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Evaluating outlet working fluid's temperature by implementing closed-loop geothermal systems in decommissioned hydrocarbon wells: the case studies of San Benigno and Cinzano wells

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Abandoned hydrocarbon wells offer significant potential for extracting geothermal energy from the subsurface if effectively repurposed. Among the discussed geothermal systems, closed-loop wellbore heat exchangers (WBHEs) represent one of the most promising technologies. Simplified methods to assess the exploitable temperature potential of decommissioned wells, using coaxial and U-tube WBHEs and integrating geological and technical considerations, have been developed and are available in the literature. Such solutions are useful tools for evaluating the suitability of a selected well for geothermal repurposing during the preliminary analysis phase. This study focuses on the application of simplified approaches for the preliminary assessment of the extracted temperature following the implementation of coaxial and U-tube WBHEs in the San Benigno and Cinzano wells, leveraging on-site temperature data. These assessments allowed the identification of these wells as economically unsuitable for repurposing, unlike others studied and located within the Italian territory.

Keywords*: renewable energy, geothermal energy, abandoned hydrocarbon well, closed-loop geothermal system, wellbore heat exchanger.*

1. Introduction

Among the oldest forms of energy harnessed by humans, geothermal energy holds a unique position in the renewable energy mix due to its independence from weather conditions and its lack of reliance on fossil fuels (Taddia *et al.*, 2019). Despite its considerable potential for energy generation, geothermal development lags wind and solar due to several challenges: 1) geothermal plants are restricted to specific locations with high geothermal gradients or volcanic and hydrothermal activity; 2) they require higher initial investments; and 3) they face longer completion times due to the complexities of well drilling, especially in areas with lower geothermal gradients (Jello & Baser, 2023). Drilling costs are a major barrier to geothermal development. One promising solution is the repurposing of abandoned and depleted hydrocarbon wells. Abandoned hydrocarbon wells comprise both boreholes liquidated due to the depletion of oil and gas resources as well as negative exploratory wells. Consequently, many of them turn out to be in areas characterized by favorable geothermal parameters, which often translates into significant geothermal potential (Caulk *et al.*, 2017).

Over time, researchers have focused on developing different approaches to tap into deep geothermal energy resources. As reported by Lo Russo *et al.*, 2020, while most studies on repurposing abandoned petroleum wells have primarily explored open-loop systems while abstracting a geothermal fluid (Liu *et al.*, 2018; Kharseh *et al.*, 2019; Santos *et al.*, 2022), there has been a recent interest in closed-loop techniques. In a closed-loop system, fluid circulates continuously through a single well in a closed circuit via a wellbore heat exchanger (WBHE). The WBHE consists of insulated tubing inserted into the well, with an open end at the bottom for fluid production. Shallow WBHEs are commonly utilized as a dependable heat source for direct applications (Ahmed *et al.*, 2022; Barbieri *et al.*, 2022). Currently, the two most implemented WBHE types are the U-tube and the coaxial or double-pipe systems. U-tube heat exchangers are placed inside the well before filling the surrounding annulus with grouting material. In the coaxial or double-pipe system, the inner pipe serves as the tubing itself, while the outer pipe is the casing surrounding it. External and internal diameter sizes in coaxial WBHE significantly influence fluid velocity and, thus the heat exchange processes. Various configurations have been implemented and analyzed by several authors (Alimonti *et al.*, 2016; Blank *et al.*, 2021). Compared to coaxial heat exchangers, U-tube heat exchangers have a reduced surface area available for heat exchange and accommodate a smaller volume of working fluid (Harris *et al.*, 2022; Alimonti, 2023). Moreover, the recent development of Eavor-Loop™ technology (Vany *et al.*,2020) and U-shaped configurations have introduced new challenges for the preliminary estimation of potential outlet temperatures from closed-loop geothermal systems, including the consideration of horizontal wells drilled in the most thermally favorable geological layers (Xiao *et al.*, 2022).

