INFLUENCE OF THE HEAT-SOURCE COST ON GEOTHERMAL ORCS

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ABSTRACT

The influence of the cost of the heat source on the performance and configuration of the economically optimal ORC is investigated in this work. This optimal ORC is obtained by performing a system optimization, in which the most important components (heat exchangers, cooling system and turbine) are optimized together with the configuration of the cycle. Minimization of the LCOE (Levelized Cost of Electricity) is chosen as the objective function.

As a result, the LCOE for both water and air-cooled ORCs is given as a function of the heat-source cost and heat-source-wellhead temperature. With these data, an estimation of the LCOE of a geothermal project can be made, based on the depth of the wells and the expected wellhead temperature. By comparing the obtained LCOE with expected electricity prices, the profitability of the project can be estimated.

1. INTRODUCTION

Low-temperature geothermal heat sources are widely available (Tester et al., 2006; IEA, 2011), but the heat-to-electricity conversion efficiency is very low due to the low temperature of the heat source. In many regions in the world, the geothermal heat sources do not manifest at the surface, but drilling of wells is necessary. These wells are often very expensive due to the relative high drilling depth.

In this paper, the combined influence of the drilling costs of the heat source and the temperature of the heat source is investigated. Contour maps of the LCOE (Levelized Cost of Electricity) of economically optimal ORCs are calculated as a function of these two parameters. This LCOE is the fixed electricity price needed to obtain break even at the end of the project. Also the influence of these parameters on the design and performance of the power plants is investigated.

A system optimization is performed, so that the configuration of the main components (heat exchangers, turbine and cooling system) are optimized together with the configuration of the cycle itself. The results in this paper are calculated with a previously developed code and the details of the modeling can be found in Walraven et al. (2015b).

2. MODEL

2.1 ORC

Organic Rankine cycles (ORCs) with different configurations (recuperated, subcritical or transcritical) are modeled in this paper, of which the scheme is given in figure 1. All the possible heat exchangers (economizer, evaporator, superheater and recuperator) are shown, but they are not always necessary. Air-cooled condensers (ACC) or wet cooling towers (WCT) connected to a condenser, and if necessary a desuperheater, can be used for cooling.

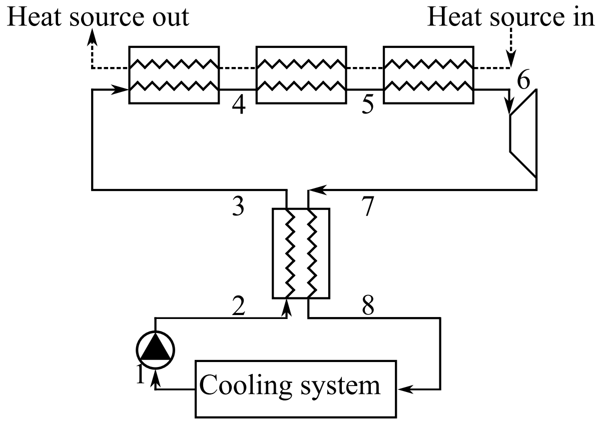


Figure 1: Scheme of a single-pressure, recuperated ORC.

It is assumed that state 1 is saturated liquid and that the isentropic efficiency of the pump is 80%. More information about the modeling of the cycle can be found in Walraven et al. (2013). An axial-inflow, axial-outflow turbine is modeled, based on the results of Macchi and Perdichizzi (1981).

2.2 Shell-and-tube heat exchangers

Figure 2 shows a TEMA E shell-and-tube heat exchanger with its basic geometrical characteristics, which is the only type of heat exchanger used in this paper. The geometrical characteristics are the shell outside diameter D_s, the outside diameter of a tube d_o, the pitch between the tubes p_t, the baffle cut length l_c and the baffle spacing at the inlet $L_{b,i}$, outlet $L_{b,o}$ and the center $L_{b,c}$. More information about the modeling of the heat exchangers can be found in Walraven et al. (2014).

