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TRANSGEO

PROOF-OF-CONCEPT STUDY ON REUSE OF ABANDONED WELLS FOR HYDROTHERMAL ENERGY (HE) PRODUCTION

TRANSGEO Deliverable 1.1.3

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Executive Summary

Hydrothermal systems (HE) are perhaps the best-known and most widespread systems for geothermal energy production worldwide. There are numerous types, suitable for both heat and power, and combined heat and power generation. In the following study, we will focus primarily on low- and medium-temperature, low-enthalpy hydrothermal systems, as such projects are typically feasible in the area under study. For these projects, a pair of production and injection wells is required to ensure sustainability. The production well generates hot water, whose thermal energy can be used for either electricity or heat generation; the latter typically involves the installation of heat exchangers or heat pumps, after which the used water circulating in the closed system is reinjected. For such a project to be successfully implemented using decommissioned hydrocarbon wells, several conditions must be met. Assessing the integrity of the wells is essential in every case. A detailed analysis of data from the wells, the geological environment, and the market is also indispensable. The feasibility of such projects is most often limited by financial constraints; without external support, the project's payback period can render it uneconomical.

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.

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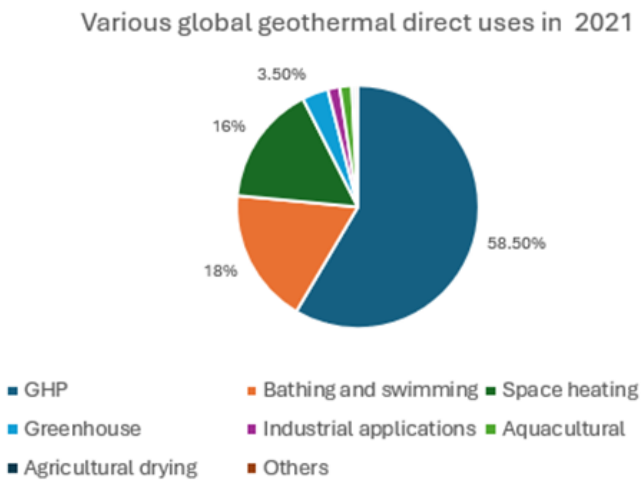
General description of technology

Hydrothermal Energy systems utilize the heat from liquid-dominated geothermal reservoirs, where liquid water is the mobile phase. Liquid-dominated geothermal reservoirs, which are low- to medium-temperature systems, are distributed throughout the world and are not restricted to volcanic regions. They may also be found as warm groundwater in sedimentary formations. Below, we summarize our experiences only with projects involving low- and medium-enthalpy heat production, as this technology is the most widespread in the Central European region, and the three pilot projects examined also fall into this category.

Ideally, during the extraction of hydrothermal heat energy, thermal water heated by the temperature of deep-seated rocks is extracted through a production well—typically using, e.g. an electric submersible pump (ESP)—and, via a heat exchanger, or, if higher temperatures are required, a heat pump, to the system to be heated without the thermal water mixing with the water circulating in the closed system for heating purposes. The cooled thermal water is then reinjected into the original reservoir using a reinjection well, thereby ensuring the sustainability of the hydrothermal system. The average temperature of hydrothermal systems ranges from 40–50 ˚C to 150–190 ˚C, and their average depth ranges from 800–1,000 m to 4,000-5,000 m.

In case of indirect use of geothermal energy used as heat without further conversion into other types of energy. Direct utilization of geothermal energy for applications requiring heating or cooling increased by 50% between 2015 and 2020 (EGEC, 2022). However, geothermal heating and cooling is quite hard to assess as a global market, especially because its data collection is challenging (EGEC, 2022). More than 88 countries use different type of geothermal energy for heating and cooling, in which geothermal energy is used 58.5% for geothermal heat pumps, 18.0% for bathing and swimming, 16.0% for space heating, 3.5% for greenhouse and covered ground heating, 1.6% for industrial applications, 1.3% for aquacultural pond and raceway heating, 0.4% for agricultural drying, 0.2% for snow melting and cooling, and 0.2% for miscellaneous applications (Figure A1). The installed capacity and thermal energy available worldwide today are 107,727 MWt and 1,020,887 TJ/yr (283,580 GWh/yr.), respectively (Lund & Toth, 2020).



1. Figure: Various global direct uses in 2021 (Data source: Lund and Toth, 2020).

Direct or non-electric use of geothermal energy refers to the immediate use of the energy for both heating and cooling applications. Geothermal direct use goes back to when people used hot springs for bathing, cooking food, and loosening feathers and skin from games. Today, the primary forms of direct use include heating swimming pools and baths or therapeutic use (i.e., balneology), space heating and cooling (including district heating), agriculture (mainly greenhouse heating, crop drying, and some animal husbandry), aquaculture (heating mainly fishponds and raceways), and providing heat for industrial processes (for both heating and cooling). One of the main advantages of the direct use of geothermal energy is that it can use low-to-moderate resource temperatures (<150°C). The other advantage is that it can be found, often at shallow depths, almost anywhere in the world.

Hydrothermal energy is producing hot water from a permeable reservoir with an, e.g. ESP via a production well. At the surface, the heat is transferred to a secondary cycle via a heat exchanger. After that, the cooled water is pumped back to the reservoir via an injection well. The reinjected water ultimately heats up again due to natural heat flow in the Earth.

