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Criteria catalogue for well repurposing

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D 1.3.1: CRITERIA CATALOGUE FOR WELL REPURPOSING

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0. Executive Summary

This report was prepared by the consortium of the project TRANSGEO to provide the deliverable D1.3.1, "Criteria catalogue for well repurposing." The criteria catalogue summarises, evaluates and weighs all relevant factors affecting the repurposing potential of wells and surface infrastructure, including technological, geological, thermal, political and socio-economic factors. This work is a result of the project partners' research into criteria affecting reuse of abandoned wells for applications in industry, agriculture and municipalities, with special attention to heating and the conditions required for an economically feasible reuse of existing wells for different applications. The report reflects the views of the authors.

The criteria catalogue provides a systematic framework for assessing the feasibility of converting abandoned oil and gas wells for geothermal energy production. It has a dual purpose: on the one hand, to assess the market, technological, and geological conditions that influence feasibility, and on the other hand, to define the key concepts and parameters that determine the applicability of different geothermal technologies.

The catalogue provides a conceptual basis for the development of a relational database and decision tree, which facilitates the development of an online decision support tool. Within this framework, two separate but overlapping data collection objectives can be identified: (1) collecting the parameters necessary for selecting the technology feasible for a given well and market, and (2) collecting the design parameters related to the implementation of a given technology.

Each prerequisite parameter can be categorized according to its impact on technological applicability using a so-called traffic light system. In this system, green indicates that a given parameter meets the requirements of the given technology; yellow indicates uncertain or conditionally-applicable cases that require further investigation; and red indicates exclusion, i.e., that the technology is not applicable for the given parameter value. This color-coded classification provides a clear visual summary of the feasibility of a given well.

Harmonized datasets enable consistent classification of wells and integration with complementary maps depicting market, technological, and geological conditions. These maps can serve a visual or analytical function, depending on whether they provide contextual information or define the boundary conditions for the feasibility analysis.

The result is a structured decision-making framework that can identify the geothermal conversion potential of individual wells according to specific market, technological, and geological conditions.

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

Generally, a criteria catalogue has a dual purpose. On the one hand, it reviews and evaluates, from the point of view of feasibility, all the conditions that may influence the feasibility of a given objective; on the other hand, it defines all the concepts that are related to the given objective and its feasibility. In this case, the objective is the geothermal reuse of abandoned oil and gas wells. Feasibility has market, technological, and geological conditions and, related to these, market, technological, and geological risks.

The following **Market conditions** must be taken into account:

- the location of the well, its distance from various market players;
- the market's heat and/or electricity demand, i.e., the size of the market;
- the method of use, i.e., whether the project can only be used for heat production, or for both heat production and storage, or, where applicable, for electricity production;
- economic considerations, i.e., the conditions under which the project will be profitable;
- social and societal aspects, such as the community acceptability of the project, protection of natural values, protection of jobs;
- analysis of changes in the environment resulting from the technologies used;
- legal framework, i.e., whether the project can be implemented within the given legal boundary conditions.

Generally, at the level of definitions, it is necessary to define market participants (users, data owners, etc.), indicators of market size and type, types of costs necessary for implementation, indicators of return on investment, and the most important factors to be taken into account in the social, societal, and legal framework. In all cases, particular attention must be paid to exclusionary factors.

Technological conditions include

- an overview of applicable technologies and the conditions for their application;
- the structure and technological characteristics of the available well;
- the examination of the technological suitability of the well and the methodology used for determining this;
- tasks related to ensuring the technological suitability of the well, i.e., ensuring the suitability of the well for the project, including conclusions that can be drawn from the history of the well;
- knowledge of interactions within the water, gas, cement/grout, casing (casing/tubing);
- in certain projects, the technological conditions for reinjecting the produced water.

Generally, at the level of definitions, the most important technological parameters related to the construction of the well, the tests related to the survey of the wells, the applicable technologies, and the concepts related to technological implementation must be defined.

Geological conditions include

- the suitability of the wider (basin-level) and immediate geological environment of the well, including the characteristics of the rock and its fluid content;

- the suitability of the reservoir's mineralogical, geochemical, hydrogeological, water chemical, petrophysical, rock mechanical, and thermal parameters, including the testing methodology;
- knowledge of interactions within the reservoir (water-rock, water-water compatibility);
- analysis of changes in the geological environment resulting from the technologies used.

The most important parameters and concepts related to the geological environment and the reservoir must be defined, and the most important measurement methods, their problems, the concepts related to interactions within the reservoir, and the processes occurring as a result of the applied technology (e.g., rock-water interaction, etc.) must be described.

The criteria catalogue forms the basis of the database and decision tree, which is the starting point for well assessment IT tool development. Data collection can basically serve two different, overlapping purposes. On the one hand, data are needed to decide which technology is feasible for a given well and market (prerequisite parameters), and on the other hand, data must be collected to examine the implementation of a given technology (design parameters). In this case, the criteria catalogue focuses only on the first purpose (analysis of prerequisites) and merely lists the design parameters.

Knowing the prerequisite parameters, i.e., the factors necessary for decision-making, we can identify the data fields necessary for selecting a given technology, i.e., the data without which we cannot decide on the applicability of a given technology. These data can be organized into a relational database. Based on the relational database and the criteria catalogue, a decision tree can be created, which is essentially a query system that helps select the geothermal technologies that can be implemented in each well.

The individual prerequisite parameters can be classified into three categories in terms of the applicability of a given technology: the given technology is applicable according to the given parameter, its applicability is questionable, or it is not applicable. The simplest visual representation of this is the so-called traffic light system, which uses green, yellow, and red colours to indicate the above answers. The end result for each technology is a table that analyses the factors influencing each technology separately and contains a green-yellow-red colour code.

2. The structure of the criteria catalogue and the decision tree

2.1. Direct and indirect approach of decision tree

Geothermal projects based on abandoned hydrocarbon wells can basically be approached in two ways: market-based approach and well-based approach.

In the case of a market-based approach, we have a specific market whose needs have been assessed. The market may be a power market and/or a heat market. Depending on the nature of the potential customer, it may be an agricultural, industrial, or municipal user, but in reality, since the market is given (the customer is given), it only plays a role in whether we offer the opportunity to other types of customers to join the project. For example, in the case of the energy market, the sale and market of the heat produced must also be considered, and in the case of heat production, the use of waste heat may also be an important consideration (e.g., cascade systems). Subsequently, the range of technologies can be narrowed down to those that are suitable for the given market. This is followed by an assessment of the suitability of the selected technology, i.e., whether the conditions for its application exist in the given area. The conditions for application include technical, geological, and legal conditions, as well as the acceptability of the technology. Once these have been examined, i.e., we have a suitable technology that is suitable for serving the given market, and there are no legal or social obstacles to the feasibility of the technology, then comes the financial question, i.e., how much will implementation cost? In this case, options must be considered, i.e., in addition to energy production, the usability of the heat market must be taken into account, and it is also worth considering related technologies. Once this is known, the question may arise as to who is suitable for financing the investment(s) and implementing the technology.

In the case of a well-based approach, we have an abandoned well. The first step is to assess the condition of the well, i.e., we need to know whether it can be made suitable for a geothermal project at all. The first step is to examine technological suitability. The second step is to examine the geological conditions. Based on the conditions, it is possible to calculate how much electrical and/or thermal energy can be generated by applying individual technologies or a combination of technologies under the given circumstances. Different sets of parameters play a role for each technology. Next, the market opportunities must be examined, followed by the legal conditions and the technological acceptability and acceptance. From this point on, the sequence is the same as in the direct case, i.e., if there are no legal or social obstacles to the feasibility of the technology, then the financial question arises, i.e., how much will implementation cost. This is followed by an examination of the options, financing, and technological implementation.

In the case of abandoned hydrocarbon wells, although both approaches can be used, **the well-based approach is** likely to be **used more frequently**, so its decision tree is described in detail.

2.2. Developing a unified conceptual system

Creating a relational database is usually a significant challenge, as the data comes from different countries and different periods. Each country uses a different coordinate system to describe the location of wells, which also varies over time within a given country, as deep drilling has been carried out for more than a century. During this time, not only have coordinate systems changed, but in some cases, the basis for determining altitude above sea level has also changed. The first task is therefore to standardize the coordinate system (X, Y, Z coordinates). When mapping, it is advisable to choose a system that is easy to use and an environment that is platform-independent and generally used, as this ensures the long-term availability of the system.

Each country uses its own nomenclature to name the wells drilled in the country. These names, especially the short names of the wells, overlap in some places, so it is advisable to eliminate name conflicts between countries. This is particularly important when using short names as the primary key in the database. The point-like representation of boreholes and the resolution of conflicts in the relational database allow for the unambiguous execution of mathematical operations during map representation, which plays a key role in determining the various distances required for classification (market delineation).

The wells are classified based on the parameters available in the database. It is therefore important to define these parameters precisely before data collection begins and to collect the data in a uniform format. This also includes the standardization of different units of measurement. This task is not trivial, as the data very often originate from different types of measurements, which can often be converted into each other. This can also cause problems in some cases, so it is worth establishing category-level classifications with boundaries (e.g. good, medium, poor; petrological categories, etc.) by setting classification boundaries based on consensus.

When plotting wells on a map, it is necessary to use auxiliary maps that help assess the market, technological, and geological risks of the wells. Two different types of maps must be distinguished. One provides informative data and helps the user to visualize the given area (e.g., geological and geothermal maps, etc.), while the other type is necessary for determining boundary conditions (market, nature conservation, etc.), i.e., it involves mathematical operations. These maps come in different formats, usually with different content for each country and different resolutions. If possible, it is advisable to standardize the format of the maps and integrate them into the system on this basis, because otherwise we may experience significant distortions and disturbing differences in resolution. This is especially true for maps needed to define boundary conditions.

2.3. The technologies examined and the decision tree

The technologies examined are described in detail in the TRANSGEO project's summary study D1.1.6 Engineering workflows for retrofitting abandoned wells [1]. This also includes a detailed bibliography on the technologies. As it plays a fundamental role in defining the criteria, a brief description of the technologies is in the criteria catalogue, focusing strictly on the conditions for the feasibility of the technology in an existing well.

Due to the multitude of parameters required for each technology, it is worth performing sensitivity analyses to select the appropriate parameter set that is actually necessary for modelling, i.e., to optimize the number of parameters to be considered. There are a number of mathematical methods for optimizing the parameter field, e.g., principal component analysis, factor analysis and machine learning algorithms.

During decision making, we only consider those parameters that make it possible to use the given technology, because in most cases the design parameters are not available or can only be estimated.

