHE method, except modelling of such systems is a bit complicated giving variable injection of heat from the surface with different temperatures. However if the heat pump district heating system or a local heating system is connected to BTES then risk would be significantly lower, because the heat pump could effectively work with a low temperature range of 10-20°C. If direct heating is used from BTES, then there is a risk related to model prognosis.

ATES - High risk related to this method refers to exploration of an aquifer and determination of its hydraulic parameters and boundaries. There would need to be a high level of certainty that an aquifer is of confined type. If there is a case of leaky aquifer, or even unconfined type, and if exploration methods were not adequate to determine this with high degree of confidence, it could result in complete failure of this system.

HE - This method is most complicated to develop and with highest risks involved, as it comprises the entire technical-technology of an oil industry related to geophysical and geological exploration, drilling and confirmation of resource, well testing and reservoir engineering of multiple well system multi-decade operation with isothermal flow. There are so many risks involved with this method that it would take an entire project of its own to describe each of them. All kinds of risks are imposed here, ranging from geological and petrophysical risks, drilling prolongation risks, faults boundaries, flow capacity, early cold breakthrough risks etc.

EGS - Risks involved with this method are mostly related to fracturing prediction model and real fracture extent in reservoir. It is very hard to model such systems and to exactly determine heat transfer before actual well testing. Also, currently there is a ban in the EU for mass fracturing which this method comprises. This technology always arouses climate activists nutheads whose actions can completely shut down exploration licences due to unjustified claims of daunting induced seismicity and fearmongering towards local communities.

10. What are measures to mitigate the implementation and production risks for each method DBHE, BTES, ATES, HE, EGS? Please describe the risk for each method.

Geothermal method	**Major failure sources**	**Method to avoid/prevent**
DBHE	Well integrity	Pressure test, cement bond test
BTES	Well integrity	Pressure test, cement bond test
ATES	Drilling	Drilling safety

	Reservoir presence with good porosity, permeability, temperature and water flow rate	Well logging, Core Analysis
HE	Drilling	Drilling safety
	Well testing	Well testing safety
	Reservoir presence with good porosity, permeability, temperature and water flow rate	Well logging, Core Analysis
	Presence of reservoir with certain properties for injection	Well logging, Core Analysis
	Seismic induced earthquake due to injection	Management of injection flow rates
EGS	Hydraulic fracturing	Adequate fracture pressure modelling

D. Social analysis

Data in this section concerns evaluating the social aspects of implementation and usage of repurposing technologies.

1. What is the general attitude of reusing old wells by reuse methods DBHE, BTES, ATES, HE, EGS on a well which is active / shut in / abandoned? Please describe each method, which would be more acceptable.

For now, there is not a lot of interest to invest in either of the reuse methods since projects with classic geothermal reservoirs and geothermal brine production are just starting to develop with more intensity. Such projects are expected to develop up to 2030 and beyond. However, hydrothermal energy (HE) is expected to develop at the existing hydrocarbon fields with proven bottom type aquifers and existing wells. It is estimated that the reuse methods DBHE, BTES, ATES and EGS will come more into the spotlight in 10 or 20 years, as existing classic geothermal reservoirs are in production and licences awarded. Even though the idea of reusing existing wells is interesting to investors they have yet to see the benefits of revitalising wells especially from the economic standpoint. The biggest issue to be expected in the general public is with the EGS method due to fears of induced seismicity and fracking.

2. What is the opinion of end users (customer groups industry, agriculture and municipality) regarding the use of old wells? Are there any concerns or restrictions? Please provide description and case studies of good practice if any.

End users are very interested in using old wells, especially for heating purposes. For now, mostly municipalities are exploring options of producing geothermal brine for district central heating (DCH) purposes. The biggest concern is connected to facilitating the finances, since developing geothermal projects is capital intensive, as well as fulfilling exploratory licence obligations within the given time framework and obtaining exploration licence. Agriculture manufacturers have also expressed interest in using geothermal energy for greenhouse heating. The biggest issue for them is the location of their agricultural area and whether there is an existing well and geothermal reservoir that could be used.

3. What would be the benefits for the society regarding the reuse of existing wells for implementation of reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method.

As the production of fossil fuels is expected to decline, there is fear that oil and gas workers would be left without jobs. However, these skilled workers could easily transfer their knowledge and skill sets to jobs connected to exploring and developing geothermal projects. This is valid for all reuse methods. New well drillings would be reduced and the cost of energy could be reduced due to lower capital cost when compared to drilling a completely new geothermal well.

4. What would be the risks for society regarding the reuse of existing wells for implementation of reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method.

There are no expected risks for society in regard to using either of the reuse methods. People like money from the concessions, with the exception of the six environmentalists in Croatia.

5. What would encourage the potential investors within customer groups (industry, agriculture and municipality) to invest in one of the defined reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method if applicable.

Sole motivation and encouragement to invest in any system is to have lower heating costs than the current operating system (i.e. natural gas/fuel oil/LPG). Ecological benefit encouragement is not enough as a standalone motivation, unless dictated by legal framework.

6. Is there any doubt by the local community regarding implementation of reuse methods DBHE, BTES, ATES, HE, EGS because of leak of trust or bad experience in the past? Please describe each method.

Since none of these methods is yet implemented in Croatia, there were also no bad experiences in the past or leak of trust. However, due to experiences with the induced seismicity connected with the EGS project worldwide (for example in Basel, Switzerland) there is already fear of it happening in Croatia, especially with the experiences of earthquakes in 2020. Also, hydraulic fracturing, which is necessary to develop EGS projects, also has negative perception due to experiences from the oil and gas industry. This is mostly due to experiences of water and environmental pollution in the USA.

Appendix 3 – Questionnaire Germany

A. Author and country

Author	Katrin Sieron, Sebastian Weinert (LBGR)
Organisation	LBGR
Country	Germany
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1. General status: Are there any geothermal projects in your country currently going on? What is the acceptability of such projects by users and the local community? Please provide a short description.

Not at the moment (state Brandenburg and in the case of **Reuse**), but there are “future projects” as for example Velten, Pritzwalk (temporarily abandoned Geothermal wellbores).

The enlisted projects do not necessarily comprise “reused wells”, but all geothermal projects in each state that are either under construction or in the planning phase. **The already working/producing projects of each State are enlisted under C-7 with P_{therm} and P_{el}.**

Other states:

According to the webpage www.geothermie.de, there are several locations indicated with currently working geothermal energy extraction sites, but also projects under construction and future projects in the planning phase. Nevertheless, the information has to be taken with caution, as some of the latter may have been already cancelled or be planned with no precise date in near future. Also, other projects might exist that are not enlisted.

Brandenburg State:

*Potsdam: under construction (1 already working, 8 more planned until 2030; 160 Mio Euro; source: https://www.maz-online.de/lokales/potsdam/geothermie-potsdams-erste-erdwaerme-bohrung-ist-ein-erfolg-waerme-fuer-6900-haushalte-aus-der-tiefe-PP5FMVUDLBDNFOLY2YJFMHN76M.html

*Prenzlau: planning phase; Hydrogeothermie (HE?)

*Neuruppin: planning phase; Hydrogeothermie (HE?)

*Brand: planning phase; Hydrogeothermie (HE?)

Berlin:

Berlin Adlershof: under construction; Aquiferspeicher (ATES)

Berlin I+II+III: planning phase; Hydrogeothermie (HE)

Mecklenburg Vorpommern State:

*Schwerin: under construction; Hydrogeothermie (HE)

*Göhren-Lebbin: planning phase; Hydrogeothermie (HE)

*Karlshagen-Usedom: planning phase; Hydrogeothermie (HE)

*Kaiserbäder-Usedom: planning phase; Hydrogeothermie (HE)

Hamburg:

Hamburg-Tiefstack: Aquiferspeicher (**ATES**); under construction

Hamburg-Wilhelmsburg: Hydrogeothermie (**HE**); under construction

Niedersachsen State:

* Horstberg neu: Hydrogeothermie (HE), planning phase

*Bentheimer Wald: Hydrogeothermie (HE), planning phase

*"Poggenpohl": Hydrogeothermie (HE), planning phase

*Soltau: Hydrogeothermie (HE), planning phase

*Munster-Bispingen: Hydrogeothermie (HE), planning phase

*Burgwedel: Hydrogeothermie (HE), planning phase

*Kleefeld I: Hydrogeothermie (HE), planning phase

*Bad Bevensen "Ilmenau I": Hydrogeothermie (HE), planning phase

*Uelzen I: Hydrogeothermie (HE), planning phase

*"Altwarmbüchener Moor": Hydrogeothermie (HE), planning phase

*Hannober-Buchholz: Hydrogeothermie (HE), planning phase

*Göttingen: research

Nordrhein-Westfalen State:

*Aachen-Weisweiler: under construction; T_{max}: 150°C; Depth: 5000m

*Aachen"GEOobservatorium": Hydrogeothermie (HE), planning phase

*Düsseldorf: Hydrogeothermie (HE), planning phase

*Krefeld: Hydrogeothermie (HE), planning phase

*Duisburg: Hydrogeothermie (HE), planning phase

*Bochum (Fraunhofer IEG): Hydrogeothermie (HE), planning phase

*Bochum (Stadtwerke): Hydrogeothermie (HE), planning phase

*Hagen: Hydrogeothermie (HE), planning phase

*Münster: Hydrogeothermie (HE), planning phase

Hessen State:

*Frankfurt am Main: under construction: research

*Darmstadt: under construction; Erdwärmesondenspeicher/Forschung (DBHE?)

*Lampertheim I+II: Hydrogeothermie (HE), planning phase

*Ried: Hydrogeothermie (HE), planning phase

Rheinland-Pfalz State:

*Ingelheim: Hydrogeothermie (HE), planning phase

*Mainz: Hydrogeothermie (HE), planning phase

*Eich-Hamm: Hydrogeothermie (HE), planning phase

*Lutrina: Hydrogeothermie (HE), planning phase

*Worms-Silbersee: Hydrogeothermie (HE), planning phase

*Ludwigshafen I “Ludwig”: Hydrogeothermie (HE), planning phase

* Ludwigshafen II “Therese”: Hydrogeothermie (HE), planning phase

*Bad Dürkheim “Flaggensturm”: Hydrogeothermie (HE), planning phase

*Schifferstadt “Rhein-Pfalz”: Hydrogeothermie (HE), planning phase

*”Kerner”: Hydrogeothermie (HE), planning phase

*Lingenfeld: Hydrogeothermie (HE), planning phase

*”Grumbeere”: Hydrogeothermie (HE), planning phase

*”Storchenaue”: Hydrogeothermie (HE), planning phase

*”Löwenherz”: Hydrogeothermie (HE), planning phase

*”Kaltenbach”: Hydrogeothermie (HE), planning phase

*Haßloch “Taro”: Hydrogeothermie (HE), planning phase

*“Rift”: Hydrogeothermie (HE), planning phase

Baden-Württemberg state:

*Graben-Neudorf: under construction; Hydrogeothermie (HE)

*Hardt: Hydrogeothermie (HE), planning phase

*Mannheim: Hydrogeothermie (HE), planning phase

*Weinheim-Süd: Hydrogeothermie (HE), planning phase

*Waghäusel: Hydrogeothermie (HE), planning phase

*Dettenheim „Erlich“: Hydrogeothermie (HE), planning phase

*Grenzach-Whylen “Grenzacher Horn”: Hydrogeothermie (HE), planning phase

*Eggenstein-Leopoldshafen “KIT Campus Nord”: Hydrogeothermie (HE), planning phase

*Karlsruhe-Neureut: Hydrogeothermie (HE), planning phase

*Römerbad: Hydrogeothermie (HE), planning phase

* Ortenau: Hydrogeothermie (HE), planning phase

*Freiburg: Hydrogeothermie (HE), planning phase

*Bad Waldsee I+II: Hydrogeothermie (HE), planning phase

Bayern State:

*Altötting: Hydrogeothermie (HE); under construction

*Tüßling: Hydrogeothermie (HE); under construction

*Kirchweidach II: Hydrogeothermie (HE); under construction

*Geretsried: Forschung (research); under construction

*Rupertiwinkel "Ruperti II": Hydrogeothermie (HE), planning phase

* Gauting I + II: Hydrogeothermie (HE), planning phase

* Gräfelfing/Planegg: Hydrogeothermie (HE), planning phase

*München-Allach »Karlsfeld Ost«: Hydrogeothermie (HE), planning phase

*München-Feldmoching: Hydrogeothermie (HE), planning phase

*»BMW Milbertshofen«: Hydrogeothermie (HE), planning phase

*München-Freimann: Hydrogeothermie (HE), planning phase

*Neuperlach »Michaelibad«: Hydrogeothermie (HE), planning phase

*Pullach Süd: Hydrogeothermie (HE), planning phase

*Vaterstetten: Hydrogeothermie (HE), planning phase

*Palling: Hydrogeothermie (HE), planning phase

*Traunreut / Waging am See: Hydrogeothermie (HE), planning phase

*Traunstein: Hydrogeothermie (HE), planning phase

*Taching am See »GT Törring«: Hydrogeothermie (HE), planning phase

Info from publications:

Planned HDR

"The Leibniz Institute for Applied Geophysics (LIAG) is currently investigating the petrothermal potential of a 10 km × 12 km area in the Erzgebirge (Saxony) [7]. The idea is to develop the first petrothermal project in Germany."(Agemar et al., 2014)

"Operating deep DBHEs in Germany exist in Arnsberg (North Rhine-Westphalia) with a total depth of 2835 m heating a spa, Prenzlau (Brandenburg, 2786 m, used for district heating) and Heubach (Hesse) providing heat for industry (773 m)."

"The most important geothermal projects in north-eastern Germany include the heating plants in Waren and Neustadt-Glewe as well as the heat storage facility in Neubrandenburg which exploit the sandstones of the Rhaetian/Liassic aquifer complex."

"Presently, there are 180 geothermal direct-use installations in operation. The installations comprise district heating, space heating in some cases combined with greenhouses and thermal spas. Most of the district heating plants are located in the Bavarian part of the Molasse Basin. From 2003 to 2013, the annual power production increased from 0 GWh to 36 GWh. At the end of 2013, geothermal power generation in Germany reached an installed capacity of 27.1 MW_e. However, most geothermal energy is used for heating. From 2003 to 2013, the annual production of geothermal district heating stations increased from 60 GWh to 530 GWh. In 2013, the total installed capacity for geothermal heat production reached 250 MW. Buildings are responsible for about 40% of final energy consumption in Germany. There is still an enormous potential for geothermal direct use installations. Deep geothermal energy accounts for 0.62‰

of total heat supply and 6.92‰ of heat supply from renewable energy sources. Geothermal power production is growing rapidly but on a very small level. It merely accounts for 0.06‰ of total power production and 0.23‰ of green power production in Germany.

2. Do some geothermal projects include **repurposed old wells**? If yes, what is the user experience and acceptability of the local environment where it is implemented? Please provide a short description.

No, we don´t have any at the moment (State Brandenburg), but as mentioned in 1), there are future projects that include old wells that are still not plugged.

3. Are there any **reuse projects** implemented or in the planning phase? Please indicate the name and a short description, if possible.

One in the planning phase (Brandenburg State; in other States, there maybe more): Crude oil and natural gas drilling project (industry), with indication of a second use for Geothermal energy if not successful and/or after exploiting oil/gas; Geothermal use practically might happen after 10-20 years. There are approximately twenty more that are in the first steps of getting the necessary permits (confidential information).

4. Is there a promotion of potential reuse of wells in your country? Do investors/state/others show interest in well reuse? If so, please provide a short description.

National, regional, local energy plans - yes (at least planning phase) e.g. https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2022/11/20221111-geothermie-fuer-die-waermewende.html; companies show interest in reuse - yes (we know of 2 Municipal utilities in the state Brandenburg)

B. Demand patterns for different customer group

Data in this section concerns the knowledge about energy consumption, willingness on changing the current energy source, suitability of geothermal energy regarding the current energy supply chain, …

1. What is the general energy demand of industry, agriculture, and municipalities in your country? Please describe each customer group.

* In **2020**, **industry in Germany consumed 3,747 petajoules of energy**. That was 1.9% less than in 2019. As the Federal Statistical Office (Destatis) also reports, the majority of this, 88%, was used for energy purposes, for example for generating electricity and heat.

The remaining 12% of energy sources were not used for energy purposes and were used, for example, to produce chemical products, fertilizers or plastics. As in previous years, the most important energy sources in industry were natural gas (31%), electricity (21%), mineral oils and petroleum products (16%) and coal (16%).

The largest energy consumer in 2020 was the chemical industry with a share of 29%, followed by metal production and processing with 22% and coking and mineral oil processing with 10%. However, in the chemical industry, more than a third of the energy sources (35%) were used as raw materials for chemical products and therefore not for energy purposes. Based solely on energy use, metal production and processing had the highest share at 24%, followed by the chemical industry with 22% and coking and mineral oil processing with 10%. (source: https://www.destatis.de/DE/Presse/Pressemitteilungen/2021/12/PD21_551_435.html)

*private households: 3 703 Petajoules (2021)

* Production of agricultural, forestry and fishing products 233 Petajoules (2021)

Source: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/energiefluesse-emissionen/Tabellen/primaerenergieverbrauch.html

Final energy consumption by sector (2021) 2407 Terawatt-hours

***Industry – 699 TWh total or 29,0 %**

- petroleum products – 25 TWh

- gases – 250 TWh

- electricity (incl renewable energies) – 213 TWh

- district heating – 48 TWh

- renewable heating – 34 TWh

- other energy sources – 15 TWh

- brown and black coal – 115 TWh

*** private households – 670 TWh or 27,8%**

- petroleum products – 92 TWh

- gases – 282 TWh

- electricity (incl renewable energies) – 127 TWh

- district heating – 58 TWh

- renewable heating – 107 TWh

- brown and black coal – 4 TWh

*** transport – 653 TWh or 27.1%**

- petroleum products – 605 TWh

- gases – 2 TWh

- electricity (incl renewable energies) – 12 TWh

- biofuels – 34 TWh *** commerce, trade and services - 385 TWh or 16,0%** - petroleum products – 79 TWh - gases – 115 TWh - electricity (incl renewable energies) – 144 TWh - district heating – 10 TWh - renewable heating – 37 TWh Source: https://www.umweltbundesamt.de/daten/energie/energieverbrauch-nach-energietraegern-sektoren#entwicklung-des-endenergieverbrauchs-nach-sektoren-und-energietragern Energy consumption agriculture (2000) – 197.246 Terajoule Source: https://de.statista.com/statistik/daten/studie/487804/umfrage/energieverbrauch-in-der-landwirtschaft-in-deutschland/

2. How many users have experience with using geothermal energy? Which is the preferable technology by end users? Please describe each customer group.

Only 8 geothermal energy stations (36 MW power in total; 17 MW continuously working) used for heating and electricity production (the latter is still negligible – only about 0.1 TWh) Source: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/bmwi_de/marktanalysen-photovoltaik-geothermie.pdf?__blob=publicationFile&v=7 * 2022 – about 245 GWh electricity produced by geothermal energy stations (little importance in Germany, but increasing tendency/trend * heat – about 9% (near-surface geothermal energy) Source: https://de.statista.com/statistik/daten/studie/233222/umfrage/stromerzeugung-aus-geothermie-in-deutschland/ Heat pump systems: ca 440,000 42 deep geothermal stations (360 MW together)

Source: https://www.deutschlandfunk.de/geothermie-in-deutschland-roadmap-zeigt-entwicklungspotenzial-100.html

Hydrothermal Geothermal energy preferred in Germany (ATES)

Sources: https://www.tagesschau.de/wissen/klima/geothermie-107.html

https://www.geothermie.de/fileadmin/user_upload/Aktuelles/BVG_Poster_Tiefe_Geothermie_2023_24_web.pdf

Geothermal energy companies as well as municipal and private energy suppliers that have been supplying district heating from deep geothermal energy to their customers for up to 20 years (potential interested stakeholders?): AFK Geothermie; bayernwerk; BEE (Bundesverband Erneuerbare Energie e.V.); EWG (Energie Wende Garching); Erdwärme Grünwald; Geothermie Unterhaching; GeoVOL (Regenerative Energie Unterföhring); IEP (Innovative Energie Pullach); SWM (Stadtwerke München); WVI (Wärmeversorgung Ismaning); AGFW; Josef Weiß Elektrotechnik GmbH; BauIndustrieBayern; Fraunhofer IEG; Pfaffinger Unternehmensgruppe; Arvensteyn; Vulcan Energy Zero Carbon Lithium; VKU (Verband Kommunaler Unternehmen e.V.); GEF IngenieurAG; Fahrenheit Cooling Innovation; Erdwerk; IGA (International Geothermal Association); Enerchange (agentur für erneuerbare Energien); Drees&Sommer; Kraftanalagen Energies&Services; Stadtwerke Schwerin; NW Assekuranz (Global Insurance Broking); Bosch; Badenova Wärmeplus; Atlas Copco; Isoplus Fernwärmetechnik; Ing Kess gmbh; Georg-August-Universität Göttingen; ,MVV; BakerHughes; GeothermieUnterschleißheim AG; GMK; Klinger Fluid Control

Source: https://waermewende-durch-geothermie.de/

3. Under which circumstances would current users be willing to change the energy source they are using right now? Would any of the defined customer groups be interested in a local accessible energy source?

As there are only a few projects, we do not have much information about this. In the following, we present relevant information extracted from publications respect to Germany (and Europe).

ENGINE project = Enhanced Geothermal Innovative Network for Europe (European project in FP6 (2005-2008); practice handbook with a special focus on EGS technolgy was published.

http://engine.brgm.fr/Deliverables/Period2/ENGINE_D36_WP5_NonTechnicalBarriers_IE_29102007.pdf

societal acceptance nore than 10 years ago:

(1) “People who are not familiar with the opportunities and benefits from the use of geothermal energy and who have only little knowledge about technology tend to have prejudices [...]”

(2) "Often these people have had, or have heard about, negative experiences of not-comparable projects and transfer this experience to new geothermal power and/or CHP plants. […]"

(3) "Renewables are often related to subsidies which finally have to be paid by the public not knowing that this is also considerably true for fossil fuel energy (in the past and still in the present) […]"

(4) "[we need to consider the] perception of public and politicians and of local authorities and plant affected people […]"

(5) "[…] so far the role of deep geothermal energy is perceived as playing a small role compared to solar and wind."

(6) "[…] lack of awareness of the benefits […]"

(7) "[A project] affects mobility, health, environment, labour market, attractiveness/image of a community."

(8) "[…] weighing pros and cons is dependent on present situation and given alternatives […]"

(9) "Adequate communication is crucial – not too early and not too late."

(10) "[…] bottom-up projects with local participation seem to be (more) successful."

(11) "The public trustworthiness of the plant owner and operator can play a central role in the acceptance of a geothermal plant and the acceptance of the energy delivered to the community from this owner / operator."

(12) "The acceptance of geothermal energy in the public and by politicians and administrative facilities needs to be improved […]

Leucht et al 2010 – The role of societal acceptance in renewable energy innovations´ breakthrough in the case of deep geothermal technology.

Societal acceptance in its three key dimensions: (1) socio-political acceptance; (2) community acceptance and (3) market acceptance (Wüstenhagen 2007)

"Considering the experiences of the latest conferences in Germany on geothermal energy, we can confirm **lacks of political and market acceptance deriving mainly from the risk awareness of politicians and investors regarding the reservoir finding and economical exploitation**. The factor of uncertainty is still a variable in the main fields of action in deep geothermal technology that can be indentified e.g. in accounting procedures, exploration tools like seismic metering and computed simulation models, concerning long-term plant operation as well as in understanding the different types of deep geothermal technologies (EGS, Hot-dry-rock, Hydrothermal etc.). So far civil society was hardly presented in the conference topics but certain problems were already raised such as the effects of seismicity on residential areas and general communication problems…"

"In Soultz the EGS project affected the natural and social environment in three areas: (1) seismicity, (2) noise at the project site during drilling and during power production and (3) bacteria in the reinjected cooling water in a nearby lagoon"

"First results considering a **societal acceptance approach** (The target regions for this news analysis were Germany, Baden, Brühl, Stuttgart, Southwest-Germany and Basel)

Regarding **the hardware dimension**:

(1) Some technical aspects of deep geothermal plants (like drilling and production) still have problematic impacts on the ecological and the social environment (noise, seismicity, etc.).

(2) Yet a risk management and the development of "emergency" action plans are still not enough considered in the management of deep geothermal projects.

Regarding the **software dimension**:

(3) Different actors have to be considered in different decision-making processes along the phases of planning, implementation and operation of a deep geothermal project.

(3) Communication plays a crucial role in societal acceptance processes. The media analysis showed a difference in controlled vs. not controlled communication around a project: As Basel applies a highly controlled information politics to the public the interpretations of the incident in the news were rather limited. Whereas in Staufen the unexpected event showed a high potential for dramatization and link people's evoked emotions with geothermal technology.

(4) Regarding the issue of acceptance chains the news analysis shows that people think all the geothermal projects are somehow connected. In general people do not seem to consider the differences between different types of technologies as well as they have difficulties to evaluate the related effects and risks. Events like (induced) seismicity stimulate "waves" of reactions, especially to people being sensitive of this topic because they have in some way related experiences. (notes for **Improving societal acceptance** are also mentioned in the paper)

Knoblauch et al 2019 – Siting deep geothermal energy: acceptance of various risk and benefit scenarios in a Swiss-German cross-national study

Highlights: study of public acceptance of various deep geothermal energy scenarios; Induced seismicity risk is most important for acceptance of deep geothermal energy; Heat benefits are appreciated but they do not fully compensate for induced seismicity risk; The Swiss public is more accepting deep geothermal energy scenarios than the German public; Policies to site deep geothermal energy projects in remote areas seem to be most promising.

