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30 May 2026

Chapter

Perspective Chapter: Repurposing Wells for Geothermal Use – The Role of Geological Conditions on Wellbore Heat Exchanger Performance

Martina Gizzi, Fatemeh Hosseinpour, Federico Vagnon, Glenda Taddia and Stefano Lo Russo

Abstract

Repurposing wells in Italian oilfields presents a significant opportunity for renewable energy production. This chapter investigates the thermal performance of coaxial and U-shaped wellbore heat exchangers (WBHEs) for geothermal energy recovery in decommissioned wells. Three sites with distinct geological characteristics—Villafortuna 1, Tempa Rossa, and Gela 38—were selected to assess the influence of site-specific factors, well depth, and exchanger design on the heat transfer process. Semi-analytical models are implemented in Python codes to evaluate the thermal profiles of the working fluid in both configurations. Results indicate that the geothermal gradient and well depth are key parameters affecting heat exchange performance, with Villafortuna 1 exhibiting the highest outlet temperature due to its elevated geothermal gradient. For specific working fluid's flowrate values, the U-shaped WBHE consistently outperformed the coaxial system, achieving higher outlet temperatures due to an increased heat exchange surface and the inclusion of a horizontal section at maximum depth. While fluid properties and thermal conductivity were confirmed as critical parameters, pressure drop effects were not explicitly considered and warrant further investigation. The approach proposed serves as a useful methodological tool for the preliminary assessment of the feasibility of converting selected hydrocarbon wells; the described insights offer valuable guidance for improving WBHEs design and advancing geothermal energy recovery technologies, supporting the transition toward sustainable energy solutions.

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

1. Introduction

With the cessation of extraction activities, a significant number of hydrocarbon wells are decommissioned and abandoned, often resulting in severe environmental and economic consequences. Precise estimates of the number of decommissioned wells each year are not readily accessible in the literature. Where available, the figures reported by different authors in various sources seem inconsistent. Following what was reported by Zhu et al. [1], about 20–30 million abandoned oil wells exist worldwide. Reference [2] reported that the total number of documented orphaned wells in the United States exceeded 80,000 from June to September 2021 and 122,000 from January to April 2022, representing 2 and 3% of all the estimated abandoned wells in the United States. In Gianoutsos et al. [3], 117,672 orphaned wells in 27 States were documented by the US Geological Survey (USGS) [4, 5]. Basic data on onshore wells in European countries can be obtained from the primary regulatory authority's data centre or website, such as the UK Oil and Gas Authority or the Italian Ministry of Environment and Energy Security. This data includes key essential attributes associated with each well while avoiding the provision of information regarding the status of the infrastructure following abandonment or decommissioning [6, 7].

Addressing the legacy of decommissioned sites is an environmental imperative and an opportunity for innovation and progress. Effective management of these sites can mitigate environmental impacts while contributing to broader sustainability goals. For instance, repurposing abandoned infrastructure can support renewable energy initiatives, including geothermal energy production and carbon capture and storage projects. By integrating decommissioning efforts with the transition to cleaner energy, the industry can demonstrate its commitment to responsible resource management, transforming a historical challenge into a pathway for sustainable development. Geoscience disciplines possess significant potential to contribute to this effort, mainly through their expertise in subsoil characterisation. Rather than being abandoned, unused wells can be repurposed for geothermal energy production and heat storage. This provides a sustainable energy source to support local communities and industries during the energy transition.

Geothermal energy is the heat stored beneath the Earth's surface, while the subsoil's temperature difference is termed a 'Geothermal Gradient'. The potential for its economic use depends on various factors, including the geological and thermophysical conditions, such as the subsoil's temperature, the flow rate, and the degree of mineralisation of geothermal waters in the analysed area. These conditions influence the viability of utilising thermal resources in different geological contexts, offering multiple possibilities for harnessing this renewable energy source. Geothermal energy, electrical, and direct-use technologies are growing worldwide in application, including district heating and/or space heating using heat pumps, commercial treatments, agricultural purposes (e.g., greenhouses), fish farming, and other purposes [8]. The direct use of geothermal energy is becoming increasingly accessible as it relies on existing technologies and straightforward engineering solutions. One of the most significant costs in non-electrical geothermal projects is the drilling and casing of low-temperature wells. However, the abundance of existing wells, infrastructure, and geological data from oilfields presents a unique opportunity for geothermal development. By leveraging these resources, new geothermal projects can reduce capital expenditures, minimise risks, and avoid many challenges associated with starting a new project. This approach not only makes geothermal energy more affordable but also enhances the sustainability and efficiency of these projects [9–11]. Oil companies have the option to convert abandoned wells into geothermal wells by sealing the bottom with insulation and installing a closed-loop pipe system, that is, wellbore heat exchanger (WBHE), applicable to both horizontal and vertical wells [12, 13]. Unlike traditional open-loop geothermal systems, closed-loop systems circulate heat carrier fluids within a WBHE without extracting ground fluids from the surrounding geological formations. This configuration also ensures that working fluids are kept separate from the surrounding geological formations, reducing the potential for corrosion and scaling problems. Given their demonstrated advantages, more studies on WBHE technologies continue to be published in the literature. Pioneering authors like [14–17] have started to explore the potential of coaxial WBHE for geothermal energy extraction. Drawing on the studies published over the last 20 years, the key findings were summarised by Harris et al. [18], along with several other researchers who presented a review of previous scientific work on the application of WBHE in abandoned wells [19–21]. Despite promising results, as shown by Alimonti et al. [22], challenges such as low heat recovery efficiency persist, requiring further research and improvement. Besides, the development of the Eavor Loop design has introduced new challenges in estimating potential outlet temperatures, particularly considering horizontal wells drilled in thermally favourable geological layers. Introduced in 2019, such innovative closed-loop geothermal technology is designed to extract geothermal energy more efficiently than traditional systems. It utilises an underground network of pipes through which a working fluid circulates in a closed circuit, eliminating the need for hydraulic fracturing fluids. Similar to other single-well WBHEs, the primary limitation is that heat is extracted solely through conduction, which limits the heat recovery rate due to the absence of convection. Besides, repurposing long horizontal wells and implementing a U-tube-shaped closed-loop system (U-shaped WBHE) could increase the heat exchange surface area and improve heat recovery [23, 24].

Despite some recent successful theoretical geothermal experiments in oilfields worldwide, specific challenges remain in the large-scale utilisation of geothermal resources in oilfields. The primary factors hindering geothermal energy exploitation in oilfields are lower heat recovery efficiency than conventional geothermal plants, inadequate assessment and planning, and a lack of knowledge about wells' integrity and accessible underground data.

Converting an existing facility into a geothermal plant is challenging, particularly in regions close to urban areas [25]. To perform a preliminary evaluation of the potential for converting a hydrocarbon well to a geothermal closed-loop system located in a specific geological context, it is essential to use analytical and/or semi-analytical tools for pre-assessing productivity, such as determining the maximum working fluid outlet temperature. This chapter builds upon the research conducted over time on coaxial and U-shaped WBHE. After discussing methods that can be used to describe the heat exchange processes, it presents a simplified approach for assessing the feasibility of a selected well to be converted for new geothermal purposes. In detail, it introduces the functions of developed open-access Python codes for the analysis of coaxial and U-shaped WBHE systems. Data from three decommissioned hydrocarbon wells, that is, Villafortuna 1, Tempa Rossa, and Gela 38, in Italy, were used to test such tools. The results, focusing on the output temperature of the selected working fluid, emphasise the significant influence that geological context and technical input parameters concerning the fluid and the geometric setup can have on heat exchange processes.