	Technology	EGS	HS	DBHE	BTES	ATES
1	Goal	Electricity (and heat)	Heat			
	Well/Market	W/M				
	Heat storage	Production			Storage/production	
	Well status Well integrity Protected areas	Pr?/Shut-in/TA/PA?/U? No, possible?, proven? Yes, No?	Pr?/Shut-in/TA/PA?/U? No, possible?, proven? Yes, No?	Pr?/Shut-in/TA/U? No, possible? Yes, No?	Pr?/Shut-in/TA/U? No, possible? Yes, No?	Pr?/Shut-in/TA/PA?/U? No, possible?, proven? Yes, No?
2	Market	M/I	M/A/I			
3	Geology BHT Depth Well distance	Cl, Ca, M/P >90 oC >1000 <2 km	Cl, Ca >35 oC >400 <2 km	Cl, Ca, M/P >20 oC >400 irrelevant	Cl, Ca, M/P < 100 oC 3000>D>400 <2 km	Cl, Ca, M/P any >400 <2 km
4	Mineralogy Water chemistry Gas content Porosity Permeability Water flow rate Productivity Index Minimum casing Impermeable layers Reservoir thickness	qualification qualification qualification < 10% (< 30?) < 10 exp(-14) (-12?) < 50 (< 100?) < 10 >=7 (<7?) No importance irrelevant	qualification qualification qualification > 30% (any?) >10 exp(-12) (-14?) < 100 > 10 >=7 (<7?) No importance >10 (>5?)	irrelevant irrelevant irrelevant any any irrelevant irrelevant >=7 (<7?) No importance irrelevant	irrelevant irrelevant irrelevant any <10 exp(-12) (any?) irrelevant irrelevant >=7 (<7?) No importance irrelevant	qualification qualification qualification > 30% (>10?) any > 100 (>50?) > 10 >=7 (<7?) need >10 (>5?)

Table 1. Summary of criteria for evaluating the suitability of existing wells for different geothermal reuse technologies.

2.3.1. Aquifer Thermal Energy Storage (ATES)

This technology offers an environmentally friendly alternative to traditional fossil fuel-based systems for heating and cooling buildings, which emit greenhouse gases, and is one of the few technologies capable of storing large amounts of energy. ATES systems, which can be single-well, dual-well, or multi-well systems, are open systems suitable for heat production and storage that use natural aquifers as heat storage and transfer media.

ATES systems operate on a seasonal basis. Their operating principle is that water is stored in separate cold and hot water reservoirs in such a way that in winter, water is produced from the hot water reservoir, the heat contained therein is transferred to a working fluid via a heat exchanger and, after cooling, the water is injected back into the cold water system. In summer, water is produced from the cold water system in a similar manner, but for cooling purposes, and the used water is injected back into the hot water reservoir. The wells must be installed at a distance from each other so that the hot and cold storage zones are separated and no thermal breakthrough occurs within a season. Basically, three types of ATES can be distinguished based on storage temperature, depth, and purpose: shallow, low-temperature (> 30 °C, <100 m, building or district heating and cooling), medium temperature, variable depth (30 °C< T < 50 °C, building or district heating), higher temperature, greater depth (> 50 °C, 400-1000 m or deeper, larger district heating network).

The uniqueness of an ATES lies in the fact that it must be designed according to site-specific requirements, including geological and climatic conditions, heating/cooling demand, energy source, integrated facilities, and environmental and energy regulations.

Chapter "F" of "TRANSGEO Project, Deliverable 1.1.6: Engineering workflows for retrofitting abandoned wells, 2024" [1] contains a detailed description of the technology, its boundary conditions, and the parameters required for modelling. These are listed below at the level of modelling parameters. The decision tree lists the parameters that are suitable for assessing whether the technology can be implemented in a given well. Although the decision may be influenced by a number of parameters, the criteria catalogue focuses primarily on those parameters for which information is available from the drillings.

For an ATES, the most important parameters are as follows:

Geological parameters:

reservoir geometry, depth and effective thickness of porous reservoirs, their porosity, permeability (reservoir transmissivity), thermal conductivity, volumetric heat capacity, formation compressibility, static temperature and pressure of the producing zone, total dissolved solids in water, water salt content, water density, water thermal conductivity, water dynamic viscosity, and reservoir temperature.

Technological and design parameters:

borehole/casing inner (or drift) diameter, borehole length, borehole technical structure (well structure), well inclination, number of wells, injectivity and productivity index, well inclination, water flow rate, water temperature in wellhead and reinjection temperature.

Decision tree for the application of ATES technology in existing wells:

For ATES, the most important parameters (prerequisites) to be taken into account when assessing the technological suitability of a well are the depth of the well, the temperature of the well at a depth of 400–1000 m, the depth of the cement plugs, the type of rock, the porosity and permeability of the reservoirs, the volume flow rate at the wellhead, the thickness of the reservoir, the depth of the deepest point of the 7-inch pipe (casing) diameter, the distance from the market, and whether investment in the area is prohibited. However, in the case of abandoned wells, a preliminary investigation is necessary to check the integrity of the well, with particular regard to the section above the upper cement plug. The productivity index and the thickness and quality of the interbedding layers between the reservoirs as well as the groundwater flow velocity and the reservoir cap rock quality would be important parameters, but in most cases these are not available. The application of this technology is sensitive to investment costs, so costly operations (e.g., drilling through cement plugs, examining deeper layers) are only recommended on the basis of a preliminary cost-benefit analysis. Appendix 1 shows the decision tree for ATES.

2.3.2. Deep Borehole Heat Exchanger (DBHE)

This technology is suitable for extracting smaller amounts of heat, but it appears to be applicable in most abandoned wells that are in good condition because no permeable reservoir is needed. In the literature, the terms medium-depth and deep borehole heat exchangers are used interchangeably, and there is no depth limit for when a system is considered deep. In China and Central Europe, boreholes deeper than 200 m are often classified as deep, while in Northern Europe, 400 m is considered the limit. Others consider 3000 m or 1000 m to be the limit.

The operating principle is that a high heat capacity fluid (e.g., water) suitable for heat transport is circulated in a closed system, which absorbs heat from the rock at greater depths and transfers it to a heat exchanger on the surface. DBHE projects are typically implemented as coaxial systems. The advantage of a coaxial DBHE system is that it is suitable for meeting higher heating demands and requires less space than a conventional many wells, or horizontal installation shallow geothermal BHE. Its use can be particularly advantageous in densely populated areas with spatial constraints. The disadvantage is that its installation is much more expensive and complicated than that of a conventional shallow geothermal BHE, and it requires careful planning, especially in the case of multiple boreholes.

There are basically two types of coaxial DBHE technology. In one case, the bottom of the borehole is sealed with cement and the system has a ring arrangement, where the injection takes place in the outer ring (annulus) and the well produces in the inner, shorter pipe (tubing). Less efficient is centred inflow, where injection takes place in the inner pipe and the well produces from the annulus, and the U-tube arrangement, where injection takes place in two separate pipe systems that are closed at the bottom. Additionally, there are many other variants that may differ in size, material, and internal layout.

The Thermal Response Test (TRT) provides essential information on thermal reservoir properties for DBHE design, and continuous monitoring of the system is recommended.

Chapter "C" of "TRANSGEO Project, Deliverable 1.1.6: Engineering workflows for retrofitting abandoned wells, 2024" [1] contains a detailed description of the technology, its boundary conditions, and the parameters required for modelling. These are listed below at the level of modelling parameters. The decision tree lists the parameters that are suitable for assessing whether the technology can be implemented in a given well. Although the decision may be influenced by a number of parameters, the criteria catalogue focuses primarily on those parameters for which information is available from the drillings.

For DBHEs, the most important parameters are:

Parameters relating to geological conditions for the stratigraphic:

the rock temperature at the bottom point of the installed system (BHT), geothermal gradient, static temperature of the rocks in the layer column, thermal conductivity, density, heat capacity, effective porosity of the layers, thermal conductivity, heat capacity, density, and flow velocity of the pore fluids in the layers.

Technological and design parameters:

Inner (or drift) diameter of the borehole/casing, length of the borehole, technical structure of the borehole (well structure), thermal conductivity, density, and heat capacity of cement/grout, thermal conductivity, density, and heat capacity of insulation material and inner and outer pipes, (thermal conductivity, density and heat capacity of pipes and grout used in other technologies), number of wells, layout configuration (with coordinates) and configuration of the technology used (coaxial system), flow rate of the heat transfer fluid, temperature of the fluid at the bottom of the system and outlet temperature, volume ratio of the fluids used in the case of a fluid system, surface temperature, operating time, heat exchanger parameters, efficiency, temperature of the return fluid.

Decision tree for the application of DBHE technology in abandoned wells:

For DBHEs, the most important parameters (prerequisites) to be taken into account when assessing the technological suitability of a well are the inner (or drift) diameter of the borehole/casing, the depth of the well, the BHT, and the estimated temperature at the bottom of the 7" inner pipe (casing) diameter, the depth of the deepest point of the 7-inch pipe (casing) diameter, the distance from the market, and whether the investment is prohibited in the given area. However, in the case of abandoned wells, a preliminary investigation is necessary to check the integrity of the well, with particular regard to the section above the upper cement plug. The application of this technology is sensitive to investment costs, so costly operations (e.g., drilling through cement plugs, examining deeper layers) are only recommended on the basis of a preliminary cost-benefit analysis. Appendix 2 shows the decision tree for DBHE.

2.3.3. Borehole Thermal Energy Storage (BTES)

BTES are closed-loop, seasonal systems suitable for heat production and storage, which use the rocks surrounding the well, or in some cases the soil, to store heat by conduction. It is possible to design shallow (20-200 m deep wells 2-5 m apart) and deep BTES systems (usually single-well), although due to the cost, mostly shallow systems exist. The surrounding rock is heated in a multi-well system, where wells located in the centre are suitable for heat production. There are basically three types of BTES systems in terms of their objectives:

- Large-scale BTES designed for seasonal heating and cooling needs, recommended for users with high, predictable seasonal energy demands, where the initial investment is justified by long-term operating savings, such as heating industrial plants or large residential buildings.
- BTES designed to maximize the efficiency of new or existing buildings, for users who can design the system from the ground up or are building a new facility, allowing for optimization of layout and soil conditions for both heating and cooling;
- and simple, smaller, less complex (single-well) BTES for individual users, e.g., homes, small businesses.

BTES systems represent a combination of ATES and BHE/DBHE systems. The working fluid circulates in U-tubes or coaxial pipes made of different materials, similar to BHE/DBHE, and generates heat in winter when connected to BHE/DBHE, while in summer the excess heat generated, e.g. from solar collectors or waste heat, is stored in the rock via the transfer fluid to the extent of the rock's thermal conductivity and heat storage capacity. Heat storage is similar to ATES, but unlike ATES, it is a closed system and is used when there is no suitable water storage layer for ATES or when storage capacity is limited.

Heat losses depend on subsurface properties, borehole layout, regional groundwater flow, and surface heat losses. The efficiency of BTES increases with decreasing thermal conductivity of the rock, as this results in higher temperatures in the borehole environment. At the same time, low thermal conductivity hinders the heating of the system, i.e., the efficient filling of the storage facility with heat, so rock with medium thermal conductivity may be optimal. In zones with high groundwater flow, thermal insulation with heat-reducing grout can minimize heat loss. In other zones, heat-enhancing grout is typically used to increase heat transfer from the borehole to the storage volume. Groundwater flow is undesirable because the convective heat transfer associated with groundwater flow negatively affects the performance of the heat storage system, as the stored heat would be carried away from the storage by the moving groundwater.

Similar to DBHE design, a Thermal Response Test (TRT) provides essential information for BTES design. Continuous monitoring also plays an important role in BTES.