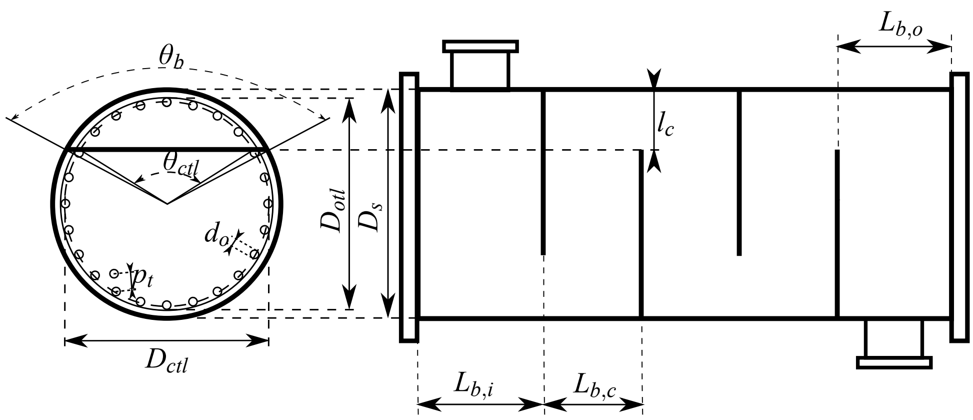


Figure 2: Shell-and-tube geometrical characteristics. Figure adapted from Shah and Sekulić (2003). See also Walraven et al. (2014).

2.3 Cooling system

Figure 3 shows the geometry of the air-cooled condenser (ACC) modeled in this paper. The tube-bundle geometry is determined by the tubes' small width W_s, the fin height H, the fin pitch S, the tubes' large width W_l and the length of the tubes L_t. In an A-frame ACC the tube bundles are placed at an angle θ with the horizontal. More information about the modeling can be found in Walraven et al. (2015a).

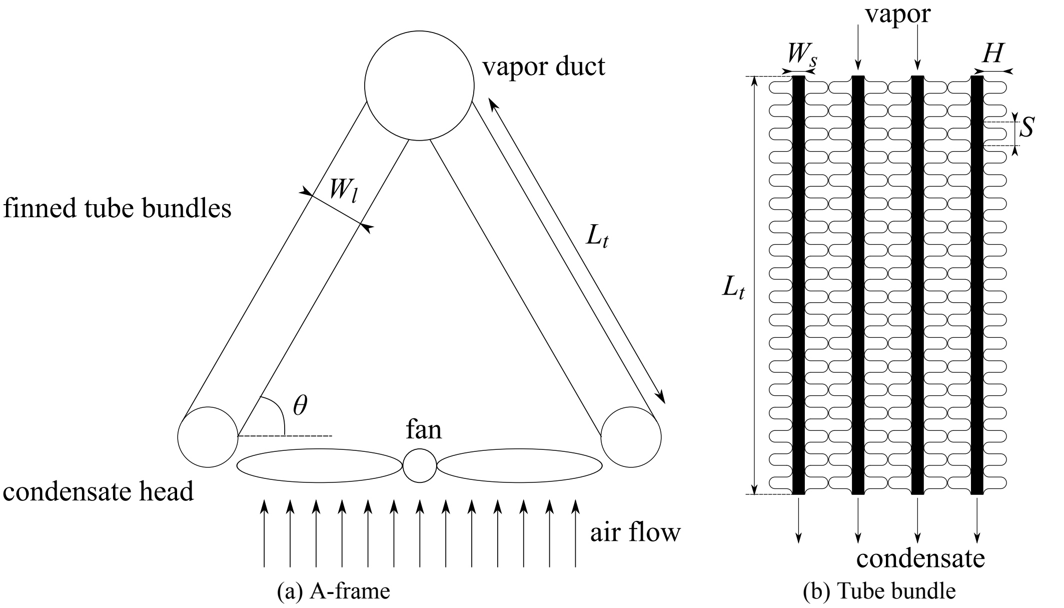


Figure 3: Geometry of an A-frame air-cooled condenser (a) and the bundle geometry of flat tubes with corrugated fins (b).

