Exergy Performance of a Wellbore Heat Exchanger Coupled With a ORC Plant: Comparison of Two Different Case Studies

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ABSTRACT

This paper analyses the use of a WBHX plant coupled with an ORC power plant in two different case studies: the depleted geopressurized oil field of Villafortuna Trecate and the magmatic area of Campi Flegrei. A comprehensive thermodynamic assessment of the WBHX – ORC plant has been carried out analysing each component, including the cooling tower and ancillary equipment. Different organic fluids have been tested in order to find the most advantageous in the two different cases. The concept of exergy, which is the maximum work output that could be obtained from a system, has been used to compare the performance of two case studies, assessing thermodynamic losses. Results show the relevance of the ancillary system in the assessment of system feasibility that may result in the actual limiting factor for geo-power production.

1. INTRODUCTION

Since 2000, several researches have been focused on the possibility to produce geothermal energy without brine extraction, using a deep borehole heat exchanger. The device, named WellBore Heat eXchanger by Nalla et al. (2005) is made by two coaxial tubes inserted into the well (Fig.1). This solution avoids costs and consequences related to the extraction, handling, and reinjection of geothermal fluids. The main weakness is the low heat transfer effectiveness and the high pumping work, with respect to the conventional geothermal wells. Anyway, the WellBore Heat eXchanger could represent an opportunity for the exploitation of unconventional geothermal systems, in which the brine is absent or it requests special treatment techniques.

The extracted heat can be used for the production of thermal power or electricity with an Organic Rankine Cycle plant (Alimonti and Soldo, 2018). Despite the deep borehole heat exchanger has been applied only in two abandoned wells in Switzerland (Kohl et al., 2002), the study of the performance of the WBHX is widely treated in literature, focusing the analysis on the operational parameters, design characteristics, thermal properties of the formation and the heat carrier fluid. The results indicate that the most influencing parameter of heat extraction is the residence time of the fluid in the device (Alimonti and Soldo, 2016), which is function of flow rate and diameters. The insulation of the internal pipe is necessary in order to avoid heat exchange losses (Kujawa et al., 2006; Wang et al., 2009). The temperature of the extracted fluid is directly proportional to the geothermal gradient, the thermal conductivity and the volumetric heat capacity of the ground (Bu et al., 2012; Templeton et al., 2014). Concerning the working fluid, two different solutions are available: a heat carrier fluid in the WBHX and a low boiling point fluid in the ORC plant, or a unique working fluid (iso-pentane, iso-butane, R134a and R245fa) for the coupled WBHX-ORC plant. According to the results the water is the most efficient heat carrier fluid in the WBHX.

The analysis of literature indicates that the deep borehole heat exchanger may produce a maximum wellhead temperature of 150 °C, the produced thermal power is in the range 0.15÷2.5 MW and the electricity in the range of 0.25÷364 kW.

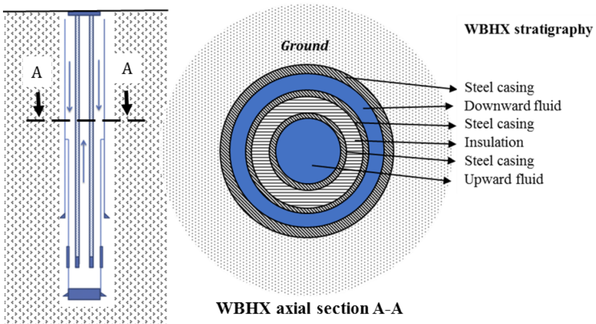

Figure 1: The WellBore Heat eXchanger.

The exergy, also called available work, is a measure of to the maximum work output that could theoretically be obtained from any system interacting with a given environment which is at constant pressure and temperature (Di Pippo 2004). The exergy analysis is useful to identify both maximum theoretical performances and the inefficiencies of a system and its components. About 50 papers are available in literature regarding the WBHX, but only two of them (Feng et al., 2015; Mokhtari et al., 2016) include a thermodynamic assessment of the ORC based on the energy and exergy balances: none of these studies accounts for the energy losses due to the cooling tower.

This paper analyses the use of a WBHX plant coupled with an ORC power plant in two different case studies: the depleted geopressurized oil field of Villafortuna Trecate and the magmatic area of Campi Flegrei. A comprehensive thermodynamic assessment of the WBHX+ORC plant has been carried out analyzing each component, including the cooling tower and ancillary equipment. Different organic fluids have been tested in order to find the most advantageous in the two different cases.

2. THE CASE STUDIES

In order to identify the most suitable condition for the application of the deep borehole heat exchanger, two different geothermal environments have been selected: a magmatic area with a very high geothermal gradient, and a geoppressurized reservoir.

2.1 Campi Flegrei

The Campi Flegrei area is a caldera of 12 km located in the N-W limit of the Napoli gulf, Italy (Fig. 2). The area is part of the Neapoletan volcanoes district, which includes also Ischia island and Somma-Vesuvius volcano.

Figure 2: Campi Flegrei caldera (Carlino et al., 2012).

The geothermal potential of the area has been studied with exploration campaigns and scientific researches. 117 wells have been drilled in the area (26 in Campi Flegrei) reaching the maximum depth of 3046 m. The investigations have demonstrated that fluids with high temperatures are present at relative shallow depths in the area of Campi Flegrei. A hot and saline geothermal system with a high geothermal gradient (100÷170 °C/km) is present in the subsoil of Campi Flegrei. A magmatic source seems to be located at the depth of 8-10 km, with a thickness of almost 1 km and a diameter equal to that of the caldera. At a depth greater than 3-4 km, the fluids circulate very slow and the heat is transferred due to conduction. In the shallower layers (0-2 km) an advective transport takes place, because of the high permeability due to the fracturing system.