Chapter "D" of “TRANSGEO Project, Deliverable 1.1.6: Engineering workflows for retrofitting abandoned wells, 2024” [1] contains a detailed description of the technology, its boundary conditions, and the parameters required for modelling. These are listed below at the level of modelling parameters. The decision tree lists the parameters that are suitable for assessing whether the technology can be implemented in a given well. Although the decision may be influenced by a number of parameters, the criteria catalogue focuses primarily on those parameters for which information is available from the drillings.

From a BTES perspective, the most important parameters considered in modelling the system are as follows:

Parameters relating to geological conditions for the stratigraphic:

The most suitable rocks for BTES installation are tight clay, till, limestones, sediments with low permeability, or un-fractured crystalline rocks. Other important parameters include the rock temperature at the bottom of the installed system, geothermal gradient, static temperature, thermal conductivity, density, heat capacity, effective porosity, thermal conductivity, heat capacity, density, and flow velocity of the pore fluids in the rocks, and the static water level. The permeability of the rocks in the layer column is only an important modelling parameter in cases where the water flow rate is significant at given depths.

Technological and design parameters:

Inner (or drift) diameter of the borehole/casing, length of the borehole, technical structure of the borehole (well structure), thermal conductivity, density, and heat capacity of cement/grout, thermal conductivity, density, and heat capacity of insulation material and inner and outer pipes (thermal conductivity, density and heat capacity of pipes and grout used in other technologies), number of wells, layout configuration (with coordinates) and configuration of the technology used (coaxial system), flow rate of the heat transfer fluid, temperature of the fluid at the bottom of the system and outlet temperature, volume ratio of the fluids used in the case of a fluid system, surface temperature, operating time, heat exchanger parameters, temperature of the return fluid

Decision tree for the application of BTES technology in abandoned wells:

In the case of BTES, the most important parameters (prerequisites) to be taken into account when assessing the technological suitability of a well are the inner (or drift) diameter of the borehole/casing, the depth of the well, the BHT, and the estimated temperature at the bottom of the 7" inner pipe (casing) diameter, the depth of the deepest point of the 7-inch pipe (casing) diameter, the distance from the market, and whether the investment is prohibited in the given area. However, in the case of abandoned wells, a preliminary investigation is necessary to check the integrity of the well, with particular regard to the section above the upper cement plug. The application of this technology is sensitive to investment costs, so costly operations (e.g., drilling through cement plugs, examining deeper layers) are only recommended on the basis of a preliminary cost-benefit analysis. Furthermore, in addition to heat consumers, heat generators, heat sources are also required here. Appendix 3 shows the decision tree for BTES.

2.3.4. Hydrothermal Energy Production (HE)

In hydrothermal energy systems, which operate as open systems, geothermal fluids (warm/hot fresh/salt water, or steam or a combination of water and steam) are produced from subsurface geothermal reservoirs. The degassed, often inhibitor-treated, warm/hot water or steam releases its heat through heat exchangers, which then, depending on the purpose of energy production, either drives a turbine and generates electricity or is fed via a heat exchanger into a heating system as a heat source. The cooled water is then, with a few exceptions, reinjected into the reservoir used for production, i.e. in the case of hydrothermal systems it is always worth considering a combination of production and injection wells. During reinjection, it is necessary to inject the cooled water at such a distance that thermal breakthrough cannot occur within the planned operating phase, i.e. the storage remains operational in the long term. Depending on the enthalpy/temperature, we can distinguish between low-enthalpy (low-medium temperature) and high-enthalpy (high temperature) systems. Depending on the water phase, we distinguish between liquid-dominated, two-phase and vapor-dominated hydrothermal systems. In Central Europe, and especially in the context of well reuse, liquid-dominated, low-enthalpy systems are typically involved, therefore the criteria catalogue and the decision tree also focus on these systems.

Although HE systems are the most commonly used geothermal energy type, they are the most complex to exploit. Many parameters can only be estimated with great uncertainty, as adequate information about the reservoirs is not available or they are inaccessible in the case of abandoned hydrocarbon fields.

Chapter "E" of “TRANSGEO Project, Deliverable 1.1.6: Engineering workflows for retrofitting abandoned wells, 2024” [1] contains a detailed description of the technology, its boundary conditions, and the parameters required for modelling. These are listed below at the level of modelling parameters. The decision tree lists the parameters that are suitable for assessing whether the technology can be implemented in a given well. Although the decision may be influenced by a number of parameters, the criteria catalogue focuses primarily on those parameters for which information is available from the drillings.

From a HE perspective, the most important parameters considered in modelling the system are as follows:

Parameters relating to geological conditions for the stratigraphic:

The most suitable rocks for HE installation are porous (effective porosity), permeable sandstones and fractured carbonates. Other important parameters are the geometry and storage capacity of the reservoir, reservoir's static temperature, mineral composition, reservoir pressure, the quality of the cap rock, the underground flow rate of the reservoir fluid, its chemical composition, gas and salt content, the internal structure of the reservoir (interbedding, flow unit size), and parameters related to formation damage.

Technological and design parameters:

Inner (or drift) diameter of the borehole/casing at reservoir depth, length of the borehole (MD and TVD), inclination, wellbore technical structure (well structure - casing, tubing), well integrity (cementing status, scaling, corrosion, position of cement plugs, tools left in the well), fluid pressure and temperature measured at the wellhead, annual volume of produced water, volumetric flow rate, status of existing perforation, status of the wellhead, chemical composition and temperature of the reinjected water.

Decision tree for the application of HE technology in abandoned wells:

In the case of HE, the most important parameters (prerequisites) to be taken into account when assessing the technological suitability of a well are the borehole/casing internal (or drift) diameter and static temperature at reservoir depth, the effective porosity and permeability of the reservoir, the volume flow rate and temperature of the produced water at the wellhead, the depth of the deepest point of the 7-inch pipe (casing) diameter, the distance from the market, and whether the investment is prohibited in the area. However, in the case of abandoned wells, a preliminary investigation is required to fully verify the integrity of the well. The tests involved in introducing this technology in abandoned hydrocarbon wells are costly, but almost negligible compared to the investment costs of such projects, if we are looking at high-temperature projects, even suitable for power generation. Appendix 4 presents the HE decision tree.

2.3.5. Enhanced Geothermal Systems (EGS)

EGS systems are a geothermal technology to access so-called petrothermal systems, which are low permeability, high temperature rocks at great depths, with engineered fracture networks, which produce heat by a fluid circulating through the fracture network, which acts as a subsurface heat exchanger between the hot rock and the cold injected working fluid (e.g., water). The injected fluid heats up when it comes into contact with the rock and returns to the surface through the production wells, where it releases its energy through a heat exchanger. Increasing the productivity and injectability of geothermal wells is achieved by hydraulic, thermal or chemical well stimulation.

EGS systems are systems suitable for electricity generation, however, waste heat can also be sold if there is a suitable market. In the case of EGS, it is important to consider that the elevated pressures during stimulation and the contact of low-temperature water and high-temperature rock during injection can induce seismicity.

Chapter "G" of "TRANSGEO Project, Deliverable 1.1.6: Engineering workflows for retrofitting abandoned wells, 2024" [1] contains a detailed description of the technology, its boundary conditions, and the parameters required for modelling. These are listed below at the level of modelling parameters. The decision tree lists the parameters that are suitable for assessing whether the technology can be implemented in a given well. Although the decision may be influenced by a number of parameters, the criteria catalogue focuses primarily on those parameters for which information is available from the drillings.

From a EGS perspective, the most important parameters considered in modelling the system are as follows:

Parameters relating to geological conditions for the stratigraphic:

The most suitable rocks for EGS installation are those with poor permeability, good heat storage capacity, high strength, stiffness and brittleness (e.g., granites). Other important parameters are reservoir temperature, pressure, thermal conductivity, volumetric heat capacity, porosity, permeability, permeability anisotropy, reservoir thickness and transmissivity, formation damage, injected fluid temperature, chemical composition, gas content, total dissolved solids (TDS), pH, dynamic viscosity, density, salinity and pressure, and fracture properties such as fracture height, depth, half-length, width.

Technological and design parameters:

Inner (or drift) diameter of the borehole/casing at reservoir depth, length of the borehole (MD and TVD), inclination, wellbore technical structure (well structure - casing, tubing), well integrity (cementing status, scaling, corrosion, position of cement plugs, tools left in the well), fluid pressure and temperature measured at the wellhead, effective surface of induced fracture system, chemical composition , pressure and temperature of the reinjected water, productivity and injectivity index.

Decision tree for the application of EGS technology in abandoned wells:

In the case of EGS, the most important parameters (prerequisites) to be taken into account when assessing the technological suitability of a well are the inner diameter of the casing at the reservoir depth, the estimate of the static temperature, the effective porosity and permeability of the reservoir, as well as the distance from the market and whether the investment is not prohibited in the given area. Importantly, however, in the case of abandoned wells, the integrity of the well requires a preliminary investigation in all respects. The tests involved in implementing this technology in abandoned hydrocarbon wells are costly, but almost negligible compared to the investment costs of such projects. Appendix 5 presents the EGS decision tree.

2.4. Market considerations related to the decision tree

The market can be divided into two parts, the market of direct users, such as agriculture, municipalities, or industry, and the market of indirectly affected companies, organizations, and individuals, such as companies participating in the implementation, experts, tender and its management, and end users. This catalogue basically focuses on direct users, because their decisions determine the list of indirect stakeholders.

It is important for direct users, i.e. municipalities, industry, and agriculture, to reduce greenhouse gas emissions at reasonable costs and risks. Converting abandoned hydrocarbon wells into geothermal wells can be an excellent way to do this.

Hydrocarbon production wells are usually located outside populated areas, often in agricultural or uncultivated areas, and in some cases in nature conservation areas. This significantly narrows the usability of the wells and their scope due to economic considerations (investment costs, return on investment). In the case of large amounts of heat or electricity production (HE, EGS), a heating or power plant can be installed further away from populated areas, however, in the case of smaller amounts of heat production and especially heat storage, the investment cannot bear the costs of building heat pipelines (ATES, BTES, DBHE), therefore these must be used practically locally, i.e. it is very important that the distance from the heat market can be measured.

The exact geographic position of the well is precisely known. The automatic measurement of the distance from the heat market based on objective grounds assumes the exact map position of the heat market players, which is not known in most cases. In order to measure the distance from the heat market, it is necessary to take into account commonly used maps such as CORINE, which covers the given cultivation production methods for Europe, the map of Natura 2000 areas, and the contour maps of municipalities, especially municipalities with more than 5,000 inhabitants. The distance from a given area can be determined by automation in two ways, either based on the closest point of the area's contour, or on a highlighted point of the area (e.g. the centre of a circle that can be drawn in the area, the centre of gravity of the area, the geometric centre of the area, etc.). A good solution would actually be to select the heat market players individually and measure the distance from them, but this is not possible in most cases in reality and would require a disproportionate amount of work in terms of clarity. Therefore, especially if the goal is to characterize the heat market of a larger area, a compromise solution must be found. The simplest way to do this is to use the closest distance between the contour of the given area and the well, which is of course biased, since the heat market is expected to be further away, but the exact size and location of the heat market must be examined during the specific project planning.