Another cooling option is the use of a wet cooling tower (WCT) connected to a condenser and, if necessary, a desuperheater. A mechanical-draft wet cooling tower is shown in figure 4. The height of the inlet H_i, the height of the fill H_{fi}, the height of the spray zone H_{sp} and the width of the tower W_t are shown in the figure. The reader is referred to Walraven et al. (2015b) for more information.

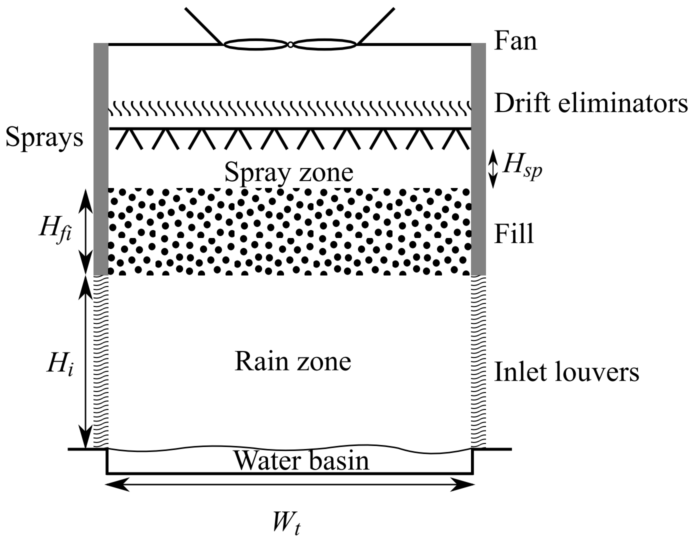


Figure 4: Geometry of an induced mechanical-draft wet cooling tower. Figure adapted from Kloppers (2003).

3. OPTIMIZATION

A *system* optimization is performed by optimizing the cycle parameters and the configuration of all the components together. The software packages CasADi (Andersson et al., 2012) and WORHP (Büskens and Wassel, 2013) are used for the optimization. The models themselves are developed in Python and the fluid properties are obtained from REFPROP (Lemmon et al., 2007).

3.1 Objective function

The objective of the optimization is to minimize the levelized cost of electricity (LCOE). This LCOE is the constant electricity price needed during the lifetime of the power plant to reach break even over the lifetime of the project. The LCOE is calculated in €/MWh$_e$ as (D'haeseleer, 2013)

$$\text{LCOE} = \frac{C_{EPC} + \sum_{t=1}^{t_{LT}} \left[\left(C_{O\&M,t} + C_{water,t} \right) (1+i)^{-t} \right]}{\sum_{t=1}^{t_{LT}} \dot{W}_{net}\, N\, (1+i)^{-t}}, \tag{1}$$

with C_{EPC} the engineering, procurement & construction overnight cost (EPC) of the installation, t_{LT} the lifetime of the installation, $C_{O\&M,t}$ the operations and maintenance cost in year t which is assumed to be 2.5% of the investment cost of the ORC per year (IEA, 2011), $C_{water,t}$ the water cost in year t, $\dot{W}_{net}$ the net electric power output, which takes an electric generator efficiency of 98% into account, expressed in MW$_e$, N the number of full-load hours per year (an availability of 95% is assumed) and i the discount rate. The EPC cost consists of two parts: the cost of the drilling $C_{drilling}$ and the cost of the ORC C_{ORC}. More information about the cost of the ORC can be found in Walraven et al. (2015b).

3.2 Optimization variables

The optimization variables of a single-pressure, recuperated cycle are the temperature before the turbine, the saturation temperature at the pressure before the turbine, the pressure at the inlet of the pump, the mass flow of the working fluid and the effectiveness of the recuperator (Walraven et al., 2013).

The optimization variables of each shell-and-tube heat exchanger are the shell diameter D_s, tube-outside diameter d_o, tube pitch p_t, baffle cut l_c and the distance between the baffles $L_{b,c}$ (Walraven et al., 2014).