The deep borehole heat exchanger has been applied in the area of the wells Mofete 1 (MF1), Mofete 3d (MF3d) and Mofete 2 (MF2). The thermo-physical properties of the area are calculated using the average values weighted on the thickness of the layer (λ = 2.5 $Wm^{-1}K^{-1}$; ρ = 1900 $kg \cdot m^{-3}$; cp = 1220 $Jkg^{-1}K^{-1}$). The average geothermal gradient is almost 150 °C/km (Fig. 3).

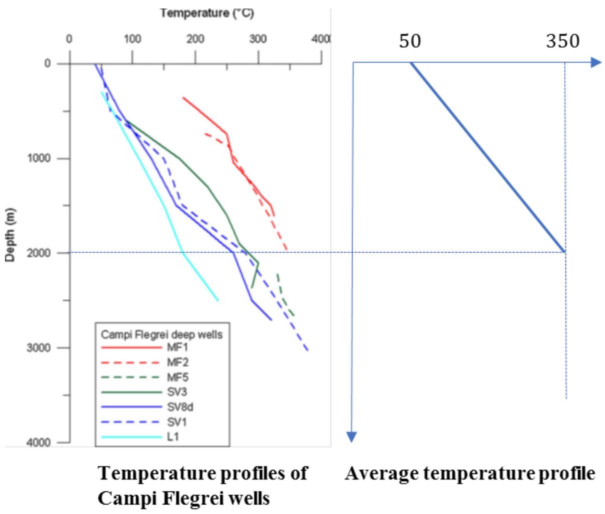

Figure 3: Temperature versus depth.

2.2 Villafortuna Trecate

The Villafortuna Trecate reservoir, one of the largest European oilfields active since 1984, has been selected as second case study. The site is located in the northern Italy (Fig. 4). The field is in a mature stage, several wells are always open and only few are producing with different water cuts.

Figure 4: Villafortuna Trecate oilfield.

The Villafortuna-Trecate field consists of an alpine compressional structure involving a pre-existing Mesozoic extensional relief. The petroleum system is wholly developed inside a Triassic depositional sequence: two reservoirs, made of dolomitized carbonate platforms rocks (Monte San Giorgio Dolomite, Anisian; Dolomia Principale, Campo dei Fiori Dolomite and Conchodon Dolomite, Norian-Rhaetian) and the source rock deposited in an anoxic intra-platform basins. The hydrocarbons were produced from Middle Triassic source rock formations (Besano Shales and Meride Limestone) which lie inside the Villafortuna-Trecate structure.

The oil field is connected with a large, active aquifer where a constant temperature and pressure is sustained. When fluids are extracted from the reservoir, water and heat will be replenished by such a boundary. There are two dolomite reservoirs in the oil bearing intervals – Conchodon and Monte San Giorgio. The geothermal system is characterized by a normal geothermal gradient of 2.5°C each 100 m depth (Fig.5). The main reservoir is at 5700-6100 m depth, the bottom-hole temperature is about 166 °C and the average static pressure is 850 bar (Alimonti and Gnoni, 2015). The properties of rocks are have been considered to be uniform with depth (λ = 2.5 $Wm^{-1}K^{-1}$; ρ = 2600 $kg\cdot m^{-3}$; cp = 800 $Jkg^{-1}K^{-1}$). The porosity of the field is extremely low, which is only 3-5 %. However, thanking to the naturally fractured network, a relatively high permeability of 600md exists in the Conchodon dolomite reservoir (Botto and Ghetto, 1994). Additionally, the fracturing network helps heat to be transferred into produced fluids by means of convection.

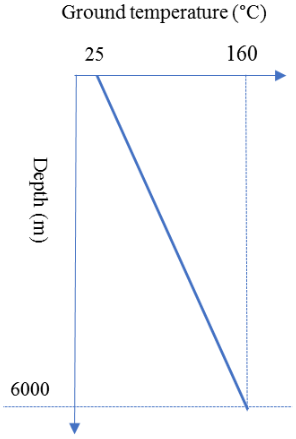

Figure 5: Villafortuna Trecate temperature profile.

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3. ENERGY AND EXERGY ANALYSIS

3.1 Methods

In this work, we refer to the reference WBHX – ORC system showed in Figure 6. We evaluated the energy and the exergy balances of each components according to the general Equation:

$$\dot{H}_{f,in} + \dot{Q} = \dot{H}_{f,out} + \dot{W} \quad [1]$$

where:

- $\dot{H}_f$ is the enthalpy of the fluid(s) entering/leaving the device, evaluated according to the reference state $h_{f,0}$, namely:

$$\dot{H}_f = \dot{m}_f h_f = \dot{m}_f (h_f - h_{f,0}) \quad [2]$$

- $\dot{Q}$ is the total thermal power(s) exchanged at the control surface of the device;
- $\dot{W}$ is the mechanical/electrical power transfer(s) at the control surface of the device (e.g. turbines, pumps, and fans).

The corresponding general exergy balance reads (Kotas, 1995):

$$\dot{Ex}_{f,in} + \dot{Ex}^{\dot{Q}} = \dot{Ex}_{f,out} + \dot{Ex}^{\dot{W}} + \dot{I} \quad [3]$$

where:

- $\dot{Ex}_{f,}$ is the physical exergy of the fluid(s) entering/leaving the device, evaluated according to the ambient state $(h_{f,a}, s_{f,a})$, namely:

$$\dot{Ex}_f = \dot{m}_f ex_f = \dot{m}_f [(h_f - h_{f,a}) - T_a (s_f - s_{f,a})] \quad [4]$$

- $\dot{Ex}^{\dot{Q}}$ is the exergy associated with the thermal power exchange(s) at the control surface of the device, namely:

$$\dot{Ex}^{\dot{Q}} = \int_A \dot{q} \left(\frac{T - T_a}{T}\right) dA \quad [5]$$

- $\dot{Ex}_{\dot{W}}$ is the exergy associated with a power transfer(s) at the control surface of the device. It exactly corresponds to the power transfer(s) $\dot{W}$.
- $\dot{I}$ is the exergy destruction associated with the irreversibly production rate.