Industrial users need to ensure the heating, cooling and electricity supply of a given industrial site or factory unit. In the case of industrial producers, individual heat requirements arise, i.e. in some cases, factories, warehouses, and workshops with high heat requirements can use enough heat on their own, i.e. they can also represent a market outside of residential areas (e.g. industrial parks). In some cases, the electricity produced can also be used in its entirety. Industrial users can use heat in a wide range of heat intervals in different segments of industry, which must be reviewed. Based on the Lindal diagram, taking the EU into account, the following industrial technologies can be considered:

Industry	temperature demand
Hydrogen production	~160 - 200°C
Ethanol, biofuel production	~140 - 170°C
Cement and aggregate drying	~125 - 150°C
Refrigeration and icemaking	~90 - 160°C
Lumber drying	~90 - 150°C
Fabric Dyeling	~90 - 120°C
Pulp and paper processing	~80 - 145°C
Drying	~80 - 120°C
Food Processing	~55 - 90°C
Concrete block curing	~50 - 80°C
Cooking, blanching, pasteurization	~45 - 100°C
Biogas production	~30 - 45°C
Snow melting, de-icing	~20 - 55°C

Table 2. Geothermal energy uses in the industry (modified from Lindal, 1973 [2]).

Agricultural heat consumption may be significant, but their electricity consumption is often limited. Thus, EGS and HE projects suitable for electricity generation only make sense if the combined heat and power can be sold and electricity can be fed into the electricity system.

Agricultural users can use heat in a wide range of temperatures in different segments of agriculture, which should be reviewed. Based on the Lindal diagram, the following agricultural technologies can be considered, taking the EU into account:

Agricultural production branch	temperature demand
Beat sugar evaporation and pulp drying	~100-140°C
Onion and garlic drying	~100-130°C
Wood drying	~95-145°C
Fruit and vegetable drying	~60-90°C
Greenhouse heating	~40-80°C
Mushroom culture	~40-60°C
Aquaponics (hydroculture)	~20-65°C
Soil warming	~5-30°C

Table 3. Geothermal energy uses in the agriculture (modified from Lindal, 1973 [2]).

Municipalities either try to reduce the costs of electricity and heat supply for their own buildings by using renewables (direct heating), or they try to optimize and reduce the costs of heating a given part of the settlement (district heating). In the case of municipalities, therefore, a minimum building complex is needed that can effectively use the heat produced, which can also be related to the number of residents. In most cases, it can be said that settlements with a population of more than 5,000 people can operate a district heating system, and here a sufficient number of local government institutions (town hall, sports hall, school, hospital or other health institution, etc.) can be effectively connected to the system.

Municipalities	**temperature demand**
Binary geothermal power plants	~95 - 180°C
Heating of buildings and domestic hot water production	~40 - 145°C
Bathing, wellness	~25 - 40°C
Geothermal heat pumps	~4-30°C

Table 4. Geothermal energy uses in the municipalities (modified from Lindal, 1973 [2]).

Economical parameters:

CAPEX, OPEX, electricity price (EUR/MWh_e), gas price (EUR/MWh_t), heat price (EUR/MWh_t), COP, annual heat production (MWh_t), annual power production (MWh_e), heat and cold demand, amount of energy required for operation, heat losses of surface technology, distance to different market

Decision tree elements:

For the markets, only the distance from well to different types of market can be calculated. It is possible to map energy use, heat demand, heat centres, and ongoing geothermal projects, but these have not been directly integrated into the decision tree.

3. Factors most influencing the selection of a given technology

The following section presents the factors that form the basis of the decision tree and that can be used to determine which geothermal technology can be used for a given drilling project and which markets can be considered for sales. Wells can be classified into three categories in terms of their suitability for a given technology. Suitable (green) wells are those for which, based on preliminary knowledge, the given geothermal technology can be applied. Wells for which key information is missing may also be suitable! Uncertain (yellow) are wells where, based on existing data, doubts may arise regarding the given technology and therefore the wells in question must be examined in detail based on the uncertain aspects. The third group includes wells that are rejected from the point of view of the given technology (red).

The parameters necessary for planning and implementation have been mentioned in connection with the individual technologies, but as they are not related to the main issue, i.e., the selection of geothermal technologies applicable in a given well, they will not be discussed in detail in this chapter.

3.1. Decision factors

3.1.1. Well status

Well's current operational function. [3]

Note: The status of the well is an important starting point for selecting geothermal technologies.

Producing / active well

A well producing fluids (gas, oil or water). [4]

Note: After hydrocarbon wells have been depleted, they may be suitable for geothermal projects. When wells are taken out of production, with proper planning, it is possible to determine which geothermal technology the well is suitable for, i.e., it is possible to plan hole enlargement, the position of cement plugs, perforation, the necessary geophysical measurements, the market, etc. In other words, active wells allow early well assessment and seamless reuse after the end of production, which makes them very suitable for reuse. The main drawback is that the transformation cannot happen before the end of the original purpose of the well.

Shut-in well

An inactive well should be classified as shut-in when the well (temporarily) stopped production and the wellhead is closed. A shut-in well may have tubing and packer, which isolates the interior of the casing above the packer from the completion interval. A well may also be shut-in without a packer which exposes the interior of the casing to any fluids from the completion interval.

Shut-in wells may have been removed from active service in anticipation of workover, temporary abandonment, or plugging and abandonment operations. Generally, the wellbore condition is such that its utility may be restored by opening valves or by energizing equipment involved in operating the well. Shut-in status should begin three months after production, injection, disposal, or workover operations cease [5]

Note: Depending on their condition, shut-in wells may be suitable for geothermal projects, provided that the appropriate technology is selected. They are most suitable for reuse as the well has not been plugged with cement yet, but regular operation already stopped.

Partly (temporarily) abandoned / suspended / idle (long-term shut-in) well

An inactive well should be classified as "temporarily abandoned (TA)" when the completion interval is isolated. The completion interval may be isolated using the bridge plug method, the cement squeeze method, or the balanced cement plug method. As an alternative to the bridge plug method, isolation of the completion interval may also be achieved by installing a plug in an existing packer which does not have tubing.

Temporary abandonment should be used when an operator is holding a wellbore in anticipation of future utilization, such as in an enhanced oil recovery project. TA status should begin the day after the completion interval has been isolated from the wellbore [5].

Note: Depending on their condition, temporarily abandoned wells may be suitable for geothermal projects, provided that the appropriate technology is selected.

Plugged and abandoned well

The sealing and permanent isolation of a wellbore. There are typically regulatory requirements associated with the P&A process to ensure that strata, particularly freshwater aquifers, are adequately isolated. In most cases, a series of cement plugs is set in the wellbore, with an inflow or integrity test made at each stage to confirm hydraulic isolation. [6]

Note: Wells that have been permanently abandoned have in some cases been backfilled to the surface or cemented (with cement plugs from the surface). In most cases they are not suitable for geothermal purposes, especially not for closed loop or storage applications, but the information that can be obtained from them can be very useful in the design of geothermal projects planned in their vicinity, provided that there is a suitable market.

Wells under development

A well in the drilling or completion phase before start of production.

Note: In most cases, planned or under construction hydrocarbon wells will not serve geothermal purposes, but if they prove to be barren, they can be converted into geothermal wells. In the 1970s and 1980s, a number of barren hydrocarbon wells in Hungary were converted into geothermal wells and handed over to local authorities or for agricultural purposes.

3.1.2. Well integrity

"Well integrity" means the quality or condition of a wellbeing structurally sound with competent pressure seals by the application of technical and operational solutions that prevent uncontrolled fluid release or migration of annular fluids into protected groundwater throughout the well life cycle [7].

Note: The integrity of abandoned wells, especially older ones, is generally unknown, but it is a key factor in determining whether a given well can be used for geothermal purposes. If an investor plans to use an abandoned well for geothermal purposes, it is essential to examine the integrity of the well in advance.

Corrosion

Wearing away due to chemical reactions, mainly oxidation (see oxidation-reduction, oxide). It occurs whenever a gas or liquid chemically attacks an exposed surface, often a metal, and is accelerated by warm temperatures and by acids and salts. Normally, corrosion products (e.g., rust, patina) stay on the surface and protect it. Removing these deposits re-exposes the surface, and corrosion continues. Some materials resist corrosion naturally; others can be treated to protect them (e.g., by coating, painting, galvanizing, or anodizing) [8].

Note: If the casing or, where applicable, the tubing is corroded, it is advisable to investigate the cause. In most cases, converting these wells into geothermal wells can be costly (replacement of casing pipes, repair of damage to cement linings, etc.), so a cost analysis should be carried out first. Depending on the depth of the corrosion, these wells may still be suitable for geothermal purposes if cement plugs are installed at the appropriate depth.

Scaling

A mineral salt deposit that may occur on wellbore tubulars and components as the saturation of produced water is affected by changing temperature and pressure conditions in the production conduit. In severe conditions, scale creates a significant restriction, or even a plug, in the production tubing. Scale removal is a common well-intervention operation, with a wide range of mechanical, chemical and scale inhibitor treatment options available [9].

Note: In the case of scaling, it is questionable whether the casing/tubing can be cleaned, which can involve significant costs. In most cases, wells with this problem should not be converted into geothermal wells, or only after a cost analysis.

Mechanical damage

Damage that induces a reduction in permeability as a result of direct, nonchemical interaction between equipment or fluids and the formation is referred to as mechanical damage [10].

Note: Although a wide variety of mechanical damage can occur in wells, it is primarily worth checking for tools and equipment left in the well. Depending on their depth, these wells can still be made suitable for geothermal purposes by placing cement plugs at the appropriate depth.

Cementation

Cements are placed in the annular space of casing to provide zonal isolation in between wellbore and surface during the operational life cycle of the well or even after the abandonment. However, cement can degrade or lose its integrity through debonding either from the casing or formation and generates cracks or fractures due to varied reasons throughout the life of the well [11].

Note: Checking the condition of the cement is one of the most important things, so acoustic cement bond logs (CBL) are usually run in the well. Replacing the cement can be costly, so deciding whether a given well can be converted into a geothermal well requires a preliminary cost analysis. If the damage to the cement is in the deeper zones of the well, the upper levels may still be usable for geothermal purposes after appropriate cement plugging.

Cement plugs

A “balanced” plug of cement slurry placed in the wellbore. Cement plugs are used for a variety of applications including hydraulic isolation, provision of a secure platform, and in window-milling operations for sidetracking a new wellbore [12].

Note: In abandoned wells, cement plugs are usually placed at several levels to separate the individual production layers from each other. In the case of large-budget projects (EGS, HE), drilling through the cement plug may be within the budget. If this option is not available due to risk, the areas above the cement plugs can be used for geothermal purposes if their integrity is adequate.

3.1.3. Distance from market, protected areas

The distance from the market is fundamental in determining whether it makes sense to use a given technology. In the case of DBHE, ATES, and BTES, geothermal wells are expected to be as close as possible to market users. This distance is estimated to a maximum of 2 km. In the case of HE, greater distances are possible, and in the case of EGS projects, it is preferable to implement the project further away from populated areas for risk reduction and public acceptance reasons.

Natura 2000 areas

Natura 2000 is a network of protected areas covering Europe's most valuable and threatened species and habitats. It is the largest coordinated network of protected areas in the world, extending across all 27 EU Member States, both on land and at sea. The sites within Natura 2000 are designated under the Birds and the Habitats Directives [13].

Note: In the vast majority of cases, it is not possible to convert boreholes located in Natura 2000 areas into geothermal projects.