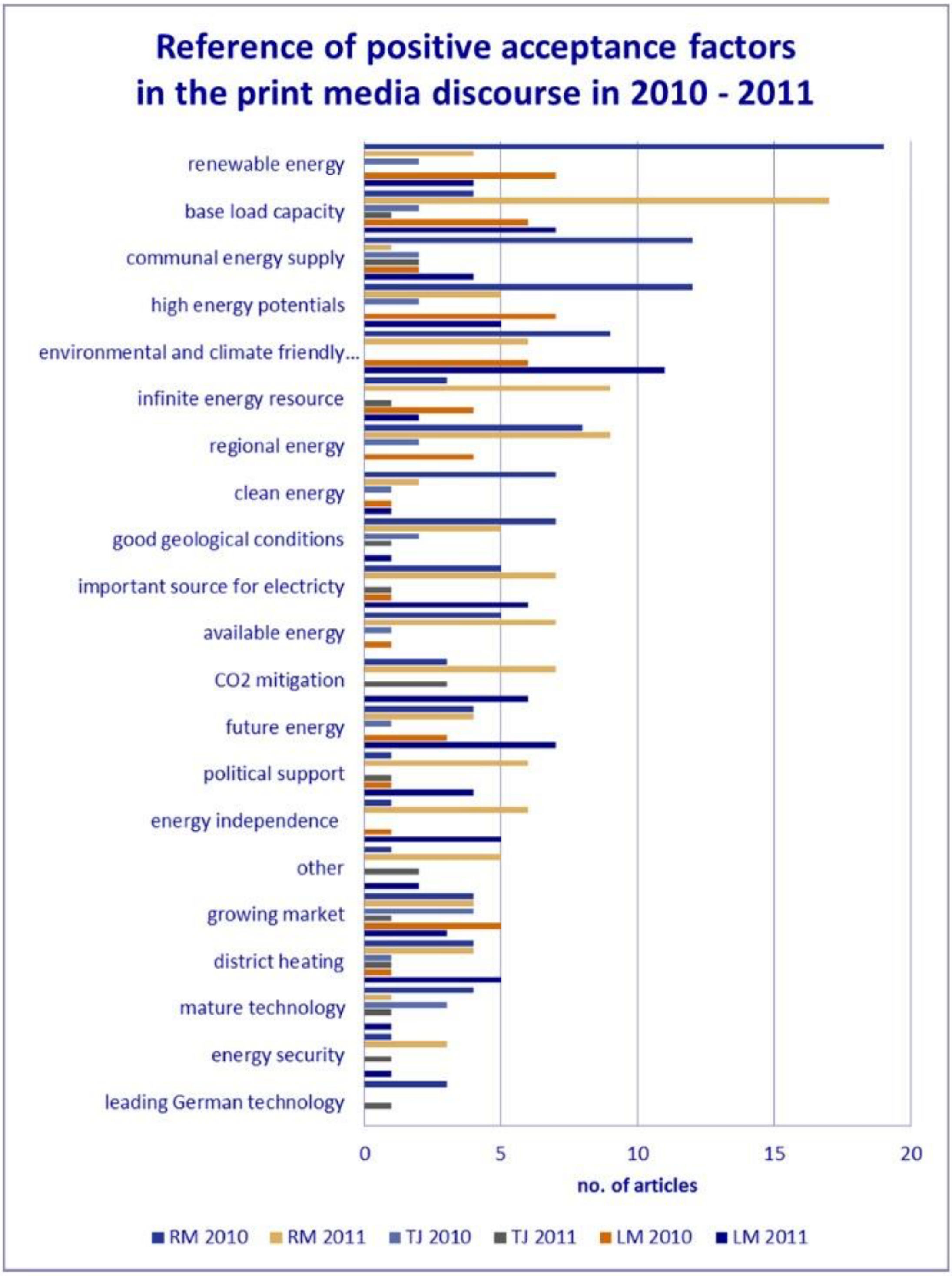
- Samples in SW-Germany (representative but educational level slightly below national level; swiss sample representative, but educational level slightly above national level) ¤could be important, as the last study mentioned here from Greece (Sardianou and Genoudi 2013), showed that acceptance increases with increasing educational level
- **Both regions had experienced induced seismicity (Switzerland: Basel, St. Gallen; Germany: Landau)**

Results: "Swiss respondents accepting all deep geothermal energy scenarios significantly more than their counterparts from RP, $F(1, 812) = 23.76$, $p < 0.001$, partial $\eta^2 = 0.03$. The difference in acceptance between countries is most pronounced when deep geothermal energy projects are sited in urban areas and thus carry high levels of induced seismic risk."

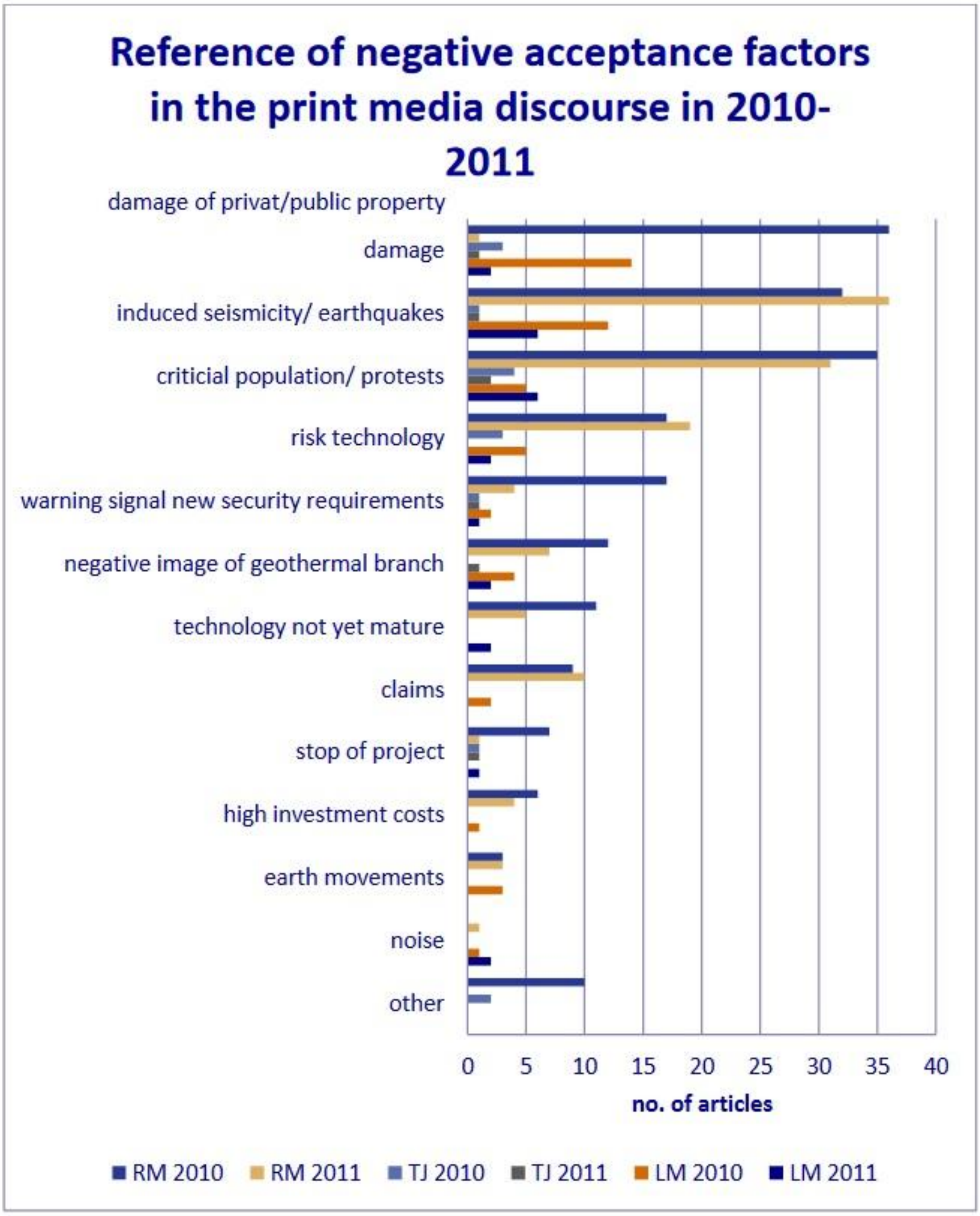
"The results of the study support our first hypothesis: **the public accepts siting deep geothermal energy projects in remote areas (low induced seismicity risk) more fully than siting them in urban areas (high induced seismicity risk), which is in line with the previous literature (Carr-Cornish and Romanach, 2014, Hoşgör et al., 2013)**. In addition, the conjoint analysis revealed that in terms of effects on acceptance, induced seismic risks have most importance among the tested attributes. This stands in contrast to previous models in which the benefits of renewable energy technologies were the best predictor of acceptance (Bronfman et al., 2012, Visschers and Siegrist, 2014). However, this result resonates with qualitative findings regarding shale gas, another subsurface energy resource (Thomas et al., 2017). Consequently, deep geothermal energy projects should be sited in remote areas, where induced seismicity risks are reduced, as highlighted in the previous literature (Bommer et al., 2015, Giardini, 2009, Majer et al., 2007, McGarr et al., 2015)."

"Conjoint and mixed multivariate statistical analyses show that the public prefers projects sited in remote areas and using residual heat for industrial applications. The results in Switzerland and Germany were rather similar, but the Swiss public was generally more positive. Importantly, induced seismic risks affected acceptance ratings most strongly."

Reith et al 2013 (deliverable 4.4 Report on public acceptance of geothermal electricity production) "Public or social acceptance was defined by (Wüstenhagen, Wolsink and Bürer 2007) as a combination of three categories, socio-political acceptance, market acceptance and community acceptance" positive acceptance factors in print media (taken from Leucht 2011)



Negative acceptance factors in print media (Leucht 2011)



- ☐ Four categories identified: Environmental issues; financial issues; “missing-involvement” issues; NIMBY issues
- ☐ The selection of environmental issues is based on (Leucht 2011) (Hagedoorn 2006) (Mannvit 2013) and (Oduor 2010).

Environmental issues:

93 % of the German population considers the enforced development of renewable energies as important or very important (Agentur für Erneuerbar Energien, n.d.). In the following, social acceptance issues with an environmental background are discussed.

Greenhouse gas emissions:

"During the production of geothermal brine, one does not only get a fluid phase at the surface but a mixture of fluids and gas. The composition of geothermal brine can differ significantly from site to site. The geothermal power plant in Bruchsal (Germany) for example has under norm conditions in a norm cubic meter a fluid/gas ratio of 2:1. Around 90 % of the gas phase consists of CO_2 (Mergner, et al. 2012). There are three main types of geothermal power plants. Binary power plants (like the geothermal power plant in Bruchsal) usually work in a closed loop system, where the produced brine is re-injected after usage in the power plant with all its ingredients. However, in dry steam and flash power plants non condensable gases like CO_2 and H_2S are separated in the condenser of the power plant. These gases are either released to the atmosphere or treated in an abatement system, while the fluid parts of the brine are usually injected into the ground (Holm, Jennejohn and Blodgett 2012)"

▫ **geothermal power plants emit considerably less greenhouse gases than fossil power plants, the fact that a renewable power plant may not be greenhouse gas neutral in its production process could cause social resistance.**

Seismicity:

"Seismicity and damage through seismicity has been detected as one of the major negative acceptance factors for geothermal power in Germany (Leucht 2011). Seismicity is induced through the reinjection of water/brine under relative high pressure into the subsurface. Through changing the pore pressure, one affects the local stress field (Rybach 2003). Although most seismic events are not within the human perception threshold of magnitude 2-3 (i.e. only measurable and cannot be noticed physically), **people are very afraid of possible damages through seismicity induced by geothermal power plants. One well known example for effects of seismicity on geothermal projects is the EGS (Enhanced Geothermal Systems) project in Basel (Switzerland). In Basel several seismic events with magnitudes up to 3.4 were felt by the local population. There were a number of approximately 2500 requests for financial compensation of damages with a value of approximately 7 million CHF**. Forced by the fact that the average of each damage was at around 500 CHF and further investigations would be more expensive than the total sum requested, the project company decided to pay without any further examination. Following the seismic events the project was abandoned (City of Basel 2010)"

"As mentioned, seismicity is caused by the injection of water under high pressure. Through a seismic monitoring and a controlled injection of water into the subsurface, seismic events can be controlled. As an example, for the handling of social resistance in context with seismicity one could take the mediation process in Rhineland-Palatinate (Germany), where different stakeholders agreed on guidelines for the operation of geothermal power plants. These guidelines specify the actions that have to be taken for measurable seismic conditions by power plant operators (team ewen 2012). Parallel the U.S. department for energy has developed the "Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems" (Majer, et al. 2012). This protocol gives project developers in the field of EGS-power plants a guideline for handling the possible risk of seismicity within their project. A special focus is kept on dealing with stakeholders from public and authorities. But also, within research new concepts for handling seismicity within geothermal projects have been developed. The GEISER project for example investigated the possibility to anticipate the effects of induced seismicity within a geological formation. The project developed models to calculate parameters of seismic events and translate them into a traffic light system. This traffic light system is a practical solution for project developers and other stakeholders to handle the risk of seismic events during stimulation (Wiemer 2013)."

Subsidence:

"Subsidence might take place, when the fluid withdrawal through geothermal power plants exceeds the natural or artificial (reinjection) inflow into the reservoir. The fluid withdrawal reduces the pore pressure in the rock formation, which finally leads to subsidence (Hole, et al. 2007) (Shibaki and Beck 2003). This effect can be observed in high enthalpy fields all over the world. In the Wairakei geothermal field in New Zealand a total subsidence of 15 m was recorded. So on average a subsidence of 400 mm/year has occurred, but this can be seen as an extreme case. In Svartsengi, Iceland one can monitor a subsidence of 10 mm/year, whereas in Lardarello, Italy the earth moves 250 mm/year (Hole, et al. 2007)."

Noise:

"**As (Leucht 2011) showed noise levels are a serious social acceptance issue for affected citizens**. During the deployment phase of a geothermal project the highest noise levels can be expected. Drilling and construction phase go along with noise levels from 45 – 120 dBa 18 (Shibaki and Beck 2003). The production of geothermal power itself causes a noise level of 55 – 70 dBa (Hagedoorn 2006)….Through sound insulation, a strategic positioning of the whole power plant (close to an already existing noise emitter) or of single components, the total noise level of the power plant can be reduced. **Taking the example of the geothermal power plant in Bruchsal (Germany), the power plant building is situated between the cooling tower (highest noise emitter) and the residential buildings (bottom, right side). So the power plant building shields the residential buildings from noise emissions…**"

Other environmental issues:

"Besides the environmental issues which have been named by Leucht (2011) as negative influence factors on social acceptance, other environmental issues also have the possibility to become a social acceptance issue. The GEOELEC-project published an environmental report (Mannvit 2013) that goes further into detail. With a growing environmental awareness, other environmental issues could come into the focus of the public."

Missing involvement issues:

"Leucht 2012), (Cataldi 2001) and (Devine-Wright 2007) recommend an involvement of local citizens into project planning and implementation. (Leucht 2012) distinguishes concerning the implementation of affected residents two approaches:

1. Acceptance as a goal of the project realization

2. Acceptance as an indicator in the process of project development"

"For approach 1 central technical details like (timeframe, location, power cycle) are already determined. As a communication strategy persuasion is the only possibility. Leucht recommends communicating this situation. A participation offer with no influence on the outcome would only lead to mistrust and aversion towards the project developers. Approach 2 doesn't have a fixed outcome. The goal is to start an open communication process, which delivers details for the site decision. The communication strategy in this case would be to negotiate about projects' details. At the end of the process stands an accepted solution for all relevant stakeholders. A challenge for the project developer is the decision on appropriate participation possibilities and the implementation of all relevant stakeholders (Leucht 2012)."

Financial issues:

"One of the results of (Leucht 2011) was that people could see **investment costs of geothermal power plants as a negative social acceptance issue.** In Germany municipalities or municipal undertakings are often involved in geothermal projects."

Nimby issues (Not-in-my-backyard issue)

"In the course of the German energy turnaround, surveys show the paradox situation that a majority (93%) of the respondents supports the enforced development of renewable energies, but the acceptance declines, when a renewable power plant is located close to their homestead (Agentur für Erneuerbar Energien, n.d.). A similar public opinion can be found in other developed countries such as Australia (Dowd, et al. 2006). In general, it appears that citizens prefer RES-technologies that are far away from their neighbourhood and rather belong to a centralized energy system with big production capacities at one point (Scheer, Wassermann and Scheel 2012)."

Practical examples for social acceptance

Italy…

France…

Germany - The **four projects are located in Bruchsal, Brühl, Landau and Unterhaching**.

All these sites are characterized by local frameworks conditions. Additionally, they differ in progress, installed capacity and social acceptance.

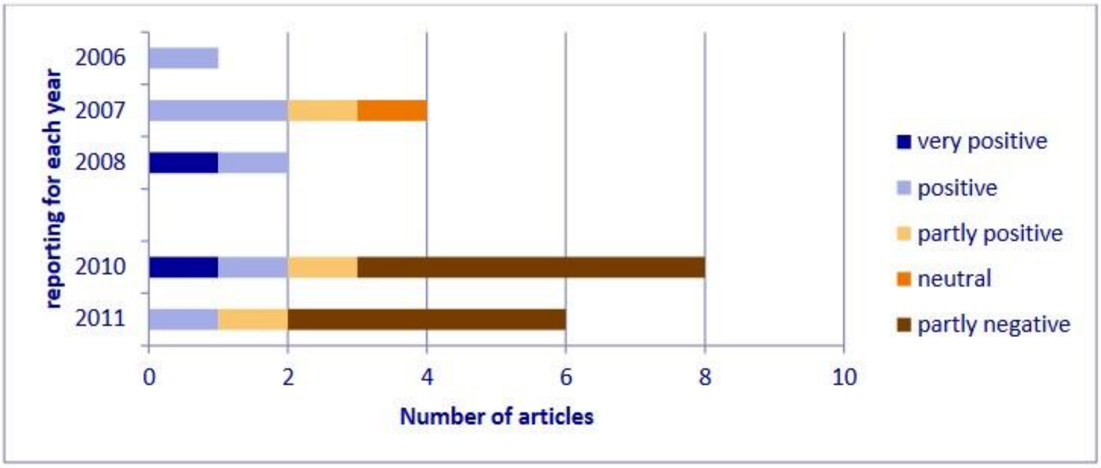


Figure 13: Reporting on the geothermal power plant in Bruchsal (Leucht 2012)

Brühl:

"The geothermal power project in **Brühl is currently in the construction phase**. At the beginning of February 2013 the first borehole was completed. In the final phase the geothermal power plant shall produce electricity with a capacity of 5-6 MWel (GeoEnergy GmbH 2013). The SA found that the **population has a strong mistrust towards the project and the project developer**. **In 2008, when the contracts between municipalities and**

project developer were signed, the public opinion was positive. But after the seismicity caused by the geothermal power plant in Landau the public opinion changed and currently there is a strong opposition with a well-connected citizens' initiative. Brühl is deeply divided because of the geothermal power project. People are scared because of the project. The public relation efforts of the project developer did not reach the public. Meanwhile public relations efforts are rather seen as propaganda (Wallquist and Holenstein 2012). In the geothermal project of Brühl, the MRA and the SA draw a similar picture. As already stated in the SA, the project has strong acceptance problems. This can also be seen in the MRA with a negative impression out of the investigation of press articles. "

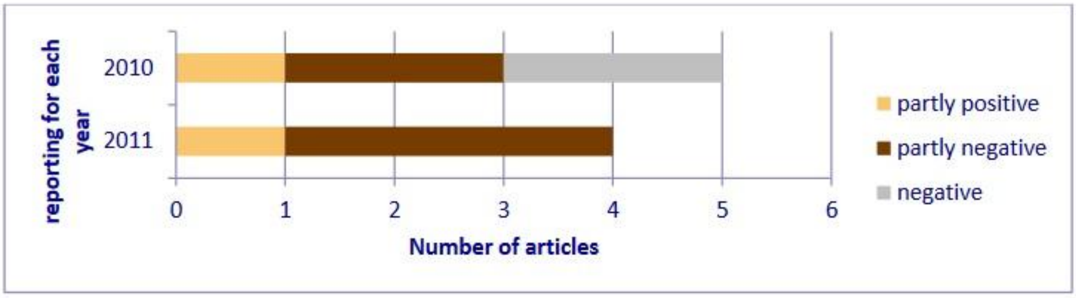


Figure 14: Reporting on the geothermal power plant in Brühl (Leucht 2012)

"The press partly sees the potential of geothermal power, but the focus is rather on social acceptance problems in the city of Brühl. The reason for this conflict lies in an unaddressed demand for information, security and citizens' participation over the whole project life, but especially after the seismic events in Landau. The project developers and the responsible persons within the municipalities did not see these needs and by this supported indirectly the formation of a strong citizens' initiative (Leucht 2012)."

Landau

"Since the end of 2007 the geothermal power plant in Landau produces electricity and heat. With a production rate of 50-70 l/s and 160°C water temperature the power plant has an electrical capacity of 3 MWel and an additional heat capacity of another 3 MWth (geox GmbH n.d.). For Landau the SA describes an ambivalent acceptance situation. **After the project start in 2007 the public and political acceptance of the project was quite high. This changed with seismic events in 2009. After the seismic events a dispute about unjustified damage claims caused the formation of a citizens' initiative. This initiative is strongly against geothermal power in Landau and in any other place in Germany**. The main part of the population has reached a condition of tolerance towards the power plant. The experience shows that one can live with a geothermal power plant and the perception for risk is rather low. On the other side relevant stakeholders do not identify themselves with the locally and environmental friendly produced energy. The whole situation is caused by a purely technical approach of the project developer. The company did not see the necessity of pro-active communication until the seismic events, when the public opinion was already against the project developers (Wallquist and Holenstein 2012). The MRA displays in Figure 15 very clearly the statements done within the SA. The positive attitude towards the power plant has changed in the press after the seismic event in 2009. The public interest can be seen by a very strong increase of press articles after the seismic events. On the other side one can see in 2011 a calming of the situation with a growing share of positive press releases."

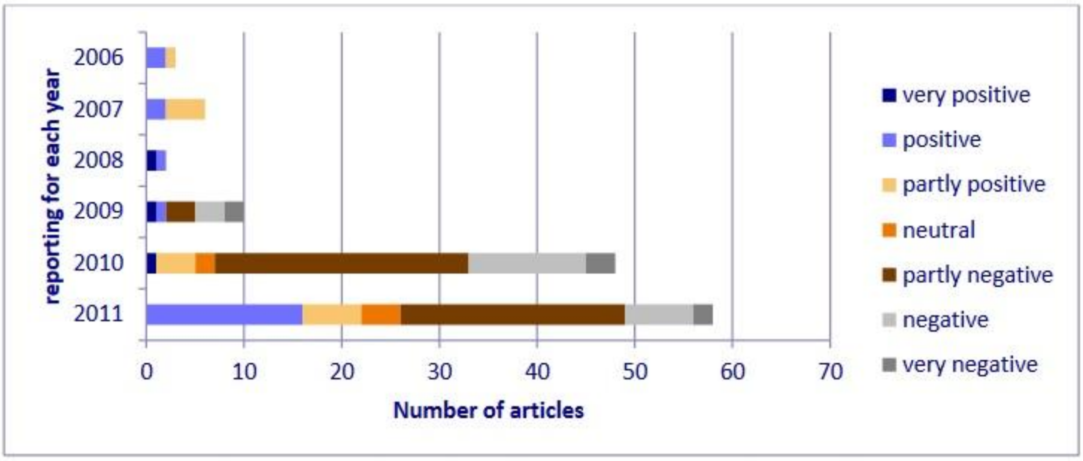


Figure 15: Reporting on the geothermal power plant in Landau (Leucht 2012)

Unterhaching

"The geothermal power plant in Unterhaching is situated in the geological region of the Bavarian Molasse Basin. With a exploration rate of 150 l/s and a temperature of ~ 130 °C the power plant is able to produce a maximum of 3,36 MWel or 38 MWth. In contrast to other investigated geothermal projects the power plant in Unterhaching is well known in the public. **People have trust in the operators and identify themselves with the innovative technology in Unterhaching. Through the heat supply of more than 5000 households, people can literally feel the benefits of the technology. On the other side, problems with the pumps and seismicity at other geothermal power locations are seen, but not rated very high. As the project came out of the local community it was and still is deeply connected to the local public**. At the beginning public relation actions were mainly based on single persons and word-of-mouth recommendation. With a growing heat network this aspect has been professionalized towards a pro-active communication. Again the impression of the SA can be proved with the MRA. In Unterhaching a general positive attitude towards geothermal power can be observed.... The pro-active communication policy and a strong identification of the public with the project operator lead to high acceptance (Leucht 2012)."

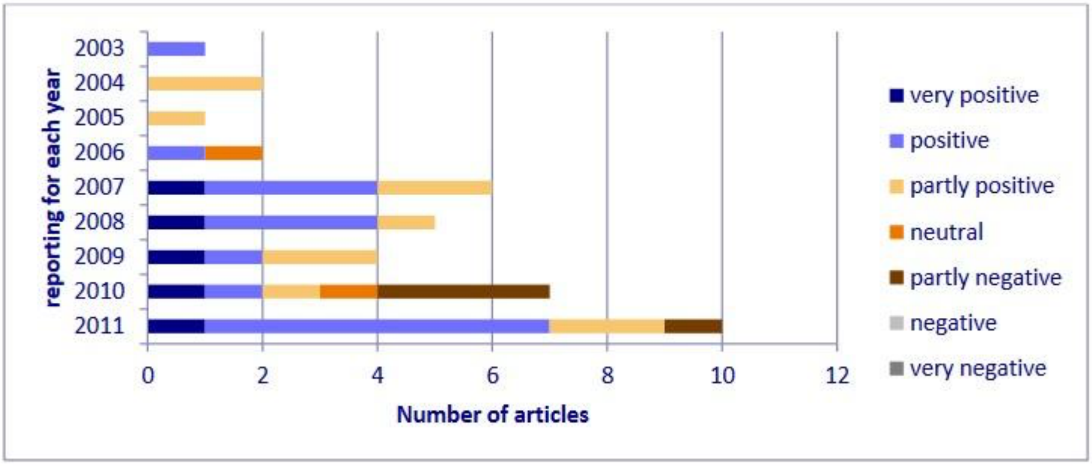


Figure 16: Reporting on the geothermal power plant in Unterhaching (Leucht 2012)

Benighaus and Bleicher 2019 – Neither risky technology nor renewable electricity: contested frames in the development of geothermal energy in Germany

https://doi.org/10.1016/j.erss.2018.08.022

Highlights: Case study of two communities to analyze local understandings of and collective beliefs towards geothermal energy; Mapping of arguments on geothermal energy and their distribution in different communities; Different frame preferences in local communities; local understandings of geothermal energy are shaped by historical and recent developments in the communities; Framing struggles in communities are relevant for local responses on energy technologies.