Despite the promising results obtained, as shown by Alimonti *et al.*, 2018, challenges in implementing closed-loop geothermal systems, such as low heat recovery efficiency, persist, requiring further research and improvement. Indeed, the main limitation of closed-loop systems is that heat is extracted solely through conduction. Without convection, this naturally restricts the heat recovery rate to the relatively small heat transfer area of the wellbore. As a result, the heat recovery rate and the power generated are usually very low, which may not justify the investment. The existence of numerous valid tools and codes for the implementation of WBHEs in decommissioned oil wells allows, not only for modeling the thermal behavior of the closed-loop systems but also for conducting an adequate preliminary analysis of the potential performance of the chosen site. Gizzi, 2021 has proposed a valuable simplified tool for preliminarily assessing the feasibility of converting hydrocarbon wells into geothermal ones using coaxial and U-tube BHEs, with potential applications in various industrial and agricultural sectors in selected Italian hydrocarbon sites. Building on the tool proposed by the above-reported author and using the Python programming language (Van Rossum, 1995), two different Italian decommissioned hydrocarbon wells located in the Piedmont Region, i.e., San Benigno and Cinzano, were tested. The results, in terms of the output temperature of the selected working fluid, obtained for the coaxial and U-tube configurations, were analyzed and compared with those obtained for other test sites evaluated in the past.

2. Materials and Methods

2.1. Closed-loop geothermal systems: Wellbore Heat Exchangers (WBHEs)

Two main types of closed-loop systems have been described to harness geothermal energy from disused wellbores in oilfields: coaxial or double-pipe systems (Figure 1a), and U-tube systems (Figure 1b). The proposed systems extract heat from the ground without the need to extract or re-inject geothermal fluids (Raos *et al.*, 2019). In a U-tube WBHE, fluid is pumped through one tube and exits through another. In coaxial WBHEs, the working fluid is injected into the outer pipe (injection pipe), flows down to the bottom of the exchanger, and is heated by the surrounding rocks. Once the fluid reaches the bottom of the well, it ascends through a thinner inner pipe (extraction pipe). The space between the inner pipes is filled with grout, and the bottom of the well is sealed. Heat transfer occurs between the geological formation and the fluid in the injection pipe, and between the fluid in the injection pipe and the fluid in the extraction pipe. In coaxial and U-tube WBHE, as the fluid flows, it is heated by the thermal reservoir and then exits to connect with a power generator or a heat user.

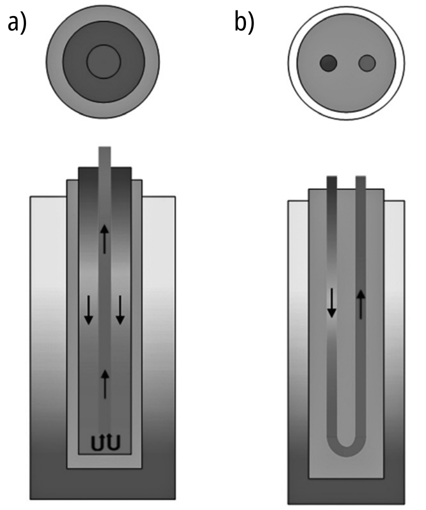

Fig. 1 – Different closed-loop system types: a) coaxial or double-pipe; b) U-tube. Modified from Raos *et al.*, 2019.

Simplified approaches for modeling geothermal heat exchange employing coaxial and U-tube WBHEs installed in a vertical hydrocarbon well and the associated thermal resistance systems are proposed in Gizzi, 2021. Following what was described in Hasan *et al.*, 2018 and Nian *et al.*, 2018 for coaxial WBHEs, by assuming that the propagation of heat in the reservoir occurs by conduction, the heat extraction from formation is assumed equal to the heat flux through the outside surface of the wellbore (interface of wellbore/ rock formation) to the injected fluid (Eq.1):

$$\frac{dQ}{dz} = 2\pi r_w k_w \left(T_{f0} - T_w\right) \qquad (1)$$

where T_W is the temperature at the interface of the wellbore and the formation, and k_W the heat transfer coefficient between the outer-pipe fluid and the wellbore exterior. At the bottom of the well, the heated fluid is forced to enter and flow through the inner pipe of the coaxial WBHE. As it rises towards the wellhead, heat transfer occurs exclusively through the wall of the inner pipe. Thus, dQ_{i0}/dz is determined by considering the temperature difference between the outer-pipe and inner-pipe fluids, as well as the estimated thermal resistance of the insulation (2):

$$\frac{dQ_{i0}}{dz} = 2\pi r_0 k_{i0} \left(T_{fi} - T_{f0}\right) \qquad (2)$$

where T_{fi} is the fluid temperature in the inner pipe, k_{i0} is the heat transfer coefficient between the outer pipe and inner pipe and R_{i0} is the thermal resistance between the outer pipe and inner pipe.