Municipality

The CORINE Land COVER nomenclature (CLC) was used to identify municipalities, covering the areas defined under CLC Artificial surfaces 111, 112 and 142, which are continuous urban fabric, discontinuous urban fabric and sport and leisure facilities, respectively. Geothermal objectives played a primary role in the selection of areas, i.e., geothermal projects that could be implemented in connection with municipal areas.

Note: **Residential areas** is a collective name for all areas belonging to municipalities. **Population** size is additional information regarding the scale of the project.

111: The continuous urban fabric class is assigned when urban structures and transport networks are dominating the surface area. > 80% of the land surface is covered by impermeable features like buildings, roads and artificially surfaced areas. Non-linear areas of vegetation and bare soil are exceptional [14].

112: The discontinuous urban fabric class is assigned when urban structures and transport networks associated with vegetated areas and bare surfaces are present and occupy significant surfaces in a discontinuous spatial pattern. The impermeable features like buildings, roads and artificially surfaced areas range from 30 to 80 % land coverage [15].

142: This class is assigned for areas used for sports, leisure and recreation purposes. Camping grounds, sports grounds, leisure parks, golf courses, racecourses etc. belong to this class, as well as formal parks not surrounded by urban areas [16].

Note: In the case of municipalities with fewer than 5,000 inhabitants, it is necessary to examine whether direct heating can be implemented by connecting several buildings in series.

Municipality above 5000 inhabitants

Due to their size, municipalities with more than 5,000 inhabitants play a key role in geothermal projects from an economic perspective. Their polygons are derived from administrative maps.

In settlements with more than 5,000 inhabitants, it is expected that more buildings and housing estates can be connected to a direct heating system or to an existing district heating system.

Industry

The CORINE Land COVER nomenclature (CLC) was used to identify industries, covering the areas defined under CLC Urban fabric 121, which are defined under industrial or commercial units. Geothermal objectives played a primary role in the selection of areas, i.e., geothermal projects that can be implemented in connection with industrial areas.

121: Buildings, other built-up structures and artificial surfaces (with concrete, asphalt, tarmacadam, or stabilised like e.g. beaten earth) occupy most of the area. It can also contain vegetation (most likely grass) or other non-sealed surfaces. This class is assigned for land units that are under industrial or commercial use or serve for public service facilities [17].

Agriculture

The CORINE Land COVER nomenclature (CLC) was used to identify agricultural areas, covering the areas defined under CLC Agricultural areas 211, 212, 221, 222, 242, 243, which are Non-irrigated arable land, Permanently irrigated land, Vineyards, Fruit trees and berry plantations, Complex cultivation patterns, Land principally occupied by agriculture, with significant areas of natural vegetation, respectively. Geothermal objectives played a primary role in the selection of areas, i.e., geothermal projects that can be implemented in connection with industrial areas.

211: Cultivated land parcels under rainfed agricultural use for annually harvested non-permanent crops, normally under a crop rotation system, including fallow lands within such crop rotation. Fields with sporadic sprinkler-irrigation with non-permanent devices to support dominant rainfed cultivation are included [18].

212: Cultivated land parcels under agricultural use for arable crops that are permanently or periodically irrigated, using a permanent infrastructure (irrigation channels, drainage network and additional irrigation facilities). Most of these crops cannot be cultivated without artificial water supply. Does not include sporadically irrigated land [19].

221: Areas planted with vines, vineyard parcels covering >50% and determining the land use of the area [20].

222: Cultivated parcels planted with fruit trees and shrubs, intended for fruit production, including nuts. The planting pattern can be by single or mixed fruit species, both in association with permanently grassy surfaces [21].

242: Mosaic of small cultivated land parcels with different cultivation types -annual crops, pasture and/or permanent crops-, eventually with scattered houses or gardens [22].

243: Areas principally occupied by agriculture, interspersed with significant natural or semi-natural areas (including forests, shrubs, wetlands, water bodies, mineral outcrops) in a mosaic pattern [23].

Well distance / well closer than 1,500 m

In the case of the ATES, HE, and EGS projects, since both production and injection take place here, investment costs can be reduced if we consider a pair of abandoned wells (doublets) rather than just one well. The answer to this question is provided by the actual distance of abandoned wells within 1500 m, if such wells are located in the vicinity of the originally investigated well.

3.1.4. Technical parameters originating from well reports

Bottom Hole Temperature (BHT)

The temperature in the borehole at total depth at the time it is measured. In log interpretation, the bottomhole temperature (BHT) is taken as the maximum recorded temperature during a logging run or preferably the last of a series of runs during the same operation [24].

Note: In most cases, especially for older wells, actual BHT data are not available. If there is a measurement value in the well, the geothermal gradient can be calculated from it and the temperature at any depth can be estimated. If BHT data is not available, but a temperature map for a given depth in the area, or another equivalent heat map and the average surface temperature were available, it can be still possible to estimate the geothermal gradient and thus estimate the temperature at any depth in the well. This means that the temperature can be estimated for the given depth of the well in virtually all cases.

Temperature measurement is a fundamental task in the geophysical measurements required to reopen a well. The estimated value must be overwritten with the actual measurement.

True Vertical Depth (TVD)

The vertical distance from a point in the well (usually the current or final depth) to a point at the surface, usually the elevation of the rotary kelly bushing (RKB). This is one of two primary depth measurements used by the drillers, the other being measured depth. TVD is important in determining bottomhole pressures, which are caused in part by the hydrostatic head of fluid in the wellbore. For this calculation, measured depth is irrelevant and TVD must be used. For most other operations, the driller is interested in the length of the hole or how much pipe will fit into the hole. For those measurements, measured depth, not TVD, is used. While the drilling crew should be careful to designate which measurement they are referring to, if no designation is used, they are usually referring to measured depth. Note that measured depth, due to intentional or unintentional curves in the wellbore, is always longer than true vertical depth [25].

Note: In most cases, TVD is not available. It can be estimated based on inclination data, but most older wells are not significantly inclined, so the difference between MD and TVD values is not significant in terms of estimating the geothermal potential of the well.

Measured Depth (MD)

The length of the wellbore, as if determined by a measuring stick. This measurement differs from the true vertical depth of the well in all but vertical wells. Since the wellbore cannot be physically measured from end to end, the lengths of individual joints of drill pipe, drill collars and other drill string elements are measured with a steel tape measure and added together. Importantly, the pipe is measured while in the derrick or laying on a pipe rack, in an untensioned, unstressed state. When the pipe is screwed together and put into the wellbore, it stretches under its own weight and that of the bottomhole assembly. Although this fact is well established, it is not taken into account when reporting the well depth. Hence, in virtually all cases, the actual wellbore is slightly deeper than the reported depth [26].

Note: The measured depth of the well is available in almost all cases.

Casing diameter

Casing diameter is the diameter of the pipe used to support a borehole, with key measurements being the outer diameter, which is how the casing is identified, and the inner diameter (or drift diameter), which is the minimum internal size a tool must be able to pass through [27]. An example of which casing diameters fit in which borehole diameters is provided in Figure 1.

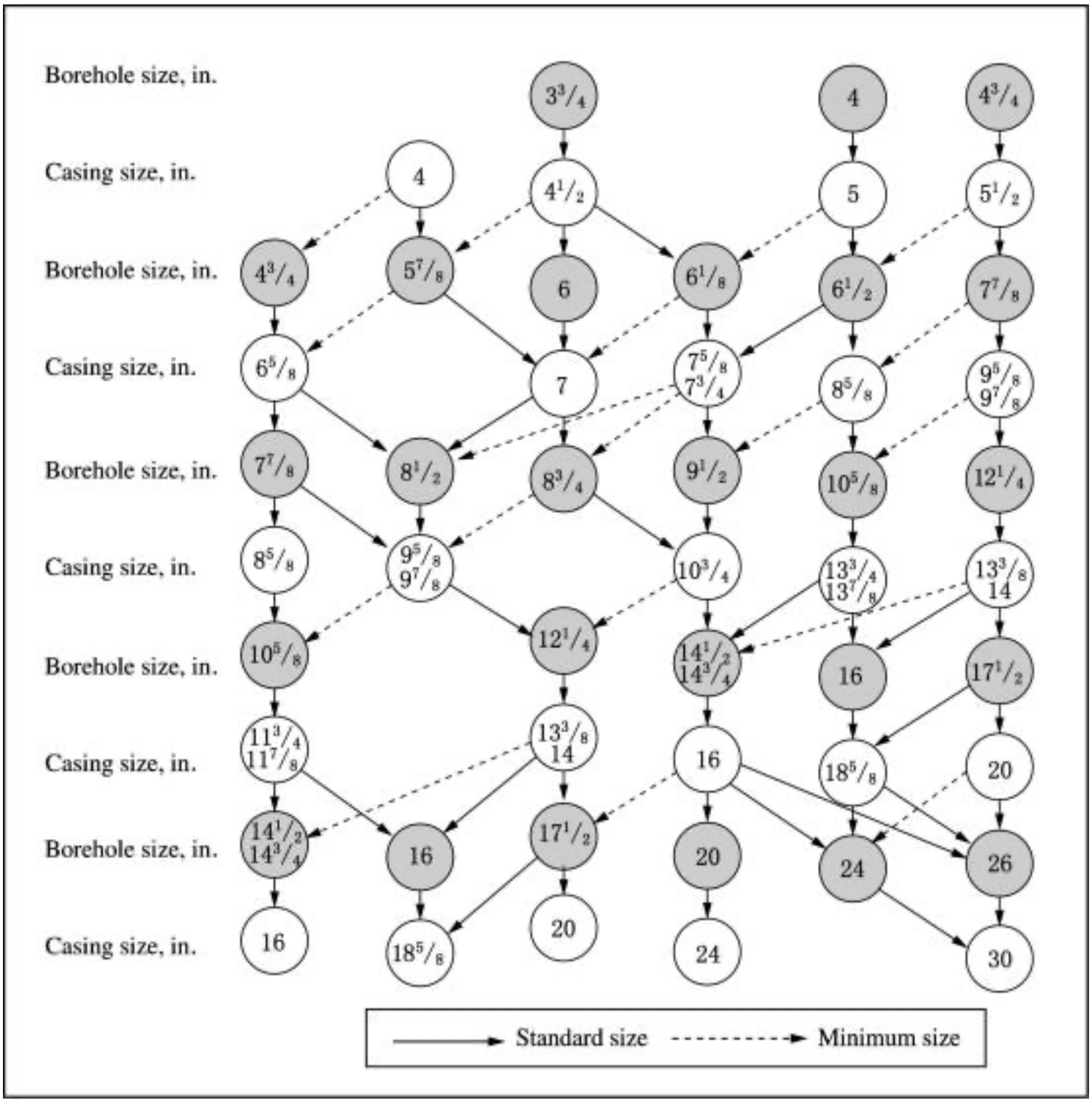

Figure 1. Hole Structure of Standard Casing Size Series [28]

3.1.5. Geological parameters

Reservoir

A reservoir is a subsurface space, natural or artificial, that stores liquids or gases like water, oil, natural gas, or carbon dioxide. These reservoirs can be natural geological formations, such as porous rock layers (aquifers for water or petroleum reservoirs for oil and gas) or man-made structures created to store fluids for various purposes, from water management to energy storage. Based on their subsurface characteristics, reservoirs can be classified as fracture-dominated/karstic reservoirs and porous reservoirs, and can be closed or open reservoirs.