2. Heat transfer processes in deep reservoirs

In deep hydrocarbon reservoirs, temperature differences between materials result in the movement of thermal energy, known as heat transfer [26]. Whenever a temperature difference exists between wellbores and the surrounding geological formations, energy exchange occurs. The processes of conduction and convection drive energy transfer within wellbores during heat extraction. Conduction refers to heat transfer through direct contact between substances, such as solids or stationary fluids, where a temperature gradient is present. The rate of heat transfer per unit area, q_x, by conduction in the x-dimension (one-dimensional perspective) through a plane wall is described by Eq. (1) [27]:

$$q_x = -\lambda_s A \frac{dT}{dx} \tag{1}$$

The term dT/dx represents the temperature gradient in the x-direction, which indicates heat flow, while the positive constant λ_s denotes the material's thermal conductivity. This relationship is known as Fourier's law of heat conduction, named after the French mathematical physicist Joseph Fourier, who significantly advanced the analysis of conductive heat transfer. The inclusion of a negative sign ensures compliance with the second law of thermodynamics, indicating that heat flows from warmer to cooler areas along the temperature gradient.

Convection refers to heat transfer between two surfaces, mediated by a moving fluid and achieved through molecular interactions. The primary mechanisms for this heat transfer are diffusion and advection, with advection representing the energy transfer resulting from bulk fluid movement in the presence of a temperature gradient. The overall impact of convection is expressed using Newton's law of cooling, described by Eq. (2) [27]:

$$q = hA(T_w - T_\infty) \tag{2}$$

In this context, T_∞ refers to the temperature of the free stream outside the velocity boundary layer, while T_w signifies the surface temperature where convection occurs. The convective heat transfer coefficient, represented by h, is influenced by the geometry of the system, the fluid's thermodynamic properties, the solid medium's thermal characteristics, and the system's boundary conditions. Standard tables and empirical values of h values exist for fluids and flow situations that are commonly encountered. Additionally, for circular tubes, h can be determined through the Nusselt number Nu and correlation functions found in the literature (Eq. (3)):

$$h_f = \frac{Nu\lambda_f}{2r} \tag{3}$$

where $2r$ is the equivalent diameter of the circular tube.

The relationship between conduction and convection in fluid flow through circular tubes, characterised by a temperature difference between the fluid and tube walls, can be approximated using experimentally derived correlations that vary by flow conditions and geometry. The most prevalent correlations for forced convection in circular tubes are designed for turbulent and laminar flow regimes [28].

Understanding how heat transfer modes affect wellbores in oilfields is essential for estimating the exchange rate under specific geological conditions while planning a new geothermal energy project. Additionally, accurately interpreting the physical behaviour of heat transfer in various WBHE configurations is vital for assessing the viability of utilising abandoned wells to exploit geothermal resources in sedimentary basins. The subsequent chapter outlines the coaxial or double-pipe and U-shaped configurations of vertical wellbore heat exchangers utilised for harnessing geothermal energy from decommissioned oilfield boreholes. Following this, pertinent references were presented to the principal models employed to simulate the heat transfer between WBHE pipes and the adjacent subsurface.

3. Closed-loop geothermal energy systems: Coaxial and U-shaped WBHEs

Researchers have recently concentrated on coaxial or double-pipe and U-shaped configurations of vertical WBHE to tap into geothermal energy from abandoned oilfield boreholes. These systems efficiently extract heat from the ground without needing to extract or re-inject geothermal fluids [29]. In coaxial WBHEs, the working fluid is introduced into the outer pipe (the injection pipe), flowing downward to the bottom of the exchanger, where the surrounding rocks heat it. Upon reaching the bottom of the well, the heated fluid ascends through a narrower inner (extraction) pipe. The annular space between the inner pipes is filled with grout, commonly bentonite, and the well's bottom is sealed. Heat transfer occurs between the geological formation and the fluid in the injection pipe and between the fluids in both pipes. Conversely, U-shaped systems function differently. In these systems, the working fluid is pumped down one tube and returned through another. This U-shaped design features two vertical sealed sections and a horizontal wellbore that reaches the target thermal reservoir. The working fluid circulates in the sealed wellbore, moving from the vertical inlet through the horizontal section and into the production well. As it circulates, the working fluid absorbs heat from the thermal reservoir before exiting to supply a power generator or heat exchanger (**Figure 1**).

Research on actual WBHE systems, particularly experimental and pilot studies, remains limited, with most investigations focusing on theoretical modelling. The study conducted by Kolo et al. [21] significantly advances the understanding of the various methods used to model heat flux between WBHE pipes and the nearby subsurface. The chapter reviews analytical tools for heat transfer analysis in WBHEs, along with numerical discretisation techniques that effectively model the heat transport processes in coaxial WBHEs and their surrounding formations. The earliest advancements in integrating horizontal sections with vertical heat exchangers emerged around the middle of the last decade. In Feng et al. [30], researchers proposed using coaxial heat exchanger designs within directionally drilled wells featuring a vertical well paired with a horizontal branch. Specifically, they recommended placing the heat exchangers within a relatively short section of the horizontal well section (ranging from 152.5 to 610 m) to harness the highest temperatures in a geothermal reservoir. In 2020, Toews et al. [24] shared findings from a full-scale demonstration project involving a multilateral closed-loop geothermal system. Situated near Sylvan Lake, Alberta, Canada, the project includes two 2.5 km long multilateral horizontal wellbores linked to two 2.4 km deep vertical wellbores, forming a U-shaped closed-loop geothermal system. The heat exchangers employed in the wellbores depend solely on conductive heat transfer, and a straightforward analytical equation was utilised to estimate the outlet temperature from the horizontal lateral well. This equation follows the method established by Ramey [31] for vertical wellbores, based on the critical assumption that heat transfer is due to quasi-steady-state radial heat conduction from the rock into the fluid moving through the wellbore. Therefore, assumptions and simplifications must be made to avoid complex derivations and calculations when developing such a mathematical model of the WBHE that can be

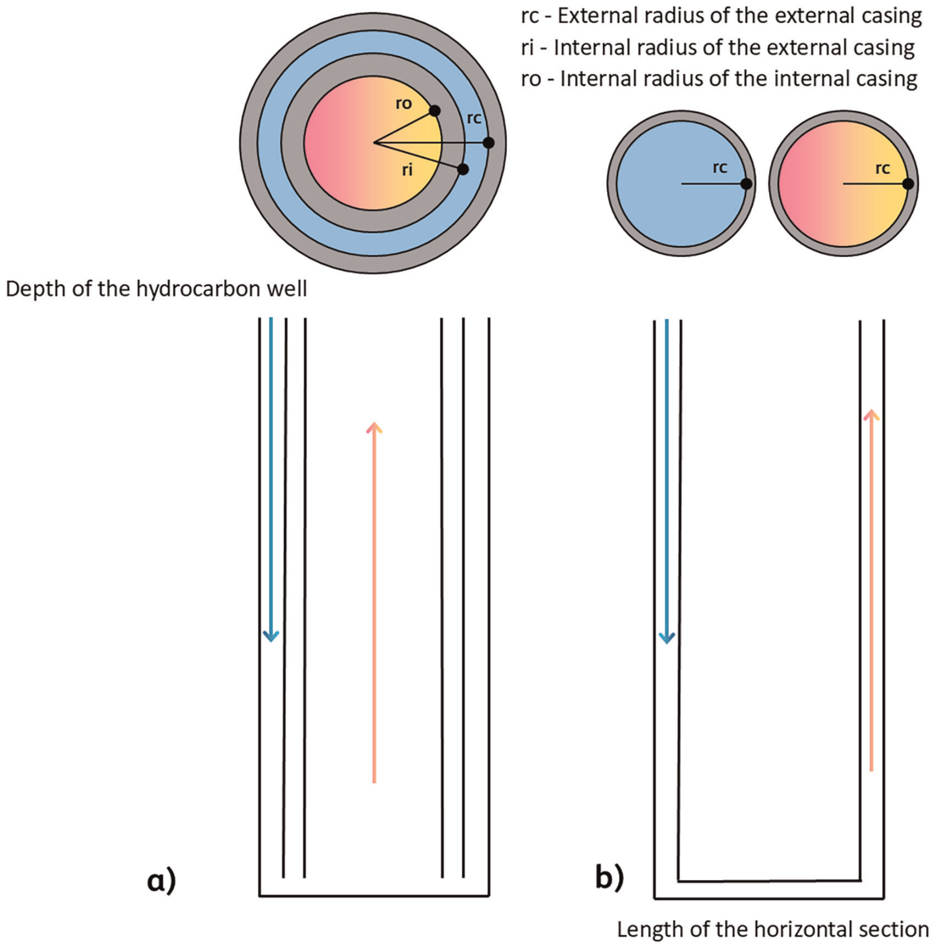

Figure 1.
Simplified configuration of a coaxial (a) and U-shaped WBHE (b).