The First-Law efficiency can be expressed by the ratio between the net work/power output and the inlet energy/power streams. In this work, we refer to the following expressions for direct or inverse energy conversion systems, respectively:

$$\eta^I = \frac{\dot{W}_{out} - \dot{W}_{in}}{\dot{H}_{f,in} - \dot{H}_{f,out}} \text{ or } \eta^I = \frac{\dot{H}_{f,in} - \dot{H}_{f,out}}{\dot{W}_{in}} \quad [6]$$

The Second-Law efficiency is the ratio between the actual exergy output (product) and the required exergy input (fuel). η^{II} does not have a unique expression, but it depends on the specific component to be analyzed. With reference to the purposes of this work, we refer to heat exchangers, power turbines, and pumps. The following expressions apply:

$$\eta_T^{II} = \frac{\dot{W}_{out}}{\dot{Ex}_{f,in} - \dot{Ex}_{f,out}} \quad \eta_P^{II} = \frac{\dot{Ex}_{f,in} - \dot{Ex}_{f,out}}{\dot{W}_{in}} \quad \eta_{HX}^{II} = \frac{\dot{Ex}_{f,out}}{\dot{Ex}_{f,in}} \quad [7]$$

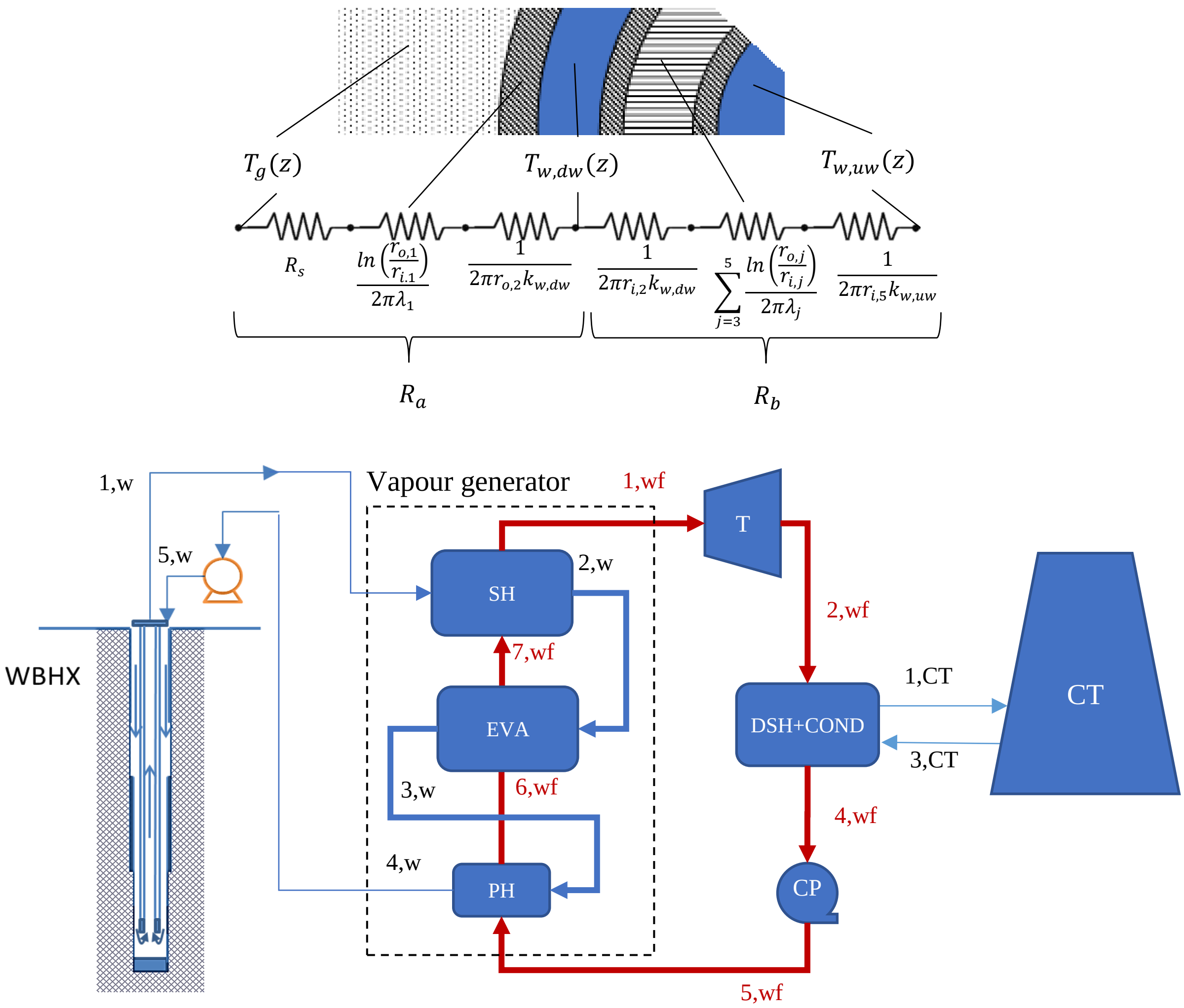


Figure 6 - Scheme of the analyzed WBHX – ORC system.

3.2 WBHX and geothermal source modeling

This section describes both the coaxial well and the ground source. The ground source is assumed as a purely-conductive medium with the thermo-physical properties reported in Section 2.1 and 2.2. The undisturbed thermal gradient is assumed as linear with the depth for both of the case studies.

The heat exchanged between the circulating fluid and the undisturbed ground is evaluated through the set of thermal resistances shown in Figure 6.

R_s is the transient thermal resistance between the external well casing surface and the undisturbed ground. It is evaluated through the model presented in Alimonti and Soldo (2016) and it accounts for the actual radius of thermal influence due to the undergoing heat extraction. It can be evaluated as:

$$R_s = \frac{1}{2\pi\lambda_s}\ln\left(\frac{2\sqrt{\alpha_s t}}{r_{o,1}}\right) \qquad [8]$$

In this work, we refer to the ground status after one year of continuous operation. This period corresponds to the time required to obtain an increase rate of the ground thermal resistance, R_s, lower than 10%/yr. In other words, after one year, the ground source can be practically assumed as stationary.