On the other hand, to calculate the temperature profile in the U-tube configuration using a one-dimensional heat exchange approach, the model with a set of equivalent thermal resistances and specific radius configurations, as described by Ruiz-calvo *et al.*, 2015, was employed. At each depth, six thermal resistances were considered, including the thermal properties of the ground, the grout, and the pipes. According to both selected models, heat propagation in the reservoir occurs through conduction, while inside the wellbore tubes, heat transfer takes place through both conduction and convection. The reservoir model was developed with the assumption of a single well positioned at the center of a circular reservoir, where the temperature profile in the radial direction was considered constant. As a result, no temperature gradient existed in the annulus or the inner tube. The presence of turbulent flow promoted enhanced mixing, which reduced the radial temperature gradient. Temperature variation occurred only within the annulus and along the vertical direction of the inner tube. Therefore, the temperature profile was unidirectional, varying solely in the vertical direction. For both analyzed WBHEs, the properties of the heat carrier fluid were assumed to remain constant. Since the fluid used in this study was water at 100°C and 2 bar, no variations were expected due to pressure and/or temperature gradients. Using water as a working fluid in WBHEs has several benefits: it is not harmful to the subsurface in case of leakage, it has a good heat capacity rate, it is affordable and does not impose extra costs; it is accessible and requires less pumping energy for circulation compared to other carrier fluids. The model was constructed under steady-state conditions, meaning there were no temperature fluctuations over time, and every point within the tubes (both the annulus and the inner tube) maintained a consistent temperature throughout the system's lifecycle. Additionally, the resistance due to the tube thickness was considered negligible. The tube material's high thermal conductivity (15 W/mK) rendered its resistance insignificant compared to other resistances in the system. To estimate the resistance associated with the rock, a period of 3 years was used. In the case of the U-tube configuration, heat exchange was assumed to occur over half the area of the casing pipe, while the interaction between the downward and upward tubes was neglected.

Both the proposed models follow the path of the working fluid with an approach that could be called step-by-step. In detail, they considered intervals of length *dz* in which the inlet and outlet temperature were calculated by solving the energy balance equation for each considered volume *dv*. For the estimation of the energy exchange in the radial direction, the mean value of the temperature in the volume *dv* was used, calculated using the arithmetic mean. All the energy exchanged in the radial direction in the volume *dv* was absorbed by the water, i.e., the selected working fluid. The structure of the codes implementing the above-described heat exchange models is shown in Figure 2.

3. Case studies

Italy's hydrocarbon occurrences can be categorized into three primary tectono-stratigraphic systems due to its intricate geological and sedimentary history: i) the carbonate Mesozoic substratum of the foredeep/foreland area and the external thrust belts, ii) thrusted terrigenous Oligo-Miocene foredeep wedges (Southern Alps, Northern Apennines, Calabria, and Sicily) and iii) terrigenous Pliocene-Pleistocene successions of the late foredeep basins of the Apennines, in both the Central and Northern Adriatic Sea and the Po Plain (Bertello *et al.*, 2010). The proposed study examines San Benigno and Cin-

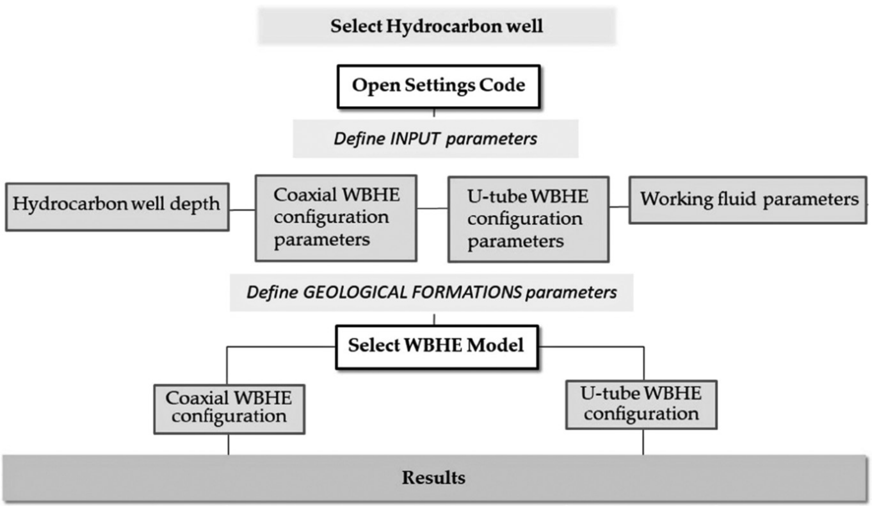

Fig. 2 – Python codes simplified research flowchart (from Gizzi, 2021).