Generally, direct-use systems are typically composed of three components:

- A production facility – usually a production well – to bring the hot water to the surface;
- A mechanical system – piping, heat exchanger, controls – to deliver the heat to the space or process
- A reinjection system – injection well, or storage pond / river (in worst case) – to receive the cooled geothermal fluid.

Heat demand represents a significant share of final energy consumption for space heating, especially in cold countries for agricultural and industrial processes. Geothermal heat production systems may meet the demand by simply providing fluids at the required temperature. For example, the water circulating through the network of pipes, beams and panels of the heating systems of a building may be kept constant in the summer by exchanging heat with groundwater fluids at a temperature of 18°C. If a groundwater fluid temperature of 30°C is discharged, it can for example be used to pasteurize milk in a cheese factory (Manzella, A., 2017).

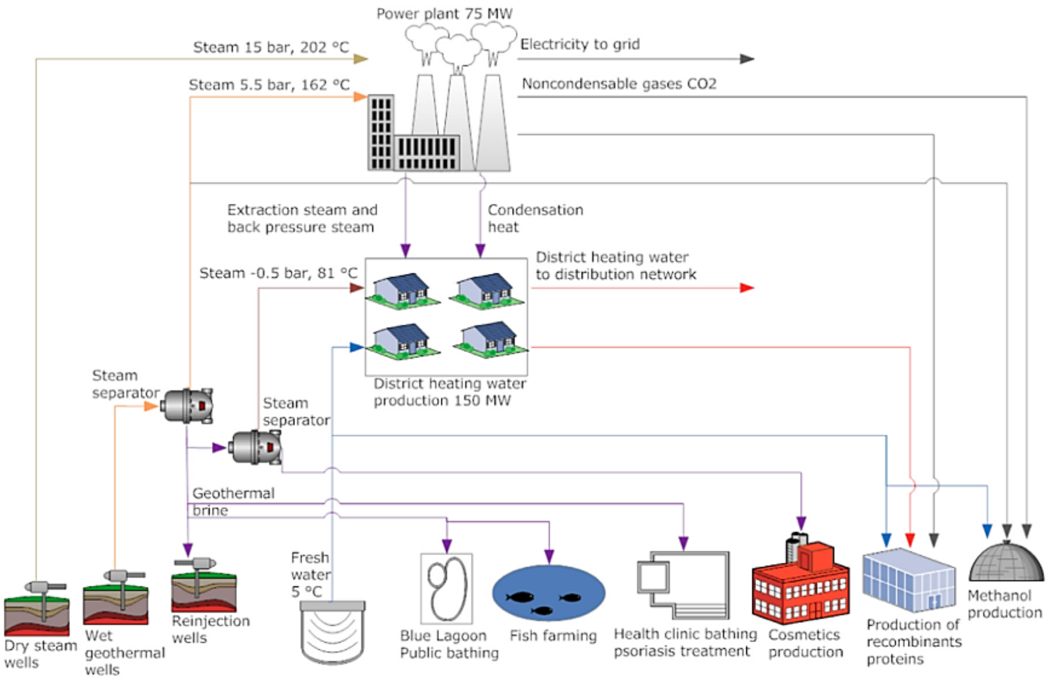
Recent research has demonstrated the positive impacts of cascade applications in geothermal development. The use of geothermal resources in cascade configurations includes not only electricity generation but also the direct use of thermal energy (Pujol, M., et al., 2015; Shortall, R., et al, 2015), drying and dehydration processes, heat pumps, fish farming and swimming pools for recreational activities. Cascading systems allow multiple applications of combined heat and power (CHP) linked to the same geothermal resource. In the cascade design, different temperatures of the same geothermal fluid are used in staging and successive applications in a sequence that requires lower temperatures downstream (Bloomquist, G., et al., 2013; Glassley, W.E., 2015). Gudmundsson (1988) exemplifies the cascade system by a facility that uses geo-fluid for different applications. The geo-fluid leaving the power plant at an optimum temperature is used to heat a cucumber and tomato greenhouse, then piped through cabbage, carrots, and other vegetable fields. This is an example of power generation, greenhouse, and soil heating as cascading uses. Figure A2 provides an example of a combined heat and power configuration in a multipurpose cascade design. In Figure 2, Valdimarsson (2015) illustrates how the same geothermal heat flow (at 202 °C and 162 °C) is used to produce electricity, then, when it leaves the power plant (at 81 °C), it is used for district heating purposes and finally at a lower temperature, the geo-fluid is applied in other different uses. In Figure A3 the so-called Lindal diagram illustrates the different direct geothermal applications.

Municipalities

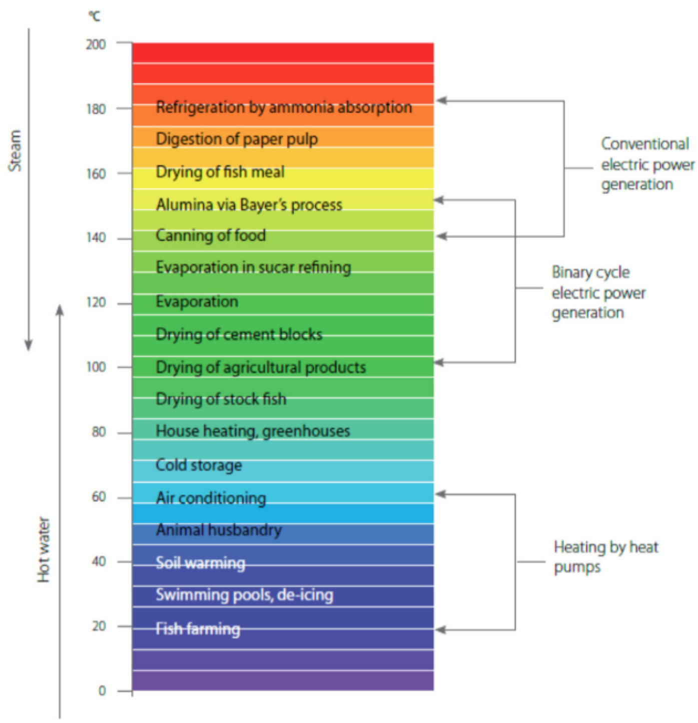
Although the use of geothermal waters dates back thousands of years (baths, balneology, tourism) and is of outstanding importance internationally, we will focus exclusively on hydrothermal heating systems, as this is the most relevant use case for abandoned hydrocarbon wells.