In the case of the database, we consider the perforated layers to be reservoirs in a first approximation. On the IT tool display interface, the reservoirs are marked by these perforated layers.

Reservoir thickness

The modelled thicknesses of the aquifers are gross values. This means that the depth of the base has been subtracted from that of the top. Although only layers known to contain a significant amount of sand(stone) have been modelled, all aquifers also contain to a certain extent of layers with a permeability so low that they contribute little or nothing to water production. These layers often consist of clay(stone) or shaly sand. For a correct calculation of the geothermal potential, the gross thickness of the aquifer must be corrected for the layers that do not contribute to production [29] leading to the effective reservoir or payzone thickness.

Note: In the case of databases, we can usually calculate the length of the perforation and use this as the layer thickness to start with. The IT tool display interface shows these perforated layer thicknesses for reservoirs.

Mineralogy

The mineral composition of rocks plays a very important role in open-loop technologies, where water-water and water-rock interactions fundamentally influence the operation of the system. Therefore, this factor must be examined in all cases when these technologies (ATES, HE, EGS) are used.

Water composition

The water content of reservoir pores plays a very important role in open-loop technologies, where water-water and water-rock interactions fundamentally influence the operation of the system. Therefore, the composition of water must be examined in all cases where these technologies (ATES, HE, EGS) are used. During water-rock interaction, especially in high-temperature geothermal systems (EGS, HE), water can dissolve large amounts of minerals from rocks, which, without the use of appropriate inhibitors, can be deposited in the production pipe and significantly reduce the performance of the well. The three main mechanisms of scaling are pressure and temperature changes, the mixing of incompatible brines, and brine evaporation. This leads to mineral ions clustering, nucleation, crystal growth, and deposition on well surfaces, which can eventually plug equipment and restrict flow. In addition, water with a given composition also poses a corrosion risk. During reinjection, water-water and water-rock interactions, especially in high-temperature geothermal systems (HE, EGS), can significantly reduce the efficiency of injection/reinjection and cause damage to the formation. The vast majority of well integrity problems are related to water. The total dissolved salt content of the water can be a good first approximation.

Gas content

The free gas in the pores of the reservoirs, or the gas content dissolved in water, especially CO_2 and, in the case of depleted oil wells, CH_4, can cause numerous problems due to the increase in volume caused by changes in gas pressure. On the one hand, gas content contributes to greenhouse gas emissions from geothermal power production, which, although much lower than that of fossil fuels, can be significant in some cases.

CO_2's role in scaling is complex and context-dependent, but generally, it can either cause or prevent scaling. It can lead to scale formation by dissolving minerals like calcite in water, and then releasing them as the CO_2 degasses and pressure decreases, increasing the concentration of dissolved calcium and carbonate ions. However, high CO_2 partial pressures also create acidic conditions that increase the solubility of carbonate scale, thereby preventing scaling.

Porosity

The percentage of pore volume or void space, or that volume within rock that can contain fluids. Porosity can be a relic of deposition (primary porosity, such as space between grains that were not compacted together completely) or can develop through alteration of the rock (secondary porosity, such as when feldspar grains or fossils are preferentially dissolved from sandstones). Porosity can be generated by the development of fractures, in which case it is called fracture porosity. Effective porosity is the interconnected pore volume in a rock that contributes to fluid flow in a reservoir. It excludes isolated pores. Total porosity is the total void space in the rock whether or not it contributes to fluid flow. Thus, effective porosity is typically less than total porosity [30].

Note: Effective porosity plays a key role in open-loop systems because it essentially determines the amount of water stored in the reservoir. Primary porosity is particularly important in geothermal systems formed in sedimentary rocks (ATES, HE), while fractured porosity is important in HE in carbonates and in EGS in all compact rocks suitable for EGS system development. In close-loop systems, rock porosity is of secondary importance, but the heat capacity of the rock and the water it contains influences the efficiency of heating the fluid circulating in the closed system.

Permeability

The ability, or measurement of a rock's ability, to transmit fluids, typically measured in darcies or millidarcies. Formations that transmit fluids readily, such as sandstones, are described as permeable and tend to have many large, well-connected pores. Impermeable formations, such as shales and siltstones, tend to be finer grained or of a mixed grain size, with smaller, fewer, or less interconnected pores. Absolute permeability is the measurement of the permeability conducted when a single fluid, or phase, is present in the rock. Effective permeability is the ability to preferentially flow or transmit a particular fluid through a rock when other immiscible fluids are present in the reservoir (for example, effective permeability of gas in a gas-water reservoir). The relative saturations of the fluids as well as the nature of the reservoir affect the effective permeability. Relative permeability is the ratio of effective permeability of a particular fluid at a particular saturation to absolute permeability of that fluid at total saturation. If a single fluid is present in a rock, its relative permeability is 1.0. Calculation of relative permeability allows for comparison of the different abilities of fluids to flow in the presence of each other, since the presence of more than one fluid generally inhibits flow [31].

Note: The permeability of rocks is an important property in open systems. Excellent permeability is an important prerequisite for ATES and HE systems, while very low permeability is important for EGS systems. In ATES systems, it is important that the hot and cold water storage tanks are separated from each other, which is often achieved by rock layers with very low permeability. Permeability is a directional property, and it is particularly important to consider its anisotropy in EGS systems. It is important to note that permeability is a surface-type quantity (m^2) and should not be confused with hydraulic conductivity, which is a velocity-type quantity (m/s).

In closed-loop geothermal systems, permeability plays a secondary role. Rocks with high permeability, especially when associated with high subsurface water flow rates, reduce the efficiency of DBHE and BTES systems and when fast natural groundwater flow (e.g., >10 m/year) occurs heat storage may not be possible as the stored heat would be transported away by the flowing groundwater.

Flow rate / volumetric flow rate (Q)

The volumetric flow rate measured at the wellhead plays a fundamental role in the selection of HE systems as the applicable geothermal technology. It is also an important design parameter for geothermal systems.

Injectivity index

The injectivity index (II) is defined as the instantaneous measure of a reservoir's ability to accept fluid, calculated in terms of the instantaneous external filter cake resistance, near-wellbore damaged zone resistance, and undamaged zone resistance, represented by the equation II = qi/dP [32] where qi is the injection rate.

Note: Injectivity index plays a role particularly in EGS projects, but it must also be taken into account in the reinjection wells of HE and ATES projects.

Productivity index

The productivity index PI describes the ratio of the production rate to the pressure drop. The index is usually determined from hydraulic tests although it has to be considered that in the case of short test periods the drawdown has not reached its maximum due to the existence of an unsteady state. However, the productivity index is not solely dependent on the properties of the subsurface geology, but also on the properties of the well (wellbore storage, skin effect). The productivity index can be estimated mathematically as PI = Qo/Dp, where Qo is the production rate.

If the fracturing pressure of the rock mass is not exceeded (elastic or pressure mechanical deformation), the injectivity index is identical to the productivity index in the case of an ideal aquifer with the same fluid properties. However, because the pressure differences to be applied in this case are dependent on the viscosity and density of the fluid, and because the viscosity in particular is very strongly temperature-dependent, the injectivity index in a geothermal well (injection of cooled water) is often several times smaller than the productivity index (production of hot or warm water). This means that a higher pressure difference must be applied to inject the cooled water than is required to produce warm water at the same rate [33].

3.2. Other important additional information

Long name / Well long name

The long name of the wells.

Well identifier

In some cases, such as the German Molasse Basin, wells have unique identifiers.

Cadastral number

A cadastral number is a unique, alphanumeric identifier assigned to a specific property serving as its official identification in land records. It is used to keep precise records of a property's location, boundaries, and characteristics for purposes such as tax management, legal transactions, and territorial planning. For example, water wells are marked with a separate cadastral number in Hungary.

Drilling year

By convention, the year of drilling is the year in which drilling commenced. This often does not correspond to the year in which drilling was completed. The drilling year can help in screening younger wells that are expected to be more suitable for conversion to geothermal wells.

Data owner

The data controller who has the drilling data.

Well owner

The owner of the well and the associated area. In some cases, the data owner and the well owner are separate entities.

Well type

In this case, the question is what purpose the well was drilled for.

Wellhead status

In this case, it means that it is operational or not operational.

4. Application of the Criteria Catalogue

As mentioned above, the TRANSGEO database and decision tree are based on the criteria catalogue, which together form the basis of the Well Assessment IT tool. The Well Assessment tool is an online interface (www.transgeo.eu) that provides a preliminary assessment of each well based on the criteria, i.e., using the criteria as a filter system, it is possible to determine the suitability of each well for specific technologies. Of course, the more accurate and diverse the information available in the database, the more accurate the estimate for a given well will be in terms of its subsequent geothermal use.

The criteria catalogue, and the decision tree created from it, can be extended later to include modelling and implementation parameters, and the limits of certain parameters (e.g., flow rate) can be refined based on experience.