solved analytically. Despite the limitations, the authors found that it still closely matches the Eavor Lite field data and the more complex numerical models described in References [23, 24]. The main limitation of the proposed analytical model is that it ignores heat transfer in the vertical wellbore segments. Reference [18] proposed an approach for extracting geothermal energy from abandoned oil and gas wells using directionally drilled wells, thereby improving the existing designs by eliminating internal piping and maximising contact with high ground temperatures. The proposed geometry was studied numerically to determine the system's outlet temperatures and heat extraction rates for predicting thermal energy extraction and electrical power production. Reference [32], working on multiple laterals, demonstrated that closed-loop geothermal systems can provide reasonable temperature and heat duty for over 30 years when installed in a suitable geological setting. Using two analytical methods, results indicate that the closed-loop geothermal system is sensitive to reservoir thermal conductivity, which controls the level of outlet temperature and interference between wells over time. In Ref. [33], the two configurations of coaxial and U-shaped exchangers were set up to analyse the performance and evaluate the best operational configuration. As already proposed in Ref. [34], the modelling of the two systems for capturing heat from the subsoil is based on a one-dimensional, quasi-stationary model, which assumes that the heat exchange with the rock system takes place in a radial direction by conduction and varies in time. The heat transfer between the ground and the WBHE is evaluated using a semi-analytical approach based on the thermal resistances of the components of the WBHE described in Ref. [35] and also applied in Ref. [7].

4. Heat transfer in coaxial and U-shaped WBHEs

As reported by Nian and Cheng [36] and Blank et al. [37], the general energy balance of the fluid in the injection pipe of a coaxial WBHE can be expressed in Eq. (4):

$$\frac{\partial\Big((\rho c)_f A_0 T_{fo}\Big)}{\partial\tau}+\frac{\partial\Big((\rho c)_f A_0 v_f T_{fo}\Big)}{\partial z}=-\frac{dQ}{dz}+\frac{dQ_{i0}}{dz} \tag{4}$$

where T_{fo} refers to the fluid temperature in the outer pipe, A_0 denotes the outer pipe area, and v_f indicates the fluid velocity. The term dQ/dz is the heat extraction from the formation per unit well depth (W/m). Furthermore, $dQio/dz$ defines the heat flux from the inner pipe to the outer pipe; despite insulation being employed to minimise heat loss from the inner pipe fluid, some heat can transfers between the two pipes. Consequently, the energy equation for the inner tube can be represented by the following Eq. (5):

$$\frac{\partial\Big((\rho c)_f A_i T_{fi}\Big)}{\partial\tau}+\frac{\partial\Big((\rho c)_f A_i v_f T_{fi}\Big)}{\partial z}=-\frac{dQ_{i0}}{dz} \tag{5}$$

By assuming steady heat transfer and constant heat flux in wellbore components (insulation, casing, grout), heat extraction from the formation is assumed to equal the heat flux at the wellbore's outer surface (the boundary between the wellbore and rock formation) to the injected fluid (Eq. (6)):

$$\frac{dQ}{dz}=2\pi r_w k_w\left(T_{f0}-T_w\right)=\left(T_{f0}-T_w\right)/R_w \tag{6}$$

where T_w is the temperature at the interface of the wellbore/formation, r_w is the radius of wellbore outside, k_w is the heat transfer coefficient between outer pipe fluid and wellbore exterior, R_w is the thermal resistance between the outer pipe and surrounding rocks.

At the bottom of the well, the heated fluid enters and moves through the internal pipe of the coaxial WBHE. As it ascends to the wellhead, heat is only transferred through the wall of the inner pipe. Therefore, $dQio/dz$ is calculated by factoring in the temperature difference between the fluids in the outer and inner pipes and the estimated thermal resistance of the insulation (Eq. (7)):

$$\frac{dQ_{i0}}{dz}=2\pi \mathrm{r}_0 k_{i0}\left(T_{fi}-T_{f0}\right)=\left(T_{fi}-T_{f0}\right)/R_{i0} \tag{7}$$

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.

4.1 Coaxial WBHE: Coefficient of heat exchange between the outer-pipe fluid and the wellbore exterior

An accurate estimation of the parameter k_w is crucial for assessing heat exchange between the fluid in the outer pipe and the geological formations. In the case of coaxial WBHE, the heat exchange coefficient of the injection pipe can be represented as the sum of heat transfer components based on thermal resistance values *(R_w)* (Eq. (7)) [35, 36]:

$$R_w = \ R_s + R_a + R_c \tag{8}$$

R_s, a time-dependent function, reflects the thermal resistance from conductive heat transfer in the rock, while R_a indicates the thermal resistance caused by convection into the pipe. R_c represents the thermal resistance from conductive heat transfer through the well's casing. The conductive term prevails in evaluating the total thermal resistance; consequently, the thermal exchange is directly proportional to the convective transfer coefficient.

Conductive thermal resistance *(R_s)* can be expressed as follows (Eq. (9)):

$$R_s = \frac{1}{2\lambda_s} In \frac{2\sqrt{\alpha_s t}}{r_w} \tag{9}$$

where λ_s (W/mK) is the thermal conductivity of the rock and, α_s (m/s) is the thermal diffusivity of the rock, r_w is the radius of the outside wellbore (**Table 1**). In Eq. (9), the numerator of the argument of the natural logarithm represents the time-dependent radius of the thermal influence of the well (r_s). This parameter considers the change, over time, of the heat flux into WBHE surrounding geological formations.

Convective thermal resistance *(R_a)* can be determined by the following equation (Eq. (10)):

Coaxial wellbore heat exchanger-geometric parameters	Symbol	Unit of measure
Outer pipe area	A_0	[m^2]
Inner pipe area	A_i	[m^2]
Radius of outside wellbore	r_w	[mm]
The external radius of the external casing	r_c	[mm]
The internal radius of the external casing	r_i	[mm]
The internal radius of the internal casing	r_0	[mm]
Thicknesses of the pipe exchanger	d	[mm]
Depth	z	[m]

Table 1.
Coaxial WBHE–geometric parameters.

$$R_a = \frac{1}{2r_c h_f} \tag{10}$$

where r_c is the external radius of the external casing, h_f is the convective heat transfer coefficient, calculated using Eq. (3) and by using the Nusselt number (Nu) and the form of the Dittus-Boelter equation assuming turbulent flow inside the tubes (Reynolds number ≥ 104) [28]:

$$Nu = 0.023\,Re^{\,0.8} Pr^{0.4} \tag{11}$$

where $Pr = \frac{\rho c_f \mu}{\lambda_f}$ and $Re = \frac{\rho v_f 2r_c}{\mu}$.