"Case studies in two different mountainous rural areas in Germany: the **community of Meiningen in the federal state of Thuringia and the community of Schneeberg/Bad Schlema in the federal state of Saxony. Geothermal energy research projects involving the drilling of exploration wells were planned in both communities. The aim of the projects was to investigate the potential of deep geothermal energy by creating engineered geothermal systems** (Breede et al., 2013). In newspaper articles and interviews, the initiators and facilitators of the project ideas – researchers, state ministries and some local actors – emphasized the scientific nature of both projects, including the open-ended nature of the research results. At the time of writing, none of the exploration wells had been realized. **Both projects were accompanied by public debates in the local media and during public assemblies. While in Schneeberg/Bad Schlema the public response can be described as 'interested', in Meiningen engagement with the project idea took the form of protest and was more intense.** …….. Some participants within this group also supported the argument that the region might benefit from outstanding technological innovation related to geothermal energy (e.g. a consequent boost in international reputation). In doing so, they linked the emerging technology frame with the regional development frame. **To explain this pattern in Schneeberg/Bad Schlema, it is necessary to highlight that this region is a former mining region. Mining history itself is not a common point of reference for making sense of geothermal energy technology** – only half of the participants in Schneeberg/Bad Schlema (seven out of 14) used this argument in their statements. **However, the positive attitude towards innovative technologies is grounded in this history and experience.**

Participants where clearly aware that the mining sector, which has contributed to regional income in the past, depends on technological innovation. Thus, these actors are familiar with and support the idea that innovative technologies for exploiting underground resources (formerly ores, nowadays energy) need to be developed, and that such development could be advantageous for the region…… In contrast, the environmental frame was most attractive for the group of interested citizens in Schneeberg/Bad Schlema and it was clearly more salient than all the other frames. **The argument that was raised by far the most within this group, was groundwater contamination**. In part, this dominance can be explained by referring to recent history. In Schneeberg/Bad Schlema uranium mining was carried out until the late 1980s. Since the 1990s, environmental contamination and the remediation of uranium has been an issue of high relevance and part of the lived reality of many people in the region. These developments are alive in the collective memory…. Most striking in this regard is that within the group of interested citizens, the risk frame was only referred to three times. Thus, this frame is not salient at all. This finding contradicts an assumption, often cited in the literature, that geothermal energy is increasingly perceived as a risky technology…. In conclusion: the community of Schneeberg/Bad Schlema so far has no shared understanding of geothermal energy and different local groups have their own priorities when it comes to interpretation."

Meiningen

"Frame patterns in the community of Meiningen differ remarkably from those in Schneeberg/Bad Schlema and are characterized by greater homogeneity between the two groups. **Most remarkable is the importance of the risk frame for both groups in Meiningen**. Key arguments were that **geothermal energy might damage buildings and the unresolved issue of insurance. The importance of the risk frame corresponds with the environmental frame in both groups, notably the argument on potential seismic events."**

▫conclusions: "Our findings make it clear that no simple solution exists for planning and realizing geothermal energy projects based on enhanced geothermal systems within and with local communities. Frames used by local actors are taken from the media, or grounded in tradition and collective memory, as well as influenced by recent developments. Thus, local understanding of geothermal energy is as heterogeneous as local communities themselves and is shaped by historical and recent developments, and local cultures of conflict resolution. This supports the findings of Blumer et al. too, which state that positive attitudes of the local population towards deep geothermal energy are influenced by the population's subjective perceptions and shared understandings…"

Renoth et al 2023 – social acceptance of geothermal technology on a global view: a systematic review

"Due to an increasing focus on the acceptance of the geothermaltechnology in the scientific community and literature during the past decade, we carried out **an up-to-date literature review**. In doing so, we considered a large number of publications that contain numerous different aspects of the social acceptance of geothermal energy and technology all over the world.":

Discussion – central acceptance factors

"Within the most researched acceptance category, project organization and process, the factor of **trust in key actors is dominant**. There appears to be a lack of trust in decision-makers (Karytsas et al 2019; Pellizzone et al., 2016; Cuppen et al., 2020; Zaunbrecher et al., 2018), the government (Ibrohim et al 2019; Dowd et al 2011; Hariyadi et al., 2019), and companies (Vargas-Payera 2018; Cavot et al 2019), which overall seem to affect the social acceptance of geothermal projects. One consequence is the **lack of belief in information provided by some of the stakeholders** (Pellizzone et al., 2016). **Honesty** is a central aspect, which can strengthen or weaken the trust in stakeholders (Hall et al 2015). **Recently founded companies, unknown ones, and companies that are not based locally are often times associated with a deficit of experience**, which in turn affects trust within the local community (Cavot et al 2019). Zaunbrecher et al. 2018 considered **confidence in stakeholders and common values with the actors of the geothermal project as essential factors for social acceptance** (Zaunbrecher et al., 2018). To increase or rebuilt trust in stakeholders, **regular citizen involvement in the projects can be used as a supportive measure** (Pellizzone et al., 2016; Ratio et al 2019; Pellizzone et al., 2015). Relationships and personal experiences can also boost the trust among stakeholders (Hymans 2021)."

"The characteristics of the acceptance factor information about the **project are openness and transparency** (Ratio et al., 2020, Hall et al 2015; Yasukawa 2019), information asymmetry (Contini et al., 2019) and the amount and type of information distribution (Vargas-Payera 2018, Ejderyan et al., 2019, Higgins et al 2017; Malo et al 2019). **For the flow of information, time is an important aspect. Information about the project should be delivered to the stakeholders as soon as possible** (Ejderyan et al., 2019, Higgins et al 2017). A communication strategy is also recommended to avoid or minimize suspicion about the project due to poor communication of the project development (Ratio et al 2020, Vargas-Payera 2020). **According to Kluge and Ziefle 2016 local newspapers, direct mail, and websites are the preferred information channels**.

Environmental impact addresses the **social acceptance from an ecological perspective**. This acceptance factor summarizes a number of environmental aspects. **Seismicity and groundwater pollution** are excluded and addressed in separate acceptance factors due to their prominence (i.e., numerous mentions) in the literature. The **acceptance factor of environmental impact deals with specific risks, e.g., environmental pollution** (Karytsas et al., 2019; Qorizki et al., 2021; Chavot et al., 2019), **soil contamination** (Pellizzone et al., 2016, Malo et al., 2019), or the **irreversibility of environmental damage** (Balzan-Alzateet al., 2021; Kubota et al., 2013). Furthermore, **uncertainty about the effects of geothermal projects on the environment** (Vargas-Payera 2018; Trevisan et al. 2013) and positive associations with this type of energy generation (Cousse et al 2021; Higgins et al., 2017, Çetiner et al 2016; Mosly and Makki 2018, Wahyudi et al., 2019) are included in this factor. Although fracking was also mentioned and fits within this factor, it does not seem to play a central role (Cuppen et al 2020)."

"**Seismicity is a geothermal-specific acceptance factor**. Studies found that induced **seismicity is an essential point of concern for citizens regarding geothermal projects** (Dowd et al., 2011; Kunze and Hertel 2017; Carr-Cornish and Romanach 2014; Chavot et al 2018; Kluge and Ziefle 2016; Knoblauch et al 2019; Pellizzone et al 2016, Balzan-Alzate et al 2021; Çetiner et al 2016; Knoblauch et al 2018; Malo et al 2019; Yasukawa et al 2018). According to several studies, the general **notion within communities is that seismicity seriously affects both the community and the environment** (Dowd et al., 2011; Kunze and Hertel 2017; Chavot et al 2019). In a study by Cousse et al. 2021 seismic risk is seen by the participants as a critical risk in the light of geothermal project planning, an effect that can be reduced with more detailed information about the controllability of those risks. **Cuppen et al. described a "spill over" effect of induced seismicity from other technologies, such as shale gas exploitation, which can decrease the social acceptance of geothermal energy significantly** (Cuppen et al 2020). According to Knoblauch et al. 2018, there is "a statement of uncertainty and limited expert confidence" regarding the seismic potential in geothermal technology that also reduces social acceptance. However, **information about geothermal technology and on how to control potential seismic activity can mitigate the negative impact on social acceptance** (Dowd et al., 2011; Cousse et al. 2021; Chavot et al 2019). Another approach to **reduce the risk of seismicity is to focus on geologically stable regions** (Kunze and Hertel 2017) (e.g., cratons). The study of Romanach et al. 2015 shows that the risk of seismicity is not the central point of concern in Australian media."

"This leads to the acceptance factor general knowledge about geothermal energy, which also influences social acceptance. Overall, the **general knowledge about geothermal energy and technology appears to be low** (Dowd et al., 2011, Vargas-Payera 2018; Higgins et al., 2017; Hosseini et al., 2018, Contini et al., 2019, Malo et al., 2019; Zaunbrecher et al., 2018, Pellizzone et al., 2015). That **lack of knowledge often creates reservations about, or even the rejection of, geothermal projects** (Ibrohim et al., 2019; Vargas-Payera 2018, Carr-Cornish and Romanach 2014; Kluge and Ziefle 2016; Wahyudi et al., 2019, Pellizzone et al., 2015). In some of the investigated groups there was very little knowledge about whether geothermal energy and technologies could have a positive or negative impact on the environment (Çetiner et al., 2016). Contini et al. 2019, therefore, recommend to increase the social acceptance of geothermal projects by deepening that knowledge, which tends to improve the social acceptance along the way (Higgins et al 2017). An important goal is to raise awareness and to avoid a lack of information and knowledge before and during geothermal projects (Dowd et al 2011, Hosseini et al., 2018). The transfer of knowledge can be achieved, for example, by workshops that bring together citizens and scientific specialists, or by topic-related meetings and conferences (Dowd et al 2011, Hosseini et al., 2018)."

"The distribution of benefits and costs between actors within the community addresses the cost-benefit ratio and allocation of costs and benefits to the different stakeholders. Allansdottir et al. (2019) point out that the **perception of risks has a bigger impact on social acceptance than benefits** (Allansdottir et al., 2019). In several countries such as Canada, Colombia, Belgium, and France this aspect seems to be highly relevant for the acceptance of geothermal projects (Balzan-Alzate et al., 2021). Both the **financial and the legal dimension play an important role in the cost-benefit ratio in the communities** (Kunze and Hertel 2017 ; Vargas-Payera 2018). For instance, an **earthquake insurance for local citizens can, to some extent, alleviate their uncertainty** (Kunze and Hertel 2017). **Furthermore, the local stakeholders and especially the local communities can be won over with financial benefits**, as in the promulgation of the Department of Energy Act in the Philippines 1992 (Ratio et al., 2019). The potential of **geothermal energy as a personal cost reducer is perceived as a positive aspect** (Trevisan et al., 2013). Another aspect of this acceptance factor is the **high upfront expenditure seen as a major investment risk** (Hymans 2021; Kubota et al., 2013; Radzi and Droege 2014; Zaunbrecher et al., 2018). One suggested solution is an amendment of the national policy framework to balance out the different energy forms and, at the same time, lower the risks for the implementation of geothermal projects (Hymans 2021). A boost for regional economic development and national and social welfare provided by geothermal energy is generally seen as a positive effect (Qorizki et al., 2021)."

"**Another important environmental acceptance factor is groundwater pollution.** The main concern is the contamination of groundwater when geothermal technology is installed and used, this concern is seen by study participants across different countries (Carr-Cornish and Romanach 2014; Chavot et al., 2018; Chavot et al., 2019; Malo et al., 2019). The concern is mainly rooted in **the possibility of water contamination during the drilling process** (Ibrohim et al., 2019; Cousse et al., 2021; Romanach et al., 2015; Yasukawa et al., 2018). Another reason can be a technology spill-over, perhaps as a consequence of bad experience with other subsurface technologies in the past (Cuppen et al., 2020). The negative aspect of groundwater pollution is predominantly relevant to agriculture, which can be seriously hampered by soil and subsurface contamination (Ibrohim et al., 2019). However, there were also responses that see no negative effects (Carr-Cornish and Romanach 2014). An environmental management program can help prevent environmental damage and demonstrate ecologic responsibility (Ibrohim et al., 2019). Again, a possible reason for the wide concerns is the lack of knowledge about geothermal energy and technology (Malo et al., 2019).

The social acceptance factor labeled opportunities for participation and consultation in planning and permitting process describes the **possibility of involving local citizens in a geothermal project**. The opportunity to be involved in decisions and to be an equal participant within a project is of high interest and relevance to the local communities (Kluge and Ziefle 2016; Yasukawa 2019). Carr-Cornish et al. found that many citizens think they are not involved deeply enough in Australian geothermal projects while Vargas-Payera indicated that local communities in Chile were not sufficiently included in decision-making processes (Vargas-Payera 2018; Carr-Cornish and Romanach 2014). It is shown that active and frequent involvement of citizens in geothermal projects increases the social acceptance of those projects (Pellizzone et al., 2016; Ratio et al., 2020; Contini et al., 2019; Malo et al., 2019; Ratio et al., 2019) … Practical implementation of participation can, e.g., be a telephone hotline for the public, open house days, tours of operating geothermal facilities, roundtable discussions with project managers, or other information events (Kluge and Ziefle 2016)."

"The next acceptance factor focuses on the perception of the maturity of the geothermal technology. According to a survey carried out in France, **geothermal technology and the companies working in this field are deemed rather immature** (Chavot et al., 2019). Blumer et al. (2018) suggested the personal opinion about geothermal energy and technology strongly depends on personal experiences and familiarity with the topic. According to Cousse et al., (2021) the notion of an immature state of geothermal technology also seems to be linked to a certain fear of triggered seismicity. In that study, the concerns seem to be more pronounced in the context of deep geothermal projects rather than shallow geothermal projects and can be reduced with increasing information about the geothermal technology. Furthermore, information and knowledge about controlling seismic risk leads to a more positive view on the maturity of geothermal technology."

"**In Germany, geothermal technology is widely perceived as relatively prone to failure compared to other technologies** (Trevisan et al., 2013). However, concerns about technology uncertainty are also prominent in Australian media, where they are among the top two points of concern (Romanach et al., 2015). In Switzerland, the maturity of the geothermal technology is one of the four most critical topics discussed in the media (Stauffacher et al., 2015).”

“The **economic dimension is expressed by the acceptance factor local profits and income**. Local profits can be realized through cost savings for energy and an increase of the economic efficiency that benefits the communities (Cousse et al., 2021; Trevisan et al., 2013; Yasukawa et al., 2018). In two studies the communities see geothermal as a potential threat to their local industry, such as farming or fishing, mainly because of the perceived risk of water pollution or shortage (Ibrohim et al. 2019; Hariyadi et al., 2019). Ibrohim et al. (2019) described the fears of the local people in Indonesia, according to whom employment within geothermal projects may only last until the infrastructure has been built and they have been replaced by professional workers. In contrast, studies in Canada and Australia suggest the local communities see geothermal projects as a good opportunity to create jobs (Malo et al., 2019; Romanach 2015). Overall, financial benefits to the local communities tend to support social acceptance (Ratio et al., 2019). Pellizzone et al. (2016) note, however, that geothermal projects and infrastructure in Italy may give way to financial speculation, in turn compromising social acceptance. **In summary, geothermal energy and technology are mostly associated with a positive impact regarding local benefits, profit, and income.**”

“The acceptance factor of health and well-being deals with aspects that directly affect the local community. Aspects supporting acceptance are, e.g., the linkage of geothermal plants with water treatment and new ways to access hot water supplies (Çetiner et al., 2016). A disadvantage associated with this acceptance factor is the fear of adverse effects on citizens’ health (Karytsas et al., 2019). Furthermore, **the fear of noise and air pollution with smelly emissions tends to lower the acceptance** (Pellizzone et al., 2016; Qorizki et al., 2021; Malo et al., 2019; Romanach et al., 2015; Ratio et al., 2019).

“**Grid infrastructure deals with energy security** (Carr-Cornish and Romanach 2014; Radzi and Droege 2014; Romanach et al., 2015) **and possible effects** (Pellizzone et al., 2016; Çetiner et al., 2016; Chavot et al., 2019) **on the grid infrastructure due to geothermal projects**. It can affect local businesses and their energy supply (Chavot et al., 2019). There is a wide notion that the usage of geothermal energy within in the power infrastructure can cause some degree of independence as the energy is commonly produced in close proximity (Cousse et al., 2021). The anticipated potential of a geothermal project within the local grid can lead to a positive change of social acceptance within the community (Chavot et al., 2019).”

“In the governance acceptance category, **the acceptance factor plans in politics is the most discussed one**. Political conditions in a region (Hymans and Uchikoshi 2021; Hymans 2021; Stauffacher et al., 2015) and political influence on geothermal projects (Qorizki et al., 2021; Kubota et al., 2013; Rosso-Cerón and Kafarov 2015; Yasukawa 2019) both affect social acceptance. Political strategies can either support or weaken the framework and conditions for successful geothermal projects (Kubota et al., 2013; Rosso-Cerón and Kafarov 2015).”

The social acceptance factor economic burdens and benefits focuses on monetary aspects. The **costs and yield for energy are one issue** (Chavot et al., 2019; van der Zwaan et al., 2019), particularly when there is the concern of low amounts of produced electricity

(Chavot et al., 2019). Moreover, the expectation of lower prices compared to fossil energy can affect the acceptance of geothermal projects (van der Zwaan et al., 2019), as do energy costs and affordability on an individual scale (Trevisan et al., 2013). However, economic prospect, e.g., the potential impact of geothermal energy and technology on employment (Qorizki et al., 2021; Yasukawa 2019), is also a relevant aspect of this acceptance factor."

"Another social acceptance factor in the category of municipality are the socio-psychological characteristics. This acceptance factor focuses on **individual experiences with geothermal energy and technology**, although there is also some overlap with other acceptance factors (e.g., of socio-cultural nature). Negative experiences, such as earthquakes or accidents at geothermal sites, individually affect social acceptance (Karytsas et al., 2019; Blumer et al., 2018; Baek et al., 2021). Conversely, negative experiences with other energy projects can also support the social acceptance of the geothermal approach (Zaunbrecher et al., 2018).

Water use is a key aspect of the acceptance factor use of resources (Dowd et al., 2011; Balzan-Alzate et al., 2021; Malo et al., 2019; van der Zwaan et al., 2019)."

As the **result of several studies in this literature review, the most researched aspect for generating and utilizing social acceptance is trust in key actors**, as is the case in other energy projects (Greenberg 2014; Peñaloza et al., 2022; Segreto et al., 2020; Enserink et al., 2022). **The same holds true for the social acceptance factors of information about the project, distribution of benefits and costs, and opportunities to participate and consult in planning and permitting processes** (Peñaloza et al., 2022; Segreto et al., 2020; Enserink et al., 2022)."

"In contrast to these analogies there are also **differences,** which demonstrate the special role of geothermal projects with respect to social acceptance. Some of these aspects depend more on the technology. Whereas locality and distance can be important factors at wind farms or biogas sites (Segreto et al., 2020; Enserink et al., 2022; Ellis and Ferraro, 2016), the actual location of geothermal energy plants only seems to play a minor role in the researched papers. A number of social acceptance factors are unrelated to other renewable energy technologies, such as seismicity, groundwater pollution, and the knowledge about geothermal energy… These aspects also show the social complexity, particularity, and unique selling point of geothermal projects."

"Furthermore, larger-scale international changes can heavily affect social acceptance, such as the geopolitical developments with the conflict between Russia and Ukraine in early 2022. The latter apparently caused a boost of geothermal energy and energy independence in many European countries (steffen and Patt, 2022). Although sometimes hard to predict, the impact of such global-scale events should be kept in mind when researching into the social acceptance of geothermal energy and other energy sources and technologies.

Sardianou and Genoudi 2013 (**for Greece**; "The aim of this study is to examine the determinants that affect consumers' intention towards the adoption of renewable energy sources in the residential sector")

DOI:10.1016/j.renene.2013.01.031

“This study presents insights into the determinants of consumers' willingness to adopt renewable energies in the residential sector. The empirical analysis is based on the estimation of binary probit regression models. Empirical **results suggest that middle-aged and highly educated people are probably more willing to adopt renewable energy sources in their home**. In general, income positively affects consumers' acceptance of renewable energy projects in the residential sector.”

4. Would the end user consider geothermal energy usage nevertheless it can cover the base load and they need a backup for peak loads? Is this a major obstacle for the end user’s or do they see potential in it?

If the project to provide geothermal energy is already costly, maybe peak loads could be backed up with an additional system, so that it won´t be an issue.

5. Are there any potential customer groups who would be satisfied only with base load energy supply? If yes, please provide the information regarding user, energy load needed and preferable technology, if applicable.

We do not know at this moment.

C. Economic analysis

Data in this section concerns evaluating the economical side of implementation and usage of repurposing technologies in the energy supply chain.

1. What is the optimal transfer distance of energy for recognized reuse methods DBHE, BTES, ATES, HE, EGS? Depending on flow rate and temperature? Please describe each method.

There is not much explicit data for Germany. There shouldn´t be any difference between a new drilling and a reused one. Heat/ energy loss depends on heat exchanger/power plant system and the district heating network used. Kavvadias and Quolin 2018: *heat transmission remains restricted to decentralized systems, aiming to cover the local end-user needs – but more interest in heating and cooling strategies abd the Energy Efficiency Directive (EED). *So far, there has been a lot of discussion on district heating systems technology and potential enhancements but little discussion on the costs and the economic distance of heat transmission from the supply to the consumption point; either it is an individual

consumer or a district network. In most studies the heat supply is already part of the district network and it is analysed as a component of its distribution pipeline.

*projects that utilize heat as long distance energy carrier are not as mature as in the electricity sector, among others for the following reasons:

* Electrical flows have a higher density than physical thermal flows (~0.5MW/mm2 for a high voltage direct current line vs. ~0.001 MW/mm2 for heat transmission lines) and are therefore more cost effective

* Long distance transmission in electric lines is made possible by increasing the voltage, thus decreasing the current. This cannot be transposed to heat lines, in which high temperatures entail higher thermal losses and low exergetic efficiencies on the production side

* Electricity transmission and distribution losses are in average 8.2% in the world. Typical heat distribution losses vary between 4% and 20%, depending mainly on the linear heat density

However, using heat as energy carrier also presents a number of benefits, among which:

* Thermal storage (sensible heat) is orders of magnitude more costeffective, even when comparing to the cheapest source of large scale electricity storage, namely hydroelectric energy

* Exergy losses are much lower when satisfying end use heating purposes. This allows multiple utilization of energy streams, and waste heat energy streams from many industrial processes can be reused

https://www.sciencedirect.com/science/article/pii/S0306261918302058

specific cases (cited in Kavvadias and Quolin 2018):

*Ammar et al (2012): steam with a temperature of 120–250 °C can be transported over approximately 3–5 km while water with a temperature of 90–175 °C can be transported over 30 km. For lower grade heat, other sources cited in that same report mentioned that 15 km is the economic limit. http://dx.doi.org/10.1016/j.apenergy.2011.06.003

* Kapil et al. [2012] developed a model that takes into consideration capital costs, market heat purchase price and heat losses. Considering 62MW of low grade heat, they concluded that the break-even point for economic heat transfer distance is 86.5 km, with the assumption that 1% of heat is lost for every km of distance from the source to the DH network. However, the operating cost for pumping has not been considered in this simple calculation for the feasible distance of heat transmission. http://dx.doi.org/10.1016/j.energy.2011.12.015

* A review on real projects and industry practices indicated similar facts while being skewed on the upper end demonstrating that even higher distances are feasible

* In Helsinki, the Vuosaari power plant is connected to the central city area, by an approximately 30 km long tunnel, which is the longest continuous district heating tunnel in Europe. 2010. http://www.decentralized-energy.com/articles/print/volume-11/issue-3/features/carbon-free-nuclear.html

* In Denmark the distance from the CHP to the city centre of Aarhus is 20 km and the length from the CHP to the other end is around 45 km. The total length of the transmission network without considering distribution including a power station in one end, a waste incinerator along the line, and decentralised peak boilers is 130 km.

* The longest bulk heat transmission distance in Europe is found in Czech Republic, Prague. It is the line from the Melnik power station to the centre of Prague, whose length is 67 km for a direct distance of 32 km. This transmission pipe is for a large part above ground surface

http://doi.org/10.2790/47209

* In Switzerland, a nuclear power plant in Beznau, supplies 81MW of heat through a 31 km main pipeline to various surrounding cities http://www.axpo.com/content/dam/axpo/switzerland/erleben/dokumente/axpo_KKB_prospekt_en.pdf.res/axpo_KKB_prospekt_en.pdf

*Another study for a Swedish industrial plant assumes a 30 km distance to the nearest district heating network

http://dx.doi.org/10.1016/j.enpol.2008.07.017

* In addition to the above examples, some new feasibility studies of new projects explore the transmission of larger amounts of heat at various temperatures. Safa (2012) states that new developments in insulation and pumping technologies may give hope in a near future for applications over long or even very long distances (> 100 km). In his case study, a 150 km long main transport line exhibits losses representing less than 2% of the total transported power.