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6. Appendix

Appendix 1

Criteria	Source	Categories	ATES	Comment	Data source
First round criteria					
Well status	Database	producing / active			Surface location/surface location data/well status if no data than grey and no role on decision
		shut-in		Other connecting info: Cement plugs	
		partly (temporarily) abandoned / suspended / idle (long-term shut-in)			
		plugged and abandoned			
		under development			
Well integrity	Database (corrosion, scale, mechanical damage, state of cement coating, cement plugs)	none			well data/well integrity well history/cement plug if no data than grey and no role on decision **no enough data, but it is crucial info**
		corrosion		corrosion	
		scaling		scaling	
		mechanical damage		On the basis of Surface Location/Trapped -lost equipment	
		cement coating		cement coating	
		cement plugs		position of cement plugs	
		proven			
Well is outside of the protected areas	Map - Natura 2000 areas	yes		Other connecting info:	Map- Natura 2000
		no		Closest Natura 2000 area	https://natura2000.eea.europa.eu/
MUNICIPALITY: Well distance from the border of municipality (distance between well and nearest boundary point of a given area) [km]	Map - Query polygons of municipalities with more than 5000 inhabitants from the ESRI database	inside		Other connecting info, which doesn't have role in rating but have to check it:	Map - municipality poligons with more than 5000 inhabitants - ESRI
		<2			
		10>d>2		Containing municipality (CLC 111, 112, 142)	
		>10		Closest residental areas	
INDUSTRY: Well distance from the border of industrial or commercial units [km]	CORINE	inside		Other connecting info, which doesn't have role in rating but have to check it: Closest industrial area (over pop. 5000)	CORINE -Closest industrial area (CLC 121)
		<2			
		10>d>2			
		>10			
AGRICULTURE: well distance from complex cultivation patterns or agro-forestry [km]	CORINE	inside			CORINE - Closest agricultural area (CLC 222, 242, 211, 212, 221, 243)
		<2			
		>2			
Bottom Hole Temperature (BHT) [$^{\circ}$C]	Database	<20		Other connecting info which doesn't have role in rating but have to check it:	Surface location/Surface location data/Calculated BHT
		35>T>20			
		60>T>35		Depth at 20 $^{\circ}$C	
		100>T>60		Depth at 35 $^{\circ}$C	
		T>100		Depth at 60 $^{\circ}$C	
Depth (TVD, if not data then use MD) [m]	Database	<400			Surface location/Well trajectory data/TVD or MD
		1000>D>400			
		3000>D>1000			
		>3000			
Well distance [km]	Generated map - need the full drilling point map including the active wells	<2		This is for information only and does not affect the decision.	On the basis of the well coordinates
		>2			
		no data			
2nd round criteria - Reservoir info/reservoir overall					
Reservoir info / reservoir overall	if no data than grey and no role on decision				
Geology	database	clastic sediments		sand, clay, marl, sandstone, siltstone, mudstone, tuff, loess, etc.	Well/well test result/rock type if no data than grey and no role on decision
		carbonates		limestone, dolomite	
		metamorphic/plutonic		metamorphic and igneous rocks without tuff	
Mineralogy	database	if have data then could be important or irrelevant		Have to check it	You should check the reports or "Laboratory measurements" tab. Under well test result in case of mineralogy column.
Water composition	database	if have data then could be important or irrelevant		Have to check it	You should check the reports or "Laboratory measurements" tab. Under well test result in case of salinity column.
Gas content	database	if have data then could be important or irrelevant		Have to check it	You should check the reports or "Laboratory measurements" tab. Under well test result in case of gas content column.
Porosity [%] [text]	database	>30		good	Well/well test result/porosity if no data than grey and no role on decision
		30>Fi>10		medium	
		<10		poor	
Permeability [m^2] [text]	database	>10exp[-12]		good	Well/well test result/permeability if no data than grey and no role on decision
		10exp[-12]>k>10exp[-14]		medium	
		<10exp[-14]		poor	
Flow rate [l/s]	database	<10			Well/well test result/PWFR if no data than grey and no role on decision
		10-100			
		>100			
Productivity Index [L/s/MPa]	database	<10			Well test results/PI no enough data
		>10			
minimum casing diameter ["]	database	>=7		Connecting data:	Surface location/Casing data
		<7		casing gets larger than 7" at ... m(... $^{\circ}$C)	if no data than grey and no role on decision
Thickness of the reservoir [m]	database	<5			Well test results/thickness
		5-10			
		>10			
The following is for information purposes only and does not affect the decision.					
Goal		Electricity			
		Heating		suitable	
Heat storage		Production		suitable	
		Storage		suitable	

Evaluation

Compliant / Suitable		A well is suitable for ATES if - shut-in or partially abandoned, but not cement plugged into a given depth;
Uncertain		A well may be eligible for ATES if - acive or under development;
Rejected / Non suitable		The well is rejected if - plugged and abandoned;
Not categorized		If there is no data on depth, temperature and reservoir thickness.

Decision tree for assessing the suitability of reusing an existing well for ATES

Appendix 2

Criteria	Source	Categories	DBHE	Comment	Data source
First round criteria					
Well status	Database	producing / active			Surface location/surface location data/well status if no data than grey and no role on decision
		shut-in		Other connecting info: Cement plugs	
		partly (temporarily) abandoned / suspended / idle (long-term shut-in)			
		plugged and abandoned			
		under development			
Well integrity	Database (corrosion, scale, mechanical damage, state of cement coating, cement plugs)	none			well data/well integrity well history/cement plug if no data than grey and no role on decision **no enough data, but it is crucial info**
		corrosion		corrosion	
		scaling		scaling	
		mechanical damage		On the basis of Surface Location/Trapped -lost equipment	
		cement coating		cement coating	
		cement plugs		position of cement plugs	
		proven			
Well is outside of the protected areas	Map - Natura 2000 areas	yes		Other connecting info: Closest Natura 2000 area	Map- Natura 2000 https://natura2000.eea.europa.eu/
		no			
MUNICIPALITY: Well distance from the border of municipality (distance between well and nearest boundary point of a given area) [km]	Map - Query polygons of municipalities with more than 5000 inhabitants from the	inside		Other connecting info, which doesn't have role in rating but have to check it: Containing municipality (CLC 111, 112, 142) Closest residental areas	Map - municipality poligons with more than 5000 inhabitants - ESRI
		<2			
		10>d>2			
		>10			
INDUSTRY: Well distance from the border of industrial or commercial units [km]	CORINE	inside		Other connecting info, which doesn't have role in rating but have to check it: Closest industrial area (over pop. 5000)	CORINE -Closest industrial area (CLC 121)
		<2			
		10>d>2			
		>10			
AGRICULTURE: well distance from complex cultivation patterns or agro-forestry [km]	CORINE	inside			CORINE - Closest agricultural area (CLC 222, 242, 211, 212, 221, 243)
		<2			
		>2			
Bottom Hole Temperature (BHT) [°C]	Database	<20		Other connecting info which doesn't have role in rating but have to check it: Depth at 20 °C Depth at 35 °C Depth at 60 °C	Surface location/Surface location data/Calculated BHT
		35>T>20			
		60>T>35			
		100>T>60			
		T>100			
Depth (TVD, if not data then use MD) [m]	Database	<400			Surface location/Well trajectory data/TVD or MD
		1000>D>400			
		3000>D>1000			
		>3000			
Well distance [km]	Generated map - need the full drilling point map including the	<2		This is for information only and does not affect the decision.	On the basis of the well coordinates
		>2			
		no data			
2nd round criteria - Reservoir info/reservoir overall					
Reservoir info / reservoir overall	if no data than grey and no role on decision				
Geology	database	clastic sediments		sand, clay, marl, sandstone, siltstone, mudstone, tuff, loess, etc.	Well/well test result/rock type if no data than grey and no role on decision
		carbonates		limestone, dolomite	
		metamorphic/plutonic		metamorphic and igneous rocks without tuff	
Mineralogy	database	if have data then could be important or irrelevant		Not relevant	
Water composition	database	if have data then could be important or irrelevant		Not relevant	
Gas content	database	if have data then could be important or irrelevant		Not relevant	
Porosity [%] [text]	database	>30		Not relevant	
		30>Fi>10			
		<10			
Permeability [m^2] [text]	database	>10exp[-12]		Not relevant	
		10exp[-12]>k>10exp[-14]			
		<10exp[-14]			
Flow rate [l/s]	database	<10		Not relevant	
		10-100			
		>100			
Productivity Index [L/s/MPa]	database	<10		Not relevant	
		>10			
minimum casing diameter ["]	database	>=7		Connecting data:	Surface location/Casing data if no data than grey and no role on decision
		<7		casing gets larger than 7" at ... m(... °C)	
Thickness of the reservoir [m]	database	<5		Not relevant	
		5-10			
		>10			
The following is for information purposes only and does not affect the decision.					
Goal		Electricity			
		Heating		suitable	
Heat storage		Production		suitable	
		Storage			

Evaluation

Compliant / Suitable		A well is suitable for DBHE if - shut-in or partiallyabandoned, but not cement plugged into a given depth;
Uncertain		A well may be eligible for DBHE if - acive, plugged and abandoned, or under development;
Rejected / Non suitable		The well is rejected if - well integrity problem is proven;
Not categorized		If there is no information on depth and temperature.

Decision tree for assessing the suitability of reusing an existing well for DBHE

Criteria	Source	Categories	BTES	Comment	Data source
First round criteria					
Well status	Database	producing / active	yellow		Surface location/surface location data/well status if no data than grey and no role on decision
		shut-in	green	Other connecting info: Cement plugs	
		partly (temporarily) abandoned / suspended / idle (long-term shut-in)	green		
		plugged and abandoned	red		
		under development	yellow		
Well integrity	Database (corrosion, scale, mechanical damage, state of cement coating, cement plugs)	none	green		well data/well integrity well history/cement plug if no data than grey and no role on decision **no enough data, but it is crucial info**
		corrosion	yellow	corrosion	
		scaling	yellow	scaling	
		mechanical damage	yellow	On the basis of Surface Location/Trapped -lost equipment	
		cement coating	yellow	cement coating	
		cement plugs	yellow	position of cement plugs	
		proven	red		
Well is outside of the protected areas	Map - Natura 2000 areas	yes	green	Other connecting info:	Map- Natura 2000
		no	yellow	Closest Natura 2000 area	https://natura2000.eea.europa.eu/
MUNICIPALITY: Well distance from the border of municipality (distance between well and nearest boundary point of a given area) [km]	Map - Query polygons of municipalities with more than 5000 inhabitants from the ESRI database	inside	green	Other connecting info, which doesn't have role in rating but have to check it: Containing municipality (CLC 111, 112, 142) Closest residental areas	Map - municipality poligons with more than 5000 inhabitants - ESRI
		<2	red		
		10>d>2	red		
		>10	red		
INDUSTRY: Well distance from the border of industrial or commercial units [km]	CORINE	inside	green	Other connecting info, which doesn't have role in rating but have to check it: Closest industrial area (over pop. 5000)	CORINE -Closest industrial area (CLC 121)
		<2	red		
		10>d>2	red		
		>10	red		
AGRICULTURE: well distance from complex cultivation patterns or agro-forestry [km]	CORINE	inside	green		CORINE - Closest agricultural area (CLC 222, 242, 211, 212, 221, 243)
		<2	red		
		>2	red		
Bottom Hole Temperature (BHT) [°C]	Database	<20	green	Other connecting info which doesn't have role in rating but have to check it:	Surface location/Surface location data/Calculated BHT
		35>T>20	green	Depth at 20 °C	
		60>T>35	green	Depth at 35 °C	
		100>T>60	green	Depth at 60 °C	
		T>100	red		
Depth (TVD, if not data then use MD) [m]	Database	<400	red		Surface location/Well trajectory data/TVD or MD
		1000>D>400	green		
		3000>D>1000	green		
		>3000	red		
Well distance [km]	Generated map - need the full drilling point map including the active wells	<2	green	This is for information only and does not affect the decision.	On the basis of the well coordinates
		>2	yellow		
		no data	yellow		
2nd round criteria - Reservoir info/reservoir overall					
Reservoir info / reservoir overall	if no data than grey and no role on decision				
Geology	database	clastic sediments	green	sand, clay, marl, sandstone, siltstone, mudstone, tuff, loess, etc.	Well/well test result/rock type if no data than grey and no role on decision
		carbonates	green	limestone, dolomite	
		metamorphic/plutonic	green	metamorphic and igneous rocks without tuff	
Mineralogy	database	if have data then could be important or irrelevant	blue	Not relevant	
Water composition	database	if have data then could be important or irrelevant	blue	Not relevant	
Gas content	database	if have data then could be important or irrelevant	blue	Not relevant	
Porosity [%] [text]	database	>30	blue	Not relevant	
		30>Fi>10	blue		
		<10	blue		
Permeability [m^2] [text]	database	>10exp[-12]	blue	Not relevant	
		10exp[-12]>k>10exp[-14]	blue		
		<10exp[-14]	blue		
Flow rate [l/s]	database	<10	blue	Not relevant	
		10-100	blue		
		>100	blue		
Productivity Index [L/s/MPa]	database	<10	blue	Not relevant	
		>10	blue		
minimum casing diameter ["]	database	>=7	green	Connecting data:	Surface location/Casing data
		<7	yellow	casing gets larger than 7" at ... m(... °C)	if no data than grey and no role on
Thickness of the reservoir [m]	database	<5	blue	Not relevant	
		5-10	blue		
		>10	blue		
The following is for information purposes only and does not affect the decision.					
Goal		Electricity	red		
		Heating	green	suitable	
Heat storage		Production	green	suitable	
		Storage	green	suitable	

Evaluation

Compliant / Suitable	green	A well is suitable for BTES if - shut-in or partially abandoned, but not cement plugged into a given depth;
Uncertain	yellow	A well may be eligible for BTES if - acive or under development;
Rejected / Non suitable	red	The well is rejected if - plugged and abandoned;
Not categorized	grey	If there is no information on the status of the well, its temperature and depth.