Finally, thermal resistance to heat conduction through the casings of the well (R_c) can be determined as follows:

$$R_c = \sum_{i=1}^{n} R_{\lambda i} = \frac{1}{2}\sum_{i=1}^{n} \frac{1}{\lambda_i} In \frac{r_{c,i+1}}{r_{c,i}} \tag{12}$$

where λ_i is the thermal conductivity of the rock in correspondence with the different casings of the well. Generally, due to the high thermal conductivity of the steel piping, the total thermal resistance of the casing is negligible compared with the rock's thermal resistance.

As a result, the heat exchange coefficient k_w can be determined as follows [38, 39]:

$$\frac{1}{k_w} = \frac{2r_c}{2\lambda_s} In \frac{4\sqrt{a_s t}}{2r_w} + \frac{1}{h_f} \tag{13}$$

where r_c = r_w as the thickness of the external tube is negligible.

4.2 Coaxial WBHE: Coefficient of the heat exchange between the outer-pipe fluid and the inner pipe

Unlike in the injection pipe, the total heat flux in the upward pipe (extraction pipe) is determined by a conductive component of the composite pipe and by two convective components: one on the internal wall and one on the external wall of the WBHE. Consequently, the total heat exchange coefficient k_{i0} for the extraction pipe can be calculated as follows (Eq. (14)):

$$\frac{1}{k_{i0}} = \frac{r_0}{r_{0+d}} \frac{1}{h_i} + r_0 \sum_{i=1}^{n} \frac{1}{\lambda_i} In\left(\frac{r_{i+1}}{r_i}\right) + \frac{1}{h_0} \tag{14}$$

where r_0 is the radius of the internal casing, r_i the internal radius of the external casing, d is the thicknesses of the pipe exchanger, h_0 and h_i are the coefficients of convective heat transfer to the inner and outer wall, respectively, and λ_i is the thermal conductivity of the pipe material (air and steel) (**Table 1**).

4.3 U-shaped WBHE: Coefficient of heat exchange between pipe fluid and the wellbore exterior

As outlined in Chapter 3, a U-shaped WBHE involves pumping fluid through one tube while it exits *via* another. The U-shaped configuration includes two vertical sealed sections and a horizontal wellbore that accesses the targeted thermal reservoir at the maximum well's depth. The above-mentioned vertical sections can be depicted as two hydrocarbon wells spaced apart, as detailed in Ref. [20]. The working fluid flows within the sealed wellbore, travelling from the vertical inlet through the horizontal segment to the production well. During this flow, it gathers and loses heat from the thermal reservoir along its path, according to the subsoil's temperature conditions at different depths. Consequently, in describing the heat extraction from the formation, it is possible to assume that it is equal to the heat flux at the wellbore's outer surface (the boundary between the wellbore and rock formation) to the injected fluid for both the vertical and horizontal sections. Furthermore, the heat flux from the inner pipe to the outer pipe, as described for coaxial WHBE in Eq. (4), has not been defined. As a result, the heat exchange coefficient k_w defined in Eq. (13) can be applied to assess heat exchange between the fluid in the pipes and the geological formations for a U-shaped WBHE.

4.4 Python code implementation and input parameters definition

The previously described methods can be used to determine the preliminary temperature profiles of a selected working fluid in a specific wellbore heat exchanger. This calculation process can be automated with computational tools built using C or Python programming languages. Python, developed by Guido van Rossum in 1991 [40], is an object-oriented, high-level language which was utilised to model the analysed systems of this study. The available code versions allow for the replication and application of these analyses in new and varied research contexts. Once the input parameters are established, the temperature profile of the carrier fluid can be obtained. Below, in **Table 2** and **Figure 2**, a list of the necessary input parameters and a graphical representation of the Python code for the discussed WBHEs are proposed. In selecting input parameters and applying the above-mentioned codes, primary considerations and assumptions must be considered when modelling the coaxial and U-shaped profiles using the selected models:

- Geological Model (GM): The geological model must be defined. Since a stratigraphic variation with depth is observed, it is necessary to proceed with characterising the thermal properties of the specific geological formations involved. The horizontal section of the U-shaped WHBE will affect the geological formation it crosses. The thermal properties defined for such formations will influence the heat exchange processes.

- Geothermal Gradient (GG): Since a geothermal gradient condition characterises each specific geological context, it must be appropriately defined for the ongoing analysis. The temperature at depth Z was estimated based on the local geothermal gradient, using the following Eq. (15), where AT and B factors are defined in **Table 2**:

$$T_a(Z) = B + AT \cdot Z \tag{15}$$

- One of the sets of configurations proposed by (35) was adopted for the definition of geometric parameters related to the coaxial heat exchanger. Further studies and configuration proposals are available in References [41, 42]. The diameter size significantly influences fluid velocity, thus allowing for additional analyses that consider different configurations that can be carried out.

Input parameters	Symbol	Unit of measure	Value
Wellbore heat exchanger			
Depth	z	m	6202
Length of the horizontal section	l	m	1000
The external radius of the external casing	r_c	mm	75.0
The internal radius of the external casing	r_i	mm	69.5
The internal radius of the internal casing	r_0	mm	38.5
Thermal conductivity of the pipe material	λ_m	$W\ m^{-1}\ K^{-1}$	15
Thermal conductivity of the insulation	λ_i	$W\ m^{-1}\ K^{-1}$	0.025
Working fluid – water			
Flow rate	q	$Kg\ s^{-1}$	3–1.5
Inlet temperature	T	°C	15
Volumetric heat capacity of the fluid	ρc_f	$J\ kg^{-1}\ K^{-1}$	4215.45
Thermal conductivity of the fluid	λ_f	$W\ m^{-1}\ K^{-1}$	0.68
Density	ρ_f	$Kg\ m^{-3}$	958.40
Viscosity	μ	Pas	2.82e−4
Simulation time			
Time stop	t	Year	3
Geological formations			
Thermal conductivity of the rock	λ_s	$W\ m^{-1}\ K^{-1}$	GM
Volumetric heat capacity of the rock	ρc_s	$J\ kg^{-1}\ K^{-1}$	GM
Density	ρ_s	$Kg\ m^{-3}$	GM
Geothermal gradient			
Soil temperature profile slope	AT		GG
Soil temperature profile intercept	B	°C	CG

Table 2.
WBHEs–input parameters.

- Heat transfer mode: Heat moves through conduction in the reservoir, while conduction and convection occur within the wellbore tubes. The model presumes steady-state conditions and initial thermal equilibrium, ignoring time-dependent temperature variations; each point within the tubes consistently maintains the same temperature throughout the system's operation.

- Temperature distribution: The temperature profile is assumed to remain uniform in the radial direction. Turbulent flow within the tubes, described using (11), promotes enhanced mixing, which reduces the radial gradient. Therefore, temperature changes are only observed in the vertical direction of the upward and downward tubes, leading to a unidirectional temperature profile.

- Carrier fluid: The properties of the chosen carrier fluid, for example, water, are assumed to be constant. No variations arise from pressure or temperature gradients throughout the process.