The utilization of geothermal heat resources for direct space heating governs the direct utilization industry, with about 37% of all direct utilization development. The first known commercial utilization of geothermal heat energy was constructed in Chaudes-Aigues Cantal, France, which was constructed in the 14th century

(Bloomquist et al, 2013). Temperatures in excess of 50°C are generally advised for space heating, but resources as low as 40°C could be utilized in certain space heating requirements and circumstances.



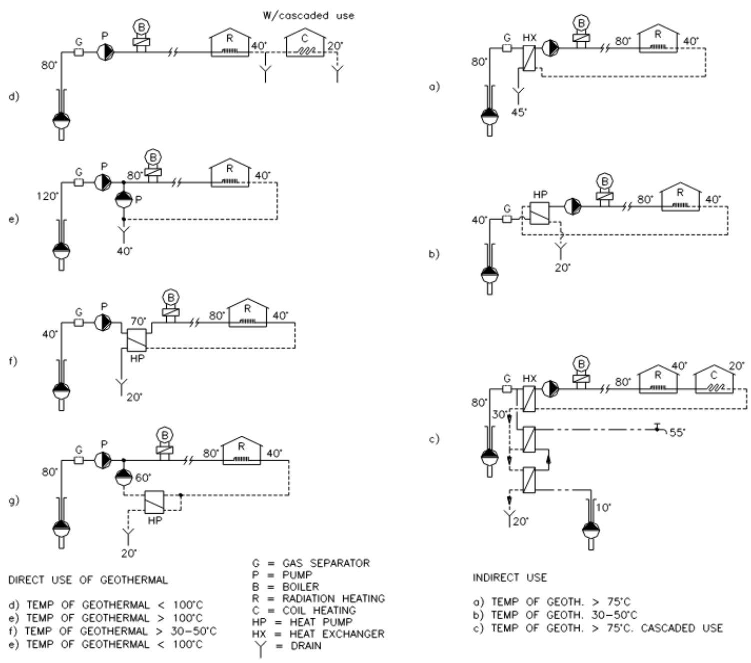
2. Figure: Cascade application of geothermal resources for the example of the Blue Lagoon, Svartsengi Resource Park, Iceland (Source: Valdimarsson, 2015).



3. Figure: Lindal diagram for direct geothermal applications (Source: USAID, 2013).

The main principle behind the use of geothermal heat is that the mass flow rate and the temperature of the geothermal source determine the reliability and the potential of the geothermal fluid in district heating applications. Similarly, the chemical composition of the brine, which might comprise some ingredients such as silica, hydrogen sulfide, chlorides, and oxygen is essential for choosing suitable materials required to design the energy conversion system. The mineral concentration in the geothermal fluid rises correspondingly with increasing temperature and the depth of the geothermal resource (Dincer & Muhammad, 2018).

Geothermal fluid with a limited concentration of 150 mg/kg of silica, less than 50 mg/kg of chlorides, and oxygen below 5 µg/kg is considered uncontaminated and can be used directly for space heating and hot tap water. Hot water is delivered to the consumers at temperatures varying from 60 to 90°C and returned at a temperature varying from 30 to 35 °C, however, use at higher temperatures is also possible; see Fig. A4. The thermal power obtained from geothermal hot water with a mass flow rate of 6 kg/s with a temperature drop from 90 to 50 °C is around one megawatt. Geothermal district heating systems are classified into two types depending on the utilization of the geothermal energy. If it is used indirectly by transferring the geothermal heat to the secondary system via heat exchangers, the district heating system is called the primary system. If the geothermal energy is used directly in the house heating system, the district system is called the secondary system (Figure A4) (Björnsson, O. B.,1999; Dickson & Fanelli, 2013).



4. Figure: Examples of district heating networks with geothermal water (Source: Björnsson, 1999).

The reuse of abandoned oil and gas wells for district heating systems is an innovative and sustainable approach being explored worldwide. These wells, often found in sedimentary basins (for example, the sedimentary basins studied in the TRANSGEO project) rich with geothermal potential, can be repurposed to harness geothermal energy for heating purposes.

In the global distribution of thermal energy used, space heating accounts for 16%, of which 91% is for district heating. Space heating, including individual space heating and district heating, has increased 68.0% in installed capacity and 83.8% in annual energy use over 2015 (WGC 2015). The installed capacity now totals 12,768 MWt, and the annual energy use is 162,979 TJ/yr. In comparison, 91% of the installed capacity and 91% of the annual energy use is in district heating (29 countries). The leaders in district heating in terms of both capacity and annual energy use are China, Iceland, Turkey, France, and Germany, whereas in the individual space heating sector in installed capacity (MWt), the leaders are Turkey, Russia, Japan, United States, and Hungary. In annual energy use (TJ/yr), the leaders are Turkey, Japan, Russia, the United States, and Switzerland, a total of 29 countries. These five leaders account for about 90% of the world's total use in district heating and about 75% of the world's individual space heating. (Lund & Toth, 2020).