The conductive thermal resistance of the well strata is evaluated through the classical heat transfer theory for cylindrical geometries. $k_{w,dw}$ is the convection coefficient within the annulus. According to Lavine et al. (2011), for fully developed turbulent flow, the convection coefficient is approximately the same on the outer and inner surface. Both Nusselt and Reynolds numbers can be evaluated considering a hydraulic diameter of D_h. Finally, $k_{w,uw}$ is the convective coefficient in the upward pipe. In this work, we used the classical Dittus-Boelter equation to calculate all the convective coefficients (Lavine et al. 2011).

3.3 Dry cooling tower and evaluation of fans power

In this study, we refer to dry cooling towers using fin-tube heat exchangers with a staggered tube arrangement with a parallel flow configuration (see Fig. 7). The required heat transfer surface and the pressure losses (i.e. fans power) are respectively evaluated with Eqs. 8 and 9.

$$\Delta P_a = \xi \frac{L}{D_{a,ch}} \rho_a \frac{w_{a,m}^2}{2} \quad [8]$$

$$\dot{m}_{wCT}\left(h_{1,wCT} - h_{3,wCT}\right) = \dot{m}_a c_a \left(T_{a,out} - T_{a,in}\right) = (UA)_{tot} LMTD \quad [9]$$

The pressure drop coefficient, ξ, was evaluated according to the correlation presented in (Branislav et al., 2006). The overall heat transfer coefficient, $(UA)_{tot}$, was evaluated according to Eq. 9 for the air side (Frass et al., 2015), the classical Dittus-Boelter equation for turbulent flow (Lavine et al. 2011) for the convective heat transfer coefficient within the ducts (water side), and the fin-efficiency model presented in proposed in (Hong and Webb, 1996) for the hexagonal geometry of staggered tube configurations.

$$Nu_a = 0.25 Re_{D_{a,ch}}^{0.625} Pr_a^{1/3} \left(\frac{D_{a,ch}}{t_l}\right)^{1/3}$$

The geometry of the dry cooling tower (i.e. the width, depth, height, number of rows, and fins spacing) was optimized to minimize the fan power at the given heat flow rate at the condenser unit (Eq. 9).

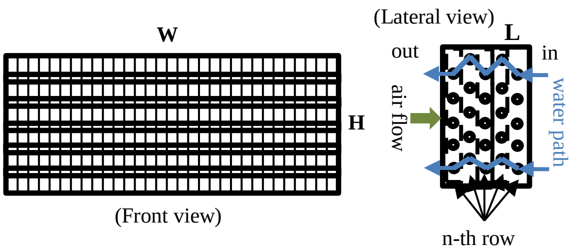


Figure 7: Front and lateral view of the fin-tube heat exchanger.

3.4 Campi Flegrei results

The overall WBHX – ORC system shown in Fig. 6 was optimized in terms of working fluid and operative parameters. Specifically, we investigated the performance of Isobutane, Isopentane, R134a, R410a, and RC318 in terms of net power output. The corresponding optimal operative parameters and thermodynamic cycle are shown in Table 1 and Fig. 9, respectively. For the Campi Flegrei case, Isobutane was found to be the operating fluid. The Fig. 8 illustrates the temperature profiles along the downward and upward duct of the WBHX and the temperature profile of the ground.

The energy and exergy balance of all subsystems and overall system are evaluated to calculate irreversibilities, First-Law (energy) and Second-Law (exergy) efficiency. The resulting energy and exergy indexes of performance are shown in Table 2. The results for Campi Flegrei case study indicate a good performance of the ORC cycle, similar to those of classical binary geothermal power plants, directly using geothermal brine (DiPippo 2012). The First-Law efficiency is equal to 11.7% and the Second-Law efficiency is about 43.6%. These values respectively decrease to 10.2% and 22.42% if we account for the overall system.

With reference to energy performances, cooling fans represents the main ancillary energy requirement, lowering the power output from 58.38 kW (net output of the ORC) to 53.26. In other words, the cooling system lowers the energy efficiency of the system of about 10%. However, this value represents an intrinsic thermal loss of the energy conversion cycle and depends on air temperature and heat transfer effectiveness of the cooling apparatus. The latter parameter has been optimized in terms of coils geometry and does not show relevant room for improvement. Indeed, its value is relatively low if compared with the classical energy expenditure for the cooling of binary power plant, i.e. 10 – 30 % of turbine output (Franco and Villani 2009).

The exergy analysis provides more information about the inefficiencies of the energy extraction and conversion. With reference to Fig. 10, we note that the ORC desuperheater/condenser causes about 36 % of the total irreversibilities. A possible solution is the introduction of a regenerative heat exchanger between the desupereating and the preheating section, downstream the turbine. However, this solution would increase the complexity and the cost of the plant. Its viability should thus be investigated through a tailored cost-benefit analysis. The electromechanical efficiencies of the components (i.e. the technology level) account for the 11% of the ORC irreversibilities. Again, the improvement of the ancillary systems does not seem the most advantageous strategy in terms of cost-benefit ratio.

Fig. 11 shows the irreversevilities of the overall WBHX – ORC system. We note that the main share of the exergy losses occurs in the borehole – ground system. As shown in Fig. 8, this exergy destruction can be ascribed to the thermal short-circuit between the downward and upward duct, but mainly to the effective thermal resistance between the circulating fluid and the undisturbed ground, R_s, that increases the temperature drop required to transfer the heat from the ground source to the fluid.