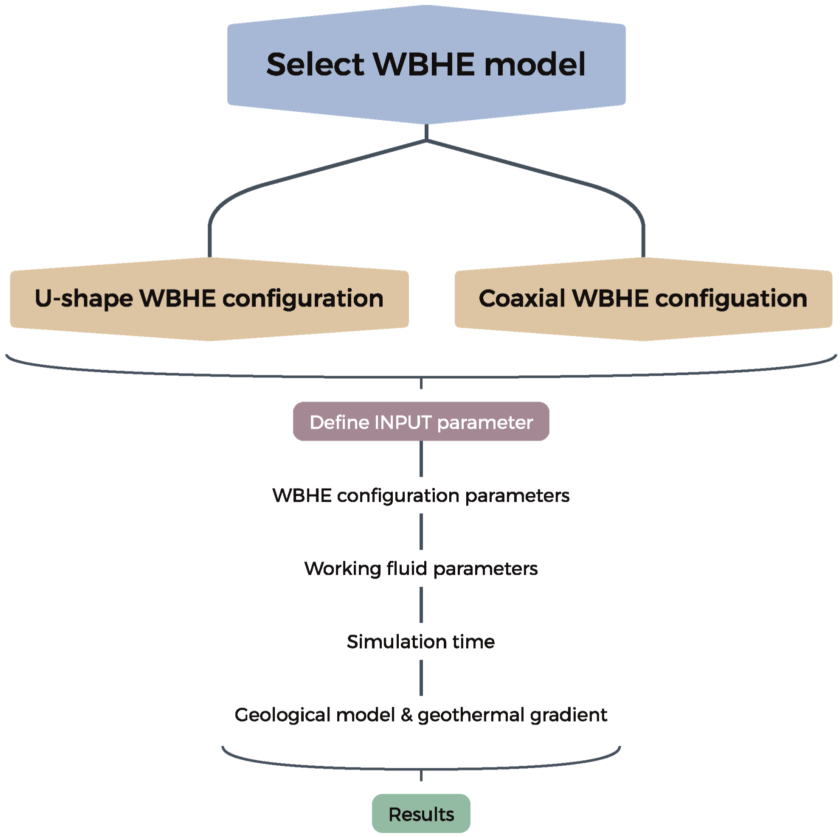

Figure 2.
Simplified structure of the developed Python code.

- Thermal Resistance: The model considers the thermal resistance from pipe thickness negligible, given that the tube material is assumed to have a high conductivity value. Therefore, its resistance is considered minor compared to other resistances in the system.

5. Case studies and applications

As mentioned in the introduction chapter, data on onshore wells in European countries can be accessed through the primary regulatory authority's data centre or website. The National Mining Office of the Italian Ministry for Economic Development (MISE) and the VIGOUR project's website provide technical information regarding productive and decommissioned hydrocarbon wells in Italy. By analysing the data available at the end of 2024 on the official website of the Italian Ministry for Economic Development (MISE), one can obtain information about 1554 wells; 43.8% of these are producing, while the remaining 54.8% are non-producing wells (**Figure 3**) [43].

Furthermore, lithostratigraphic units and temperature data visualisation can be accessed through the Italian National Geothermal Database (BDNG), established in the 1980s and managed by the Institute of Geosciences and Earth Resources (IGG) of

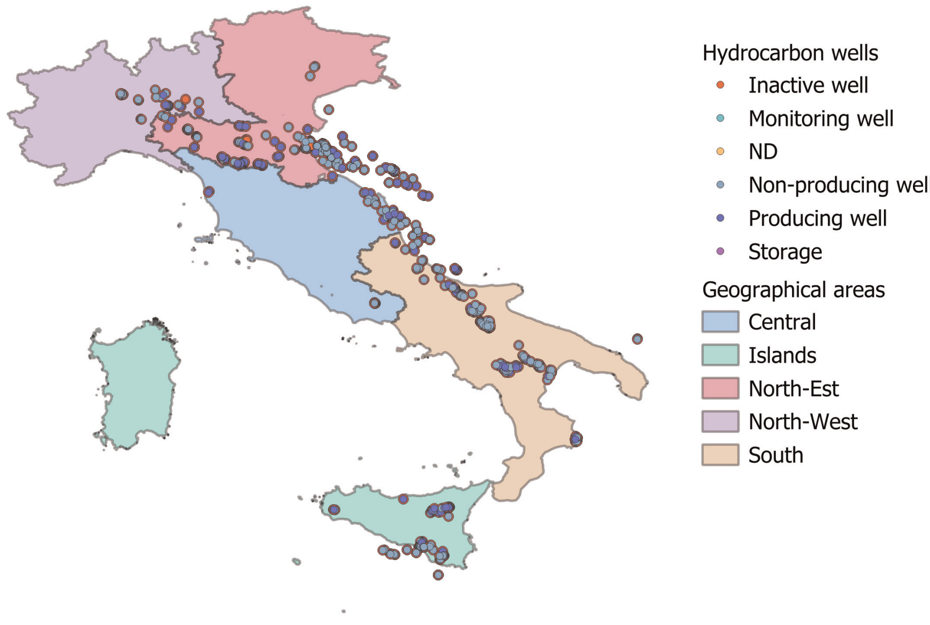

Figure 3.
Hydrocarbon wells distribution in Italy at the end of 2024.

the National Research Council (CNR) of Italy. In addition, stratigraphic profiles sourced from GEOTHOPICA, the Italian geothermal data infrastructure portal launched in 2007 by CNR-IGG, can provide extensive lithological information from well logs [44]. Beginning with temperature and stratigraphic profiles, the thermophysical properties of geological formations can be characterised, thereby defining the geological model (GM) and geothermal gradient (GG) for each selected case study.

Considering the specific geographical and geological context, it is necessary to obtain measurements and/or bibliographically available information for the characterisation of the thermal parameters of the geological formations involved. To determine heat conductivity values at the regional and local scales of Italian sedimentary basins' geological formations, Di Sipio et al. [45] investigated the thermal conductivity of 200 rock samples collected from four different regions of Southern Italy (Calabria, Campania, Apulia, and Sicily), measuring in both dry and wet conditions. Moreover, Pasquale et al. [46] utilised the framework of the MIUR–2008 project 'Geothermal resources of the Mesozoic basement of the Po Basin: groundwater flow and heat transport' to accurately estimate the thermophysical properties of a wide variety of sedimentary and volcanic rocks from the Po Basin in the Northern part of Italy, through laboratory measurements of density and porosity. In 2020, Dalla Santa et al. [47] included a new database of thermal properties for rocks and unconsolidated sediments in their work. As already reported in Reference [7], the values defined by the above-mentioned authors were used to determine the thermophysical parameters of the geological formations and the geological model associated with each of the selected case studies (**Tables 3–5**). Furthermore, the temperature profiles available for download from the Geothopica geoportal were used to establish local geothermal gradient conditions.

State	Productive, not supplying well			
Location	Piemonte Region			
Field	VILLAFORTUNA			
Depth	Lithostratigraphic formation			
		λ_s	ρc_s	ρ
m		W/mK	J/kg/K	kg/m^3
609	Terrigenous sedimentary deposits	0.30	800	1700
1258	Sand (dry)	0.30	800	1700
1405	Clay Sand	1.61	1696	1890
5493	Clastic sedimentary rocks (Sandstone, Conglomerates and Silty Marl)	3.16	821.11	2359
6202	Carbonate rocks -Calcarenite/Dolostone	3.50	810.48	2480

Table 3.
Villafortuna 1 hydrocarbon well-lithostratigraphic profile [7].

State	Productive, not supplying well			
Location	Basilicata Region			
Field	GORGOGLIONE			
Depth	Lithostratigraphic formation			
		λ_s	ρc_s	ρ
m		W/mK	J/kg/K	kg/m^3
23	Superficial sedimentary deposits	0.30	800	1700
2912	Sandstones interspersed with shale and clays	3.00	808.6	2330
5042	Clays, argillites and calcarenites	2.34	829.4	1917

Table 4.
Tempa Rossa 1D hydrocarbon well-lithostratigraphic profile [7].

State	Productive well			
Location	Sicilia Region			
Field	GELA TERRA			
Depth	Lithostratigraphic formation			
		λ_s	ρc_s	ρ
m		W/mK	J/kg/K	kg/m^3
1632	Terrigenous sedimentary deposits—Sandy Clay	1.61	1696	1890
5451	Calcareous Marl	2.17	830	1801
6189	Carbonate rocks–calcarenite/dolostone	3.50	810.48	2480
6282	Clastic sedimentary rocks—argillaceous sandstone	3.00	821.11	2330

Table 5.
Gela 38 hydrocarbon well-lithostratigraphic profile [7].