* A case study from Fortum Corporation for Loviisa Nuclear power plant concluded that available heat to be transported to the eastern Helsinki, which is about 80 km away, can reach 1 GW. The location of the Loviisa NPP site at the southern coast of Finland (approximately 75 km east of the Helsinki metropolitan area with one million inhabitants) offers a good opportunity for large-scale district heat generation for the region from the Loviisa 3 unit (Tuomisto 2013).

* An even larger amount of heat (2 GW) was considered in the work of William Orchard Partners London Ltd., using 2×2m diameter pipes. The cost of transferring this amount of heat to 140 km is about 0.0035 €/kWh for the delivered heat. Heat loss was 35MW and the pumping losses 50MW. http://doi.org/10.2790/47209

* Another category of long distance heat transmission solutions includes technologies that are not based on the transfer of sensible heat. The following technologies have been considered: chemical reactions, phase change thermal energy storage and transport, hydrogen-absorbing alloys, solid-gas and liquid-gas adsorption http://dx.doi.org/10.1016/j.rser.2008.10.004

Most of these technologies are not cost competitive yet, although the most prevalent one, phase change storage and transport, already has some commercial applications. In this technology, the heat is transported by a Phase Change Material in a container for transport by road to the user.

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Table 1
Literature review of heat transmission pipelines.

Location	Country	Heat capacity (MW)	Heat pipeline Length[a] (km)	Diameter (mm average)	Ref.
Linkoping – Mjolby	Sweden	25	28		[25]
Lindesberg	Sweden	26	17		[26]
Oslo	Sweden	275	13	600	[27]
Helsinki	Finland	490	20	1000	[20]
Turku	Finland	340	25	800	[20]
Tilburg	Netherlands	170	25	500	[20]
Diemen - Almere	Netherlands	260	8.5	700	[28]
Almere	Netherlands	170	10	500	[20]
Viborg	Denmark	58	12		[29]
Oradea	Romania	546	86.3		[30]
Akranes	Iceland	60	62	400	[31]
Aachen	Germany	85	20		[32]
Gothenburg - Mölndal	Sweden	10	1.1		[33]
Gothenburg - Kungälv	Sweden	19	22		[33]
Sankt Pölten	Austria	50	31	425	[34]
Lippendorf – Leipzig	Germany	300	15	800	[35,36]
Mannheim – Speyer	Germany	40	21.2	300	[36,37]
Boxberg - Weißwasser	Germany	40	16	400	[36]
Zolling – Flughafen München	Germany	150	28	500	[36]
NESJAVELLIR - riykjavik	Iceland	290	27	800	[38]
Kozani	Greece	137	16.5	500	[39]

[a] Distance from the CHP power plant to the centre of the supplied district heating.

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Table 2
Summary of thresholds defined by Member States under Article 14.6 of the EED.

Member State	Thresholds				
	Maximum Distance (km)	Minimum peak Heat (MW)	Minimum Heat supplied	Minimum Temperature (°C)	Minimum operating Hours per year
Austria	5	1.5	50 TJ/yr	80	1500
Cyprus					
Denmark	5			Surplus of + 10	1500
Finland	5–20			80	1500
Germany		10			
Greece			5.4 TJ/yr/km		
Ireland					1500
Italy					1500
Netherlands	3		2.5–25 TJ/yr		
Poland	20	10% of total heat supply			
Slovakia					
Slovenia			5.4 TJ/yr/km		
Sweden					
UK	2–15				

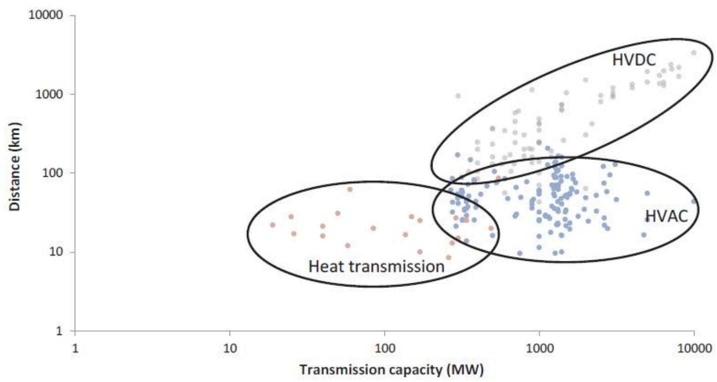


Fig. 1. Comparison of energy transmission different energy carriers.

Results: the sensitivity analysis depends on the starting point, so there were four cases examined:

- high supply Temperature (50 °C) and low delivery distance (10 km)
- high supply Temperature (50 °C) and high delivery distance (100 km)

- low supply Temperature (100 °C) and low delivery distance (10 km)
- low supply Temperature (100 °C) and high delivery distance

“**The effects of both distance and heat quantity are prevalent**. As expected, **the highest costs are obtained in the case of high distance and small heat quantities. For higher distances, capital costs become dominant and have a proportional relationship with the supply temperature because the flow rate is rising as temperature interval is falling. On the contrary, for smaller distances, the pumping costs become dominant and have an inversely proportional relationship with supply temperature.** This explains why the relationship between LCOH and heat supply temperature is inversed in the two extreme cases. Similarly, for high amounts of heat, power penalty costs becomes predominant (higher extraction temperatures have higher energy penalty from cogeneration power plants), which explains the proportional dependency of costs versus temperature, even for long distances. …Its importance has been emphasized in the recent literature (Gadd and Werner 2014). If the consumer fails to utilize the deliver heat as planned this has a big impact in the results. It is observed that in any case a smaller return Temperature is desirable. This is important in order to maximize the temperature difference and avoid increased costs related to high water flows and large pipe requirements. Another interesting behaviour is the “inversion” of the supply Temperatures profitability. In case of higher distances the effect of a smaller ΔT – as implied by a higher return Temperatures – is magnified because the piping costs become the dominant factor.”

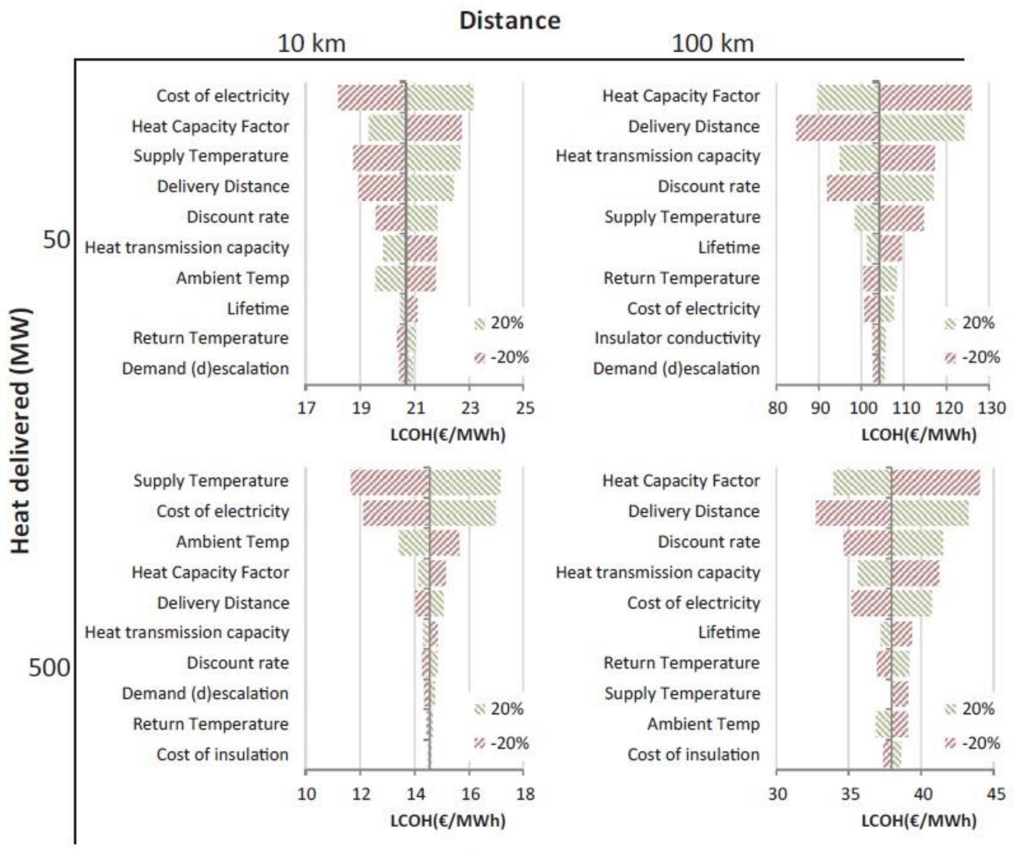


Fig. 4. The effect of ten most sensitive variables on LCOH for different distances and amounts of heat.

Conclusions: “While most literature sources use a common threshold for **feasible heat transmission distance in the range of 30-50 km, the analysis of the techno economic model suggests that longer distances are feasible for specific techno-economic parameters and market conditions. Delivering heat from a remote power plant can be more cost-effective than decentralized production even over large distances, and especially in case of high retail power prices or low wholesale power prices**. By assuming a zero net present value, the economic model also allowed to evaluate the shape of correlation between the maximum distance and the heat power. It was demonstrated that, in good approximation, the maximum delivery distance is proportional to the square root of the amount of heat transmitted.Finally, the proposed sensitivity analysis highlighted key parameters affecting the profitability of heat transmission, such as the heat transmission temperature and the electricity and heat prices. A comparison with existing installations was also performed, but should be extended in the future when more experience and cost data become available.”

2. What is the cost for implementation of reuse methods DBHE, BTES, ATES, HE, EGS on a well which is active / shut in / abandoned? Please describe each method and each type of well status.

We do not have any data on this issue in Germany (lack of real examples of reuse).

Literature:

Caulk et al 2017

“Different from EGS, DBHEs harvest geothermal energy without allowing working fluid to contact soil or rock. Instead, DBHEs use various closed loop configurations for circulating working fluid through pipes buried in the subsurface, while exchanging thermal energy with the soil….. deep DBHEs invoke the same principles as shallow DBHEs but they reach depths of 1000e3000 m where rock temperatures can exceed 85 C and raw produced fluid temperatures range from 20 to 55 C (Sapinska-Sliwa et al., 2015). Similar to EGS, the production fluid temperature of a deep DBHE strongly depends on crustal heat flow. Different from EGS, the efficiency of deep DBHEs depend on heat exchanger configuration and the host rock thermal properties instead of hydraulic properties such as porosity and permeability. In fact, heat exchanger insulation design/cost may determine deep DBHE project feasibility. …existing deep DBHEs in Germany” (and Switzerland):

Deep DBHE sites:

Aachen Germany - Peaking method=heat pump; EWT °C=25-55; depth=2500 m; flow rate 2,77 l/s

Prenzlau, Germany - Peaking method=heat pump and Gas/oil boiler; EWT °C=-; depth=2786 m; flow rate 6 l/s

“These examples make use of a coaxial tube configuration consisting of two concentric tubes: one carrying fluid down and the other carrying fluid backup through the center. This deep DBHE configuration has been investigated and proven viable in various locations around Europe….. **The economic viability of EGS and deep DBHEs depends on a variety of factors including prospecting technologies, drilling technologies, reservoir technologies, energy costs in the region, resource longevity, etc. (Tester et al., 2006).**

The reuse of abandoned wells removes prospecting and drilling risks, but the remaining factors still require focused research. For example, fracture network stimulation in a sedimentary reservoir requires different procedures compared to a similar network design in an igneous reservoir due to differences in fluid migration, pore pressures, and cementation/crystallization (Economides 2000). While the economic viability of EGS remains a research topic, deep DBHEs stem from well-established shallow DBHE technologies (Lund and Boyd 2016). Without a dependence on uncertain fracture networks, the economic viability of deep DBHEs depends almost entirely on comparable regional energy prices (**Śliwa and Kotyza, 2003). The same study concluded that plugging an abandoned well may, in some cases, be more expensive than refurbishing it for thermal extraction**. Further, a deep coaxial DBHE configuration doubles as a "maintained" plug for abandoned wells, since the efficiency of the deep coaxial DBHE depends on the continuity of the cement in the casing-rock annulus. This requirement reduces the chance for oil/gas migration to the surface or into aquifers. **Another study performed on the reuse of abandoned oil wells in Carpathians, Poland concluded that the benefits were ubiquitous with the only downside being the challenging optimization of design parameters** (Śliwa et al., 2014). **Finally, another economic benefit of retrofitting abandoned oil and gas wells is the large number wells available for upscaling DBHE extraction capacity to match larger scale EGS operations**.

Older wells (1850s spud dates) may have been plugged with brush, wood, rocks, paper, etc. according to loose regulations [1]. **Old or new, the cement plugs can be easily removed by setting up a special drill rig that breaks up and removes the well cement/debris (**pers. comm., Trusche, 2016).

3. What is the cost of surface infrastructure, depending on expected energy supply by each method DBHE, BTES, ATES, HE, EGS? Please describe each method.

*Surface structures are probably comparable, except DBHE.

*Just brine transport – varies between ca 1000 and 5000 Euro/ m (depending on the actual site – rural vs city, corresponding to Neuruppin+Prenzlau vs Potsdam city area).

*Sánchez-García, L., Averfalk, H., & Persson, U. (2022) "Construction costs of new district heating networks in Germany" (Report for sEEnergies Project, financed by Horizon 2020):

"The results for Germany show that the country has a significant potential for District Heating expansion. Approximately a quarter of the total heat demand could be supplied with a cost lower than 20 €/MWh and nearly half of the heat demand would be economically viable with a higher marginal cost of 30 €/MWh. Nonetheless, there is significant regional variation, and whilst the most urban districts (kreise) could reach penetration rates above 70% for a marginal cost of 20 €/MWh, the least dense would fall below 10% of the heat demand"

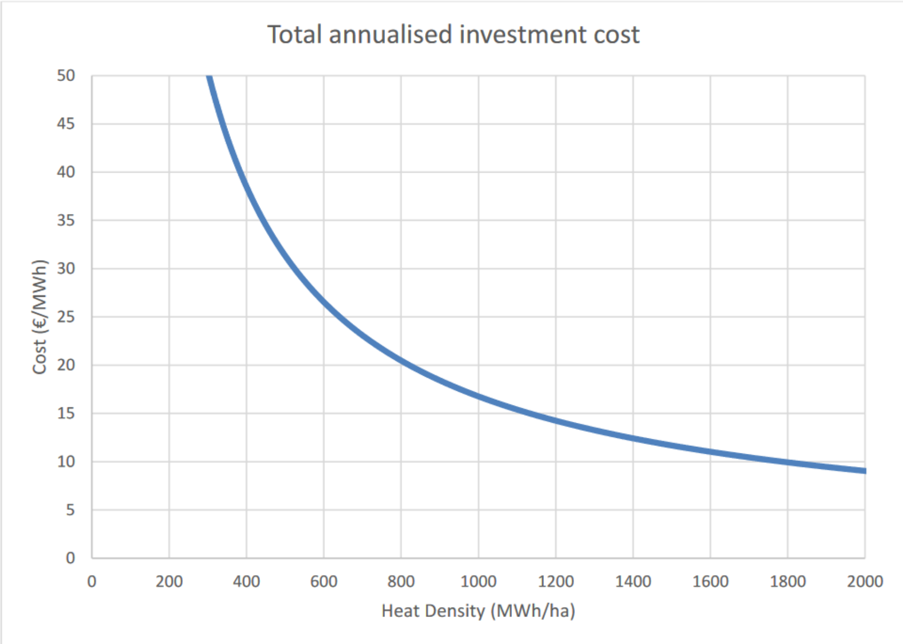
https://hh.diva-portal.org/smash/get/diva2:1702170/FULLTEXT01.pdf

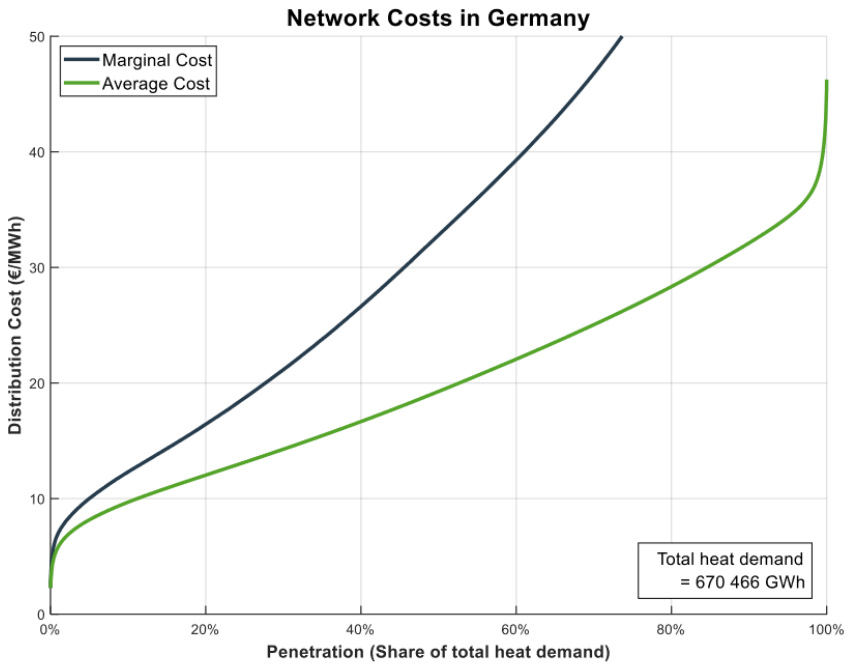
*estimation of construction costs for district heating - method by Persson and Werner 2011

The specific capital cost for a given area, Cd [€/MWh1], is the ratio between the annualised investment, $a \cdot I$ [€], in the area and the heat demanded in the same area Qs [MWh]:

*pipe costs for Germany – 664 Euro/m (diameter range between 25 and 300; AGFW, 2021)

*specific construction costs as a function of the ground heat density:





Schüppler et al., 2019 - ATES

Abstract “The objective of the present study is to analyse the economic and environmental performance of ATES for a new building complex of the municipal hospital in Karlsruhe, Germany. The studied ATES has a cooling capacity of 3.0 MW and a heating capacity of 1.8 MW. To meet the heating and cooling demand of the studied building, an overall pumping rate of 963 m3 /h is required. **A Monte Carlo Simulation provides a probability distribution of the capital costs of the ATES with a mean value of 1.3 ± (0.1) million €. The underground part of the ATES system requires about 60% of the capital costs and therefore forms the major cost factor. In addition, the ATES is compared with the presently installed supply technology of the hospital, which consists of compression chillers for cooling and district heating. Despite the 50% higher capital costs of the ATES system, an average payback time of about 3 years is achieved due to lower demand-related costs. The most efficient supply option is direct cooling by the ATES resulting in an electricity cost reduction of 80%. Compared to the reference system, the ATES achieves CO2 savings of about 600 tons per year, hence clearly demonstrating the potential economic and environmental benefits of ATES in Germany."**

Table 3 Design parameters of the considered ATES system

Parameter	Number	Unit	Lifetime (years)
Cold well	3	–	–
Warm well	3	–	–
Well depth *H*	35	m	–
Well diameter	0.8	m	–
Screen length *L*	30	m	
Heat Exchanger	1	–	20–30[a]
Submersible pump	6	–	5–7[b]
Well distance	106–318	m	–
ΔT	4	K	–
Heat pump	2	–	20–30[a, c]
ATES	–	–	> 30

[a] VDI 2067 (2012), [b]GHJ (2017), [c]Bloomquist (2000)

"Capital costs of ATES system

The parameters used to determine the capital costs of the ATES system CATES are not site-specific, which means they have a strong variability. Some component costs, such as that for the heat exchanger are derived from literature (Seider 2006; Vanhoudt et al. 2011). Others, are used from comparable shallow geothermal projects or from service catalogues (GHJ 2017; GWE 2017; LANUV 2015). In this case, an accurate and deterministic calculation of the capital costs is not feasible. Thus, a Monte Carlo Simulation with 100,000 iterations quantifies the uncertainty of each parameter. The simulation and the sensitivity analysis are both carried out with the software @Risk (version 7.5) (Palisade 2019). For every parameter, a symmetric triangular distribution bounded by a minimum, mode and maximum value is used. The most likely value is the mode while towards the minimum and maximum values the probability decreases continuously. In the present simulation, the minimum and maximum values are the best (cheapest) and worst-case (most expensive) scenarios."

Table 4 Minimum, mode and maximum values for the Monte Carlo Simulation of the C_{ATES}

Category	Component	Minimum (€)	Mode (€)	Maximum (€)
Pre-investigation/ Feasibility	Site inspection[a]	50	1216	2382
	Construction schedule[a]	5	846	1687
	Feasibility study[b]	3939	22,488	41,037
	Design planning[c]	6200	47,706	89,212
Preparation	Site equipment[a, d]	1738	7319	12,900
	Transport drilling rig[e]	767	4701	8636
	Movement drilling rig[a, d]	300	7950	15,600
	Sampling & core boxes[a, d]	924	9114	17,304
	Bore log & drilling profile[a, e]	539	803	1066
	Clear washing & pressure washing[d]	31,592	36,706	41,820
	Pumping tests[a]	26,338	35,319	44,300
Drilling	Well drilling[f]	24,780	90,825	156,870
Well piping and well installation	Filter pipe[a, d, e]	35,250	48,375	61,500
	Solid wall pipe[e]	14,160	30,881	47,602
	Centering[d, e]	24	102	180
	Bottom cap[a]	48	480	912
	Well head[a]	1166	18,313	35,460
	Water chamber[a, e]	40,800	46,305	51,810
	Shaft cover[a, d]	767	2934	5100
	Filter gravel/sand[a]	826	21,293	41,760
	Counter filter[a]	28	464	900
	Clay seal[a, d]	2687	63,077	123,467
	Submersible pumps[d]	15,570	21,585	27,600
	Stand pump[d, g]	25,200	30,823	36,446
	Well connections[a]	1204	52,298	103,392
Controlling & Monitoring	Electronic switchboard[a]	2213	50,982	99,750
	Water flowmeter[a, f]	893	9105	17,316
	Pump control system[a, e]	1779	48,350	94,920
	Site equipment monitoring well[a, e]	2100	11,550	21,000
	Movement drilling rig monit. well[a, e]	162	925	1687
	Drilling monitoring wells[a, e]	2057	30,729	59,400
	Control line[d]	15,000	20,000	25,000
	Electricity connection[d]	35,000	55,000	75,000
Piping	Horizontal piping[d]	189,815	331,988	474,161
	Pressure washing[d]	7161	8638	10,115
Building integration	Heat pump[g]	11,456	41,365	71,274
	Heat exchanger[h, i]	65,600	67,800	70,000

Each single cost item is summarised in seven different categories

[a] LANUV (2015), [b]MacKenzie and Cusworth (2007), [c]Chiasson and Culver (2006), [d]GHJ (2017), [e]LANUV (2004/2005), [f]Sanderson (2018, personal communication), [g]GWE (2017), [h]Seider (2006), [i]Vanhoudt et al. (2011)

Table 5 Input parameters to calculate the current costs of the ATES system

Parameter	Minimum	Mode	Maximum
COP heat pump $COP_{HP}^{a,b}$	4	4.5	5
Electricity costs *EC* (ct/kWh)[c]	16	16.5	17
Maintenance M_{ATES} (%)[d]	–	4	–
Replacement R_{ATES}		Table 2	
Heating period t_H (h)		2043	
Cooling period t_C (h)		1558	

[a] Boissavy (2015), [b] International Energy Agency (2007), [c] Stindl (2017, personal communication) [d] Sommer et al. (2015)

Table 6 Parameters defining the capital and current costs of the district heating supply

Category	Parameter	Minimum	Mode		Maximum
Capital costs C_{DH}	Excavation work (€/m)	101.15[a]	113.05		124.95[b]
	Piping (€/m)	232.05[b]	431.40		630.70[c]
	Contingency (%)		10[d]		
		Karlsruhe[e]	Ulm[f]	Pforzheim[g]	Emmendingen[h]
Current costs	Commodity price *CP* (ct/kWh)	5.87	5.90	8.96	8.94
	Power price *PP* (€/kW)	35.16	50.54	18.72	23.80
	Basic price *BP* (€)	191.00	558.00	–	257.04
	Efficiency for consumer η_{DH} (%)[i]	98			
	Maintenance (%)[j]	1			

[a] Stadtwerke Sindelfingen (2007), [b](2018), [c]Stadtwerke Waldkraiburg (2018), [d]HallamICS (2012), [e]Stadtwerke Karlsruhe (2018), [f] Stadtwerke Ulm (2018), [g]Stadtwerke Pforzheim (2019), [h]Stadtwerke Emmendingen (2019b), [i]Gudmundsson et al. (2013), [j]Konstantin (2017)

Results ▫

"The result of the **Monte Carlo Simulation for the capital costs of the ATES** system after 100,000 iterations is presented in Fig. 5, showing a normal distribution with a mean value of **1.285 (± 0.08) million €.** The major cost factor of about **60% is associated with the underground part consisting of six wells, pipes and groundwater measuring points.** The part of the ATES system above the ground includes the building integration (**heat pumps and heat exchanger) and contributes to 23% of the capital costs. The remaining 15% of the capital costs belong to the pre-investigations and the construction site installation.** The capital costs are dominated by well piping and well installation…. The pricing level is dependent on the service provider and the quality of the installed components. Higher costs for well piping and installation could increase the capital costs by more than 10%. Thus, the planner of an ATES system should carefully choose the components for the implementation of the wells.. according to actual requirements. Controlling and monitoring are also a significant factor when taking into account the capital costs. Accurate monitoring is crucial to assure an efficient, long-term operation of an ATES system (Kalaiselvam and Parameshwaran 2014). The building integration, including heat pumps and heat exchanger, is less sensitive to the capital costs. However, the performance of the heatpump is particularly significant to the efficiency of the ATES system and therefore to the current costs (see "Comparison" section)"

(https://geothermal-energy-journal.springeropen.com/articles/10.1186/s40517-019-0127-6)

Siddarth Durga 2020 (BTES-HP) at US

Source: https://ecommons.cornell.edu/server/api/core/bitstreams/31afcf90-a4ea-4d13-8602-93956fd683b6/content

“The capital cost of the infrastructure is primarily driven by the borehole drilling cost ($199,800), the heat pump capital ($92,148), and the installation and materials costs ($106,306). Engineering/design costs ($59,738) and contingency measures ($39,825) constitute the remaining capital investment. Meanwhile, the operation and maintenance (O&M) costs are principally driven by the consumption of electricity (71% of total O&M costs) from heat pumps (65% - $12,564/year) and fluid distribution pumps (6% - $1,021). Annual maintenance cost is assumed to be 1% of the total capital invested and is assumed to increase by 2% every year. The hot fluid stream (80oC) obtained from the CHP during the injection period is assumed to be free of cost and hence is not included in the annual O&M costs.