zano hydrocarbon wells. Both case studies are situated in Piedmont, a region in northwestern Italy. Despite being in the same geographic area, the depths and the geothermal gradient values reconstructed differ based on the specific reservoir encountered. Comprehensive details regarding litho-stratigraphic units and temperature data visualization can be accessed through the Italian National Geothermal Database, established in the 1980s and managed by the Institute of Geosciences and Earth Resources (IGG) of the National Research Council (CNR) of Italy provides this information. Besides, using the stratigraphic profiles obtained from Geothopica, the Italian geothermal data infrastructure portal, by the Institute of Geosciences and Earth Resources of the National Research Council, CNR-IGG), detailed lithological information from well logs was gathered (Trumpy *et al.*, 2017). Besides, the thermophysical parameters of the geological formations, i.e., thermal conductivity, volumetric heat capacity, and rock density, for each selected case study, were determined based on values defined by Pasquale *et al.*, 2011 and, as reported in Table 1 and Table 2.

Tab. 1 – San Benigno hydrocarbon well-lithostratigraphic profile and thermophysical parameters: thermal conductivity (λs), volumetric heat capacity (ρc_s), and rock density (ρ).

Depth m	**Litho-Stratigraphic Formation**	**Age**	**λs W/m/K**	**ρc_s J/kg/K**	**ρ kg/m^3**
260	Gray Slightly Silty Sandy Gravel	Quaternary	4.44	1175	1785
1100	Sandy Clay	Pliocene	2.45	1459	1757
2300	Marl	Miocene	2.77	1808	2278
2700	Marl	Miocene	2.77	1808	2278

Tab. 2 – Cinzano hydrocarbon well-lithostratigraphic profile and thermophysical parameters: thermal conductivity (λs), volumetric heat capacity (ρcs), and rock density (ρ).

Depth m	**Litho-Stratigraphic Formation**	**Age**	**λs W/m/K**	**ρc_s J/kg/K**	**ρ kg/m^3**
100	Gray Slightly Silty Sandy Gravel	Oligocene	4.44	1175	1785
728	Made ground (silty gravely sand)	Oligocene	5.03	1270	1916
1280	Gray Slightly Silty Sandy Gravel	Eocene	4.44	1175	1785
1378.65	Marl	Eocene	2.77	1808	2278

3.1. San Benigno Well

The San Benigno well (San Benigno Canavese, Torino province) is situated within the zone of hydrocarbon accumulation of the Italian Middle Miocene system. The system is fully developed within the Miocene sedimentary sequence. Typically, the primary reservoir depth associated with the San Benigno field ranges between 2300 m and 2700 m, with temperatures approximately around 65°C. According to information from litho-stratigraphic units and temperature data visualization presented in Table 1 and Figure 3, the stratigraphic sequence primarily consists of marl. The well under analysis reaches a maximum depth of 2700 m.

3.2. Cinzano Well

The Cinzano well (Cinzano, Torino province) is situated within the zone of hydrocarbon accumulation of the Italian Middle Eocene hydrocarbon system. The system is fully developed within the Eocene sedimentary sequence. Typically, the main reservoir depth associated with the Cinzano field ranges between 1280 m and 1379 m, with temperatures around 40 °C. As demonstrated by information related to the litho-stratigraphic units and temperature data visualization reported in Table 2 and Figure 4. Temperature data visualization for the Cinzano hydrocarbon well, the stratigraphic succession is mainly composed of marl and sandy gravel. The analyzed well has a maximum depth of about 1378 m.