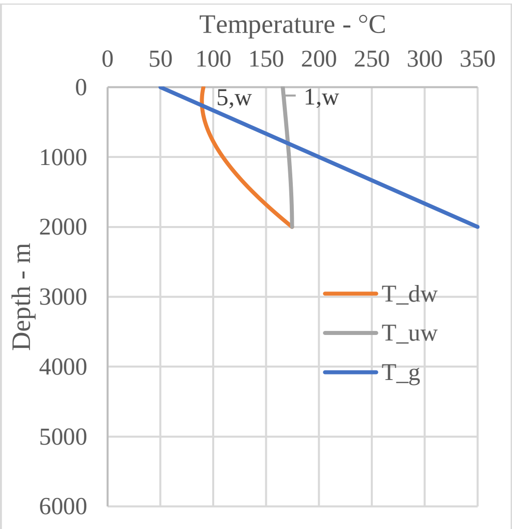
Considering that R_s is inversely proportional to the thermal conductivity of the rock and increases with the time of exploitation of the source (see Eq. 8), we see two possible improvement actions: the first consists of increasing the equivalent conductivity of the source by fracturing the rock and filling the breaks with an high conductivity material, as proposed by (Taleghani et al., 2015). Nevertheless, the authors advise against the use of fracturing techniques in Campi Flegrei region, characterized by a very high urbanization, where the social response to soil stimulation methods will be probably negative. This means that enhancement techniques of the geothermal reservoir are poorly employable in the area. A more suitable solution consists of reducing the equivalent thermal radius of the well, namely the ground region affected by the heat transfer. Under equal operating conditions, a possible improvement strategy would consist of different heat extraction profiles through the control of the flow rate over the plant lifetime. A reduced thermal radius would lead to a more sustainable and efficient operation of the WBHX and higher efficiency of the overall system.

Table 1 – Operating parameters of WBHX and ORC.

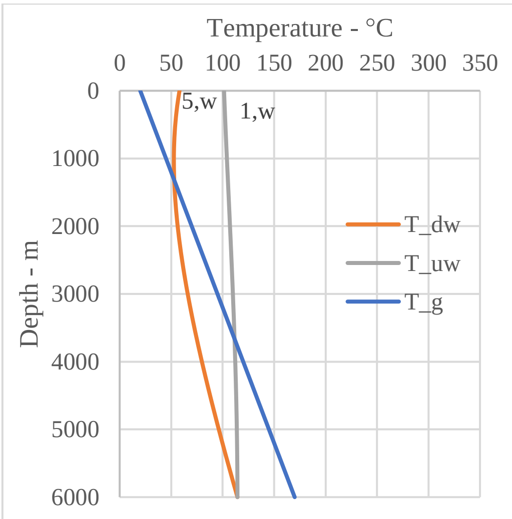
EQUIPMENT	PARAMETER	UNIT	CAMPI FLEGREI	TRECATE
WBHX	Circulating fluid		Water	Water
	Flow rate, $\dot{m}_{f,w}$	m^3/h	6	8 m^3/h
	Inlet pressure, $p_{5,w}$	MPa	2.0	2.0
	R_s(after one year of operation)	mK/W	0.31	0.32
	R_a	mK/W	0.32	0.33
	R_b	mK/W	1.90	1.90
ORC Cycle	Working fluid		2-methylpropane (Isobutane)	R410a
Vapour Generator: Pre-heater, Evaporator, Super-heater	Pressure	MPa	3.0	4.1
	Saturation temperature	°C	123.29	63.34 / 63.42
	Pinch point	K	5	5
Power Turbine	Isentropic efficiency, η_T		0.85	0.85
	Electro-mechanical efficacy, η_e		0.95	0.95
Condenser	Condensing pressure	MPa	0.55	2.5
	Saturation temperature	°C	41.33	41.25
	Pinch point	K	5	5
Circulation pump	Electrical-mechanical efficiency, $\eta_{T,em}$		0.6	0.6

Table 2: Performance indexes of the WBHX – ORC system.

Performance Index	Campi Flegrei	Trecate
First-Law efficiency of the ORC	11.67%	4.52%
First-Law efficiency of the overall system (including WBHX and cooling towers)	10.25%	2.96%
Second-Law efficiency of the ORC	43.60%	26.85%
Second-Law efficiency of the overall system (including WBHX and cooling towers)	22.42 %	9.27%
WBHX capacity	501.75 kW_{th}	393.39 kW_{th}
Net power output of the ORC, $\dot{W}_{ORC}$	58.38 kW_e	17.70 kW_e
Net power output of the overall system, $\dot{W}_{sys}$	51.28 kW_e	11.59 kW_e

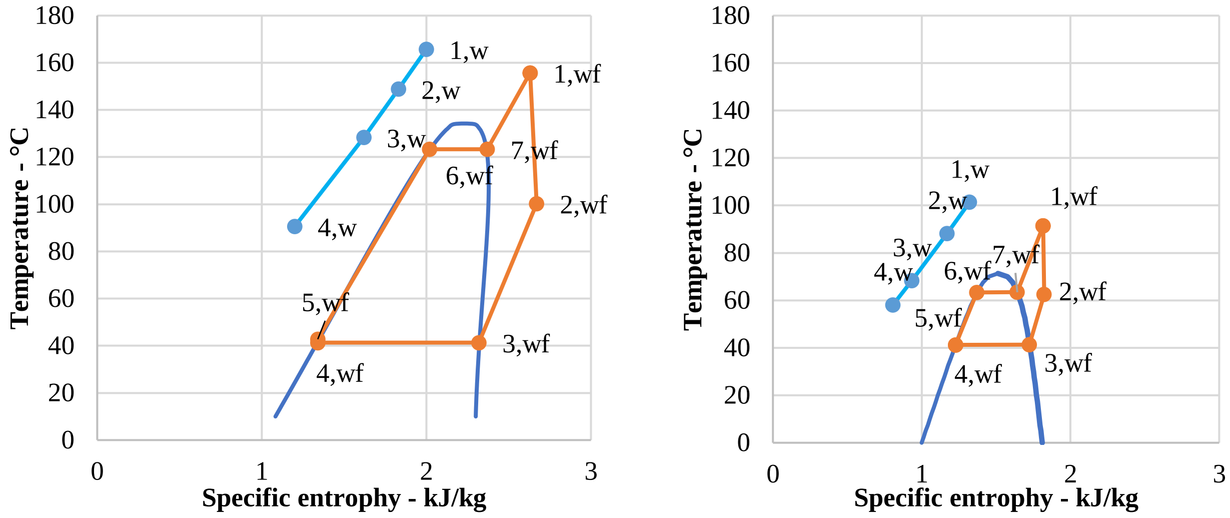


(Campi Flegrei)