The Villafortuna-Trecate field is situated in the Piemonte Region (Novara province, North-West geographic area). This hydrocarbon system represents one of the most significant oil accumulations within the Italian Middle Triassic carbonate petroleum system. The petroleum system has developed within the Triassic geological succession. Generally, the primary reservoir linked to the Villafortuna-Trecate field is identified to be at a depth ranging from 5800 to 6100 m, with a temperature of approximately 160–170°C [48]. As evidenced by information regarding lithostratigraphic units presented in **Table 3**, the stratigraphic sequence associated with Villafortuna 1 well consists predominantly of clastic sedimentary and carbonate rocks. The well under examination reaches a maximum depth of 6202 m (**Table 3**).

The Tempa Rossa 1D hydrocarbon well is situated within the Tempa Rossa oilfield in the Basilicata Region, in the southern area. This system lies within the Mesozoic carbonate substratum of the foredeep/foreland area and the external thrust belt of the southern Apennines. It hosts Italy's most significant oil and gas accumulations, namely the Val d'Agri and Tempa Rossa oilfields. The reservoirs are characterised by fractured limestones of the buried Apulia Platform, which extend in time from the Cretaceous to the Miocene [49]. Unlike Villafortuna 1, lithostratigraphic units are mainly composed of sandstone with associated shales (**Table 4**). The maximum depth reached by the analysed well is 5042 m.

The examined case study of the Gela 38 hydrocarbon well (Gela oilfield, Sicily region, Islands) pertains to the Gela field, a Late Triassic–Early Jurassic petroleum system linked to the main phase of Tethyan rifting. The reservoir consists of fractured, massive dolomites from the Upper Triassic Gela Formation [50]. Based on the available information regarding the lithological and temperature data, the stratigraphic succession in the area consists of marl, calcareous marl, and clays. The maximum depth reached by the analysed well is 3446 m (**Table 5**).

6. Results

6.1 Coaxial and U-shaped WBHEs: Output temperature analysis

The temperature profiles for the WBHEs were derived from specific geological properties obtained from selected case studies' geological models. Thermal properties for various rock formations were adopted based on those provided in **Tables 3–5**. According to the information reported in **Table 2**, among the input parameters, the inlet flow rate of the working fluid (water) and its temperature were assumed to be 3.0 kg/s and 15°C, respectively. The analysis of the coaxial WBHE performance across the three hydrocarbon wells reveals significant differences in performance, primarily driven by the geological characteristics of each site. The efficiency of heat exchange in this configuration relies on the geothermal gradient, and the thermal conductivity of the surrounding rock formations. The outlet temperatures at the surface for the three sites are as follows (**Figure 4**).

Among the three sites, Villafortuna 1 exhibits the highest thermal performance, with an outlet temperature of 89.93°C. This result suggests that the site benefits from a higher well's depth and geothermal gradient, enabling the fluid to absorb substantial heat as it descends through the wellbore. The steep temperature increase indicates effective heat transfer from the ground, making this location suitable for geothermal energy extraction.

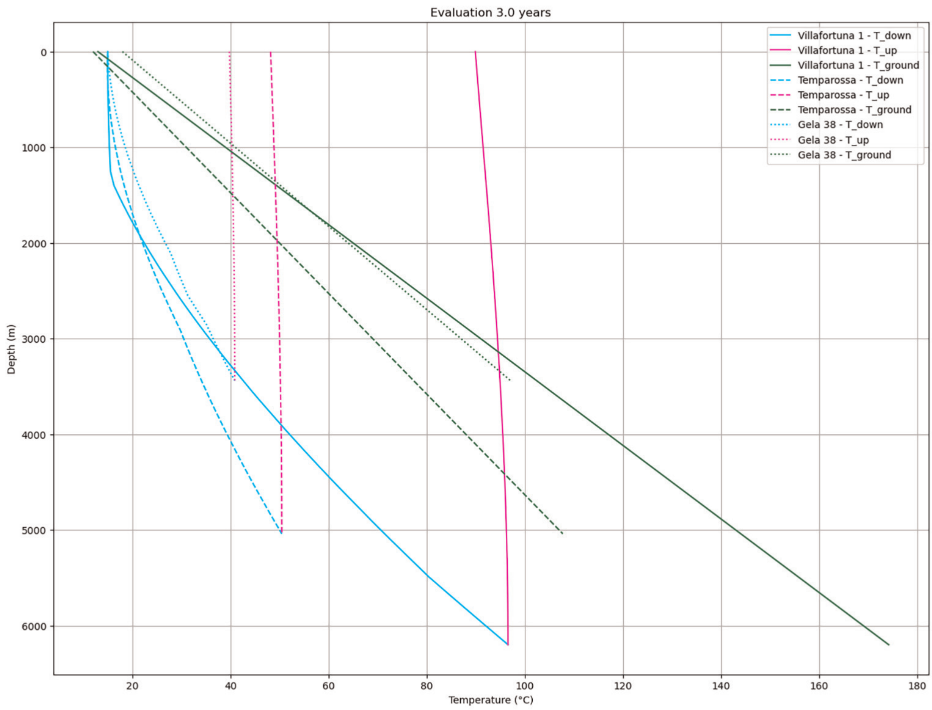

Figure 4.
Temperature distribution of the working fluid in the coaxial WBHE (flow rate: 3 kg/s).

Tempa Rossa presents intermediate thermal performance, with an outlet temperature of 48.20°C. The lower-temperature rise compared to Villafortuna 1 suggests this site has a less favourable geothermal gradient or lower thermal conductivity in the surrounding geological formations. Consequently, the working fluid absorbs less heat from the ground, resulting in a more moderate increase in temperature upon returning to the surface.

Gela 38 exhibits the least thermal enhancement, with an outlet temperature of 39.79°C. Although the initial ground temperature is higher than that at the other two sites (18°C), the overall temperature gain during fluid circulation remains limited. As a result, this well has the least potential for geothermal energy recovery among the three.

The analysis of the U-shaped WBHE across the three hydrocarbon wells highlights greater efficiency in heat exchange compared to the coaxial WBHE. This improvement is likely attributed to the increased contact area between the fluid and the surrounding rock formations, along with the enhanced heat transfer mechanisms inherent in the U-shaped configuration. The outlet temperatures at the surface for the three sites are as follows (**Figure 5**).

Villafortuna 1 exhibits the highest thermal performance, with an outlet temperature of 99.75°C. This result is significantly higher than that of the coaxial WBHE (89.93°C) and suggests that the U-shaped configuration optimises heat absorption from the ground. The improved heat transfer efficiency of this design enables the working fluid to attain higher temperatures, further enhancing its potential for geothermal energy applications.