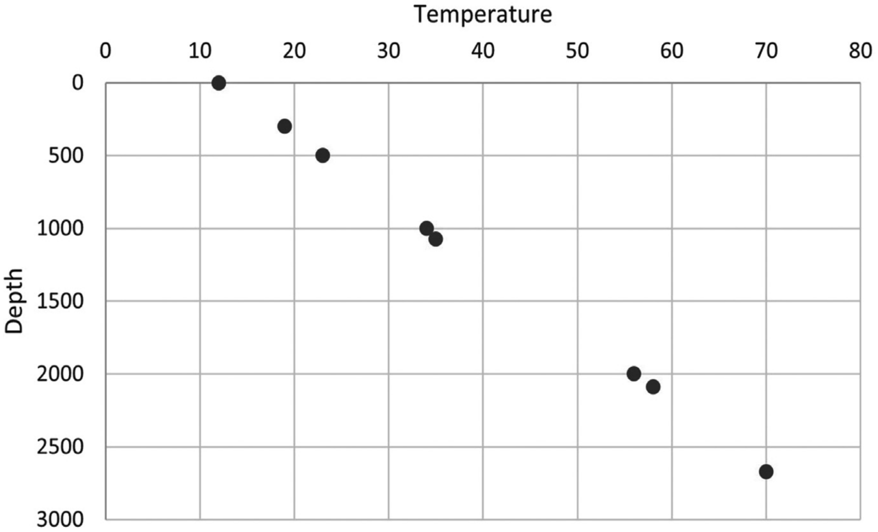

Fig. 3 – Temperature data visualization for the San Benigno hydrocarbon well.

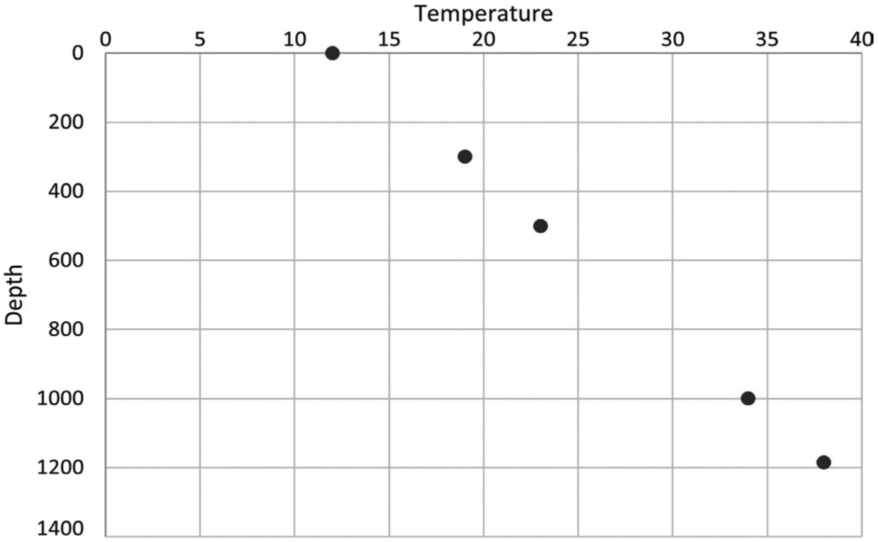

Fig. 4 – Temperature data visualization for the Cinzano hydrocarbon well.

4. Results

4.1. WBHE Systems: Output Temperature Analysis

As mentioned earlier, simplified methods for modeling geothermal heat exchange, along with the Python programming language, were used to evaluate the output temperature of the chosen working fluid in both the coaxial and U-tube configurations. The temperature profiles for these configurations were calculated based on geological formation data from the San Benigno and Cinzano hydrocarbon wells case studies. The thermal properties of the rock formations were derived from the values listed in Tables 1 and 2. Among the geometric configurations available in the literature for the coaxial WBHE, in terms of external radius and insulation radius (in millimeters), the configuration proposed by Alimonti *et al.*, 2016 was adopted. The thermal conductivity of the insulating material was set at 0.025 W/mK. It was assumed that the working fluid (water) had an inlet flow rate of 3.0 kg/s and an initial temperature of 15°C. Hence, it was also assumed that the surface temperature of the ground and the water temperature at the surface were approximately the same. In the coaxial WBHE system, as the descending water profile intersected the ground temperature, the ground started to heat the fluid, contributing positively to the heat transfer. Due to the presence of insulation, the heat exchange coefficient between the annulus and the inner tube was low, and the rise in the working fluid's temperature was mainly attributed to heat from the ground. With the working fluid's inlet temperature kept constant, the projected outlet temperatures were estimated to be 26°C for San Benigno and 19°C for Cinzano (as shown in Figure 5a and Figure 5b).