Agriculture (greenhouses)

The agricultural applications of geothermal fluids consist of plant growing temperature control in open fields and greenhouses. Thermal water can be used in open-field agriculture to heat the soil and, sometimes, to irrigate it where ponds and rivers are not available. The most common application of geothermal energy in agriculture is, however, in greenhouse heating, which has been developed on a large scale in many countries. Opening costs of greenhouse heating, which in some cases account for 35% of the product costs (vegetables, flowers, house plants, and tree seedlings), can be considerably reduced by geothermal heat (Manzella, A., 2017). As for optimized heat use, several applications of the cascade utilization of geothermal energy for agriculture have been operating worldwide (e.g. Rubio-Maya, C., et al., 2015).

Worldwide use of geothermal energy for greenhouse and covered ground heating increased by 24% in installed capacity and 23% in annual energy use. The installed capacity is 2,459 MWt and 35,826 TJ/yr in energy use. A total of 32 countries report geothermal greenhouse heating (compared to 31 from 2015 according to WGC 2015), with the leading countries in annual energy use (TJ/yr) being Turkey, China, Netherlands, Russia, and Hungary, accounting for about 83% of the world's total (Lund & Toth, 2020).

Industry (automotive industry, food industry)

The industrial use of geothermal energy dates back to the early 20th century, but its widespread adoption has accelerated in recent decades due to growing concerns about dependence on fossil fuels and climate change. Its sustainability, reliability, and cost-effectiveness make it an attractive choice for industries seeking to reduce their carbon emissions and comply with stricter environmental regulations. According to a report by the International Renewable Energy Agency (IRENA), geothermal energy can make a significant contribution to industrial decarbonization efforts, particularly in sectors that require a continuous and stable supply of heat (IRENA and IGA, 2023).

Heating is by far the largest form of energy consumption in industrial processes. Geothermal heat provides a continuous energy supply at low operating costs across a range of temperatures, loads, and capacities. This makes it particularly suitable for many industrial processes that require different temperatures for production. Market opportunities are expected in the use of geothermal energy for supply chain cooling and desalination using geothermal heat (EGEC, 2022). In the automotive industry, the demand for more environmentally friendly manufacturing processes fits well with the use of geothermal energy. With the proliferation of electric vehicles (EVs), geothermal energy can provide a sustainable energy source to meet the increased electricity demand of EV manufacturing facilities. This is the case in some countries that use—or plan to use—geothermal systems to meet the heating needs of manufacturing plants (i.e Hungary - Audi (Győr), Mercedes (Kecskemét), etc).

Furthermore, hydrothermal energy can be used in a number of food industry applications, including:

- Heating of greenhouses (25 – 100 °C) to grow fruits, vegetables, flowers, and plants
- Aquaculture (20 – 40 °C) or fish farming
- Cultivation of algae (35 – 37 °C)
- Soil heating (20 – 40 °C) to grow crops such as carrots, cabbage, and asparagus
- Irrigation (40 – 75 °C)
- Drying of food or crops (40 – 100 °C)
- Pasteurization of milk (70 – 100 °C)

- Evaporation and distillation (80 – 120 °C) for processing of milk and preparation of spirits
- Sterilization (> 105 °C)
- Refrigeration by ammonia absorption (> 120 °C)

Slovenia is the leading consumer of energy for industry purposes, accounting for nearly 46.8% of the total final consumption, followed by Germany, with 29%.

Lessons learned based on pilot sites

According to a feasibility study in the Hungarian Great Plain, five important experiences can be highlighted (Transgeo Deliverable 2.3.3). On the one hand, due to their distance from the market, most of the wells classified as suitable can be ruled out. On the other hand, the current condition of most of the wells is unknown, as they have not been inspected since their closure; only the terrain and surface infrastructure (concrete base, Christmas tree, or gate valve, etc.) have been examined. This also represents a serious data gap, which hinders the planning of geothermal projects. Assessing the condition of wells requires serious preliminary planning and involves significant costs, which increases the risk for investors. First and foremost, these costs must be effectively reduced by implementing an appropriate minimum program, but this cannot be done at the expense of safety. Thirdly, it is worth considering that, in the case of known reservoirs, the wells in question should be used exclusively for testing (rock and water sampling, vertical delineation of the reservoir) and to prepare for the drilling of a new production well in the immediate vicinity of the well. In the case of a new project, this alone can significantly reduce the risk. Fourthly, the reinjection of water into the Upper Pannonian formation (original reservoir) requires a high level of technological expertise (determination of critical flow velocity, filter design, reduction of reinjection temperature, etc.). Abandoned hydrocarbon wells may be more suitable for use as reinjection wells. Fifthly, it had to be acknowledged that local governments were not prepared in terms of the energy background of their own buildings and were therefore unable to provide data of sufficient quality for the design of surface facilities. The projects would probably be more successful if local governments could systematically assess the energy conditions of their building stock, but they lack the necessary data, human resources, and, in most cases, financial resources to do so.