The fin height H, the fin pitch S, the air velocity at the minimum cross section V_{Amin} and the number of tubes n_{tubes} are the optimization variables of the ACC and a non-linear constraint is used to limit the length of the tubes, as done in Walraven et al. (2015a).

The tower width W_t, the inlet height H_i, the relative mass flow of air $\dot{m}_{air}/\dot{m}_{brine}$, the relative cooling-fluid mass flow $\dot{m}_{cf}/\dot{m}_{brine}$ and the minimum cooling-fluid temperature T_{cf}^{min} are the optimization variables of the WCT, as explained in Walraven et al. (2015b).

4. RESULTS AND DISCUSSION

4.1 Reference parameters

The parameters of our "reference" case are given in Table 1, which are based on a proposed geothermal demonstration project in Belgium. In the next subsections, the influence of the well costs and the brine-wellhead temperature on the performance of the ORC is investigated. For each of the parameter variations, a new design optimization is performed with the optimization variables described in Section 3.2 to obtain the minimum LCOE.

4.2 LCOE

In this subsection, the optimal LCOE is given as a function of the brine-inlet temperature and the cost of the wells. They are varied between 100° - 150°C and between 0 - 50 M€, respectively.

Figure 5a shows the LCOE for air-cooled ORCs. As expected, does the LCOE increase for an increasing cost of the wells and a decreasing heat-source-inlet temperature. For the current electricity price of about

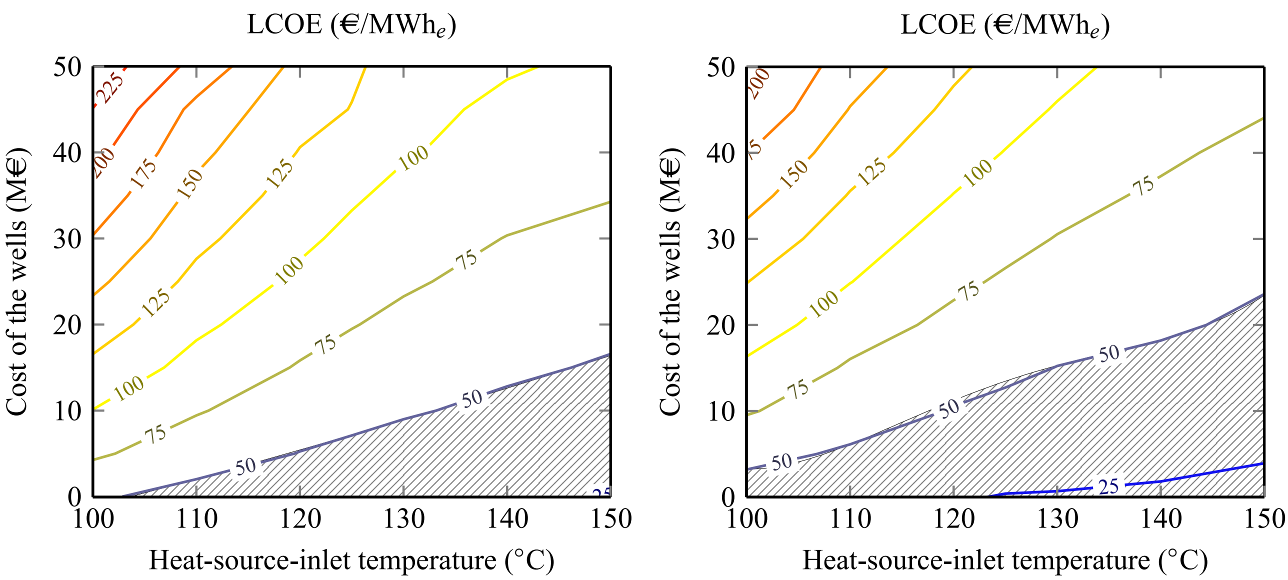
Table 1: Parameters of the reference case

Well parameters	
Brine-wellhead temperature	125°C
Brine production	194 kg/s
Well-pumps consumption	600 kW_e
Wells cost	27.5 M€

Economic parameters	
Lifetime plant	30 years
Discount rate	4 %/year
Water price	0.5 €/m^3

Environmental conditions	
Dry-bulb temperature	10.3°C
Wet-bulb temperature	8.6°C
Air pressure	1016 hPa

50 €/MWh_e, only a small part of the investigated temperature-cost range is economically interesting for the investigated reference parameters (Table 1). This "profitable" area is hatched in figure 5. For low heat-source-inlet temperatures, the distance between the LCOE contour lines as a function of the cost of the wells is very low. This is due to the low efficiency of the optimal ORCs for low temperatures.