In the U-tube WBHE setup and its corresponding temperature profile, significant temperature variations were observed in both the downward and upward tubes due to the ground's influence. Considering the fixed inlet working fluid temperature, the estimated fluid temperature at the outlet would be 24 °C (San Benigno), and 18.5 °C (Cinzano) (as shown in Figure 6a and Figure 6b).

5. Discussion and conclusions

Closed-loop heat exchangers (WBHE) enable heat extraction without producing geothermal fluids,

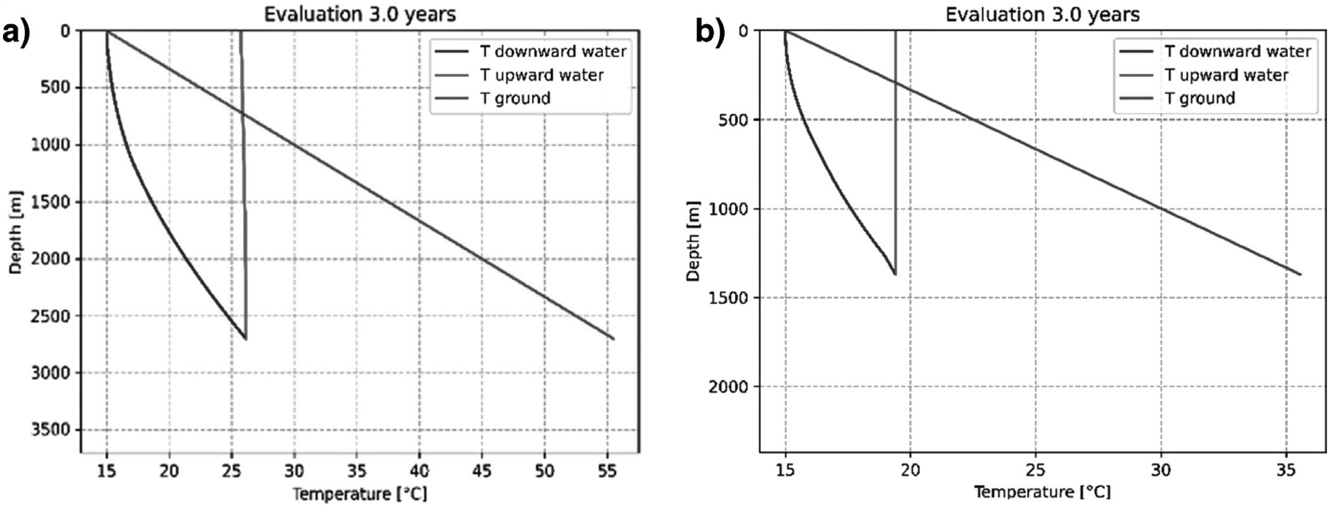

Fig. 5 – Temperature profile associated with the Coaxial WBHE configuration for the fixed flow rate (3 kg/s) and input fluid temperature of 15 °C considering the site-specific stratigraphy of (a) San Benigno (b) Cinzano well.