Table 5.6: BTES + HP project - Detailed Breakdown of Capital, Operation and Maintenance costs

Equipment/Job	Quantity required	Cost per unit	Capital Cost
Borehole Drilling	37 boreholes x 90 m depth	60 $/m (Lin, Xiaobing, et al 2019)	$199800
U-tube Installation	37 boreholes x 90 m depth	20 $/m	$66600
PE-RT pipe	3330 m	0.82 $/m	$7675
U-tube connectors	37	11.5 $/unit	$426
Thermal grout	1170 TG lite grout bags	10 $/unit ("Calculator " GeoPro Inc.)	$11703
XPS Insulation	2739 ft²	4.71 $/ft² ("Why Choose Spray Foam Insulation vs. Rigid XPS Foam Board In.")	$12900
Heat pump Capital Cost	250 KW	368.6 $/KW Staffell, Iain, et al. (2012)	$92148
Heat pump Installation Cost		10% of HP capital cost	$9215
Engineering and Design		15% of total capital cost	$59738
Contingency Cost		10% of total capital cost	$39825
		Total Capital Cost	$497817
Equipment/Job		**Cost per Unit**	**O&M Costs**
Heat pump electricity Cost		5 cents/kWh	$12564
Pump electricity Cost		5 cents/kWh	$1021
Maintenance Cost		1% of the capital cost	$4978
		Total O&M Cost	$17027/year
Revenue	**Amount**	**Cost per Unit**	**Revenue**
Natural Gas Savings	7349 MMBTU	8 $/MMBTU	$58795
Heating Provided	2714.88 MMBTU	14.22 $/MMBTU	$38600
		Revenue	$97400/year

Bujakowski et al 2020 (Poland –reconstruction of wells for geothermal energy):

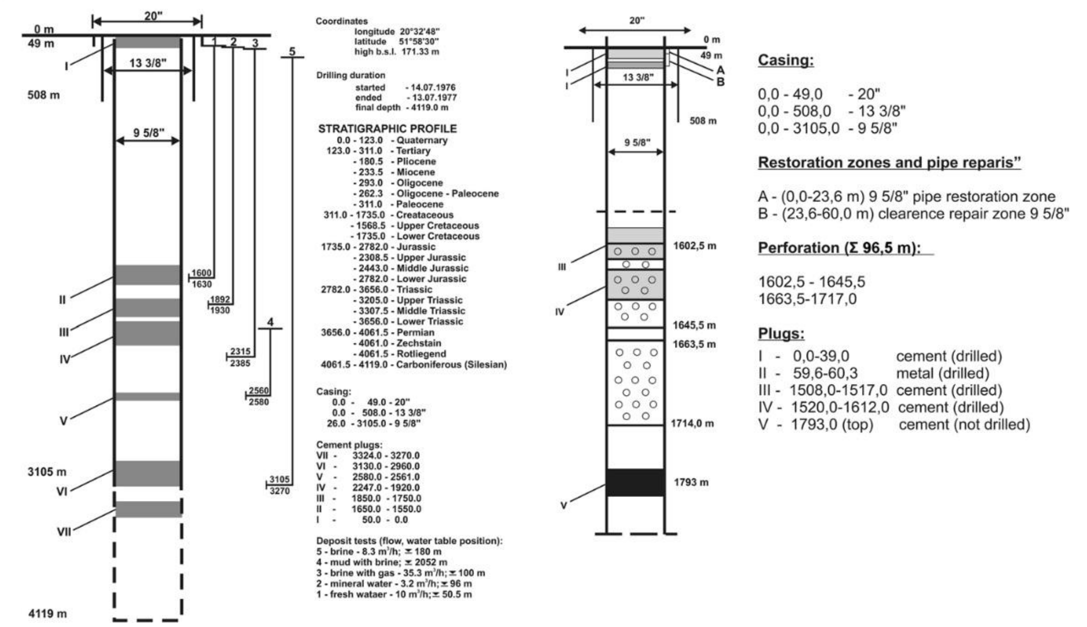


Fig. 4 Mszczonów IG-1 well—1977 (left) and post 1999 reconstruction (right) (Bujakowski et al. 2017)

Technical work, which included:

- drilling works and securing the well;
- making the reservoir accessible;
- installations and operating equipment.

Studies and reservoir tests including:

- flushing;
- measurement pumping (step-drawdown test);
- pre-operation pumping;
- hydrodynamic tests;
- geophysical studies of absorption zones;

examination of well technical condition;

- physico-chemical analysis of waters;
- mineralogical and petrographic studies;
- isotope analysis of waters.

Bujakowski *et al. Geotherm Energy* *(2020) 8:10*

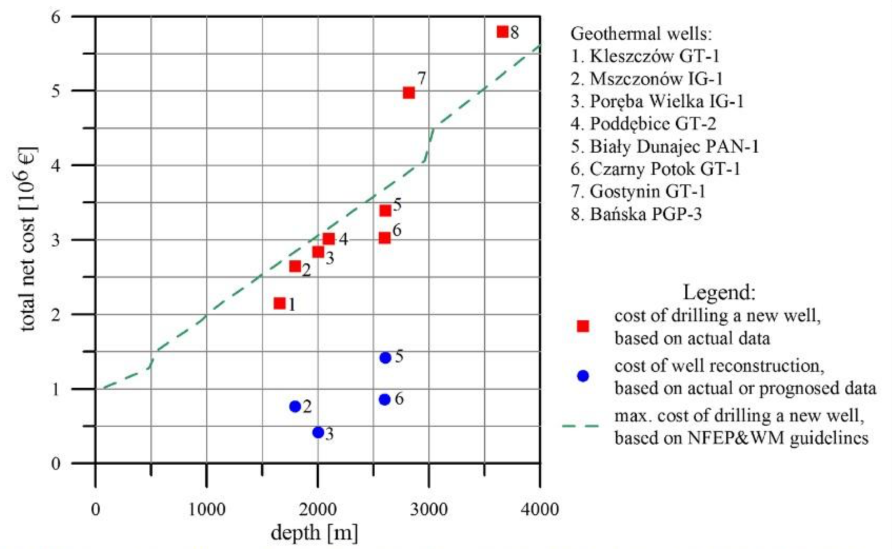


Fig. 16 A summary of the actual costs of drilling and reconstructing selected geothermal wells in Poland

For the 4 examples in Poland, costs vary between 0,8*10^6 Euro (800,000) and 1,4**10^6 Euro (1,400,000)

4. What would be the cost of production equipment for methods DBHE, BTES, ATES, HE, EGS? Well downhole equipment, wellhead, annual maintenance cost,… Please describe each method.

An estimated 60,000 Euro for maintenance (integrity check; but only every 5 years).

10m Filter line ca 10,000-20,000 euro.

Wellhead - ca 250,000 euro

Pump – 100,000 + 100,000 workover (ca every 20 years)

Lahanan and Tabares-Velasco 2017 – Seasonal Thermal-Energy Storage: A Critical Review on BTES Systems, Modeling, and System Design for Higher System Efficiency

Cost (quantitative)

ATES – low initial drilling and equipment costs, but high maintenance costs (Rad et al., 2013; Schmidt and Mangold 2006, Heseraki et al 2015)

BTES – high drilling costs, low maintenance and manufacturing costs, modular construction costs (Sibbet and McClenahan 2015; Nussbicker-Lux 2012; Gabriela 2012)

5. What would be the approximate maintenance cost for each method DBHE, BTES, ATES, HE, EGS on a 5-year production base? Well, surface equipment, piping, valves, …

On average, equipment should last ca 30 years. Pump lasts maybe 1-20 years. One time per week control (just salary costs). (No valves needed).

6. What would be the footprint of the whole installation considering well location, surface facility, piping, etc? Please provide the information for each method DBHE, BTES, ATES, HE, EGS

Some examples from Germany (just measured area in Google Earth):

Groß Schönebeck ca 2500 m^2

Potsdam (drilling location + reserve area) = 6000 m^2

7. How much energy could be produced by each method DBHE, BTES, ATES, HE, EGS in best case scenario and in worst case scenario? Please define the energy in watt (W) for each method.

The active/producing geothermal energy plants and their respective production in Watt are enlisted below (end of this document part). As the actual production in Germany is quite low (between Ptherm of 0,06 and 40 MW), we also undertook research in the existing literature:

Häring 2007:"The performance of a geothermal well depends on its productivity and the temperature of the pumped water respective steam. The productivity is a function of the inflow from the rock and the subsidence of the pressure in the borehole, which occurs due to the pumping process. The flow rate can be increased with a larger pump capacity, thereby energy consumption increases. This energy expenditure must be subtracted from the total performance of the system."

Huang et al 2022 (DBHE)

"The key component of MD-GHPs is the deep borehole heat exchanger (DBHE). Currently, the majority of research on DBHE heat transfer performance is done through field tests and numerical simulation analysis [19]. For example, Deng et al. [20] tested four projects with DBHE in cold regions, and the results showed that the **average heat extraction rate can reach 79-144 W/m and the coefficient of performance (COP) of heat pump unit can reach 5-6.** Huang et al. [21] also conducted field testing and observed that the **heat extraction rate of DBHE can reach 238 W/m and the performance coefficient of the system can reach 7.0**. In addition, Li et al. [22] conducted a 1100-h field test on a project, with findings indicating that the heat extraction **rate of DBHE can reach 108 W/m and the performance coefficient of the system can reach 4.7**.

Conclusions: The results show that the operation stability of the system is negatively correlated with the run-stop ratio, and reducing the run-stop ratio is beneficial to improve the system stability. Secondly, with the decrease of run-stop ratio of the system, the outlet water temperature of DBHE increases gradually. **Overall, the lower the run-stop ratio is, the smaller the heat loss rate is.** Most notably, the run-stop ratio is adversely connected with thermal recovery of rock and soil, as well as DBHE operation stability, **whereas the run-stop ratio is positively correlated with DBHE heat loss rate**. The heat affected radius of DBHE on the surrounding rock and soil is 91.36 m after 15 years of operation, when the run-stop ratio is 24:0. In addition, the heat affected radius of DBHE is also related to the run-stop ratio.

Actual energy production in Germany (geothermal energy); Source: www.geothermie.de

Brandenburg State:

*Neuruppin: Hydrogeothermie (**HE**?); producing since 2007; **Pt_{herm}: 1,4 MW** (Tmax: 63,4°C; Depth: 1702 m; production rate: 4,2 l/s)

*Groß Schönebeck: research (**EGS**?); since 2011; Tmax: 150°C; Depth 4309 m

*Potsdam: under construction; first drilling (20 Mio euro): Hydrogeothermie (HE?), Tmax: 47°C; **Pt_{herm}: ca. 4,3 MW** (8 more planned until 2030; 160 Mio Euro; source: https://www.maz-online.de/lokales/potsdam/geothermie-potsdams-erste-erdwaerme-bohrung-ist-ein-erfolg-waerme-fuer-6900-haushalte-aus-der-tiefe-PP5FMVUDLBDNFOLY2YJFMHN76M.html

*Prenzlau: planning phase; Hydrogeothermie (HE?); already working:Thomas-Müntzer-Platz, Prenzlau: ; **Pt_{herm}: 500 kW**; Sonde in 2800 m Tiefe, 108 °C heisses Wasser; Geothermal well Prenzlau Gt Pr 2/85 was deepened and restructured to a deep borehole heat exchanger (**DBHE**) Prenzlau Gt Pr 2a/94, source: Göthel 2014)

Berlin:

Berlin (Reichstag): Aquiferspeicher (**ATES**); Tmax: 70°; depth: 300 m; production rate: 27,8 l/s; since 1999

Saxony State:

Zwickau: Grubenwasser (mine drainage; HE?); producing; Tmax: 26°C; since 2018; Depth: 628m

Mecklenburg Vorpommern State:

*Neubrandenburg: Aquiferspeicher (ATES); producing; Tmax: 80°C; Depth: 1268 m; production rate: 28 l/s; since 1987; (https://www.gtn-online.de/projekte/aquiferwaermespeicher-fuer-ein-gas-und-dampfturbinenkraftwerk-in-neubrandenburg/: heat storage 12,000 MWh; heat extraction 8,000 MWh; heat gain: 70%)

*Waren: Hydrogeothermie (**HE**); producing; **P_{therm}: 1,3 MW**; Tmax: 63°C; Depth: 1565m; production rate: 17 l/s; since 1984;

*Neustadt-Glewe: Hydrogeothermie (**HE**); producing; **P_{therm}: 4 MW**; Tmax: 99°C; Depth: 2450 m; production rate: 35 l/s; since 1994

Niedersachsen State:

*Horstberg: Hydrogeothermie (HE); Tmax: 159°C; Depth: 3920 m

*Hannover: research; **P_{therm}: 2 MW**; Tmax: 169°C; depth: 3820 m

Nordrhein-Westfalen State:

*Marl: Sonde (**DBHE**); **P_{therm}:** 0,06 **MW**; Tmax: 20°C; Depth: 700m; since 2010)

*Essen: Grubenwasser (mine drainage, HE?): **P_{therm}: 0,8 MW**; T_{max}: 35°C; Depth: 1200m; production rate 300 l/s; since 2010)

*Bochum Werne: (mine drainage; HE?): **P_{therm}: 0,4 MW**; T_{max}: 20°C; Depth: 570m; production rate 32 l/s; since 2012)

*Arnsberg: Sonde (**DBHE**): **P_{therm}: 0,35 MW**; T_{max}: 90°C; Depth: 2835 m; production rate 32 l/s; since 2012)

*Alsdorf: research; T_{max}: 26 °C; Depth: 900m; since 2018

*Aachen-Weisweiler: under construction; T_{max}: 150°C; Depth: 5000m

Hessen State:

*Heubach/Groß-Umstadt; producing (DBHE); **P_{therm}: 0,09 MW**; Tmax: 36,7°C; Depth: 773m; production rate: 5l/s; since 2012)

Rheinland-Pfalz State:

*Landau: Sonde (DBHE), producing; **P_{therm}: 0,08 MW**; Depth: 800 m; since 2014)

*Landau: Hydrogeothermie (HE); producing (heat and electricity); **P_{therm}: 5 MW**; **P_{el}: 1,8 MW** T_{max}: 159,7°C; Depth: 3291 m; production rate: 70 l/s; since 2007)

*Insheim: Hydrogeothermie (HE); producing (only electricity); **P_{el}: 4,8 MW;** T_{max}: 164°C; Depth: 3600 m; production rate: 80 l/s; since 2012)

Baden-Württemberg state:

*Weinheim: Hydrogeothermie (HE), producing; **P_{therm}: 1,1 MW**; T_{max}: 65°C; Depth: 1150 m; production rate: 10 l/s; since 2005)

*Bruchsal: Hydrogeothermie (HE); producing (heat and electricity) **P_{therm}: 1,2 MW**; **P_{el}: 0,5 MW** T_{max}: 131°C; Depth: 2542 m; production rate: 31 l/s; since 2009)

*Pfullendorf: Hydrogeothermie (HE); producing **P_{therm}:?? ;** T_{max}: 75°C; Depth: 1530 m; production rate: 25 l/s; since 2020)

Bayern State:

*Unterschleißheim: : Hydrogeothermie (HE); producing; **P_{therm}: 8 MW**; T_{max}: 80°C; Depth: 1960 m; production rate: 93,3 l/s; since 2003)

*Erding: : Hydrogeothermie (HE); producing; **P_{therm}: 10,2 MW**; T_{max}: 65°C; Depth: 2359 m; production rate: 48 l/s; since 1998)

*Straubing: : Hydrogeothermie (HE); producing; **P_{therm}: 2,1 MW**; T_{max}: 36,5 °C; Depth: 825 m; production rate: 31,4 l/s; since 1999)

*Garching b. München: Hydrogeothermie (HE); producing; **P_{therm}: 7,95 MW**; T_{max}: 75 °C; Depth: 2226 m; production rate: 100 l/s; since 2011)

*München-Freiham: Hydrogeothermie (HE); producing; **P_{therm}:13 MW**; T_{max}: 91,9 °C; depth: 2.518 m; production rate: 121 l/s; since 2016

*Unterföhring: Hydrogeothermie (HE); producing; **P_{therm}: 10 MW**; T_{max}: 87 °C; depth: 2.124 m; production rate: 75 l/s; since 2009

*Unterföhring II: Hydrogeothermie (HE); **P_{therm}: 11,3 MW;** T_{max}: 93 °C; depth: 2.341 m; production rate 90 l/s; since 2014

*Oberhaching-Laufzorn/ Grünwald: Hydrogeothermie (HE); producing (heat and electricity) **P_{therm}: 40 MW; P_{el}: 4,3 MW;** T_{max}: 135 °C; depth: 3.755 m; producing rate: 132 l/s; since 2011

* Taufkirchen/Oberhaching: Hydrogeothermie (HE); producing (heat and electricity); **P_{therm}: 40 MW; P_{el}: 4,3 MW**; T_{max}: 136 °C; depth: 3.696 m; producing rate: 120 l/s; since 2013

*Unterhaching: Hydrogeothermie (HE); producing; **P_{therm}: 38 MW**; T_{max}: 123,7 °C; depth: 3.350 m; production rate: 140 l/s; since 2007

*Kirchstockach: Hydrogeothermie (HE); producing (heat and electricity); **P_{therm}: 12 MW; P_{el}: 5,5 MW**; T_{max}: 141 °C; depth: 3.882 m; production rate: 140,5 l/s; since 2013

*Simbach/Braunau: Hydrogeothermie (HE); producing; **P_{therm}: 9 MW**; T_{max}: 81,7 °C; depth: 1.942 m; production rate: 90 l/s; since 2001

*Waldkraiburg: Hydrogeothermie (HE); producing; **P_{therm}: 14 MW**; T_{max}: 111,5 °C; depth: 2.718 m; production rate: 80 l/s; since 2012

*Garching an der Alz: Hydrogeothermie (HE); producing (heat and electricity); **P_{therm}: 6,88 MW; P_{el}: 4,9 MW**; T_{max}: 123 °C; depth: 3.837 m; production rate: 105 l/s; since 2021

* Kirchweidach: Hydrogeothermie (HE); producing (heat and electricity); **P_{therm} : 30,6 MW; P_{el}: 0,68 MW**; T_{max}: 127 °C; depth: 3.421 m; production rate: 80 l/s; since 2013

* Traunreut: Hydrogeothermie (HE); producing (heat and electricity); **P_{therm} : 12 MW; P_{el}: 5,5 MW**; T_{max}: 120 °C; depth: 4.646 m; production rate: 168,6 l/s; since 2014

*Sauerlach: Hydrogeothermie (HE); producing (heat and electricity); **P_{therm} : 4 MW; P_{el}: 5 MW**; T_{max}: 140 °C; depth: 4.480 m; production rate: 110 l/s; since 2014

*Holzkirchen: Hydrogeothermie (HE); producing (heat and electricity); **P_{therm} :24 MW; P_{el}: 3,6 MW**; Tmax: 157 °C; depth: 5.078 m; production rate: 60 l/s; since 2018

*Mauerstetten: Forschung (research); producing; T_{max}: 130 °C; depth: 4.080 m

*Dürrnhaar: Hydrogeothermie (HE); producing (only electricity); **P_{el}: 5,5 MW**; T_{max}: 141 °C; depth: 3.926 m; production rate: 133 l/s; since 2012

8. What are the losses of energy for each method DBHE, BTES, ATES, HE, EGS from the wellhead till the heat exchanger of the end user? Please provide the information in watt (W) for each method.

Losses for district heating from Vesterlund et al., 2013

https://www.diva-portal.org/smash/get/diva2:1008413/FULLTEXT01.pdf

Abstract:

To be able to create a model that accurately describes a district heating system, it is important to identify the thermal losses and how they are distributed. However, general methods targeting the determination of losses are scarce in the literature. **In the current case the losses for a district heating system in Kiruna, a town in northern Sweden, has been estimated in the year 2010 to be 12%, which is in the range for a typical Swedish network**. Unfortunately, detailed information of the thermal losses is lacking. In this paper two methods to determine loss distribution in a district heating system are presented. Two databases of pipe lengths and diameters have been compiled for two piping categories, loops and feeds. Any missing data regarding pipe diameters in the map has then been determined with the two different methods. In the first method average pipe diameters for loops and feeds are calculated. All pipes with unknown diameter are then assumed to have the average one. The second method considers a percentage based distribution of known diameters and assigns the same distribution to the missing pipe diameters. The losses were estimated in the whole system according to the data from a pipe producer catalogue, in which losses are calculated according to current European standard. The results show that the losses in the system are similar to the losses caused by pipes with the lowest insulating capacity. By using the two methods two fictitious pipe series reproducing exactly the losses in the system are created by scaling the calculated losses of the catalogue pipe series which would give the most similar losses (the one with the lowest insulating capacity). This adjustment was +3.1% by using the first method, and +4.9% by using the second method. The major conclusion of this study is that, both methods can be used for calculating the distribution of thermal losses in the district heating system of Kiruna; moreover, this kind of analysis can be an important tool for analyzing investments in the district heating network in Kiruna.

*As a rule of thumb the **total annual losses in the network amount to around one tenth of the annual produced heat** (Frederiksen et al., 1993). These losses should be kept at a minimum to obtain a high efficiency in the network (Larsen 2002; Gabrielaitiene 2007).

The four largest parameters that affect the losses in a DH network are (Frederiksen et al., 1993):

- The amount of insulation around the pipes
- The pipe dimension
- Supply and return temperature
- The geographical distribution of the heat demand.

The amount of insulation and pipe dimension are determined when the network is created. When planning for new DHS areas, the following steps are performed:

- Pilot study for understating the existing system, possibilities for rebuilding and incorporating new parts to existing network, heat demand for the new area, etc.
- Calculations of heat transports capacity, power limits, heat losses, etc.
- Drawings to the contractor for executing the new piping.

In the planning step, heat loss data from pipe producer are used. These data arecalculated according to current standards.

*Kiruna – 190 km of pipes (since 1960); in 2010 of 259 GWh produced, 228 GWh consumed and 31 Gwh loss.

This gives a percentage loss of 12%, and according to (Çomaklı et al., 2004; Frederiksen et al., 1993; Bohm 2001; Dalla Rosa 2011) that percentage is normal for a Swedish DHS. General methods targeting the determination of losses are scarce in the literature.

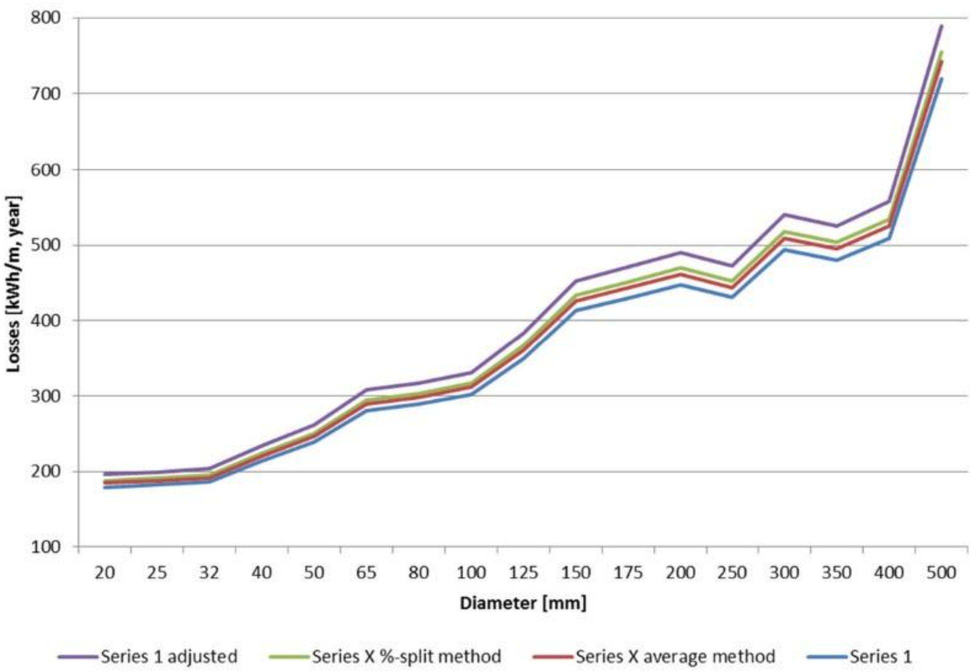
The characteristics for the network in Kiruna can be summarized as follows:

- Origin from 1960th
- Continuously developed
- Continuous maintenance
- Total losses of 12%

In overall these characteristics specify a normal Swedish DHS, and the DHS in Kiruna can be considered as a typical Swedish DHS.