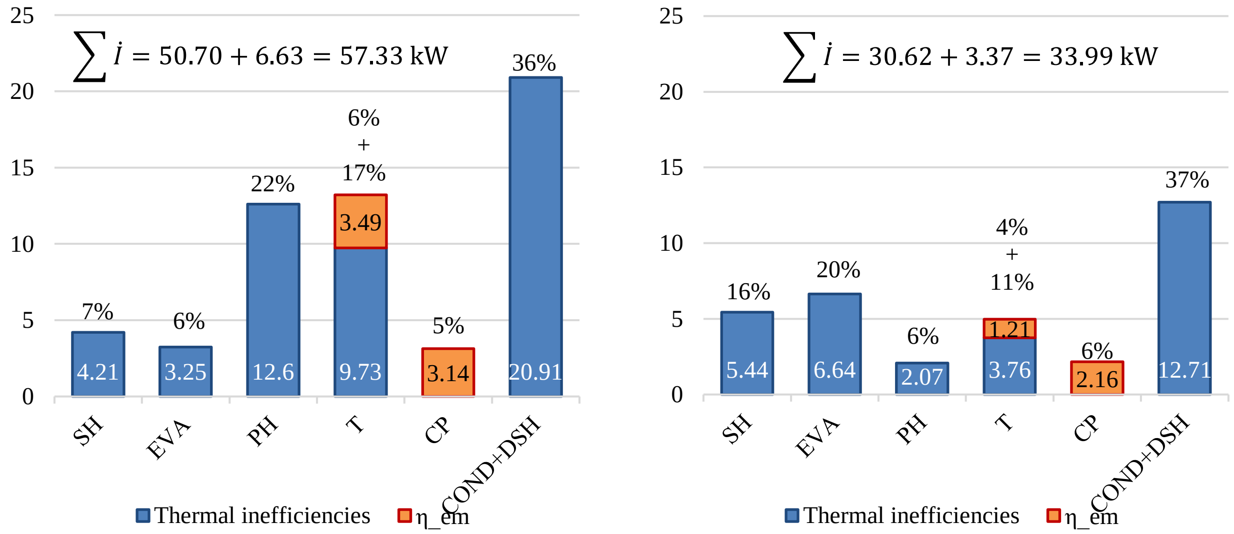
(Villafortuna-Trecate)

Figure 8 – Temperature profiles along the WBHX.



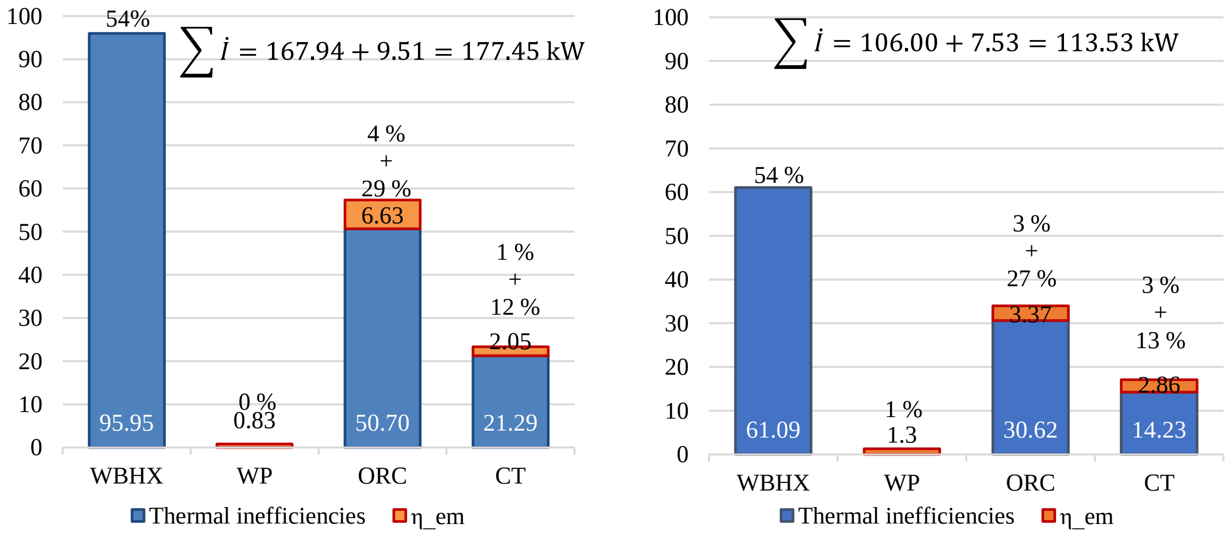
(Campi Flegrei) (Villafortuna-Trecate)

Figure 9 – Thermodynamic ORCs on the TS chart.