The findings of TRANSGEO Deliverable 2.3.4 — a feasibility study on the Mihovljan field in Croatia — show that sufficient data is available for complex modeling if active operations are currently underway in the area or have taken place in the recent past, e.g., production at the Mih-6 well and injection at the Mač-1R well. Based on a detailed analysis of the well data, a four-well (two production and two injection wells) pilot project was planned, with a duration of 27 years (1 year of preparation, 1 year of construction, 25 years of operation). A detailed economic analysis and NPV sensitivity analysis were prepared for the project. As the production wells have a relatively low water production capacity, the economic analysis predicted a loss-making project over a 25-year period in all cases examined. Most of the costs are related to revitalization and the reopening of shallower sandstone layers (high CAPEX). The total cost of converting a well in this case is practically comparable to the cost of a project involving a new well. The feasibility study has shown that, without a subsidy financing system, such small-scale revitalization projects are not economically viable for investors unless they receive co-financing from local communities or public funds. At the same time, it is important to note that it is worthwhile to consider possible uses before hydrocarbon fields are depleted and to model the geothermal potential of the area in collaboration with the hydrocarbon production company, using its long-term data series and detailed analyses.

According to TRANSGEO Deliverable 2.3.1 in the case of Ampfing, Germany, the feasibility study covered the conversion of a currently shut-in well into a hydrothermal geothermal well. This dry oil well (SCK-002B) is considered as an reinjection well in the most likely scenario and is expected to be deepened, while the production well is a newly drilled well. In contrast to the other two projects, where Upper Pannonian sandstone is the target rock, production would take place from the Upper Jurassic (Malm) limestone, which requires other processes to be taken into account in the design (karstification, dolomitization, etc.). The planned reinjection temperature of 55 °C can be further reduced by using a cascade system. Another difference is that the heat supply system is to be built up gradually, i.e., the aim is to develop a district heating system for residential and industrial areas in and around Ampfing. Therefore, cooperation between municipalities in the area is necessary to create the necessary synergies. Cooperation with other municipalities can lead to significant savings, which bring economic and ecological benefits and enable geothermal heat supply.

In each case, the starting point, the scope of available data, the areas covered by the study, and the lessons that can be learned are different. However, the final conclusion in each case is that, without financial support, it is not possible to generate profitable projects under the current economic conditions.

The three areas differ significantly from each other. In each case, the starting point, the range of available data, the areas covered by the study and the lessons that can be drawn in general are different. However, there are also generalizable experiences, which are the following:

- The costs of testing and modifying wells have a very strong influence on the feasibility of projects. These costs must be reduced, keeping safety in mind, in order for the projects to be profitable. Therefore, under the given conditions, without financial support, it is not possible to generate profitable projects in the current economic conditions.
- One of the main conditions for the feasibility of projects is accurate knowledge of the heat market, which is usually not available in sufficient quality.
- Even before abandoning hydrocarbon fields, it is worth preparing a plan for later use with the involvement of the well owner company, because after that the range of available information is significantly reduced, and and also the technical possibilities (once the well is plugged and abandoned the costs and risks increase significantly for reuse.
- In each case, it is advisable to examine different scenarios, including e.g. the use of bivalent systems, companies that can be involved in the cascade system, and the return on the project under different economic conditions (sensitivity analysis).

Requirements to reuse hydrocarbon wells for hydrothermal energy production

Table A1 summarises all the factors that need to be considered for a hydrothermal project on an abandoned well. Key parameters are highlighted with a dark background. For hydrothermal projects, with few exceptions, reinjection must be taken into account. In other words, it is always advisable to think in terms of two wells. In some cases, the abandoned oil/gas well may not be suitable for water production, but may be suitable for reinjection. The table also takes into account these factors. Basically, the parameters can be divided into three groups.

The first group describes the geological conditions of the reservoir near the well. Permeability, effective reservoir thickness and reservoir temperature largely influence the possible temperature and thermal power a hydrothermal well can produce.

The second group lists well-related factors. The most important well parameters are the location, the well status, well age, well integrity, casing diameter and its productivity or injectivity. The well factors largely influence whether it is safe to reuse the well, how much effort it takes and if the anticipated flow rates and temperatures can be produced or injected.

The third group describes the market-related factors. Key parameter is the distance of a well from the users, which determines the maximum distance for transporting the produced energy for a given yield and temperature. In addition, information on the heat/electricity demand and heat/electricity transport infrastructure is essential.

Additional parameters may also be important from the point of view of the project's planning and long-term sustainability, however, they are not decisive in terms of the project's implementation. See Appendix A in Transgeo Deliverables 1.1.6. for a full list of parameters that may be considered in planning a new project.

Based on feasibility studies, in the first round the distance to the market, its size, outlet water temperature and surface water flow (meaning production rate) are the most important parameters to consider.

Parameter	**Data source**	**Minimum/maximum value**	**Data availability (and accessibility)**
	Reservoir parameters		
Effective reservoir permeability	Well tests, Production/injection data, Laboratory tests on rock cores, Calculated from porosity	Depends on the effective reservoir thickness (typically > 10^{-13} m^2)	Good (Very poor)
Effective reservoir thickness (geometry of the reservoir)	Geological well profile, Seismic survey, Geological model	Depends on the permeability (typically >20 m)	Very good (Very good)
Reservoir temperature	Temperature log/measurement	Depending on the application (typically >35°C)	Very good (Good)
Reservoir pressure	Pressure log	Hydrostatic or overpressurized (if not used as injection well)	Very good (Good)
Effective porosity of the reservoir	Well logs, Laboratory tests on rock cores, Well tests	Typically >15 % (if not fracture dominated)	Medium (Poor)
Structural geology of the reservoir (presence and properties of fractures and faults)	Seismic survey, Geological model, Well logs	Permeable fault, fracture network or karst required in low permeability rock	Medium (Poor)
Groundwater flow velocity and direction	Hydrostatic head measurements, Calculations	-	Poor (Very poor)
Water recharge	Production history	balanced	Poor (Very poor)
Salinity of reservoir fluid	Laboratory analysis of fluid samples	No limit, the lower the better	Good (Medium)
Gas/Oil-Water contact depth	Well logs	Best if no oil or gas is present in the geothermal reservoir	Very good (Very Poor)
Gas-Water ratio / Oil-Water ratio	Production data	Best when no oil or gas is produced	Very good (Very Poor)
Injected water salinity and temperature	Measurement, Laboratory analysis, Can be changed	Similar character than original water	Limited knowledge of behaviour in reservoir
Intercalated layers	Well logging	no or thin layers	Medium