The aim of this paper is therefore to:

- Identify and quantify the heat losses in the Kiruna DHS.
- Present a method for evaluation and determine the losses in the system.
- Evaluate the proposed methods



Masatin et al., 2016 – Evaluation factor for district heating network heat loss with respect to network geometry

Abstract: The district heating (DH) networks are widely in use in northern countries. It is often necessary to compare the efficiency of different DH networks from their size and layout and for this purpose mostly the “relative heat loss” is used. Generally, this parameter gives a first impression of the network. **However, relative heat loss does not reflect the actual efficiency of pipe insulation or overall efficiency of the network; moreover, at least heat consumption density should be considered. E.g., the average**

relative heat loss in Denmark is about 20% and in Sweden only 9%. Does this mean that the Swedish network insulation is 2 times better? The data from different networks is taken in order to make an analysis and figure out a proper comparison methodology. The following main parameters are taken into account: supply, return and ambient temperatures; the network average diameter and length; annual heat consumption or linear heat density.

Conclusions: **analysis of factors influencing district heat loss - results show that most important factors are network temperature level, insulation heat transmission coefficient, network average diameter and length**. "As a result, an overall network heat transmission coefficient was found as most suitable factor for the netowkr insulation quality analysis and efficiency comparison between networks. The K-factor depends on the pipe geometry and that is why it should be used simultaneously with the average diameter of reference network. Moreover, in order to exclude the pipe and insulation material properties and thickness, the average inner diameter should be used. For a better comparison of networks, the technical evaluation factor was offered as a degree of renovation potential for the network insulation. The TEF was calculated for 14 networks with different rate of preinsulated pipes, and the correlation was confirmed.

In summary, the relative heat loss number is not a correct factor for the network evaluation, because heat loss depends on many other parameters and network insulation with high relative loss may work well and vice versa." (if a considerable amount of pipes is not underground, the TEF calc needs add correction)

Jazubek et al., 2023 – Mathematical modelling and model validation of the heat losses in district heating networks

Abstract: Today the most popular system of district heating systems is based on pre-insulated pipes arranged in parallel or twin-pipe configuration. One of the greatest difficulties with heat distribution through pipelines is thermal loss from the distribution. The most efficient solution to that problem is optimising the insulation wall thickness layer according to the pipe diameter. Heat losses should be minimised at a relatively low investment cost to find the most suitable insulation thickness economically. Numerous studies focus on analytical (1D model) calculations and numerical simulations. However, there is a research gap related to laboratory devices that allow measuring the operation parameters (fluid flow, the temperature of the fluid in the supply pipe and the return pipe). This paper presents an analysis of the heat losses from pre-insulated pipes and twin pipes in the heating system network. This study compares the heat losses in the ground calculated by analytical solution (1D model) with the measurements on the dedicated experimental setup. The calculations have been made for several heating network pipe variants: twin pipes: DN40, DN50, DN65, and their counterparts in a single parallel pre-insulated system. The insulation thickness used in all cases is 30.85 mm for DN40 and 32.00 mm for DN50 and DN65. The insulation is made of rigid polyurethane foam that meets the requirements of the PN-EN 253 standard. During the investigation, the thermal conductivity of insulation material is examined. The obtained thermal conductivity results are used in the calculations. The results from laboratory devices and analytical models have been compared, demonstrating good agreement – with a low error level in the range of approximately 8%, depending on the type of district heating pipe. The validated mathematical model of the heating network is then used to calculate the heat losses in a heating network connecting an underground storage tank with a ground source heat pump.

The economic analysis shows that after 5 y, a return on investment is expected when comparing twin-pipe systems and single-pipe pre-insulated heating networks.

Conclusions: The paper presents a method for heat loss analysis from pre-insulated pipes in comparison to twin-pipe configuration within the context of DHS. **The highest heat losses occurred in cases in pre-insulated pipes. The lowest heat loss is obtained for the twin pipe system.**

Shuai Huang et al., 2022 "Heat transfer performance of deep borehole heat exchanger with different operation modes. (DBHE)

Lanahan and Tabares-Velasco 2017 – Seasonal thermal-energy storage: a critical review on **BTES systems**, modeling and system design for higher system efficiency

ATES - The lack of insulation in this system is an important design consideration. To avoid excessive heat losses, the maximum volume to surface area ratio should be achieved through optimal borehole depth for the fluid bearing pipes (Rad et al., 2016; Dincer and Rosen 2011; Lee 2009; Ganguly and Kumar, 2015). In ATES storage, the thermal front is important for determining storage efficiency (Ganguly and Kumar, 2015). A thermal front characterizes the temperature profile between injected water into ATES, for storage, which if allowed to reach the production well will result in greater heat loss (Ganguly and Kumar, 2015). Drilling cost for ATES systems range broadly from 200 $/ft to 970 $/ft (Vanhoudt et al 2011; Sommer et al., 2015). Due to the nature of ATES open-loop configuration, typically only two boreholes are need in comparison to many for a comparable energy storage system of BTES variety and may cost significantly less.

BTES Borehole Thermal Energy Storage

"…, BTES stores thermal energy utilizing soil and rock as a thermal medium (Rad and Fung 2016; Mangold et al., 2004; Sibbet 2012; Zhang et al., 2015; McClenahan et al., 2006). BTES is a prevalent choice of seasonal storage because of its universal applicability, not limited to specific formations as with ATES and GWTES (Rad and Fung 2016; Dincer and Rosen 2011; Kalaiselvam and Parameshwaran 2014; Xu et al., 2014; Rad et al., 2013; Nussbicker-Lux 2012). However, variations in climate can impact the performance of BTES systems (Nam et al., 2015). **Limitations of BTES include the comparatively large amount of heat loss compared to insulated water tank or gravel tank systems** (Rad and Fung 2016; Schmidt and Mangold 2006). ATES and CTES systems also see an added advantage of combined short and seasonal time scale storage by combining large storage space and water as the storing medium (Nordell 2000). **A final major concern for BTES installation is the drilling cost associated with the borehole field, considerably more than in ATES configurations.** ….. Despite high drilling cost thermal energy storage using boreholes is still a cost effective option. In comparison to thermal energy storage, batteries, a competing mode of energy storage, offer an attractive energy storage solution because of reduced unit storage size. Despite this advantage, BTES storage possesses a number of promising assets. BTES systems offer increasing energy return throughout their lifespan, while battery longevity is limited by the chemical reactions utilized (Sibbet and McClenahan 2015; Geth et al., 2011). The cost of batteries ranges from $300/kWh, to $400/kWh for medium and large size storage applications such as the Tesla Powerwall (Geth et al., 2011; Nyvkist and Nilsson 2015; Gerssen-Gondelach and Faaij 2012). BTES energy storage at Drake Landing has a capital cost of $2.6/kWh (thermal) (Sibbet 2012).

BTES stores thermal energy and not electrical energy which represent significantly different capital costs.

9. What are the implementation and production risks for each method DBHE, BTES, ATES, HE, EGS? Please describe the risk for each method.

Risks/method:

DBHE: Low thermal conductivity, low groundwater flow

BTES: groundwater flow (possibly permeable fault zones), low thermal conductivity

ATES: Porosity/permeability insufficient, insufficient groundwater flow, fluid volume too small

Hydrothermal: Production rates too low, no permeability

EGS: no possibility of stimulation, natural groundwater flow too high

10. What are measures to mitigate the implementation and production risks for each method DBHE, BTES, ATES, HE, EGS? Please describe the risk for each method.

Exploration beforehand.

D. Social analysis

Data in this section concerns evaluating the social aspects of implementation and usage of repurposing technologies.

1. What is the general attitude of reusing old wells by reuse methods DBHE, BTES, ATES, HE, EGS on a well which is active / shut in / abandoned? Please describe each method, which would be more acceptable.

Revising the already producing Geothermal wells, the method employed the most would be HE (see list in C-7). As there are no real “reuse” projects currently, we do not have information about it.

2. What is the opinion of end users (customer groups industry, agriculture and municipality) regarding the use of old wells? Are there any concerns or restrictions? Please provide description and case studies of good practice if any.

We do not know at the moment (no examples in Brandenburg).

3. What would be the benefits for society regarding the reuse of existing wells for implementation of reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method.

   Valid for every method

   - use of geothermal energy
   - reduction of energy costs
   - Save drilling costs
   - projects faster
   - regional geology already known
   - Less emissions
   - Supported by public
   - Independent of weather
   - Reduces the environmental impact of drilling a new well (in terms of required energy input, land use, ...)
   - CO_2 reduction

Deep Borehole Heat Exchangers (DBHE): Efficient Heating and Cooling: DBHE systems provide efficient heating and cooling for residential, commercial, and industrial buildings, reducing energy consumption and costs. Renewable Energy: DBHE systems can facilitate the adoption of renewable geothermal energy for space conditioning, reducing dependence on fossil fuels. based on TG SWOT
Borehole Thermal Energy Storage (BTES): Seasonal Energy Storage: BTES allows excess energy to be stored in the ground during off-peak times and retrieved when needed, improving energy efficiency. Grid Stabilization: BTES systems can support grid stability by providing stored energy during peak demand periods. based on TG SWOT
Aquifer Thermal Energy Storage (ATES): Large-Scale Heating and Cooling: ATES systems are well-suited for large commercial and industrial heating and cooling applications, reducing energy costs. Sustainable Building Practices: ATES can promote sustainable building practices by using renewable geothermal energy for space conditioning. based on TG SWOT
Hydrothermal Energy (HE): Geothermal Energy Production: HE methods generate renewable electricity from geothermal resources, contributing to a low-carbon energy mix. Reliable Baseload Power: Geothermal power plants provide reliable, baseload electricity, which is essential for grid stability. based on TG SWOT

Enhanced Geothermal Systems (EGS): Expanded Geothermal Resources: EGS has the potential to unlock geothermal resources in regions where traditional geothermal systems are not feasible. Scalable Energy Production: EGS can be scaled up to generate large amounts of geothermal power, contributing to sustainable energy production. based on TG SWOT

4. What would be the risks for society regarding the reuse of existing wells for implementation of reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method.

Borehole Heat Exchangers (DBHE): Well Integrity: Over time, DBHE systems can experience well integrity issues, leading to potential leaks and system inefficiencies Environmental Contamination: Inadequate sealing can result in groundwater contamination, affecting environmental and public health. based on TG SWOT
Borehole Thermal Energy Storage (BTES): Installation Costs: The upfront costs of drilling boreholes and installing infrastructure can be high, potentially affecting project feasibility. Ground Temperature Fluctuations: Seasonal variations in ground temperatures can affect BTES system efficiency. based on TG SWOT
Aquifer Thermal Energy Storage (ATES): Water Quality Concerns: The quality of groundwater in the storage aquifer can be a concern due to potential changes in water chemistry from heat exchange. Regulatory Compliance: Compliance with water management and environmental regulations can be complex for ATES projects. based on TG SWOT
Hydrothermal Energy (HE): Geological Risk: HE projects may encounter geological challenges, like low permeability or rock fractures, limiting energy extraction. Scale Limitations: Not all locations have suitable geothermal resources for large-scale electricity generation. based on TG SWOT

Enhanced Geothermal Systems (EGS): Seismic Risk: Induced seismicity is a concern in EGS, as it involves creating fractures in hot rocks, which can potentially trigger earthquakes. High Drilling Costs: Drilling deep wells in hard rock formations can be expensive and technically challenging. based on TG SWOT

5. What would encourage the potential investors within customer groups (industry, agriculture and municipality) to invest in one of the defined reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method if applicable.

6. What would encourage the potential investors within customer groups (industry, agriculture and municipality) to invest in one of the defined reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method if applicable.

Is there any doubt by the local community regarding implementation of reuse methods DBHE, BTES, ATES, HE, EGS because of leak of trust or bad experience in the past? Please describe each method.

Appendix 4 - Questionnaire Hungary

A. Author and country

Author	György Márton, Klára Bődi, Gábor Magyar, Judit Schäffer
Organisation	CROST Nonprofit Ltd.
Country	HUNGARY
Contact	schaffer@crost.hu, bodi.klara@bvh.hu

1. General status: Are there any geothermal projects in your country currently going on? What is the acceptability of such projects by users and the local community? Please provide a short description.

Short Description:

Hungary's commitment to geothermal energy is showcased through a variety of projects, from the ambitious district heating systems like in Szeged, Győr and Miskolc to applications in balneology and agriculture.

These initiatives not only aim to reduce environmental impact but also highlight the potential of geothermal energy in replacing conventional fossil fuels across multiple sectors. Leveraging its geological features, particularly in the Carpathian Basin, Hungary utilizes approximately 1,000 active thermal wells to meet its diverse heating needs in an eco-friendly manner. The widespread support for these projects underscores the cultural acceptance of geothermal energy as a valuable and sustainable resource, reflecting its integration into Hungary's energy landscape.

Current Geothermal Projects in Hungary:

Szeged District Heating System: This significant geothermal project in Szeged aims to convert nine district heating systems to geothermal operation, with the goal of replacing natural gas with geothermal energy for heating 27,000 dwellings and 500 public buildings. With a nominal capacity of 224 MWt, the project involves drilling 9 production and 18 injection wells into the Late Miocene (Dunántúli Group) sandstone, producing thermal water at an average temperature of 90°C. Set to conclude in 2024, it's anticipated to reduce greenhouse gas emissions by 25,000 tonnes of CO_2 per year, enhancing the city's environmental sustainability.

In Tótkomlós 2 production and 2 reinjection wells were drilled in 2019-2020 to supply a future town heating project and a greenhouse park. Although the wells were successful (providing outflow temperature of 120-130 °C from a depth of 1600-1800 m from Triassic carbonate) the project is pending, as connection pipelines haven't been built yet due to the unjustified heat demand and very high prices to connect the potential users to the grid. There is a plan to use this project for power generation.

2 Industrial projects are under construction in Nyíregyháza and Nyírbátor with 1-1 production and injection wells. One production well is also being built for a new business district in Budapest. In addition, 3 agricultural wells are under authorisation in the Southern Great Plain.

Acceptability of Geothermal Projects:

The District Heating Company of Szeged analysed the perception of geothermal energy in the CROWDTHERMAL project and developed a public engagement approach using a wide range of social media. The general public and local communities in Hungary view geothermal projects positively, appreciating their contribution to reducing carbon emissions, enhancing energy security, and providing sustainable and environmentally friendly heating solutions. This positive reception is bolstered in regions benefiting significantly from these projects, particularly in balneology and agricultural applications, like greenhouse heating, demonstrating the versatility and community-wide benefits of geothermal energy.

2. Do some geothermal projects include repurposed old wells? If yes, what is the user experience and acceptability of the local environment where it is implemented? Please provide a short description.

New exploration licensing legislation since March 2023 has led to abandoned wells being used primarily as test wells, particularly for high enthalpy systems. Moreover, the practice of converting old wells for geothermal use significantly lessens the environmental footprint compared to new drilling operations. This alignment with local and national sustainability objectives highlights Hungary's dedicated commitment to sustainable energy practices. The country's approach not only demonstrates the potential for renewable energy to meet diverse needs but also sets a precedent for environmental stewardship and sustainable development.

3. Are there any reuse projects implemented or in the planning phase? Please indicate the name and a short description, if possible.

Borehole heat exchangers (DBHE) with a concentric “pipe-in-pipe” structure is capable of extracting heat without fluid production from a depth of up to 3000 m. The advantage of DBHEs is that the even “dry” or abandoned oil and gas wells can be utilized. Such a pilot system was built in Kiskunhalas using an abandoned CH-well with an installed capacity of about 200 kW (WeHEAT pilot project).

In addition, it is common to refurbish wells with reduced yields to operate at higher yields and outflow temperatures. Such a project has been started in the case of the Szentes Hospital with the collaboration of the University of Szeged.

4. Is there a promotion of potential reuse of wells in your country? Do investors/state/others show interest in well reuse? If so, please provide a short description.

In Hungary, there is growing interest and support for well reuse, especially from public and private investors. Recognising this demand, the government has created a database of unused wells and made it possible to buy them, although sometimes the legal status of wells is not fully clarified.

However, buying such a well also involves a risk, because the technical condition of the well and its suitability for geothermal use are not always known. But after the purchase, the buyer is responsible for any remediation of the well.

B. Demand patterns for different customer group

Data in this section concerns the knowledge about energy consumption, willingness on changing the current energy source, suitability of geothermal energy regarding the current energy supply chain, …

1. What is the general energy demand of industry, agriculture, and municipalities in your country? Please describe each customer group.

Hungary's primary energy use in 2021 was 1,044 PJ according to the new EU calculation methodology. Final energy consumption in 2021 was 789 PJ under the old methodology, which is 802 PJ under the new methodology. Residential energy accounted for 34% of final energy use, transport for 26%, industry for 25% and trade and services for 11% in 2021.

Final primary energy consumption by sector:

- Industry: 198 PJ
- Transport: 205 PJ
- Households: 269 PJ, of which 75% heating/cooling
- Agriculture: 28 PJ
- Trade, other services: 87 PJ

Energy use in the industrial sector increased by 53% between 2005 and 2021, the highest rate of change of all other sectors. Energy use in transport and agriculture increased by around 20% compared to 2005. Energy use in households has decreased by 5% (but this fluctuates), while energy use in trade and other services has decreased significantly by almost 40%.

The energy intensity of the Hungarian economy (final energy intensity of GDP) remains high relative to the EU total, almost double the EU average of 159 toe/million€, compared to an EU average of 82 toe/million€.

Buildings accounted for 42% of Hungary's final energy consumption in 2021. Based on the energy condition of buildings, it is estimated that around 126 PJ could be saved through cost-optimal renovation.

In 2021, the share of renewable energy sources in gross final energy consumption in Hungary was 14.11%. Overall, 69.2% of renewable energy use in 2021 was for heating and cooling, 20.2% for electricity generation and 10.6% for transport. The share of renewable energy in electricity consumption was 13.66% in 2021 (mainly photovoltaic). The share in transport is 6.2%, while the share in heating and cooling is the highest at 18%, mainly through household biomass use.

Hungary's annual geothermal production reaches 6.5 PJ, of which about 75% is used for energy, with an installed capacity of 1 GW_t. Share of geothermal energy in total renewable energy consumption for heating and cooling is only 6,7%.

2. How many users have experience with using geothermal energy? Which is the preferable technology by end users? Please describe each customer group.

According to the last country update (2022) there were of about 984 active thermal water wells. Since then, about 20 thermal wells have been constructed until now, so overall, there are about 1700 hot water wells in Hungary, out of which around 1000 are active thermal wells.

It is important to mention that out of the cca. 1700 hot water wells, around 300-400 were formerly unsuccessful hydrocarbon research wells (especially in the period 1960-1970) or sometimes depleted hydrocarbon production wells which were transformed to geothermal wells, mainly used by agricultural cooperatives for greenhouse heating. So, there are several examples in Hungary for reusing former research or depleted hydrocarbon wells to HE wells, although the completion of these well transformations were rarely documented and the transformation was usually done with no quality control.

Concerning the cca 1000 active wells, approximately 92% are production wells and only 8% are injection ones. 40% agriculture, 33 % district and space heating, 25 % balneology and the rest is industrial use. The number of users benefiting from geothermal energy is substantial, especially in sectors like agriculture, district heating and balneology.

In agriculture, the nearly 100 users typically prioritize the efficiency and cost-effectiveness of geothermal heating for greenhouses.

Geothermal district heating is available in a total of 21 settlements out of the total of 94 district heating systems (Barcs, Bóly, Cserkeszőlő, Csongrád, Gárdony, Győr, Hódmezővásárhely, Kistelek, Makó, Miskolc, Mórahalom, Nagyatád, Orosháza, Szarvas, Szeged, Szentes, Szentlőrinc, Szigetvár, Szolnok, Vasvár, Veresegyház) where thermal water partially replaces gas-based heating, depending on local conditions. Despite the 21 geothermal DH systems, the total share of produced geothermal heating energy out of the total DH heating energy is rather low, only 2.8%.

There are 162 thermal baths in the country, with 42.8 million visitors in 2022. End-users in the balneological sector prefer technologies that provide a steady supply of hot water, while those in district heating value the reliability and sustainability of geothermal sources. 102 balneological wells are used for heating purposes, corresponding to about 70 baths.

3. Under which circumstances would current users be willing to change the energy source they are using right now? Would any of the defined customer groups be interested in a local accessible energy source?

Users are generally open to changing their energy source if it leads to cost savings, improved efficiency, and environmental benefits. A local, accessible energy source such as geothermal is particularly attractive due to its sustainability and potential for reducing dependence on imported fuels. The agriculture and district heating sectors show high interest in local geothermal sources, aligning with their energy needs and sustainability goals. However, as district heating is officially priced in Hungary, operators are not interested in investing.

4. Would the end user consider geothermal energy usage nevertheless it can cover the base load and they need a backup for peak loads? Is this a major obstacle for the end user's or do they see potential in it?

End users in Hungary are increasingly considering geothermal energy for base load requirements, especially in sectors like district heating and agriculture. The need for backup systems for peak loads is recognized and not seen as a major obstacle. Innovative projects, like those in Szeged, demonstrate the integration of geothermal energy into existing infrastructure, proving its feasibility and potential even when supplementary systems are required for peak demand periods. The same is the situation in the project of Nagyatád geothermal system for utilisation of geothermal waste heat, where the base load heating demand of municipality buildings is covered by geothermal energy and the peak heating capacity is covered by gas boilers. This is a cost-effective solution as in this bivalent heating system the geothermal heating should cover approx. 70% of the total heating capacity need of the buildings, the rest remains to be covered by gas boilers. Considering the total heating energy need, in this bivalent system the geothermal heating covers approx. 90-95% of the total heating energy need of the municipality buildings, while only 5-10% is needed to be supplied by fossil energy. This means that a bivalent geothermal heating system is cost-effective as only approx. 70% of the total heating capacity need should be built in as geothermal heating capacity which results in considerable investment costs savings, nevertheless this bivalent system can generate over 90% of reduction of total fossil energy consumption.

5. Are there any potential customer groups who would be satisfied only with base load energy supply? If yes, please provide the information regarding user, energy load needed and preferable technology, if applicable.

There are customer groups in Hungary that are primarily interested in geothermal energy for base load supply. Balneological facilities, including spas and thermal baths in Budapest and other regions, predominantly utilize geothermal energy for their constant heating needs. Additionally, the agricultural sector, particularly for greenhouse heating in areas like the southern Great Plain, relies on a stable base load supply from geothermal sources. The specific energy load varies across applications but is substantial. Preferred technologies include direct-use geothermal systems, which offer a consistent and efficient supply of thermal energy suitable for these continuous requirements.

C. Economic analysis

Data in this section concerns evaluating the economical side of implementation and usage of repurposing technologies in the energy supply chain.

1. What is the optimal transfer distance of energy for recognized reuse methods DBHE, BTES, ATES, HE, EGS? Depending on flow rate and temperature? Please describe each method.

DBHE, BTES, ATES: For systems with a heat pump (15-20°C), energy can be efficiently transferred over shorter distances, up to a kilometre. For direct heat use with medium temperature (35-60°C), proximity is key, ideally within a few hundred meters.

HE: High-temperature geothermal brine thermal power plants are usually built close to the production well, but the greatest distance is 9 km in Miskolc. In this case, the cost of the insulated pipeline may exceed the cost of drilling the well. The injection well are usually 1 km from the production well. But this may vary depending on the geology.

EGS: A petrothermal EGS system is not yet in operation in Hungary. It is planned that production and injection wells would be deviated near the power plants.

2. What is the cost for implementation of reuse methods DBHE, BTES, ATES, HE, EGS on a well which is active / shut in / abandoned? Please describe each method and each type of well status.

Below are the estimations for total costs of implementation of different reuse methods, including workover, surface equipment, piping equipment and downhole equipment – see excel sheets for details.

DBHE: transforming a well to DBHE well costs around €700,000.

BTES, ATES: not yet in Hungary. Cost of implementation of BTES or ATES is estimated to approx. €600,000-700,000.

HE: Drilling of two new wells (production and reinjection wells) with a depth of 2,000 metres costs around €6 million, while the cost of transforming two 2,000-metre abandoned wells to geothermal production and reinjection wells costs around €900,000-1,000,000.

EGS: not yet in Hungary. Cost of implementation of transforming two 3,000-metre abandoned wells to EGS wells is estimated to approx. €1,600,000.

3. What is the cost of surface infrastructure, depending on expected energy supply by each method DBHE, BTES, ATES, HE, EGS? Please describe each method.

See excel sheets for detailed cost estimations.

4. What would be the cost of production equipment for methods DBHE, BTES, ATES, HE, EGS? Well downhole equipment, wellhead, annual maintenance cost,… Please describe each method.

See excel sheets for detailed cost estimations.

5. What would be the approximate maintenance cost for each method DBHE, BTES, ATES, HE, EGS on a 5-year production base? Well, surface equipment, piping, valves, …

DBHE, BTES, ATES: not yet in Hungary HE: around €100,000 EGS: not yet in Hungary

6. What would be the footprint of the whole installation considering well location, surface facility, piping, etc? Please provide the information for each method DBHE, BTES, ATES, HE, EGS

DBHE: 2,000 m2 BTES, ATES: not yet in Hungary HE: A minimum of 2,000 m2 per production and recovery well is required, including surface facilities. EGS: not yet in Hungary

7. How much energy could be produced by each method DBHE, BTES, ATES, HE, EGS in best case scenario and in worst case scenario? Please define the energy in watt (W) for each method.

DBHE: 300-900 kWt/well BTES, ATES: not yet in Hungary HE: 1-20 MWt/well EGS: not yet in Hungary

8. What are the losses of energy for each method DBHE, BTES, ATES, HE, EGS from the wellhead till the heat exchanger of the end user? Please provide the information in watt (W) for each method.

DBHE: almost 0 BTES, ATES: not yet in Hungary HE: 0.02-0.2 MWt/well EGS: not yet in Hungary

9. What are the implementation and production risks for each method DBHE, BTES, ATES, HE, EGS? Please describe the risk for each method.

DBHE (Borehole Heat Exchangers): This method has a low implementation and production risk in Hungary due to its straightforward operation based on heat diffusion principles. The availability of data from old wells, including temperature measurements and lithology, is beneficial for predictive DBHE system models. The completion process of DBHE systems mirrors that of oil wells, minimizing operational risks.