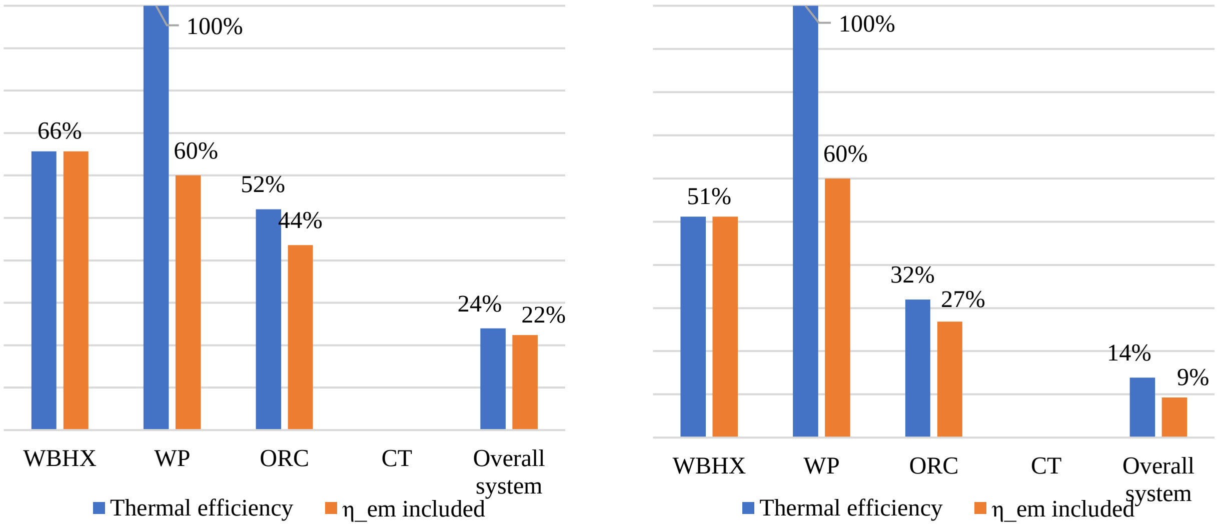
(Campi Flegrei) (Villafortuna-Trecate)

Figure 10. Irreversibility production rate for each ORC component.



(Campi Flegrei) (Villafortuna-Trecate)

Figure 11. Irreversibility production rate for the WBHX – ORC subsystems.



(Campi Flegrei) *(Villafortuna-Trecate)*

Figure 12. Second-Law efficiency values for the main components of the overall system

3.1 Villafortuna Trecate results

As for the Campi Flegrei case study, the overall WBHX – ORC system shown in Fig. 6 was optimized also in the case of Villafortuna Trecate. We investigated the performance of the same working fluid (i.e., Isobutane, Isopentane, R134a, R410a, and RC318) in terms of net power output. For the Villafortuna Trecate case, R410a was found to be the best fluid. The corresponding optimal operative parameters and thermodynamic cycle are shown in Table 1 and Fig. 9, respectively. Fig. 8 shows the temperature profiles of the WBHX.

Villafortuna Trecate has a very different geothermal context with respect to Campi Flegrei. Though the well is three times deeper, the low temperature gradient limits the temperature that can be obtained at the well head with a negative effect on the power production. Moreover, the ancillary systems require a greater share of the turbine output, even in the optimized configuration. The 6 km depth of the bore corresponds to a total of 12 km path for the fluid. The related pumping power is a limiting factor for the thermal power to be extracted by the WBHX and subsequently for the power generation. Indeed, the pumping power increase to the power of three with the well flow rate, while the ORC power output increase with a lower rate.

Fig 13 shows a sensitivity analysis of the system performances depending on the well flow rate. We note that both WBHX capacity and ORC net output would benefit from higher flow rates, as the heat extracted from the ground and power generation would increase. However, we also note the reduction of the wellhead temperature that results in lower efficiencies and, even more, rise of pumping energy. For value higher than 8 m^3 / h the ORC production is not sufficient to compensate the losses in terms of efficiency and ancillary systems, thus the overall performance decreases. In the optimal configuration (i.e., $\dot{m}_{f,w} = 8\ m^3/h$), more than 18% of the net ORC output is used to run the well pump (3.5 kW). The cooling system requires about 3 kW, reducing the net output or another 16 %. Shortly, the ancillary systems use about 35% of the already-low ORC output (17.7 kW_{el}).

The exergy analysis of the ORC cycle leads to considerations similar to the case of Campi Flegrei. In the ORC, the great share of the irreversibility production is due to the desuperheating-condenser device (~ 36%). However, as for Campi Flegrei, a regenerative heat exchanger is expected to be not feasible in a such small system. Moreover, also the improvement of the electromechanical components does not seem cost-beneficial as the elctromechanical efficiencies only account for ~ 10 % of the total irreversibility production.

Regarding the overall system, the analysis of the irreversibility production rates (Fig. 11) reveals that the WBHX is the main source of exergy destruction also in the Villafortuna-Trecate case. The exergy efficiency of the WBHX is lower than the corresponding value of Campi Flegrei (51% vs 66%). This lower value cannot be ascribed only to the heat exchange with the ground, as the two R_s values are practically the same. The greater depth increases the relevance of friction losses and thermal short-circuit between the upward and downward ducts (see Fig. 8). Since the pumping losses related to the depth of the well, a possible improvement would consist of increasing the thermal insulation between the two pipes, thus increasing the temperature at the wellhead.

In any case, the power production in Villafortuna-Trecate context does not seem viable through a WBHX – ORC technology. The heat extracted via the WBHX may be used for direct applications, like district heating plant. This solution increases the lifetime of existing fields, avoiding costs and impacts related to drilling operations of new geothermal wells.