			(Poor)
Mineralogy of the reservoir rock	Laboratory analysis of rock samples	Depending on the injected fluid	Medium (Poor)
Formation damage	Well tests, Partly repairable	Insignificant damage	Medium (Poor)
Well parameters			
Well location	GPS	Accessible, not located in a protected area	Very good (Very good)
Well status	Mining authorities	Shut-in or active is best, but also abandoned wells can be used	Very good (Very good)
Well age	Mining authorities, End of well report	<30-60 years	Very good (Very good)
Well integrity (wellhead, casing, cement quality along the well)	Well logging, Pressure testing	No leakage and no signs of significant casing or cement degradation	Good (Poor)
Casing diameters (inch)	End of well report, Well logging	>= 7 inch	Very good (Medium)
Productivity Index (L/s/MPa)	Well test, Production data	> 10 L/s/MPa	Very good (Very poor)
True vertical depth (TVD)	Well logging, Calculation, End of well report	> 1000 m	Very good (good)
Measured depth (MD)	Well logging, End of well report	-	Very good (Very good)
Perforation number, depth and quality	Given, changeable (e.g., re-perforating)	-	Medium (Very poor)
Surface facilities	Well owner	-	Very good (Medium)
Market parameters			
Distance to energy consumer (km)	GPS, Maps	0 - 10 km	Good (Good)
Required thermal/electrical power output of the hydrothermal system	Heat/electricity consumers	1-50 MW	Good (Good)
Existing infrastructure (e.g., heat transport lines)	Heat/electricity network operators	The more infrastructure that can be reused the better	Very good (Very good)
Possibility of multiple/cascade use	Heat/electricity consumers	yes	Medium (Medium)
Minimum lifetime of the hydrothermal wells and the heat demand	Economic analysis	> 20 years	-

Table A1: Parameters determining successful reuse of hydrocarbon wells for hydrothermal energy production. The most important parameters are highlighted with a dark background.

Workflow to reuse hydrocarbon wells for hydrothermal energy production

Investors have two options for the reuse of abandoned oil and/or gas wells. Either there is an abandoned well with suitable properties for hydrothermal geothermal use and they look for a geothermal market, or there is an existing market and they look for a well with the right parameters. The investor's objective may also be to generate electricity and/or heat. Electricity production is usually carried out by professional companies, often energy companies with significant capital, appropriate knowledge, geological models and professional background. Since these are high-risk projects and there are relatively few abandoned oil/gas wells that meet the necessary criteria, the following discussion will focus on the more common and more market-demanding thermal projects.

In all cases, it is worth starting from the assumption that the project is triggered on a strictly business basis, by investor demand. If the investor has a market, it is likely that they know the market well, have appropriate calculations and will be looking for wells with the right yield and temperature. However, in some aspects this is the relatively easier case. So, let us start from the assumption that a well (rarely a pair of wells) of unknown condition is available and the investor is looking for a market for it, i.e. the market has to be investigated.

1. First, it is worth obtaining information on the ownership of the well. The first step is to find out whether the well can be purchased or put to use.
2. This is followed by gathering information on the well and its surroundings, reviewing and interpreting well logs, surface geophysical surveys, well history, well structure, yield and temperature data, and if these indicate that the well is prospective, assessing the geothermal potential of the well and preparing a portfolio.
3. In parallel, a detailed assessment of the market demand for heat, identification of potential users and their heat demand, and, in the case of electricity generation, an assessment of the energy demand and available energy infrastructure are done.
4. If the market and well are available, a pre-feasibility study should be prepared for decision making. This should include an overview of the geology and hydrogeology of the area, the temperature, yield and chemistry of the water to be extracted, the technical conditions of the well as known from daily reports, documents and other sources (e.g. tacit knowledge), a list and evaluation of the workover activities required, an estimate of the amount of energy that can be extracted based on available production data, and an analysis and evaluation of the heat market and its economics.
5. On the basis of the pre-feasibility study, the investor can decide whether to proceed with the project and implement risk mitigation measures if required to proceed with the project.
6. If the investor wishes to proceed with the project, the operator must obtain the right to control the well (if it is not the owner of the well), and the necessary permits. On the basis of documentation in accordance with the regulatory requirements, it is advisable to inspect the well condition and production conditions, including cementing, reservoir permeability, perforation quality, well at-rest measurement and test production, and in the case of injection wells, test injection (well logging and well tests).
7. On the basis of the above, it is advisable to prepare a feasibility study containing a detailed technical, market and economic analysis and a risk analysis for the construction of the well pair.
8. On the basis of the feasibility study, if the investor decides to launch the project, it is necessary to obtain the ownership of the well or the right to exploit the well if the investor does not own it. Subject to regulatory requirements, the investor must obtain a concession right or the necessary permit, with a few country-specific exceptions (e.g. balneology and agricultural use in Hungary), and must implement the project in accordance with the legal requirements.