BTES (Borehole Thermal Energy Storage): Similar to DBHE, but with slightly more complex modelling due to variable heat injection temperatures. In Hungary, connecting BTES to a heat pump district heating or local heating system can mitigate risks, allowing for efficient operation at 10-20°C. Direct heating from BTES may carry model prognosis risks.

ATES (Aquifer Thermal Energy Storage): The primary risk involves exploring an aquifer and accurately determining its hydraulic parameters and boundaries. In Hungary, there's a need for high confidence that an aquifer is of the confined type to avoid the risk of system failure in cases of leaky or unconfined aquifers if exploration methods don't provide a high degree of certainty.

HE (Hydrothermal Energy): Developing HE is complex and carries high risks, involving geophysical and geological exploration, drilling, well testing, and reservoir engineering. The risks in Hungary are diverse, including geological, drilling prolongation, fault boundaries, flow capacity, and early cold breakthrough risks. This method requires careful planning and risk management due to its comprehensive technical demands. The drilling and operation of injection wells in porous reservoirs is particularly risky.

EGS (Enhanced Geothermal Systems): EGS risks are mainly associated with the prediction of fracturing models and the actual extent of fractures in the reservoir. Modelling and determining heat transfer are challenging prior to well testing. Environmental regulations restrictions on fracking further complicate the situation, as well as potential opposition from climate activists, which could affect exploration permits due to concerns about induced seismicity and environmental impacts.

10. What are measures to mitigate the implementation and production risks for each method DBHE, BTES, ATES, HE, EGS? Please describe the risk for each method.

In all cases, it is important to take precautions in the design and technical control of the construction. In addition, for HE and EGS, the establishment of a risk management fund at European level would be of crucial importance.

D. Social analysis

Data in this section concerns evaluating the social aspects of implementation and usage of repurposing technologies.

1. What is the general attitude of reusing old wells by reuse methods DBHE, BTES, ATES, HE, EGS on a well which is active / shut in / abandoned? Please describe each method, which would be more acceptable.

In Hungary, interest in reuse methods like DBHE, BTES, ATES, and EGS is still budding, as the focus remains on developing projects leveraging classic geothermal reservoirs and brine production, which are gaining momentum and expected to grow until 2030 and beyond. Hydrothermal energy (HE) development is anticipated around existing hydrocarbon fields with proven aquifers and wells.

It's predicted that interest in DBHE, BTES, ATES, and EGS will increase in the next 10 to 20 years as more classic geothermal reservoirs come online and licenses are awarded. While the concept of revitalizing existing wells for geothermal use is intriguing to investors, the economic benefits need clearer demonstration. Moreover, public concern regarding the EGS method, especially fears of induced seismicity and fracking, poses a significant challenge to its acceptance.

2. What is the opinion of end users (customer groups industry, agriculture and municipality) regarding the use of old wells? Are there any concerns or restrictions? Please provide description and case studies of good practice if any.

Generally considered risky, they are mainly considered as monitoring or test wells. The condition of the well can usually only be assessed once the investor has bought the well, which is a significant risk.

3. What would be the benefits for society regarding the reuse of existing wells for implementation of reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method.

In particular, in the case of ATES, HE and EGS, hydrocarbon reservoirs in depletion should be abandoned so that the well can be used with little investment.

4. What would be the risks for society regarding the reuse of existing wells for implementation of reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method.

In the case of DBHE and BTES, good thermal conductivity may be difficult to achieve, while in the case of ATES, HE and EGS, inadequate cementation and corrosion of the casing may be a problem, possibly scale precipitation.

5. What would encourage the potential investors within customer groups (industry, agriculture and municipality) to invest in one of the defined reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method if applicable.

If old or unused wells could be inspected in advance without an obligation to buy. Also, specific EU and National grant schemes could foster reuse of abandoned wells.

6. Is there any doubt by the local community regarding implementation of reuse methods DBHE, BTES, ATES, HE, EGS because of leak of trust or bad experience in the past? Please describe each method.

In the case of HE, the old well design was not suitable for water production, as abandoned hydrocarbon wells are generally smaller in diameter. This is a particular problem in case of sand invasion and a filter has to be installed later. This is not always the case.

Appendix 5 - Questionnaire Slovenia

A. Author and country

Author	Matej Prkič
Organisation	LEAP
Country	Slovenia
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1. General status: Are there any geothermal projects in your country currently going on? What is the acceptability of such projects by users and the local community? Please provide a short description.

In 2023, a geothermal project took place: Construction of the reinjection well Mt-9 in the area of the thermal spa (Terme 3000 – Moravske Toplice) to return thermomineral water back to the aquifer.

One DBHE on a old gas well and one HE on an old oil well

In the current year (2024), a mining project is being prepared for the construction of a pumping-reinjection system for the exploitation of geothermal energy in the Dobrovnik area. Geothermal energy will be used as the primary emergent for heating the greenhouse.

Regarding the acceptance of the use of geothermal energy, local communities as well as municipalities are very inclined to create such projects.

Key factors influencing the acceptability of geothermal projects:

Environmental Impact: Geothermal energy is generally considered a clean and renewable energy source with lower greenhouse gas emissions compared to fossil fuels. However, concerns about potential environmental impacts such as land use, water consumption, subsurface effects, and air emissions can affect the acceptability of geothermal projects. Projects that prioritize environmental sustainability, minimize impacts on natural habitats, and adhere to stringent environmental regulations are more likely to be accepted by the local community.

Health and Safety: Local residents may have concerns about potential health and safety risks associated with geothermal projects, such as air emissions, groundwater contamination, induced seismicity, or exposure to hazardous substances. Comprehensive risk assessments, transparent communication, and adherence to strict health and safety standards are essential for addressing these concerns and building trust within the community.

Economic Benefits: Geothermal projects can bring economic benefits to local communities through job creation, tax revenues, and local procurement opportunities. Projects that demonstrate tangible economic benefits, contribute to local economic development, and provide opportunities for local employment and business involvement are more likely to be accepted by the community.

Community Engagement: Meaningful engagement with local stakeholders, including residents, businesses, indigenous communities, and environmental groups, is crucial for gaining

acceptance of geothermal projects. Open communication, public consultations, and opportunities for community input in project planning, decision-making, and implementation processes can help build trust, address concerns, and foster collaboration. **Cultural Considerations:** Geothermal projects may impact cultural heritage sites, traditional land use practices, and sacred or culturally significant areas for indigenous communities and local residents. Respect for cultural values, consultation with indigenous groups, and efforts to mitigate impacts on cultural heritage are essential for ensuring the acceptability of geothermal projects.

2. Do some geothermal projects include repurposed old wells? If yes, what is the user experience and acceptability of the local environment where it is implemented? Please provide a short description.

Geothermal projects in Slovenia Pilot geothermal power plant on an existing gas well Pg-8 (NE part of Slovenia), pilot project. The feature of using a geothermal gravity heat pipe is in a closed coolant circuit, where only one dry well is required for operation. The already existing but abandoned well Pg-8 in the village of Čentiba in Lendava will be used. Pilot geothermal power plant with an electrical power of 50 kWe will be able to provide 400 MWhe of electricity annually. The project is still in the implementation phase, but according to the idea of the project, the local community and the municipality are very much in favor of using geothermal energy for the production of electricity.

3. Are there any reuse projects implemented or in the planning phase? Please indicate the name and a short description, if possible.

Potential areas in the NE part of Slovenia with the possibility of setting up a larger geothermal power plant are currently being investigated. Due to the high investment costs, areas with existing deep wells are potentially suitable. For the given project, this is the area of Lendava.

4. Is there a promotion of potential reuse of wells in your country? Do investors/state/others show interest in well reuse? If so, please provide a short description.

The actual promotion and potential use of existing wells is not directly exposed either at the national or municipal level. However, there are interests regarding the use of existing wells on the part of holders of mining rights for the use of geothermal energy and new investors for the use of geothermal energy.

B. Demand patterns for different customer group

Data in this section concerns the knowledge about energy consumption, willingness on changing the current energy source, suitability of geothermal energy regarding the current energy supply chain, …

1. What is the general energy demand of industry, agriculture, and municipalities in your country? Please describe each customer group.

The general energy demand by sector in Slovenia for 2022, based on data from the Statistical Office of the Republic of Slovenia (SURS):

Industry is the leading consumer of energy, accounting for nearly half (46.8%) of the total final energy consumption.

Transportation follows closely with 20, 3 %, highlighting the significance of fuel use in the country.

Households make up a significant portion (17,7 %) due to heating, cooking, and appliances.

Agriculture have lower but still notable shares (2,7 %).

2. How many users have experience with using geothermal energy? Which is the preferable technology by end users? Please describe each customer group.

Deep Geothermal:

Users: Data suggests around 31 users directly utilize deep geothermal energy in Slovenia (as of 2018). These include facilities like swimming pools, greenhouses, and district heating systems.

Shallow Geothermal (Ground-Source Heat Pumps):

Users: This sector shows significant growth. By 2018, estimates suggest roughly 11,182 smaller GSHP units (12 kW) and 588 larger systems (>20 kW) installed, translating to potentially tens of thousands of users.

3. Under which circumstances would current users be willing to change the energy source they are using right now? Would any of the defined customer groups be interested in a local accessible energy source?

The circumstances under which current users in Slovenia would be willing to change the energy source they are using right now include the promotion and encouragement of renewable energy through appropriate incentive legal frameworks, which aim to reduce import dependency on fossil fuels and strengthen national energy independence. Additionally, the country's plans to gradually phase out the use of fossil fuels for electricity generation may influence users to consider transitioning to alternative energy sources.

However, the specific preferences and circumstances of each customer group in Slovenia are not explicitly described in the provided search results.

4. Would the end user consider geothermal energy usage nevertheless it can cover the base load and they need a backup for peak loads? Is this a major obstacle for the end user's or do they see potential in it?

The end user's consideration of geothermal energy usage is influenced by various factors, including its ability to cover the base load and the need for a backup for peak loads. Geothermal power plants can produce electricity consistently and run essentially 24 hours a day, making them suitable for base load power generation. However, they may require a backup for peak loads. The increasing interest in next-generation geothermal technologies, which offer dispatchable, flexible electricity and significant resource potential with minimal land use requirements, could make geothermal energy more attractive to end users, despite the need for a backup for peak loads. Additionally, the promotion of renewable energy and the potential for geothermal energy to provide a sustainable alternative to fossil fuels may also influence end users' willingness to consider its usage, even with the need for a backup for peak loads.

5. Are there any potential customer groups who would be satisfied only with base load energy supply? If yes, please provide the information regarding user, energy load needed and preferable technology, if applicable.

No, the base load is always followed by peak loads. The closest to the base load needs would be the agriculture sector, but they also need to function in peak loads in case the outside temperatures are to low. Probably the geothermal could be use as base load with additional input of other renewable resources to cover the peaks when they emerge.

C. Economic analysis

Data in this section concerns evaluating the economical side of implementation and usage of repurposing technologies in the energy supply chain.

1. What is the optimal transfer distance of energy for recognized reuse methods DBHE, BTES, ATES, HE, EGS? Depending on flow rate and temperature? Please describe each method.

The optimal transfer distance of energy for various recognized reuse methods in geothermal energy systems depends on several factors, including the specific technology, geological conditions, energy demand, and economic considerations. General overview of the optimal transfer distances for geothermal reuse methods:

Borehole Heat Exchangers (DBHE):

DBHE systems typically transfer heat energy over relatively short distances, ranging from a few meters to a few hundred meters. The optimal transfer distance for DBHE systems depends on factors such as ground temperature, soil properties, and the heating or cooling load of the building or facility being served.

Borehole Thermal Energy Storage (BTES):

BTES systems are used to store thermal energy in the subsurface for later use in heating or cooling applications. The optimal transfer distance for BTES systems can vary depending on factors such as the size of the storage reservoir, the thermal conductivity of the surrounding rock or soil, and the efficiency of heat exchange processes. BTES systems can transfer energy over distances ranging from tens to hundreds of meters, depending on the specific design and operational parameters.

Aquifer Thermal Energy Storage (ATES):

ATES systems use groundwater aquifers as thermal energy storage reservoirs, typically extracting heat during the winter for heating and recharging the aquifer with cool water for summer cooling. The optimal transfer distance for ATES systems depends on factors such as aquifer permeability, hydraulic conductivity, and the distance between injection and extraction wells. ATES systems can transfer energy over distances ranging from hundreds of meters to several kilometers, depending on the geological characteristics of the aquifer and the energy demand of the system.

Hot Dry Rock (HDR) or Engineered Geothermal Systems (EGS):

HDR or EGS systems involve creating artificial reservoirs in hot, dry rock formations deep underground and circulating water or other fluids to extract heat.

The optimal transfer distance for HDR or EGS systems depends on factors such as reservoir depth, rock permeability, and the efficiency of heat extraction and circulation processes.

HDR or EGS systems can potentially transfer energy over distances of several kilometers, but the practical limits may vary depending on technical and economic constraints.

2. What is the cost for implementation of reuse methods DBHE, BTES, ATES, HE, EGS on a well which is active / shut in / abandoned? Please describe each method and each type of well status.

See the xls table

3. What is the cost of surface infrastructure, depending on expected energy supply by each method DBHE, BTES, ATES, HE, EGS? Please describe each method.

The cost of surface infrastructure for geothermal energy systems, including Borehole Heat Exchangers (DBHE), Borehole Thermal Energy Storage (BTES), Aquifer Thermal Energy Storage (ATES), Hydrothermal Energy (HE), and Enhanced Geothermal Systems (EGS), can vary significantly depending on factors such as the expected energy supply, system size, project scale, location, geological conditions, and regulatory requirements. General overview of the cost considerations for surface infrastructure based on expected energy supply for each method:

Borehole Heat Exchangers (DBHE):

Expected Energy Supply: DBHE systems typically provide space heating and cooling for residential, commercial, and industrial buildings. The cost of surface infrastructure can vary based on the heating and cooling load requirements of the buildings served by the system.

Price Range: The cost of surface infrastructure for DBHE systems can vary widely depending on project specifics such as the number of boreholes, depth of drilling, complexity of the heat pump system, and distribution network. Generally, surface infrastructure costs for DBHE systems can range from several thousand to tens of thousands of euros per well.

Borehole Thermal Energy Storage (BTES):

Expected Energy Supply: BTES systems provide seasonal thermal energy storage for heating and cooling applications. The cost of surface infrastructure can vary based on the heating and cooling load requirements and the desired storage capacity of the system.

Price Range: The cost of surface infrastructure for BTES systems can vary depending on factors such as the number and depth of boreholes, size of the thermal storage system, and complexity of the distribution network. Surface infrastructure costs for BTES systems typically range from tens of thousands to hundreds of thousands of euros per borehole.

Aquifer Thermal Energy Storage (ATES):

Expected Energy Supply: ATES systems provide thermal energy storage using groundwater aquifers. The cost of surface infrastructure can vary based on the heating and cooling load requirements and the desired storage capacity of the system.

Price Range: The cost of surface infrastructure for ATES systems can vary depending on factors such as the number of wells, depth and diameter of wells, size of pumping and distribution infrastructure, and regulatory requirements. Surface infrastructure costs for ATES systems typically range from tens of thousands to hundreds of thousands of euros per well.

Hydrothermal Energy (HE):

Expected Energy Supply: HE projects typically provide electricity generation or direct heating applications. The cost of surface infrastructure can vary based on the expected power output or heating capacity of the system.

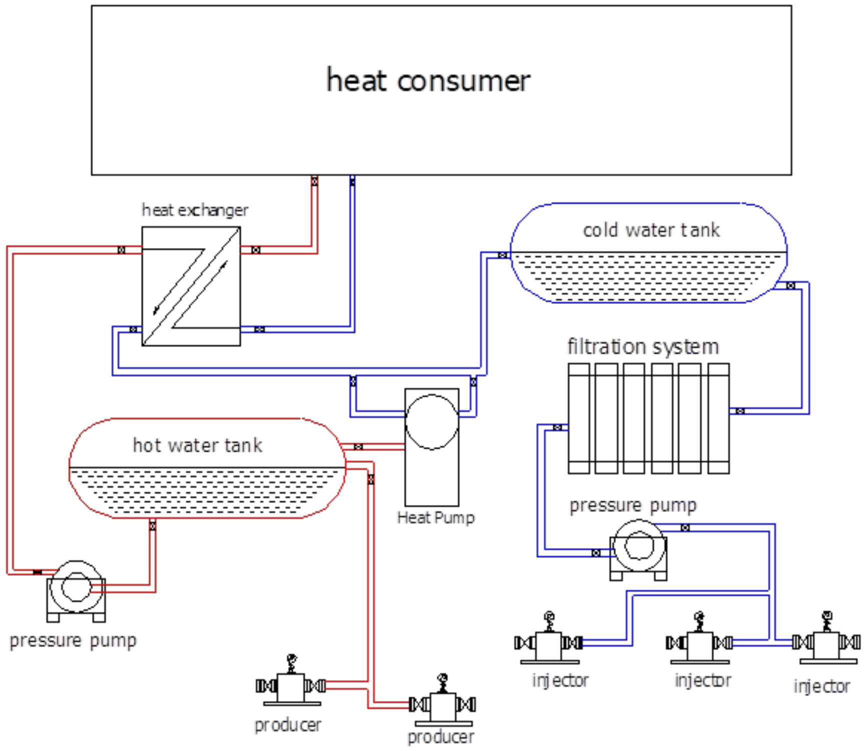
Price Range: The cost of surface infrastructure for HE projects can vary widely depending on factors such as the size of the power plant, number of production wells, complexity of surface facilities, and transmission infrastructure. Surface infrastructure costs for HE projects typically range from several million to tens of millions of euros per project.

Enhanced Geothermal Systems (EGS):

Expected Energy Supply: EGS projects provide electricity generation or direct heating applications using engineered reservoirs in hot rock formations. The cost of surface infrastructure can vary based on the expected power output or heating capacity of the system.

Price Range: The cost of surface infrastructure for EGS projects can vary significantly depending on factors such as the size and depth of the reservoir, number of injection and production wells, complexity of surface facilities, and transmission infrastructure. Surface infrastructure costs for EGS projects typically range from tens of millions to hundreds of millions of euros per project.

Typical application consiste of following components and can deviate regarding the applicable technology:



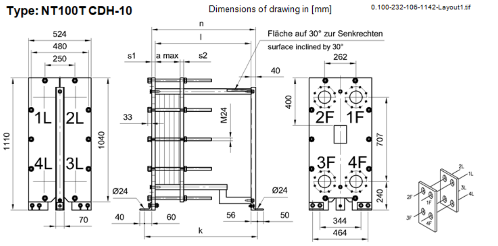
The price for a 1MW heat exchanger was last May 2023 approx. 6500 Eur, for a 5 MW we can assume to cost 4-5x that much = 26 - 32.000 EUR.

Kelvion Plate Heat Exchanger: NT100T CDH-10

Thermal data for 1 unit(s) in parallel and 1 unit(s) in series

	hot side	cold side	
Media:	Water	Water	
Media group acc. PED 2014/68/EU:	Group 2 - others	Group 2 - others	
Heat exchanged:	1034,44		kW
Mass flow:	74180	74231	kg/h
Volume flow:	75,30	75,00	m³/h / m³/h
Temperature inlet:	62,00	40,00	°C
Temperature outlet:	50,00	52,00	°C
Pressure drop:	0,30	0,28	bar
Working pressure inlet:	5,00	5,00	barg
Filling volume:	0,02605	0,02690	m³
Product properties			
Density:	985,17	989,75	kg/m³
Heat capacity:	4183,50	4180,60	J/kgK
Thermal conductivity:	0,64701	0,63594	W/mK
Dyn. viscosity inlet:	0,4523	0,6527	cP
Dyn. viscosity outlet:	0,5465	0,5286	cP
Unit Data			
Plate Type:	NT100T H		
Heat transfer area (total / per unit):	16,20	16,20	m²
Number of plates (total / per unit):	62	62	

Type: NT100T CDH-10 Dimensions of drawing in [mm] 0.100-232-106-1142-Layout1.tif



n:	835 mm	s1:	30 mm	a-max frame:	414 mm	empty weight:	387 kg
k:	911 mm	s2:	30,00 mm	a-max actual:	214 mm	max. total weight:	438 kg
l:	765 mm	h:	1110 mm			max. bolt length:	500 mm

Pos	Size	Type	Media	Side/Flow	m
1F	DN100	Rubber insert EN1092-1-PN16 EPDM	Water	hot - in	4 mm
2F	DN100	Rubber insert EN1092-1-PN16 EPDM	Water	cold - out	4 mm
3F	DN100	Rubber insert EN1092-1-PN16 EPDM	Water	cold - in	4 mm
4F	DN100	Rubber insert EN1092-1-PN16 EPDM	Water	hot - out	4 mm

Surface equipment for monitoring 15. – 20.000 EUR

Piping isolated pipes:

DN 100 PPR – 110 – 115 EUR/m

DN 100 STEAL – 100 – 110 EUR/m

DN 200 PPR – 190 – 200 EUR/m

DN 200 STEAL – 180 – 190 EUR/m

Tank HOT/COLD 120 – 150 m3 accumulation – 60.000 – 70.000 EUR/pcs
Filtration system – 150 -160.000 EUR

Heat pump – 20 – 25.000 EUR

4. What would be the cost of production equipment for methods DBHE, BTES, ATES, HE, EGS? Well downhole equipment, wellhead, annual maintenance cost,… Please describe each method.

The downhole equipment consist from:

DBHE,

- Tubing / Pipes – 2 7/8˝ - 20 eur/m
- Tubing / Pipes – 3˝ - 25 eur/m
- Tubing / Pipes – 4˝ - 30 eur/m

BTES,

- Tubing / Pipes – 2 7/8˝ - 20 eur/m
- Tubing / Pipes – 3˝ - 25 eur/m
- Tubing / Pipes – 4˝ - 30 eur/m

ATES,

- Tubing / Pipes – 2 7/8˝ - 20 eur/m
- Tubing / Pipes – 3˝ - 25 eur/m
- Tubing / Pipes – 4˝ - 30 eur/m

HE, EGS

- Tubing / Pipes - 3˝ - 25 eur/m
- Tubing / Pipes - 4˝ - 30 eur/m
- Tubing / Pipes - 5˝ - 35 eur/m
- Tubing / Pipes - 7˝ - 50 eur/m

<u>Surface pumps</u>

DBHE, BTES, ATES,

- Pleuger/Grundfos - T= 65 -> 45°C - 8.000 - 15.000 EUR - pump, motor, cable, monitoring
- Pleuger/Grundfos - T= 75 -> 65°C - 25.000 - 30.000 EUR - pump, motor, cable, monitoring

<u>ESP:</u>

HE,

- Pleuger/Grundfos - T= 75 -> 65°C - 25.000 - 30.000 EUR - pump, motor, cable, monitoring

HE, EGS

- Borets / = T = 90 - 150°C - 180 - 250.000 EUR - pump, motor, cable, monitoring

Well Head complete:

DIN - standard -> 5. - 10.000 EUR

ANSI - standard -> 15. - 25.000 EUR

API - standard -> 60. - 80.000 EUR

Maintenance:

DBHE, -> 1. - 5.000 EUR - changing some valves and check the system function

BTES, -> 1. - 5.000 EUR - changing some valves and check the system function

ATES, -> 5. - 10.000 EUR - changing some valves and check the system function

HE, -> 5. - 10.000 EUR - changing some valves and check the system function

EGS -> 15. - 20.000 EUR - changing some valves and check the system function

5. What would be the approximate maintenance cost for each method DBHE, BTES, ATES, HE, EGS on a 5-year production base? Well, surface equipment, piping, valves, …

Maintenance:

DBHE, -> 1. - 5.000 EUR - changing some valves and check the system function

- No worker required in 5 years
- Workover after 10 - 15 years in production, cost 50 - 70.000 EUR (pull and check the piping, pressure test if required, change well head equipment if required)

BTES, -> 1. - 5.000 EUR - changing some valves and check the system function

- No worker required in 5 years
- Workover after 10 - 15 years in production, cost 50 - 70.000 EUR (pull and check the piping, pressure test if required, change well head equipment if required)

ATES, -> 5. - 10.000 EUR - changing some valves and check the system function

- No worker required in 5 years
- Workover after 10 - 15 years in production, cost 50 - 70.000 EUR (pull and check the piping, pressure test if required, change well head equipment if required)

HE, -> 5. - 10.000 EUR - changing some valves and check the system function

- 1 worker required in 5 years - pump and downhole equipment inspection, cost - 35 - 40.000 EUR.
- Workover after 10 - 15 years in production, cost 50 - 70.000 EUR (pull and check the piping, pressure test if required, change well head equipment if required)

EGS -> 15. - 20.000 EUR - changing some valves and check the system function

- 1 worker required in 5 years - downhole equipment inspection, cost - 80 - 90.000 EUR.
- Workover after 10 - 15 years in production, cost 150 - 170.000 EUR (pull and check the piping, pressure test if required, change well head equipment if required)

6. What would be the footprint of the whole installation considering well location, surface facility, piping, etc? Please provide the information for each method DBHE, BTES, ATES, HE, EGS

For following technologies 2 well are taken in into account:

DBHE,

well location 2 x 7,5 m x 7,5 m = 112,5 m2

piping together 1000 m = 1000 m x 0,5 m = 500 m2

Heat exchanger and filtering system = 5 m x 5 m = 25 m2

TOTAL = 637,5 m2 total area

BTES,

well location 2 x 7,5 m x 7,5 m = 112,5 m2

piping together 1000 m = 1000 m x 0,5 m = 500 m2

Heat exchanger and filtering system = 5 m x 5 m = 25 m2 TOTAL = 637,5 m2 total area HE, well location 2 x 15 m x 15 m = 450 m2 storage tank of 2 x 100 m3 , 2,1 m high = 2 x 7 m x 7 m = 98 m2 piping together 1000 m = 1000 m x 0,5 m = 500 m2 Heat exchanger and filtering system = 15 m x 15 m = 225 m2 TOTAL = 1.273 m2 total area EGS well location 2 x 30 m x 30 m = 900 m2 storage tank of 2 x 150 m3 , 1,5 m high = 10 m x 10 m = 200 m2 piping together 1000 m = 1000 m x 0,5 m = 500 m2 Heat exchanger and filtering system = 15 m x 15 m = 225 m2 Other equipment for cooling and water treatment = 50 m x 50 m = 2.500 m2 TOTAL = 4.325 m2 total area For following technology 4 well are taken in into account: ATES, well location 4 x 7,5 m x 7,5 m = 225 m2 storage tank of 100 m3, 2,1 m high = 7 m x 7 m = 49 m2 piping together 1000 m = 1000 m x 0,5 m = 500 m2 Heat exchanger and filtering system = 5 m x 5 m = 25 m2 TOTAL = 799 m2 total area

7. How much energy could be produced by each method DBHE, BTES, ATES, HE, EGS in best case scenario and in worst case scenario? Please define the energy in watt (W) for each method.