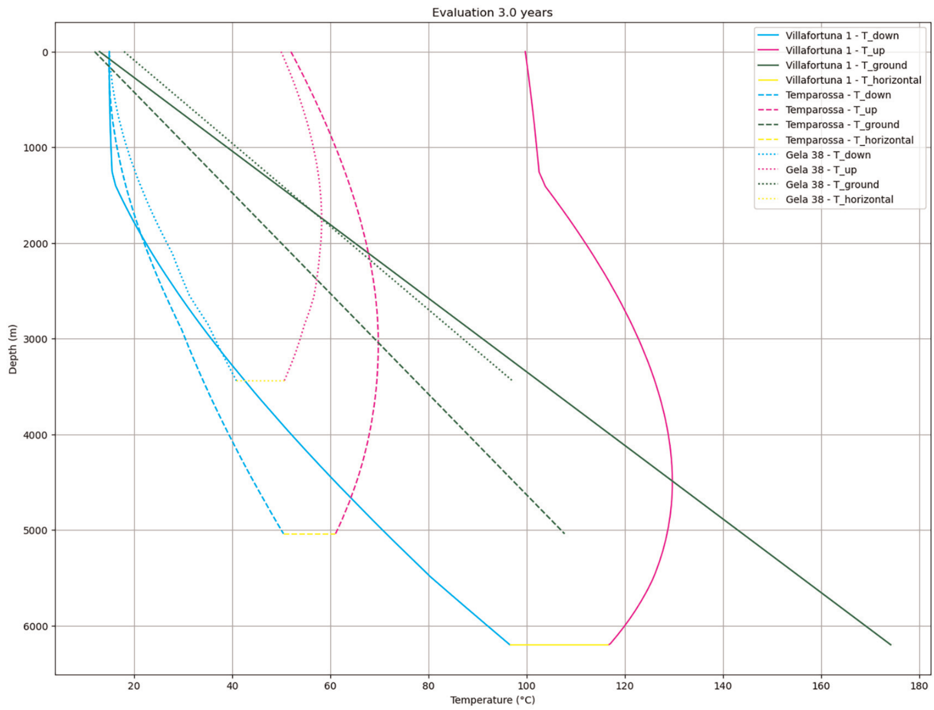

Figure 5.
Temperature distribution of the working fluid in the U-shaped WBHE (flow rate: 3 kg/s).

Tempa Rossa demonstrates an intermediate thermal performance, with an outlet temperature of 51.99°C. In comparison to the coaxial WBHE (48.20°C), the U-shaped design provides a moderate increase in thermal efficiency. The enhancement in heat exchange is likely due to improved thermal interaction between the fluid and the ground. However, the geothermal gradient at this site remains lower than that at Villafortuna 1, thus limiting the maximum achievable temperature.

Gela 38 shows the most significant relative improvement in heat exchange efficiency, with an outlet temperature of 49.99°C compared to 39.79°C in the coaxial WBHE.

The inclusion of a horizontal section at maximum depth in the U-shaped WBHE configuration plays a role in enhancing heat exchange efficiency. This section allows the working fluid to remain in contact with the hottest subsurface layers for a more extended period, increasing its thermal absorption before it begins its ascent to the surface. The thermal contribution of the horizontal section is evident when comparing the outlet temperatures of the U-shaped and coaxial WBHE systems (**Table 6**). The most significant improvements are observed in Villafortuna 1 and Gela 38, where the temperature at the outlet increased by 9.82°C and 10.20°C, respectively, compared to the coaxial system. This indicates that in sites with a high geothermal gradient at depth, the horizontal section enhances the heat transfer process. In contrast, Tempa Rossa exhibits a more modest improvement of 3.79°C, suggesting that when the geothermal gradient is weaker, the additional horizontal section has a less pronounced effect on heat absorption. Furthermore, the effectiveness of this configuration is highly dependent on the thermal conductivity of the subsurface materials; if the rock formations have poor heat transfer properties, the additional section may not yield significant advantages. Another consideration is the increase in system complexity

Site	Horizontal temperature	Temperature difference (U-shaped—coaxial)
Villafortuna 1	116.73°C	*+9.82°C* (99.75–89.93°C)
Tempa Rossa	60.99°C	*+3.79°C* (51.99–48.20°C)
Gela 38	50.56°C	*+10.20°C* (49.99–39.79°C)

Table 6.
Thermal comparison of U-shaped and coaxial configurations.

and potential installation costs, as incorporating a horizontal section necessitates more space and a more intricate design compared to simpler wellbore heat exchanger configurations.

6.2 Influence of flow rate reduction on geothermal heat recovery

Operational parameters play a significant role in determining the efficiency of the heat exchange process. Among these parameters, the inlet flow rate stands out as one of the most influential factors. Thermal profiles were recalculated by reducing the inlet flow rate from 3 kg/s to 1.5 kg/s. This reduction in flow rate was intended to increase the fluid's residence time in the system, thereby enhancing heat absorption from the surrounding rock formations.

The results varied according to the geological characteristics of each site. Among the coaxial WBHE configurations, Villafortuna 1 exhibited the most remarkable improvement, with its outlet temperature rising to 122.56°C from the original

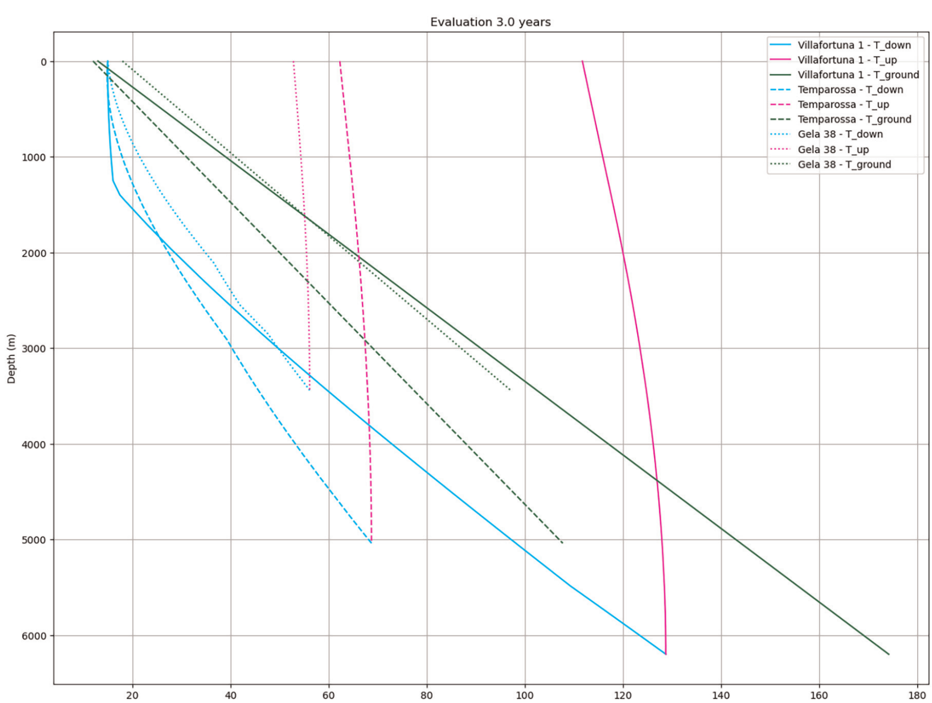

Figure 6.
Working fluid temperature distribution in the coaxial WBHE (flowrate: 1.5 kg/s).

89.93°C (**Figure 6**). The extended residence time of the fluid, resulting from the reduced flow rate, allowed for enhanced heat absorption from the surrounding rock, maximising the system's thermal efficiency. Tempa Rossa also experienced a significant boost in performance, with the outlet temperature increasing from 48.20 to 66.43°C. Although this improvement is considerable, the site's lower thermal conductivity and moderate geothermal gradient limited the overall gain compared to Villafortuna 1. Gela 38 showed the least improvement, with its outlet temperature rising from 39.79 to 54.99°C. While the reduced flow rate improved heat recovery, further improvements—such as enhanced insulation or extended well depth—may be necessary to achieve greater efficiency at this location.

In the U-shaped WBHE configuration, notable differences compared to the coaxial WBHE were observed (**Figure 7**). Villafortuna 1 previously demonstrated an outlet temperature of 99.75°C, outperforming its coaxial counterpart (89.930°C). Following the modification of the inlet flow rate, the outlet temperature in the U-shaped configuration now reaches 85.51°C. The reduction may reflect the trade-off between increased heat absorption efficiency and potential cooling effects induced by reduced fluid velocity. Tempa Rossa previously recorded an outlet temperature of 51.99°C in the U-shaped configuration, slightly outperforming the coaxial WBHE result of 48.20°C. After adjusting the flow rate, the outlet temperature now stands at 44.14°C. Gela 38 previously demonstrated an outlet temperature of 49.99°C in the U-shaped configuration, significantly better than the coaxial WBHE's 39.79°C. After modifying the flow rate, the outlet temperature now reaches 49.13°C.