Hydrocarbon wells can be reused for hydrothermal energy systems in the following ways:

1) Hot water can be co-produced with the oil or gas from the hydrocarbon reservoir towards the end of hydrocarbon production when the water-cut is high. This results in relatively low water flow rates (typically up to ~10 L/s) and energy output (few MWth) as the relative permeability of the water is reduced due to the residual oil or gas in the reservoir and sometimes due to the relatively low reservoir permeability, which is sufficient for gas production, but not sufficient for conventional hydrothermal energy production. Additionally, the pressure level may already be very low in the reservoir after many years of hydrocarbon production. To use the hot water that is produced anyway during hydrocarbon production, only a heat exchanger needs to be placed at the surface after water separation and it must be connected to the consumer.
2) Hot water can be produced from the hydrocarbon reservoir after the end of hydrocarbon production. In this case an ESP should to be installed within the water column in the well. The potentially low flow rates/capacities resulting from relative permeability, absolute permeability and pressure described above also apply to this case.
3) The well is deepened below the hydrocarbon-water contact into the aquifer. This avoids the relative permeability problem, but results in a smaller well diameter, restricting the maximum flow rates due to frictional pressure losses in the well.
4) The well is cemented back to a potential shallower geothermal reservoir and the geothermal reservoir is accessed via perforations or a side-track.
5) A hydrocarbon exploration well, which did not find oil or gas, but hot water may be used right away as a hydrothermal production or injection well without the potential challenges described in (1-3) and without the need for expensive workover operations as described in (3-4).

Based on the feasibility studies, the above can be supplemented with the following:

- There is a very common lack of data on both the reservoir and the market;

- It is preferable to model a well for possible geothermal exploitation before abandoning it;

- Hydrocarbon wells are not tested for water production purpose, i.e. they are often non-hydrocarbon related reservoirs (aquifers) have to be opened in a well for water production, independently of the hydrocarbon reservoirs. These aquifers need to be investigated separately and a test and revitalization plan needs to be prepared for them. This was true for both the Upper Pannonian sandstones and the Upper Jurassic limestones, where although the given layers were investigated from some point of view, the hydrocarbon accumulated in other layers (Lower Pannonian, Miocene and Cretaceous). Based on the above, the geothermal utilization of abandoned hydrocarbon wells is not actually aimed at the utilization of waters associated with hydrocarbon deposits.

- Before starting the project, the most important point of the feasibility study should be the study of various technical scenarios and the calculation of the return on investment of different options.

Feasibility analysis

The project involved three completely different feasibility studies for three hydrothermal systems. Although the framework was given, each study focused on different aspects. The Hungarian and Croatian pilot project targeted the Upper Pannonian poorly consolidated sandstone, while the German study presented a project based on the Upper Jurassic (Malmonian) limestone of great thickness. The main challenge identified in the Hungarian study is the integrity of the tested wells and the estimation of the data serving as the basis for the energy calculations. The Croatian study has all the necessary data, but the possibilities given by the area are limited due to relatively low reservoir permeability. The challenge in the German study is the scale of the necessary investment and the related commitment of multiple customers. Similarly, in terms of settlement size, one small town was designated for the pilot project in each of the three areas (Biharkeresztes 3921 inhabitants, Ampf ing 7161 inhabitants, Čakovec 27122 inhabitants). Another similarity is that all three projects can only be implemented cost-effectively with support.

A brief summary of the areas is as follows:

The selection of the pilot project in the Hungarian Great Plain was based entirely on the well assessment IT software and the underlying database, taking into account experiences (Szentes) and good practice (Nagyatád). At the end of the multi-round selection process, two areas remained, of which the Biharkeresztes area on the eastern border of the country was chosen for practical reasons (size of the city, number of buildings managed by the Municipality, location of wells, etc.). This area has been well explored in terms of hydrocarbons, but the wells were abandoned a long time ago and most of the research and modeling are not available. From the perspective of hydrocarbon exploration, the Lower Pannonian and Miocene layers were promising, therefore there were relatively few data on the Upper Pannonian sandstones. The well doublet Ár-2, Bi-31 were designated as production and injection wells, respectively, since both are under the management of the BVH and since Ár-2 has already been converted into a water well, although it has not been put into use. The condition of the wells is questionable, their condition assessment is necessary, for which the BVH has already requested a detailed offer. Based on the offer received, even the assessment of one well entails significant costs, so in this case, reducing this cost within the limits of reasonableness is a key issue in terms of the return on investment. On the other hand, the amount of water to be produced is 700 l/min (1008 m^3/day), its temperature (47 °C) and the planned temperature of the reinjection (21 °C) may be ideal for a bivalent (geothermal-gas) system project in terms of reducing the heating costs of the building group (11 buildings) owned by the Municipality. However, without support, the payback period is almost 27 years.

The Mihovljan oil field is located in the northern part of the Republic of Croatia, within Međimurje County, near the town of Čakovec. The area is characterized by favorable transport connectivity, developed electric power and gas infrastructure, and compliance with spatial planning documentation, which enables the potential integration of a future geothermal system into the existing energy network.