Decision tree for assessing the suitability of reusing an existing well for BTES

Appendix 4

Criteria	Source	Categories	HE	Comment	Data source
First round criteria					
Well status	Database	producing / active			Surface location/surface location data/well status if no data than grey and no role on decision
		shut-in		Other connecting info: Cement plugs	
		partly (temporarily) abandoned / suspended / idle (long-term shut-in)			
		plugged and abandoned			
		under development			
Well integrity	Database (corrosion, scale, mechanical damage, state of cement coating, cement plugs)	none			well data/well integrity well history/cement plug if no data than grey and no role on decision **no enough data, but it is crucial info**
		corrosion		corrosion	
		scaling		scaling	
		mechanical damage		On the basis of Surface Location/Trapped - lost equipment	
		cement coating		cement coating	
		cement plugs		position of cement plugs	
		proven			
Well is outside of the protected areas	Map - Natura 2000 areas	yes		Other connecting info:	Map- Natura 2000
		no		Closest Natura 2000 area	https://natura2000.eea.europa.eu/
MUNICIPALITY: Well distance from the border of municipality (distance between well and nearest boundary point of a given area) [km]	Map - Query polygons of municipalities with more than 5000 inhabitants from the ESRI database	inside	M	Other connecting info, which doesn't have role in rating but have to check it: Containing municipality (CLC 111, 112, 142) Closest residental areas Closest residental areas (over pop. 5000)	Map - municipality poligons with more than 5000 inhabitants - ESRI
		<2	M		
		10>d>2	M		
		>10	M		
INDUSTRY: Well distance from the border of industrial or commercial units [km]	CORINE	inside	I	Other connecting info, which doesn't have role in rating but have to check it: Closest industrial area (over pop. 5000)	CORINE -Closest industrial area (CLC 121)
		<2	I		
		10>d>2	I		
		>10	I		
AGRICULTURE: well distance from complex cultivation patterns or agro-forestry [km]	CORINE	inside	A		CORINE - Closest agricultural area (CLC 222, 242, 211, 212, 221, 243)
		<2	A		
		>2	A		
Bottom Hole Temperature (BHT) [°C]	Database	<20		Other connecting info which doesn't have role in rating but have to check it: Depth at 20 °C Depth at 35 °C Depth at 60 °C	Surface location/Surface location data/Calculated BHT
		35>T>20			
		60>T>35			
		100>T>60			
		T>100			
Depth (TVD, if not data then use MD) [m]	Database	<400			Surface location/Well trajectory data/TVD or MD
		1000>D>400			
		3000>D>1000			
		>3000			
Well distance [km]	Generated map - need the full drilling point map including the active wells	<2		This is for information only and does not affect the decision.	On the basis of the well coordinates
		>2			
		no data			
2nd round criteria - Reservoir info/reservoir overall					
Reservoir info / reservoir overall	if no data than grey and no role on decision				
Geology	database	clastic sediments		sand, clay, marl, sandstone, siltstone, mudstone, tuff, loess, etc.	Well/well test result/rock type if no data than grey and no role on decision
		carbonates		limestone, dolomite	
		metamorphic/plutonic		metamorphic rocks and igneous rocks without tuff	
Mineralogy	database	if have data then could be important or irrelevant		Have to check it	You should check the reports or "Laboratory measurements" tab. Under well test result in case of mineralogy column.
Water composition	database	if have data then could be important or irrelevant		Have to check it	You should check the reports or "Laboratory measurements" tab. Under well test result in case of salinity column.
Gas content	database	if have data then could be important or irrelevant		Have to check it	You should check the reports or "Laboratory measurements" tab. Under well test result in case of gas content column.
Porosity [%] [text]	database	>30		good	Well/well test result/porosity if no data than grey and no role on decision
		30>Fi>10		medium	
		<10		poor	
Permeability [m²] [text]	database	>10exp[-12]		good	Well/well test result/permeability if no data than grey and no role on decision
		10exp[-12]>k>10exp[-14]		medium	
		<10exp[-14]		poor	
Flow rate [l/s]	database	<10			Well/well test result/PWFR if no data than grey and no role on decision
		10-100			
		>100			
Productivity Index [L/s/MPa]	database	<10			Well test results/PI
		>10			no enough data
minimum casing diameter ["]	database	>=7		Connecting data: casing gets larger than 7" at ... m(... °C)	Surface location/Casing data if no data than grey and no role on decision
		<7			
Thickness of the reservoir [m]	database	<5			Well test results/thickness
		5-10			
		>10			
The following is for information purposes only and does not affect the decision.					
Goal		Electricity		suitable	
		Heating		suitable	
Heat storage		Production		suitable	
		Storage			
Evaluation					
Compliant / Suitable			A well is suitable for HE if - shut-in or partially abandoned;		
Uncertain			A well may be eligible for HE if - acive, plugged and abandoned or under development;		
Rejected / Non suitable			The well is rejected if - the rock type is metamorphic or plutonic rock;		
Not categorized			If no data on temperature, reservoir depth, reservoir rock, well depth, and neither water yield, porosity and permeability nor PI data are available.		

Decision tree for assessing the suitability of reusing an existing well for HE

Appendix 5

Criteria	Source	Categories	EGS	Comment	Data source
First round criteria					
Well status	Database	producing / active	[yellow]		Surface location/surface location data/well status if no data than grey and no role on decision
		shut-in	[green]		
		partly (temporarily) abandoned / suspended / idle (long-term shut-in)	[green]	Other connecting info: Cement plugs	
		plugged and abandoned	[yellow]		
		under development	[yellow]		
Well integrity	Database (corrosion, scale, mechanical damage, state of cement coating, cement plugs)	none	[green]		well data/well integrity well history/cement plug if no data than grey and no role on decision **no enough data, but it is crucial info**
		corrosion	[yellow]	corrosion	
		scaling	[yellow]	scaling	
		mechanical damage	[yellow]	On the basis of Surface Location/Trapped - lost equipment	
		cement coating	[yellow]	cement coating	
		cement plugs	[yellow]	position of cement plugs	
		proven	[yellow]		
Well is outside of the protected areas	Map - Natura 2000 areas	yes	[green]	Other connecting info:	Map- Natura 2000 https://natura2000.eea.europa.eu/
		no	[green]	Closest Natura 2000 area	
MUNICIPALITY: Well distance from the border of municipality (distance between well and nearest boundary point of a given area) [km]	Map - Query polygons of municipalities with more than 5000 inhabitants from the ESRI database	inside	M [yellow]	Other connecting info, which doesn't have role in rating but have to check it: Containing municipality (CLC 111, 112, 142) Closest residental areas	Map - municipality poligons with more than 5000 inhabitants - ESRI
		<2	M [yellow]		
		10>d>2	M [green]		
		>10	M [yellow]		
INDUSTRY: Well distance from the border of industrial or commercial units [km]	CORINE	inside	I [yellow]	Other connecting info, which doesn't have role in rating but have to check it: Closest industrial area (over pop. 5000)	CORINE -Closest industrial area (CLC 121
		<2	I [yellow]		
		10>d>2	I [green]		
		>10	I [yellow]		
AGRICULTURE: well distance from complex cultivation patterns or agro-forestry [km]	CORINE	inside	[red]		CORINE - Closest agricultural area (CLC 222, 242, 211, 212, 221, 243)
		<2	[red]		
		>2	[red]		
Bottom Hole Temperature (BHT) [^{o}C]	Database	<20	[red]	Other connecting info which doesn't have role in rating but have to check it: Depth at 20 ^{o}C Depth at 35 ^{o}C Depth at 60 ^{o}C	Surface location/Surface location data/Calculated BHT
		35>T>20	[red]		
		60>T>35	[red]		
		100>T>60	[red]		
		T>100	[green]		
Depth (TVD, if not data then use MD) [m]	Database	<400	[red]		Surface location/Well trajectory data/TVD or MD
		1000>D>400	[red]		
		3000>D>1000	[green]		
		>3000	[green]		
Well distance [km]	Generated map - need the full drilling point map including the active wells	<2	[green]	This is for information only and does not affect the decision.	On the basis of the well coordinates
		>2	[blue]		
		no data	[blue]		
2nd round criteria - Reservoir info/reservoir overall					
Reservoir info / reservoir overall	if no data than grey and no role on decision				
Geology	database	clastic sediments	[green]	sand, clay, marl, sandstone, siltstone, mudstone, tuff, loess, etc.	Well/well test result/rock type if no data than grey and no role on decision
		carbonates	[green]	limestone, dolomite	
		metamorphic/plutonic	[green]	metamorphic rocks and igneous rocks without tuff	
Mineralogy	database	if have data then could be important or irrelevant	[grey]	Have to check it	You should check the reports or "Laboratory measurements" tab. Under well test result in case of mineralogy column.
Water composition	database	if have data then could be important or irrelevant	[grey]	Have to check it	You should check the reports or "Laboratory measurements" tab. Under well test result in case of salinity column.
Gas content	database	if have data then could be important or irrelevant	[grey]	Have to check it	You should check the reports or "Laboratory measurements" tab. Under well test result in case of gas content column.
Porosity [%] [text]	database	>30	[red]	good	Well/well test result/porosity if no data than grey and no role on decision
		30>Fi>10	[yellow]	medium	
		<10	[green]	poor	
Permeability [m^{2}] [text]	database	>10exp[-12]	[red]	good	Well/well test result/permeability if no data than grey and no role on decision
		10exp[-12]>k>10exp[-14]	[yellow]	medium	
		<10exp[-14]	[green]	poor	
Flow rate [l/s]	database	<10	[green]		Well/well test result/PWFR if no data than grey and no role on decision
		10-100	[yellow]		
		>100	[red]		
Productivity Index [L/s/MPa]	database	<10	[green]		Well test results/PI no enough data
		>10	[red]		
minimum casing diameter ["]	database	>=7	[green]	Connecting data:	Surface location/Casing data if no data than grey and no role on
		<7	[yellow]	casing gets larger than 7" at … m(… ^{o}C)	
Thickness of the reservoir [m]	database	<5	[blue]	Not relevant	
		5-10	[blue]		
		>10	[blue]		
The following is for information purposes only and does not affect the decision.					
Goal		Electricity	[green]	suitable	
		Heating	[green]	suitable	
Heat storage		Production	[green]	suitable	
		Storage	[red]		

Evaluation

Compliant / Suitable	[green]	A well is suitable for EGS if - shut-in or partially abandoned;
Uncertain	[yellow]	A well may be eligible for EGS if - acive, plugged and abandoned or under development;
Rejected / Non suitable	[red]	The well is rejected if - T < 100 ^{o}C;
Not categorized	[grey]	If there is no temperature and depth information.

Decision tree for assessing the suitability of reusing an existing well for EGS