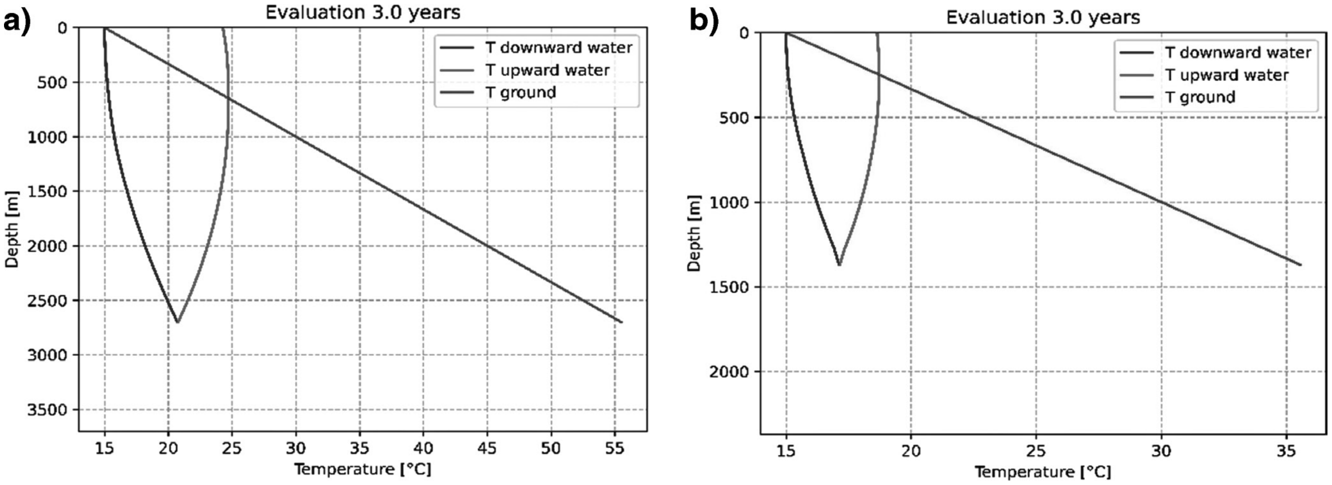

Fig. 6 – Temperature profile associated with the U-tube WBHE configuration for the fixed flow rate (3 kg/s) and input fluid temperature of 15 °C considering the site-specific stratigraphy of (a) San Benigno (b) Cinzano well.

reducing environmental impact and reinjection energy while avoiding corrosion and scaling issues. However, they exhibit lower heat recovery efficiency when compared to open-loop systems. This study evaluated the feasibility of implementing coaxial and U-tube heat exchangers in the decommissioned hydrocarbon wells of San Benigno and Cinzano, located in the Piedmont Region. The estimated outflow temperatures of the working fluids at the wellhead for the coaxial and U-tube profiles are 26 °C and 24 °C for San Benigno, and 19 °C and 18.5 °C for Cinzano, respectively, considering an inlet fluid temperature of 15 °C. When compared to results obtained in different geological contexts and for other decommissioned wells, these findings turn out to be negative. In Gizzi (2021), even with an inlet temperature of the working fluid of 50 °C and an inlet flow rate of 3 kg/s, an outlet fluid temperature of 98.6 °C was observed for the coaxial configuration, while for the U-tube it was 84 °C for the Trecate 4 hydrocarbon well (Villafortuna Trecate oilfield, Piedmont Region). Even with variable flow rates, a consistently higher outlet temperature was recorded for the coaxial configuration. In any case, such temperature values allowed for a multi-variant and comprehensive use of the resource, according to what was reported by (Kaczmarczyk *et al.*, 2020). Furthermore, when analyzing the coaxial heat exchanger system with a fixed inlet temperature of the working fluid (50 °C), Gizzi *et al.*, 2021 report an outlet fluid temperature of 100 °C for the Villafortuna 1 case study (Villafortuna Trecate oilfield). This result confirms what was previously estimated by Alimonti *et al.* (2016). Based on the coaxial configuration and considering the properties of the rocks to be uniform with depth ($\lambda = 2.5$ W/m K, $\rho_s = 2600$ kg/m^3, and cp = 800 J/kg K) and an inlet temperature of the heat carrier fluid equal to 40 °C, the exit temperature, as a function of the fluid flow rate, reached a maximum value of approximately 120 °C for an injection fluid flow rate of 10 m^3/h.

Despite the same geographical location, i.e., Piemont Region, the different geological context and therefore the petroleum system, the geothermal gradient, along with the varying depths of the analyzed wells and the associated temperature measured at the well bottom, produce results in terms of the extracted fluid temperature by different tested closed-loop geothermal systems. Unlike the results obtained for the Villafortuna 1 and Trecate 4 wells, the results for San Benigno and Cinzano do not allow for a positive assessment regarding the potential reuse of the extracted fluid following the geothermal repurposing of the well. This is true both from an energy and economic standpoint, as the costs associated with the repurposing project would not be justified by the thermal yield of the site.

Enhancing the precision of the applied models using future assessment is necessary. The basic assumption related to the constancy of the properties of the water as a working fluid can be overcome by properly analyzing the possibility of having phase change (evaporation) in the well, which would change the results. The same applies when considering alternative working fluids, with physico-chemical properties that would allow for a better result in terms of thermal output. The efficiency of the system, such as the ones analysed in this work, could be improved by using a non-aqueous working fluid. Finally, an analysis of the function of heat extraction from abandoned wells of intraformational flows and its impact on heat transfer is also required to confirm the results obtained.

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