(a) Air-cooled

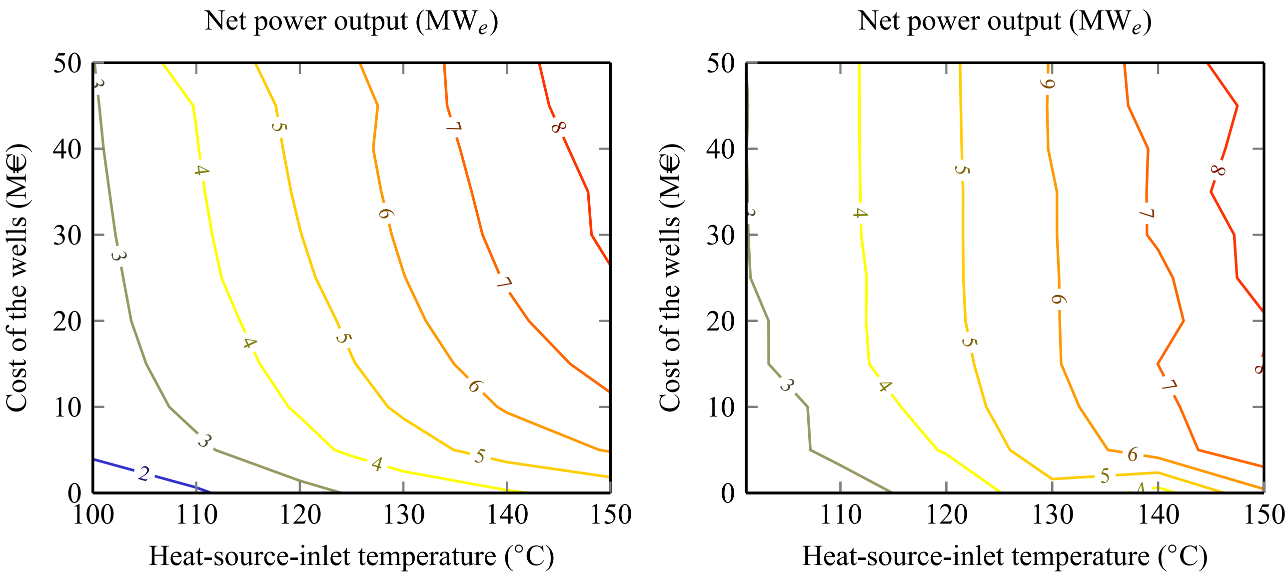
(b) Water-cooled

Figure 5: LCOE for air-cooled ORCs (a) and water-cooled ORCs (b) as a function of the heat-source-inlet temperature and the cost of the wells. The hatched area shows the region where the LCOE is lower than the assumed current electricity price of 50 €/MWh_e.

Figure 5b shows the LCOE for water-cooled ORCs. Comparison with Figure 5a shows that the LCOE for water-cooled ORCs is lower than the one for air-cooled ORCs, for the same heat-source-inlet temperature and cost of the wells. So, for the chosen reference parameters, it is better to select water cooling than air cooling.