As part of this study, 15 wells were analyzed. Based on the available well documentation, the geological, petrophysical, geophysical and production characteristics of the deposit were evaluated. Out of a total of 15 wells, of which 10 are abandoned, two production-injection well pairs were selected for further analysis. The first production-injection well consists of Mih-1 as a production well and Mih-7 as an injection well, while the second pair consists of Mih-3beta as a production well and Mih-6 as an injection well. Calculations of isothermal production and the energy potential of the geothermal reservoir were carried out for the selected well pairs, as well as a techno-economic analysis that includes an assessment of revitalization costs, investments in surface infrastructure and expected revenues.

In the Mihovljan area, although a sufficient amount of information is available, the geological, hydrogeological conditions and the location of the wells cannot be considered ideal. Although the temperature of the produced water is high (82 °C) and the temperature of the water to be injected is relatively low (30 °C), the amount of water produced from a pair of wells is only 465 m^3/day (total 930 m^3/day) and the location of the wells relative to each other results in a thermal breakthrough within 25 years. The payback period in this case is also more than 25 years and, similarly to the Hungarian example, the project can only be implemented “profitably” with adequate support, otherwise it is unprofitable.

The project planned with the municipality of Ampfing in the South German Molasse Basin in Bavaria, Germany, is based on a completely different basis. Here, a horizontally and vertically extending limestone body is located below an oil well drilled into a Cretaceous hydrocarbon reservoir rock. This well needs to be expanded in length and is planned to be converted into an reinjection well, while a new production well is planned to be drilled in the area. There is no direct data on reservoir properties, but there is a lot of data available from surrounding projects, which was taken into account as a design parameter. Thus, the expected temperature at 2370 m is 107.5 °C, which is more than the assumed needed surface flow temperature of 70 - 80 °C. The expected production rate is 80-100 l/s (6912-8640 m3/day) and the planned reinjection temperature is 55 °C. The latter can be reduced by involving additional consumers through a cascade system. The German pilot project is being built step by step, meaning that the planned number of buildings being involved and the pipeline system being constructed will happen continuously over 9 years. In the case of the project, the main issue is the involvement of the surrounding municipalities in the project, which significantly reduces the end-consumer heat price . The most important data of the pilot projects is summarized in the table below (Table E1)

Location	Hungary	Croatia		Germany	
	Biharkeresztes	Mihovljan area (Čakovec)		Ampfing	
Invesigated wells					
Production	Ár-2	Mih-3beta	Mih-6	new well	
Injection	Bi-31	Mih-1	Mih-7	SCK-002B	
age	Upper-Pannonian	Upper-Pannonian		Jurassic (Malm)	
rock	sandstone	sandstone		limestone	
avarage rock thickness (m)	52,5	35		350	
temperature of produces fluid (oC)	47	82		>80	
fluid flow rate (m3/day)	1008	930		> 6900	
injected water temperature	21	30		55	
Custumer					
primary custumer	Municipality	Municipality		Municipality	
habitants	3 921	27 122		7 161	
secondary custumer	Agriculture	Industry		Industry	
Legal/administrative steps					
data request regarding wells	Y	Y		?	
request for data on buildings	Y	Y		?	
preparation of a well inspection plan	Y	Planned		Planned	
Review of land use/spatial plans, alignment	N	Y		?	
Licensing	N	N		?	
Logging/workover activities for repurposing	The feasibility studies were based on a review of existing information, so no specific work was carried out in the field. The financial constraints of the project did not allow for this. However, in all cases, the studies estimated the tasks and costs associated with well inspection and, where necessary, well conversion.				
Surface infrastructure and connection to the custumer					
distance from the custumer based on IT tool					
Closest residental area (m)	378	no data		945	
Closest industrial area (m)	3664	no data		943	
Closest agricultural area (m)	0	no data		0	
distance from the custumer based on feasibility study (m)	2100	no data		3500	
planned connection pipelines lenght (km)	3,6	no data, only estimated costs		32,8	
planned stations	12	no data, only estimated costs		1087	
notes		near Pribislavec and Mihovljan		The wellsite is located around 3.5 km by car from the Ampfing town center.	
surface infrastructure	transport infrastructure, buildings	transport infrastructure (D-209 state road), Čakovec buildings (photovoltaic panels), transformer stations, solar energy, hydroelectric plants, pipeline route for oil		good transport infrastructure, residential buildings, indusrtrial areas nearby, future trade and service activity in Ampfing-Ost	
Estimation of the costs (CAPEX+OPEX)					
CAPEX (million EUR)	3,7	6,3		74	?
OPEX (million EUR/year)	0,038	0,204		0,3	0,3
Estimation of the revenue (year)	>25 (26,57)	>25		>20	<11
Total revenues during working (million EUR)	0,139	3,6		no data	no data
Net revenue after 25 years (million EUR), Ampfing 20 years	~-0,05	-5,9		-1,52	14,83
notes	Scenario 1	Scenario 1		Scenario 1	Scenario 2
				costs decreased by subsidy under BEW	

Table E1: Summary table of experiences from pilot projects.

In summary, it can be said that the investigated hydrothermal projects based on abandoned oil wells can only be implemented with significant financial support. The main reason for this is that hydrothermal projects require the opening of reservoirs other than those that produced hydrocarbons during hydrocarbon exploration and the inspection and making the wells suitable for production involves significant costs. It is important to note that there is great uncertainty regarding future energy prices, but systems operated in a bivalent manner (Biharkeresztes) or gradually built-up systems (Ampfing) and the reduction of the cost of well revitalization can significantly influence the return in a positive direction. Furthermore, it is advisable to examine the possibility of future hydrothermal geothermal use in the case of still operating wells in advance and plan the abandonment of the well accordingly, including a parallel energy survey of the range of users.

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