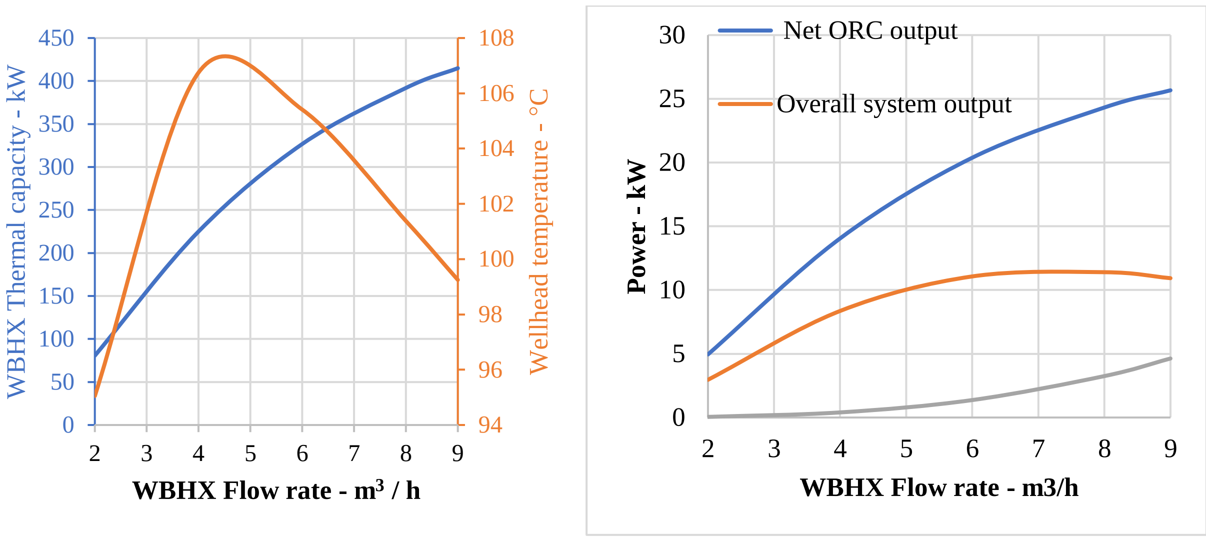


Figure 13. Operative parameters of the WBHX – ORC system as a function of the well flow rate (Villafortuna-Trecate)

3. CONCLUSIONS

The feasibility of the application of the WBHX has been demonstrated by several authors. With respect to previous works on the same subject, in this paper a comprehensive thermodynamic analysis of a possible WBHX - ORC power plant has been carried out, accounting for all system components (i.e., the ground source, the WBHX, the ORC cycle, and the cooling system). The target is to assess the real potential of the technology and to investigate the suitability of two geothermal contexts for the application of the WBHX – ORC system. Two Italian case studies, with a completely different geothermal asset, have been analysed: Campi Flegrei and Villafortuna-Trecate. The first one is part of the volcanic district of Campania region (Italy) and it is characterized by a very high geothermal gradient. Villafortuna Trecate is a depleted oil field located in the North Italy, it is characterized by a great depth and by a normal geothermal gradient.

For each case study, the state points of all subsystems have been calculated, as well as the energy and exergy performance indexes of each subsystems and the overall net power, First-Law efficiency, Second-law efficiency, and irreversibilities. The cooling tower design, the ORC operational flow rates and pressures have been optimized in order to maximize the net power output of the system, reducing the ancillary energy demand.

The results for Campi Flegrei case study indicate a good performance of the ORC cycle, similar to those of classical binary geothermal power plants, directly using geothermal brine. Instead, the low temperature gradient of Villafortuna-Trecate limits the temperature that can be obtained at the well head, with a negative effect on the power production. Moreover, the ancillary systems require a greater share of the turbine output, even in the optimized configuration. The overall analysis of the two case studies indicate that the cooling system has a strong impact on the energy efficiency of the system. However, this value represents an intrinsic thermal loss of the energy conversion cycle and depends on air temperature and heat transfer effectiveness of the cooling apparatus. Even following an optimized design, it is very hard to obtain a fans energy consumption lower than 15 % of the turbine output.

The exergy analysis of the ORC cycle highlights that the desuperheater/condenser is responsible for the main percentage of the total irreversibilities for both of the case studies. Regarding the overall WBHX – ORC system, the main share of the exergy losses occurs in the borehole – ground system due to the thermal short-circuit between the downward and upward duct, but mainly to the effective thermal resistance between the circulating fluid and the undisturbed ground.

We can conclude that the production of electricity with a deep borehole heat exchanger could be suitable only in a geothermal environment with very high bottom-hole temperature (>300 °C) at relative shallow depth. In this geothermal context, the use of a variable heat extraction strategy over the plant lifetime, may be a possible improvement strategy: in other words, the control of the flow rate and heat extraction would reduce the effective thermal resistance of the WBHX, leading to a more sustainable and efficient operation of the WBHX. The results of the analysis in case of normal geothermal gradient and very deep well (>3000 m), like depleted oilfield, discourage the use of WBHX for electrical power production, but it could be an interesting opportunity to produce thermal energy avoiding the cost and the environmental impacts of drilling new wells.

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NOMENCLATURE

c	specific heat capacity	[J/kg K]
D_h	hydraulic diameter	[m]
$\dot{ex}$	specific exergy	[kJ/kg]
$\dot{Ex}$	exergy rate	[W]
H	enthalpy	[W]
h	specific enthalpy	[kJ/kg]
$\dot{I}$	exergy destruction	[W]
L	total length of the well	[m]
$\dot{m}$	mass flow rate	[kg/s]
P	power output	[W]
p	pressure	[bar, MPa]
$\dot{Q}$	total thermal power	[W]
$\dot{q}$	heat flux	[W/m^2]
ρ	density	[kg/m^3]
R	thermal resistance	[mK/W]
r	radius	[mm]
s	specific entropy	[kJ/kgK]
T	temperature	[K or °C]

t	time	[s]
u	velocity	[m/s]
$\dot{W}$	mechanic. /electric. power	[W]

GREEK SYMBOLS

α	thermal diffusivity	[m^2/s]
η	efficiency	
λ	thermal conductivity	[W/m K]
ξ	friction factor	
ρ	density	[kg/m^3]

SUBSCRIPTS, SUPERSCRIPTS

a	ambient state
CP	circulation pump
CT	cooling tower
DSH	desuperheater
COND	condenser
dw	downward
el	electrical
em	electrical-mechanical
EVA	evaporator
f	fluid
HX	heat-exchanger
I	first-law
II	second-law
i	inner
in	inlet
o	outer
ORC	organic ranking cycle
out	outlet
P	pump
PH	preheater
s	soil property
SH	superheater
sys	overall system
T	turbine
up	upward
w	water
wCT	water in the cooling tower
wf	working fluid
WBHX	WellBore Heat eXchanger
WP	WBHX pump
0	reference state