DBHE, 0.06 MWth - 0.35 MWth. BTES (up to 37 wells with 5 m spacing) you can get out between 150 MWh/a and 17 GWh/a

ATES energy production of 3.3 MWth.

HE we can get ~10-50 MWth.

EGS we have currently the examples (~1.7 MWe; ~3.5 MWe currently) vertical wells. And up to 8 MWe when using longer laterals, larger wellbore diameter and larger spacing. Roughly you may expect 1-5 MWe or 10-50 MWth based

8. What are the losses of energy for each method DBHE, BTES, ATES, HE, EGS from the wellhead till the heat exchanger of the end user? Please provide the information in watt (W) for each method.

The losses are connected with the transfer distance of heath which can be predicted and managed by using the proper piping for instance. In practice we have exsamples:

DBHE,

Downhole losses are connected to the flowrates and the shallow aquifers cooling effect. The most affected method for losses is the DBHE in case of small diameters and flowrates and the outcome is poor. If we consider source temperatures up to 75°C by flow rate of 70-80m3/h, well depth up to 2000 m, the loses would be 25-30°C – this means 2,1 MW – 2,5 MW

BTES,

Similar is also BTES in case one or two wells are used. In case a bigger system is employed the outcome is grater and the loses are smaller.

ATES,

No info.

HE,

The loses vary regarding the flow rate and source temperature. If we consider source temperatures up to 75°C by flow rate of 70-80m3/h, well depth up to 2000 m, the loses would be 5-7°C – this means 0,42 MW – 0,58 MW

In case we have a higher source temperature up to 170° by flow rate of 150-160m3/h, well depth up to 2000 m, the loses would be 5-7°C - this means 0,966 MW – 1,352 MW

EGS

In case we have a higher source temperature up to 170° by flow rate of 150-160m3/h, well depth up to 2000 m, the loses would be 5-7°C - this means 0,966 MW – 1,352 MW

Surface

Surface losses we have an example If we flow with 58°C, flowrate 70 – 80 m3/h non isolated pipes on a distance of 700 m loos temperature of ca. 2°C (168 kW) in case we isolate the temperature loos will be between 0,4 and 0,6°C (33 kW). Basically it depends on the flow rate, bigger the mass less temperature losses are expected

9. What are the implementation and production risks for each method DBHE, BTES, ATES, HE, EGS? Please describe the risk for each method.

DBHE,

Integrity issue with the well and downhole equipment

Temperature recovery regarding the cooling effect of the method

Low temperatures and low energy outcome

BTES,

Integrity issue with the well and downhole equipment

Temperature recovery regarding the cooling effect of the method

Low temperatures and low energy outcome

ATES,

Integrity issue with the well and downhole equipment

Temperature recovery regarding the cooling effect of the method

Injection capability, permeability of the aquifer

HE,

Integrity issue with the well and downhole equipment

Chemistry of the produced brine

Skaling possibilities

Injection capability, permeability of the aquifer

EGS

Integrity issue with the well and downhole equipment

Chemistry of the produced brine

Skaling possibilities

Injection capability, permeability of the aquifer

10. What are measures to mitigate the implementation and production risks for each method DBHE, BTES, ATES, HE, EGS? Please describe the risk for each method.

DBHE,

Choose the best possible candidate for implementation, solid casing material of the existing well, integrity check lists if available, plug equipment used, etc.

Monitoring of pressure during production on the inlet and outlet side, sampling of circulation fluid each 6 months to investigate possible contamination or change in chemistry.

Annual checks of the system with a prescribed check list.

BTES,

Choose the best possible candidate for implementation, solid casing material of the existing well, integrity check lists if available, plug equipment used, etc.

Monitoring of pressure during production on the inlet and outlet side, sampling of circulation fluid each 6 months to investigate possible contamination or change in chemistry.

Annual checks of the system with a prescribed check list.

ATES,

Choose the best possible candidate for implementation, solid casing material of the existing well, integrity check lists if available, plug equipment used, etc.

Monitoring of pressure during production on the producer and injector wells, sample of circulation fluid each 6 months to investigate possible contamination or change in chemistry.

Monitor the reservoir behaviour and temperature changes is possible.

Annual checks of the system with a prescribed check list.

HE,

Choose the best possible candidate for implementation, solid casing material of the existing well, integrity check lists if available, plug equipment used, etc.

Monitoring of pressure during production on the producer and injector wells, sample of circulation fluid each 6 months to investigate possible contamination or change in chemistry.

Monitor the reservoir behaviour and temperature changes is possible.

Annual checks of the system with a prescribed check list.

EGS

Choose the best possible candidate for implementation, solid casing material of the existing well, integrity check lists if available, plug equipment used, etc.

Monitoring of pressure during production on the producer and injector wells, sample of circulation fluid each 6 months to investigate possible contamination or change in chemistry.

Monitor the reservoir behaviour and temperature changes is possible.

Annual checks of the system with a prescribed check list.

D. Social analysis

Data in this section concerns evaluating the social aspects of implementation and usage of repurposing technologies.

1. What is the general attitude of reusing old wells by reuse methods DBHE, BTES, ATES, HE, EGS on a well which is active / shut in / abandoned? Please describe each method, which would be more acceptable.

The reuse of methods in unknown and few know the potential of reuse methods DBHE, BTES, ATES, HE, EGS application. There are some example of usage:

DBHE

Positive,

- a geothermal well needed to be shut in because of to much CO2 emisions. The idea was to convert the well into DBHE. The intervention was successful. Usage could be continuetes.

Negative

- after several months of usage the temperatures drop, the flow/temperatures were not sufficient to heat the same surface area then before
- significant loos of temperature were visible in the shallow section, investigation regarding what went wrong was not performed.

HE

Positive,

- several wells were converted from oil/gas exploration to – HG production wells. All were successful with a decent flow rate.
- 2 – 3 are still in production after several years of usage.

Negative

- Skaling issues, because aggressive brine
- Sand production, because the wells were not drilled for, HE purpose.
- One project was trial to use the old well for injection. At the beginning it went well, after few weeks the injection stopped, , investigation regarding what went wrong was not performed.

BTES, ATES, EGS

- Technologies are not in use neither in planning phase.

2. What is the opinion of end users (customer groups industry, agriculture and municipality) regarding the use of old wells? Are there any concerns or restrictions? Please provide description and case studies of good practice if any.

The old well is quite good for production, for injection not so much. There are good/bad practices of usage. No major concerns exist on the local community side because they see those wells as potential for growth and development of the region. Because there are no bad practices no restrictions are in line.

Industry

- No practice of using old wells.

Agriculture

- There is 1 location which planned to use an old well. The flowrates were decent and almost at the same level than a new drilled well. Unfortunately, the company could not proceed with the project because of concession granting limitations.
- One reused well, was intended to be used as injection well, after few weeks the injection was not sufficient and the project stopped using the well, no investigation regarding what went wrong was not performed.
- Overall, the users are Thermal Baths, which are satisfied and see potential in the usage with long term benefits.

Municipality

- There are 2 locations which use old, reused wells, converted from oil and gas exploration.
- On is in progress to be developed, the licence for extraction was granted.
- Overall the users are Thermal Baths, which are satisfied and see potential in the usage with long term benefits.

3. What would be the benefits for society regarding the reuse of existing wells for implementation of reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method.

The benefits of usage DBHE, BTES, ATES, HE, EGS application:

DBHE

- Using existing wells with minimal impact to the environment,
- Small footprint
- Usage of existing infrastructure
- Reliable and easy monitoring technic.
- Potential electricity production if the well is deep enough and using supercritical substances.

BTES

- No such project in done.

ATES

- No such project in done.

HE

- Using existing wells with minimal impact to the environment,
- Usage of existing infrastructure
- Reliable and manageable source, the brine from formation is the best way for heath transfer.
- Injection needed for the application to call it renewable.

EGS

- No such project in done.

4. What would be the risks for society regarding the reuse of existing wells for implementation of reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method.

The risk of usage DBHE, BTES, ATES, HE, EGS application:

DBHE

- Integrity issue.
- Depending on the media used, potential pollution of the surface in case of leak during production.

BTES

- Integrity issue.
- Depending on the media used, potential pollution of the surface in case of leak during production.

ATES

- Integrity issue.
- Heating/Cooling effect for the underground drinking waters
- Potential change of chemistry - pumping/injection - if the system is not closed.

HE

- Integrity issue.
- Long-term Heating/Cooling effect for the underground drinking waters
- Potential change of chemistry - pumping/injection - if the system is not closed
- Injection needed, possible induced seismicity
- Depending on the produced brine, potential pollution of the surface in case of leak during production.

EGS

- Integrity issue.
- Long-term Heating/Cooling effect for the underground drinking waters
- Potential change of chemistry - pumping/injection - if the system is not closed.
- Injection needed, possible induced seismicity.
- Depending on the produced brine, potential pollution of the surface in case of leak during production.

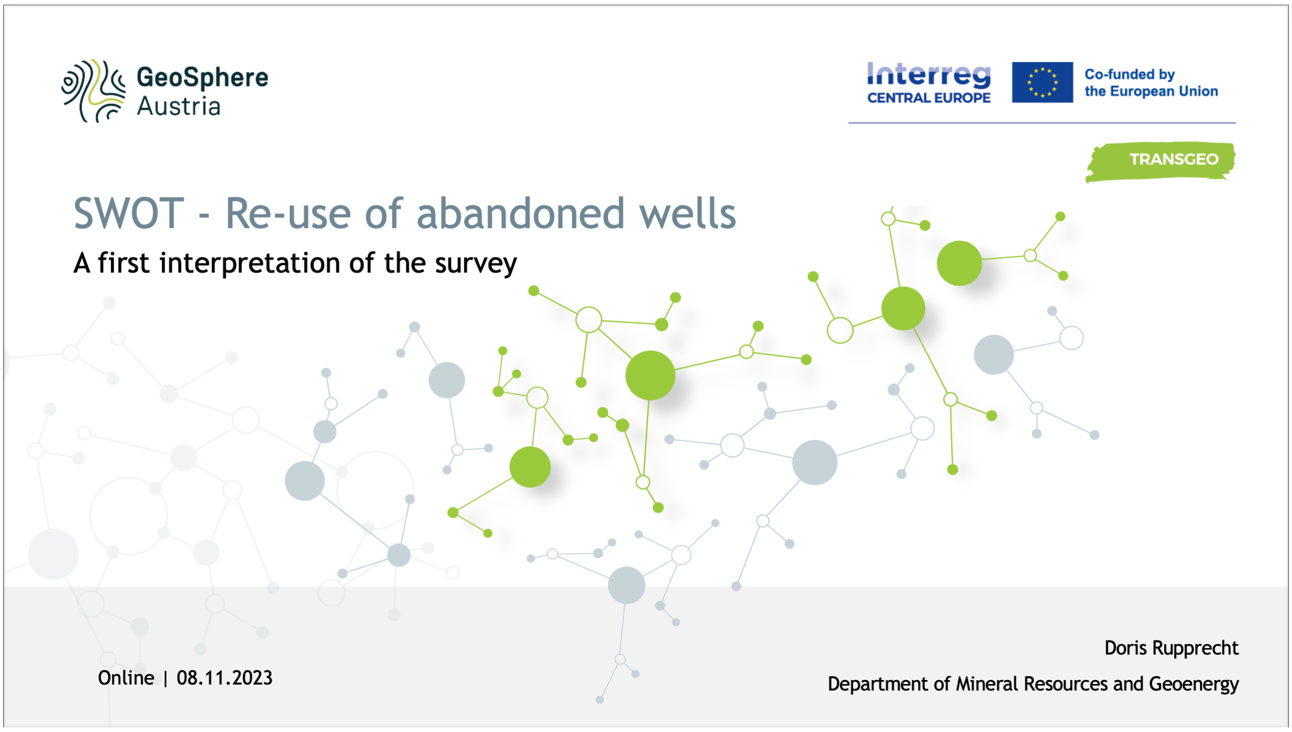
5. What would encourage the potential investors within customer groups (industry, agriculture and municipality) to invest in one of the defined reuse methods DBHE, BTES, ATES, HE, EGS? Please describe each method if applicable.

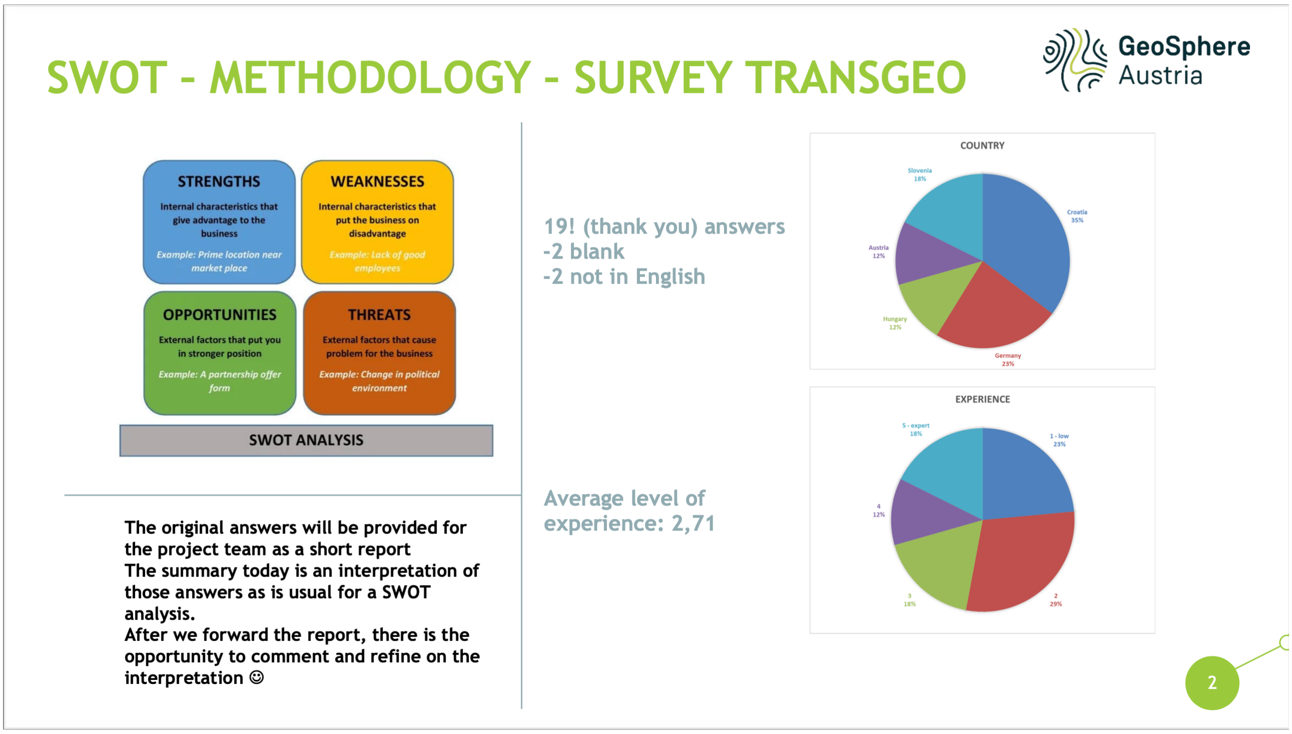
> The investors would be encouraged if there are good practices, which show reliable performance on a long-term basis.
>
> The financial aspect needs to be considered and some financing support from states would be required, because quite high initial investment cost.
>
> Energy output calculations are important to start the project, if the forecasts are not worth looking into possibilities of changing the existing system nothing will happen.
>
> The municipalities would need to take the lead to start the usage of local energy sources possibilities an encourage the investors or even contribute.

6. Is there any doubt by the local community regarding implementation of reuse methods DBHE, BTES, ATES, HE, EGS because of leak of trust or bad experience in the past? Please describe each method.

> No, because of no bad practise there is no doubt at the moment.

Appendix 6 - SWOT Analysis





SWOT – METHODOLOGY – SURVEY TRANSGEO

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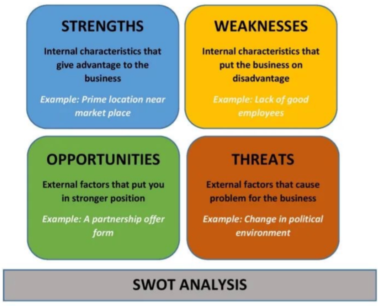

Questions "S-W-O-T"

Answers grouped to 6 "Thematic groups"

- Use of geothermal energy – operational aspects (those answers are not specific for the reuse in a technical point of view
- Re-use technical aspects – characteristic for the re-use of abandoned wells
- Risks – Aspects concerning the geology and the environment
- Cost and time for the installation
- Impacts on the region
- Social, economic and legal/regulatory aspects

Questions "Difference between the re-use methods (BHE, ATES, EG, etc.)"

No evaluation: Most of the answers relate to the geothermal aspect and are not just about re-use technology

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SWOT – DETAILS

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Strength	Counts
Use of geothermal energy (Operational apects)	22
Less emissions	3
independend by weather	2
renewable energy	1
CO2 neutral	1
available 24/7	1
base load capable	1
energy security	1
contributing energy transition	1
low OPEX	1
Re-use technical aspects	5
Different uses are possible	1
Quick and simple way to exploit geothermal ressources	1
Easy access to potential energy source	1
Application of new technologies	1
Accommodating environmental concerns about abandoned wells	1
Risks - Geology/Environment	20
Regional geology already known/reduce of geological risks/well information availabel	6
Reductions of environmental impact compared to drilling a new well - energy input, land use,...	4
Reduce prospective and drilling risks	1
Risk reduction	3
Extends the lifetime of already existing infrastructure	2
Use of existing infrastructure	3
Reduced surface foodprint	1
Cost and time	13
Reduction of costs (compared to drilling new wells)	7
Additional income due to reuse(compared to liquidation)	1
Saving costs because no dismantling/renaturisation	1
cheaper energy for heating	1
Faster investment implementation	1
cost effective	1
Regulatory benefits	1
Impactis on the region	6
Keeping mining knowledge in the region	1
support of local drilling industrie	1
Providing support for local communities and industries in teh energy transition	1
use of exisiting land use/no need to change spatial plans	1
Rehabilitation of abandoned areas	1
local employment opportunity	1
Social, economic and legal/regulatory aspects	8
Can be more socially acceptable because people are used to well operations in this regions	4
Fasten project execution/implementation (technical and regulatory aspects)	3
Supported by public	1

Weakness	Counts
Use of geothermal energy (Operational apects)	1
Maintanance costs	1
Re-use technical aspects	21
technical details of the well migth be not suitable for planned usage	3
Well integrity issues of old wells (costly and critical)	5
Geological conditions might not be suitable for the desired geothermal use	3
Old wells drilled with different standards - environmental, technical and regulatory concerns	2
potentially only a low number of old wells is suitable	1
technical challenges	1
Resource depletion	1
reduced thermal energy output	2
Old equipment must be replaced	1
Corrosion risk and deterioration of the installed materials	1
Reservoir and well conditions need to be stable	1
Risks - Geology/Environment	12
potential for contamination	1
possible unknown geological background of the wells and surrounding land	1
Data availability and reliability may not be given	1
Environmental risks (changes in flora and fauna)	1
Cost and time	
high initinal investment costs (adaption of well, special technology needed, experts rare)	6
local finance is limited	1
retrofitting can be more expensive than drilling a new well	1
Impactis on the region	5
location of the well not always next to a consumer	5
Social, economic and legal/regulatory aspects	7
Land ownership and access	1
public perception (negative due low awareness)	2
Negotiations with well owner my be difficult - liabilities	2
Administrative barriers	1
Policy uptake	1

Opportunities	Counts
Use of geothermal energy (Operational apects)	13
Reducing carbon footprint	2
Energy Independence	3
Reduction of greenhouse gas emissions	1
Aligns with the global shift towards green energy	1
clean energy production	1
energy efficiency	1
Energy storage possible	1
establish an environmentally friendly energy	1
Move to renewabel domestic energy sources	1
Energy stability	1
Re-use technical aspects	9
opportunity to test wells beforehand	1
different usage opportunities - heating, agricultural usage, balneology	1
possibility for power generation - enhancing improvements in lowT power generation	2
sustainable approach in exploration	1
Resource maximization	1
Quicker advancement of geothermal energy sources	1
Achievable geothermal technologies for small scale	1
Can open up new geothermal resources whcih would habe otherwise not been considered	1
Possibility of combining different energy sources	1
Risks - Geology/Environment	0
Cost and time	2
faster and cheaper investment realisation	2
Impactis on the region	12
Transition from hydrocarbon industry towards	3
Utalization of existing know how from hydrocarbon industry for geothermal	2
Maintain jobs in the field of geosciences also in rual	1
New cheap energy can attract industry in rural areas (e.g. agriculture)	1
strenghtens local economy	1
land use optimization	1
developement of a "forgotten" site	1
could support local heat demand	1
Revitalizing regions with a "dying" hydrocarbon	1
Social, economic and legal/regulatory aspects	6
resarch and innovation enhanced	2
enable a just transition	1
Contribution to circular economy	1
More incentives from the governments	1
Availability of foreign investors	1

Threats (Risks)	Counts
Use of geothermal energy (Operational apects)	4
geological uncertainty	2
resource depletion	1
potential cooling of the host rock	1
Re-use technical aspects	8
Conditions of the well may represent a risk during reusing	1
unexpected technical challenges	1
lack of knowlegde of former well risks	1
initial conditions decline faster than expected because of age and condition of the well	1
well integrity issues	1
technical callenges compared to drilling new wells	1
capacity is not sufficient	1
casing could collapse faster - make over well be needed soon	1
Risks - Geology/Environment	7
durability of yield of the well	1
Temperature, flow rates different than expected	1
Environmental risks/contaminations	5
Cost and time	2
unexpected project cost overruns	1
Due to well integrity issues calculating investments is more difficult - payback periods might extend	1
Impactis on the region	1
Heat costumers may leave or get bankrupt	1
Social, economic and legal/regulatory aspects	10
legal and financial penalities due to not adhering to complex regualtions	1
regulatory compliance	1
difficulities in finding new investors	1
local population against re-use - interventions	1
energy transition is very slow - no upswing of re-use	1
Legal difficulties in the transition from O&G to goethermal	1
questions of liability for well damage if the well is sold to a new owner	1
Risk that O&G companies try to sneak out their responsilbility to care for a well	1
interest of possible investors	1
funding	1

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SUMMARY – TOP ANSWERS

Strength	Counts
Geology already known	6
Lower environmental impact	4
Reduction of costs	7
Socially accepted	4
Less emissions	3
Risk reduction	3
Use of existing infrastructure	3
Fasten project execution/implementation	3
Weakness	**Counts**
No good well data available	3
Well integrity issues	5
Geological conditions might not be suitable for the desired geothermal use	3
High initinal investment costs	6
Well not always next to a consumer	5
Opportunities	**Counts**
Energy Independence	3
Transition from hydrocarbon industriy towards geothermal industry	3
Threats (Risks)	**Counts**
Environmental risks/contaminations	5

Top answers: Basically everything that was mentioned by more than 2 participants

Counts = how often something was mentioned

5

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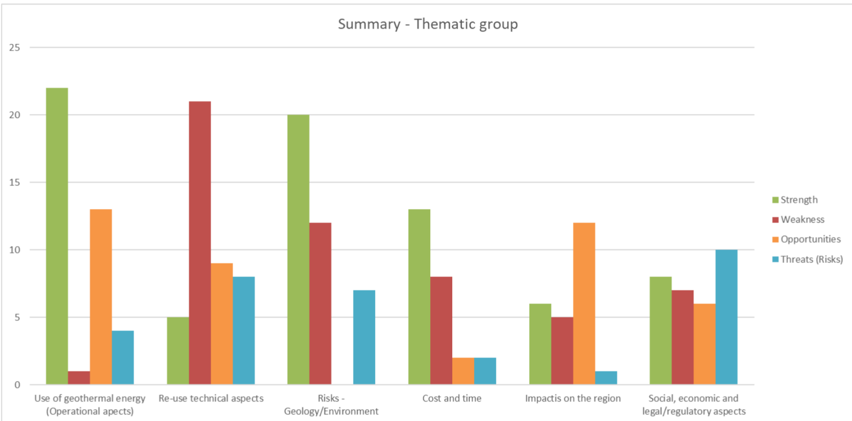
SUMMARY



Most obvious findings:

- Most strengths lie in the areas of operational aspects and the reduction of risks compared to new drillings (especially discovery risk)
- Most weaknesses lie in the technical aspects of reuse
- Most opportunities lie in the impact on the regions and the operational aspects
- Most threats (risks) are seen in the impact on/of social, economic and legal/regulatory aspects

- All thematic groups are mentioned in all S-W-O-T categories except the group “Risks” where no opportunities are seen

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Interreg CENTRAL EUROPE
Co-funded by the European Union
TRANSGEO
Transgeo
Germany, Austria, Slovenia,
Hungary, Croatia
Thank you!