4.3 Net power output and cost ORC

Figures 6a and 6b give contour lines of the net power output of air and water-cooled ORCs, respectively, as a function of the heat-source-inlet temperature and the cost of the wells. The net power output increases with increasing temperature and with increasing cost of the wells. The former evolution is the consequence of the increasing cycle efficiency with increasing temperature (Carnot). The latter evolution



(a) Air-cooled

(b) Water-cooled

Figure 6: Net power output for air-cooled ORCs (a) and water-cooled ORCs (b) as a function of the heat-source-inlet temperature and the cost of the wells.

is harder to explain. When the cost of the wells $C_{drilling}$ increases, the numerator in equation (1) increases. For an unchanged plant configuration, the LCOE would increase too. The only way to counteract this increase, is by trying to improve the net electric power of the cycle (denominator in equation (1)). This increase of the cycle efficiency can typically be done by decreasing the pinch-point-temperature differences and decreasing the condenser temperature. The consequence of these adaptations is of course that the cost of the ORC C_{ORC} will increase too. For higher well costs, a new optimum is found: the ORC generates more electric power, but also costs more.

Table 2 gives some results of the optimal configurations obtained for air-cooled ORCs at a wellhead temperature of 125°C and for different well costs. From this data, it is clearly seen that the cycle efficiency increases from 7 to almost 10% when the well costs increase from 0 to 50 M€. This is a consequence of the decreasing pinch-point-temperature difference (8 to 4°C) and the decreasing condenser temperature (42 to 28°C).

Well cost (M€)	0	10	30	50
Energetic cycle efficiency (%)	7.3	8.4	9.4	9.6
Pinch-point-temperature-difference in evaporator (°)	7.6	4.7	3.8	3.7
Condenser temperature (°)	41.7	34.4	28.7	27.7
Net electric power output (MW_e)	3.1	4.6	5.7	5.9
Brine-outlet temperature (°C)	73.3	57.3	49.8	48.9
Exergetic plant efficiency (%)	20.6	31.1	38.4	39.5
Cost ORC (M€)	10.2	17.0	26.0	28.2
Specific cost ORC (€/kW_e)	3326	3668	4539	4773
Total project cost (M€)	10.2	27.0	66.0	78.2
Specific cost total project (€/kW_e)	3326	5820	11 521	13 243
Cost ORC/total project cost (%)	100.0	63.0	39.4	36.0
LCOE (€/MWh_e)	32.2	56.4	94.4	128.3

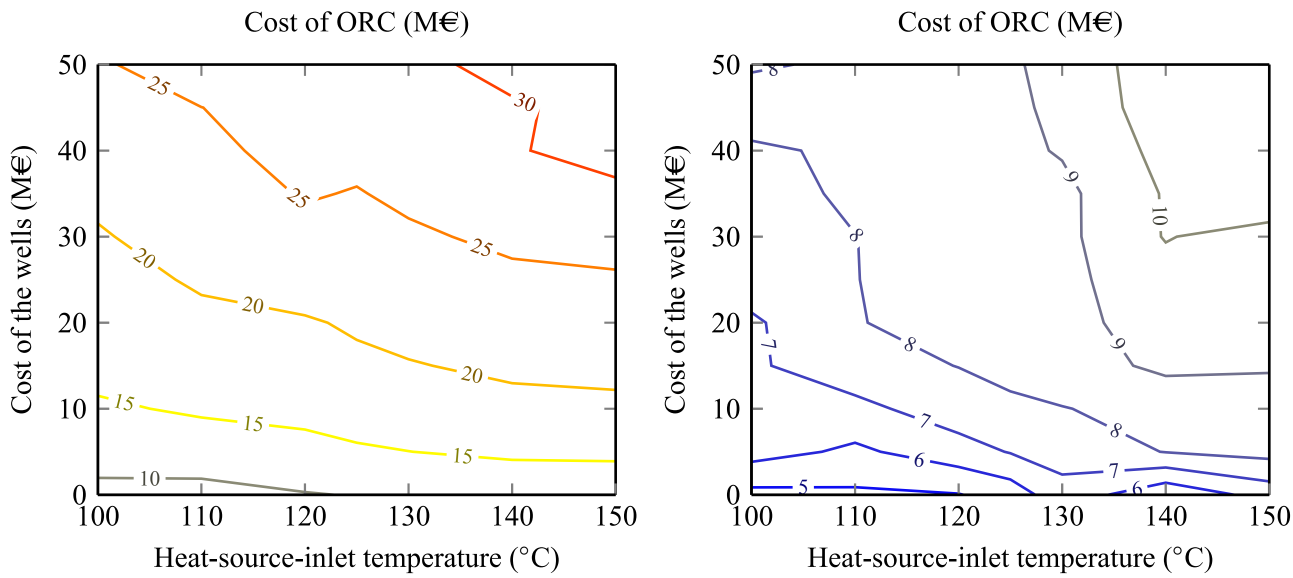
Table 2: Data of the optimal configurations obtained at different well costs at a temperature of 125°C for ORCs with an ACC.