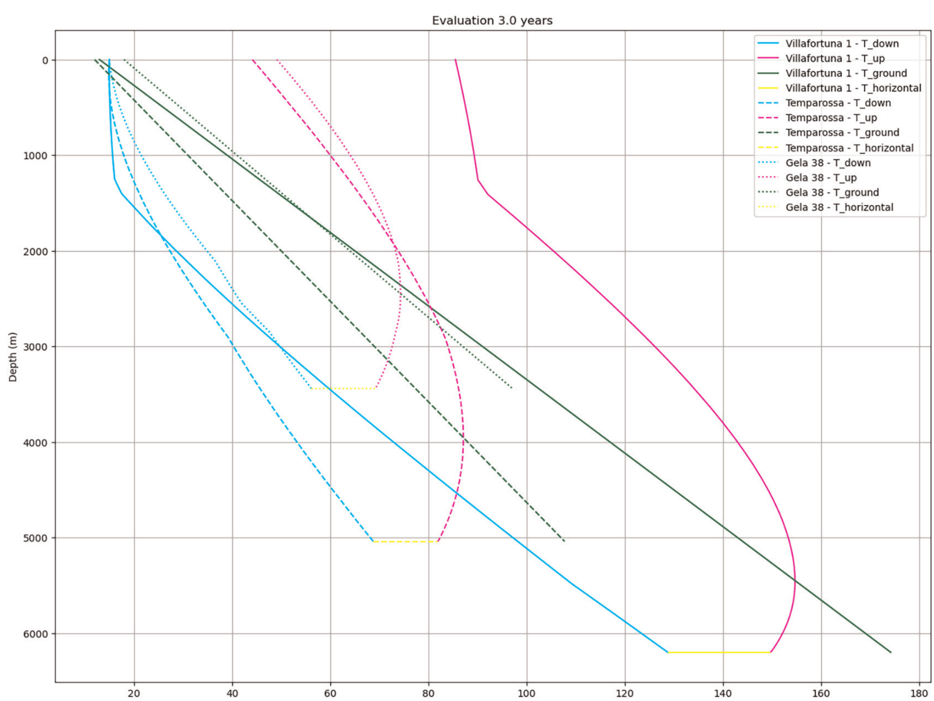

Figure 7.
Working fluid temperature distribution in the U-shaped WBHE flowrate: 1.5 kg/s).

7. Discussion

This study investigated the thermal performance of coaxial and U-shaped WBHEs in three hydrocarbon wells with distinct geological characteristics. The results demonstrated that site-specific geothermal properties, well depth, and exchanger design significantly influence heat exchange efficiency and the final outlet temperature of the working fluid. The geothermal gradient emerged as a primary factor affecting heat transfer performance. Villafortuna 1, characterised by the highest gradient among the three sites, exhibited the most substantial increase in outlet temperature in both configurations, confirming that greater geothermal energy availability enhances heat extraction. In contrast, Tempa Rossa showed more limited heat transfer efficiency, suggesting that the conductive properties of the surrounding formations play a crucial role in determining WBHE effectiveness. Gela 38, despite its relatively higher surface temperature, exhibited a lower increase in fluid temperature, indicating that the geothermal gradient at depth was insufficient to drive significant thermal gains. The comparison between coaxial and U-shaped WBHEs revealed that the U-shaped configuration consistently outperformed the coaxial system at all three sites. The key factors contributing to this enhanced performance include a larger heat exchange surface area, allowing for more significant thermal interaction between the fluid and the surrounding geological formations. The addition of a horizontal section at maximum depth, which extended the exposure time of the fluid to the highest temperature layers, increasing its thermal absorption capacity. The effectiveness of the horizontal section was particularly evident in Villafortuna 1 and Gela 38, where the increase in outlet temperature exceeded 9–10°C compared to the coaxial system. These results suggest that the horizontal section is most effective in sites with high geothermal energy availability, whereas its impact is reduced in lower-temperature environments. Additionally, the depth of the well was shown to influence overall heat exchange efficiency, as deeper wells generally resulted in higher outlet temperatures due to prolonged contact with heated geological layers. However, this effect was not linear, indicating that factors such as thermal conductivity, fluid properties, and flow dynamics contribute to overall system performance. Finally, the flow rate of the inlet working fluid played an important role in heat transfer efficiency in coaxial WBHEs. A critical factor to consider in the U-shaped WBHE configuration is the pronounced thermal dissipation effect along the fluid's upward path. This phenomenon becomes particularly relevant when fluid velocity is reduced, as the increased residence time in the riser pipe, which is exposed to the surrounding ground, can lead to significant heat loss. Such dissipation diminishes the system's overall efficiency and limits the benefits gained from reducing the inlet flow rate, especially in sites with moderate geothermal gradients or lower thermal conductivity in the surrounding formations. A fluid with a higher specific heat capacity absorbed and retained more thermal energy, while the viscosity of the fluid affected flow resistance and, consequently, overall thermal performance. Future research could further explore the optimisation of fluid properties to maximise energy extraction, particularly in low-enthalpy geothermal environments.

One crucial factor that was not explicitly addressed in this study is the impact of pressure drop on WBHE performance. Pressure losses can significantly influence fluid flow dynamics, heat exchange efficiency, and system energy consumption. This effect is particularly critical in U-shaped WBHE systems, where the extended horizontal section and longer fluid path increase the likelihood of pressure-related inefficiencies. Future research should integrate pressure drop analysis into WBHE performance models to better estimate real-world thermal outcomes and energy demands. Identifying optimal flow rates, enhancing insulation, and exploring alternative working fluids with lower viscosity may help mitigate pressure losses and improve overall system efficiency.

8. Conclusions

The findings of this study provide valuable insights for optimising WBHE systems, with practical implications for retrofitting hydrocarbon wells into geothermal energy recovery facilities. Besides, the simplified analytical approach and the associated model proposed serve as a useful methodological tool for the preliminary assessment of the feasibility of converting selected hydrocarbon wells into geothermal wells using WBHEs.

The results confirm that the geothermal gradient and well depth are the most critical factors influencing heat exchange performance, with higher gradients yielding more efficient heat extraction. The U-shaped WBHE configuration outperforms the coaxial system, demonstrating greater heat absorption due to an increased exchange surface and the introduction of a horizontal section at depth. The horizontal section at maximum depth significantly enhances heat transfer in high-gradient environments, whereas its contribution is less pronounced in low-temperature formations. However, factors such as pressure losses and working fluid properties require further investigation to ensure optimal performance under real-world operating conditions. Future studies should focus on exploring the role of different working fluids to maximise heat absorption and minimise losses due to viscosity, assessing the economic feasibility of retrofitting hydrocarbon wells, and considering cost-benefit analyses and energy recovery potential.

The results presented in this study are derived from the application of a mathematical model to case studies in which geological and thermal conditions were reconstructed. While these findings offer useful insights, their validation would benefit from future studies conducted on real sites, where the modelled heat exchanger geometries could be implemented and observed under operational conditions.

Author contributions

M.G., F.H., F.V., G.T., and S.L.R. formulated the research objectives and defined the methodological approach. M.G. and F.H. contributed to the identification of materials, the development of analytical tools, and the interpretation of results. The manuscript was written by M.G. All authors reviewed and approved the final version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

Notes

A version of the presented codes can be obtained upon request by contacting the corresponding author (martina.gizzi@polito.it).

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