The relative increase of the net electric power output is larger than the relative increase of the cycle efficiency, because the brine-outlet temperature decreases too with increasing well costs. This is again a consequence of decreasing pinch-point-temperature differences and decreasing condenser temperature, but also because of a decrease in the turbine-inlet temperature.

The consequence of the decreasing pinches and condenser temperature and the increased heat input to the cycle is that the heat exchangers become larger and more expensive. The cost of the ORC increases from 10 to 28 M€ for well costs ranging from 0 to 50 M€, or an increasing cost of the ORC with almost 200%. At the other hand does the specific cost of the ORC "only" increase with 44%.

At the other hand, does the fraction of the cost of the ORC to the total cost of the plant decrease strongly (100-36%) for the investigated increase in the well costs, which is in fact the main reason why the a more efficient and expensive ORC is optimal for higher well costs. As shown by the values of the LCOE in table 2, is the increase in the LCOE also very high due too this increase of the well costs. The increased net electric power output does not manage to compensate for this increased cost to keep the LCOE constant (equation (1)).

Going back to figure 6, it is seen that water-cooled ORCs generate more net electricity than air-cooled ORCs, but the difference is not high enough to explain the large difference in LCOE (Figure 5). This is explained by the difference in cost between the two. Figures 7a and 7b show the contour plot of the costs of the ORC. The difference is cost is a factor of two or more, in favor of the water-cooled ORCs. This is due to the very large cost of an ACC in comparison with a WCT.



(a) Air-cooled (b) Water-cooled

Figure 7: Cost of air-cooled ORCs (a) and water-cooled ORCs (b) as a function of the heat-source-inlet temperature and the cost of the wells.

The optimal ORC becomes more expensive with increasing cost of the wells, as explained above, and with increasing heat-source-inlet temperature. The latter evolution is due to the increased net power output (bigger turbine) and more heat flow (larger heat exchangers, etc.).

5. CONCLUSIONS

The influence of the cost of the wells and the heat-source-inlet temperature on the LCOE, the net power output and the cost of geothermal ORCs is investigated in this paper by performing an economic system optimization. The configuration of the components and the configuration of the cycle are optimized together to obtain the minimum LCOE.

Contour plots of the LCOE are given as a function of the heat-source-inlet temperature and the cost of the wells. With these plots, a first estimate can be made of the electricity price needed for a specific project to become economically profitable.

It is shown that the LCOE of water-cooled ORCs is lower than the one of air-cooled ORCs for the investigated parameters. This is mainly caused by the much higher cost of an ACC in comparison with a WCT, and to a lesser extent by the higher net power output of the water-cooled ORC.

NOMENCLATURE

ACC	Air-cooled condenser	
C	Cost	(€)
d_o	Diameter of a tube	(m)
D_S	Diameter of the shell	(m)
H	Fin height	(m)
H_i	Inlet height	(m)
H_{fi}	Hight fill	(m)
H_{sp}	Height spray zone	(m)
L_b	Baffle spacing	(m)
L_t	Length of the tubes	(m)
LCOE	Levelized Cost of Electricity	(€/MWh$_e$)
N	Full-load hours per year	(-)
p_t	Pitch between tubes	(m)
S	Fin pitch	(m)
WCT	Wet cooling tower	
W_l	Tubes' large width	(m)
$\dot{W}_{net}$	Net electric power output	(MW$_e$)
W_S	Tubes' small width	(m)
W_t	Tower width	(m)

Subscript

EPC	Engineering, procurement & construction
O&M	Operations and maintenance
ORC	Organic Rankine cycle

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