TECHNICAL EVALUATION OF ZEOTROPIC FLUID MIXTURES IN GEOTHERMAL ORC APPLICATIONS

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ABSTRACT

The ORC technology demonstrated to be a sustainable and reliable technology to exploit low-temperature sources, such as low-enthalpy geothermal reservoirs. In the last years, numerous studies focused on fluid mixtures in ORC applications. Heberle and Brüggemann (2015) investigated fluid mixtures as working fluid in geothermal ORC applications according to boundary conditions available in Molasse Basin, Southern Germany. The combination isobutane/isopentane appeared as the most promising one. The corresponding thermodynamic analysis revealed how the 90/10 (mole-fraction isobutane/mole-fraction isopentane) composition provides the highest turbine power output. In this work, an extended technical evaluation is provided with regard to the use of isobutane/isopentane mixtures in geothermal ORC power systems. On-design simulations are firstly performed in order to maximize the turbine power output for several mole fraction compositions. The 95/5 composition provides the highest turbine power output, 6.78 % more than pure isobutane. Later, yearly simulations considering the ORC behaviour are performed according to real ambient temperature data in Southern Germany. A comparison between on-design and average annual results is proposed. For the 95/5 composition, the annual average net power is 103 kW_{el} lower than the on-design value. Next to technical criteria also selected economic parameters are calculated: the 70/30 composition provides +7.66 % more in net cash flow than the 95/5. In principal, even though the 95/5 mixture provides the highest annual power production, the 70/30 appears more economically feasible under consideration of yearly ambient temperature profile and the corresponding ORC off-design performance.

1. INTRODUCTION

The exploitation of low-temperature geothermal source can represent a valuable opportunity to provide sustainable power generation (Bertani, 2015). In this context, the ORC technology represents a reliable solution to exploit different renewable sources (Astolfi et al. 2014). In the recent years, numerous works focused on fluid mixtures applications in ORC solutions, with regard also to geothermal energy. In particular, the ratio between the temperature glide of the working fluid during condensation and the temperature difference of the cooling medium is identified to be a criterion for the maximum power output (Andreasen et al. 2014). The mixture composition should be chosen according to good temperature glide match (Heberle and Brüggemann 2015). Andreasen et al. (2014) developed a selection and investigation of pure and mixed working fluids for low grade heat utilization with ORC. In particular, mixtures generally revealed better net power production in comparison to pure fluids application, according to heat sources at 90 °C and 120 °C. Jung and Krumdieck (2013) investigated zeotropic mixtures in air-cooled ORC geothermal applications. They demonstrated how mixtures generate higher electrical power than pure fluids. Even though the highest efficiency is reached with a mixture of 80 % isobutane and 20 % pentane, this advantage tends to be vanished due to the bigger size required for the air-cooled condenser in comparison to the isobutane pure fluid example. Based on the thermo-economic analysis of Heberle and Brüggemann (2015), an efficiency increase by using zeotropic mixtures as working fluids overcompensates additional requirements regarding the major power plant components. In case of a geothermal fluid temperature of 120 °C, R227ea and isobutane/isopentane are demonstrated to be cost-efficient working fluids.

The intent of this work is to analyse the mixture isobutane/isopentane for geothermal application more in details. In this context, a yearly simulation is performed and analyzed under technical and economic aspects. Related to the boundary conditions and analysis proposed by Heberle and Brüggemann (2015) a complete one-year simulation is carried out in order to determine the most suitable working fluid mixture composition. In particular, the applied off-design models are based on air-cooled condensers, while Heberle and Brüggemann (2015) applied water-cooled ones. Finally, selected economic parameters like net revenue and levelized cost of electricity are calculated for a wider evaluation.

2. METHOD

2.1 Boundary Conditions

In this work, the geothermal reservoir represents the lower limit of the conditions typically available in Southern Germany (Table 1). In consequence, a conservative scenario is examined in this study.

Table 1: Boundary conditions regarding the geothermal source (Heberle and Brüggemann 2015).

Parameter	**Value**
Geothermal water temperature	120 °C
Geothermal water mass flow	65.5 kg/s
Geothermal phase state	Liquid only

The considered power unit layout (Figure 1) is one-stage ORC configuration with an internal recuperator. The system relies on an air-cooled condenser, as generally occurs in binary geothermal power applications (Michaelides and Michaelides 2011).

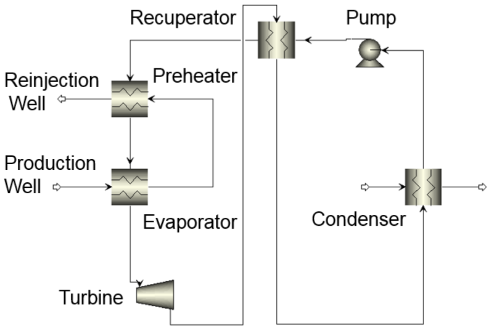


Figure 1: ORC power plant unit.

The followed boundary conditions regarding the ORC power unit are resumed in Table 2.

Table 2: Boundary conditions regarding the ORC power unit.

Parameter	**Value**
$\Delta T_{\mathrm{pp,evaporator}}$	5 K
$\Delta T_{\mathrm{pp,condenser}}$	5 K
$\Delta T_{\mathrm{pp,recuperator}}$	5 K
$\eta_{is\_turbine}$	84 %
η_{is_pump}	70 %
$\eta_{generator}$	98 %
Evaporating pressure	optimized
Pressure losses	neglected

Subcooling and superheating degree outlet the heat exchangers are neglected. The on-design ambient temperature is 10 °C, equal to the average yearly ambient temperature in Southern Germany. All the models presented in this work are simulated according to the use of Aspen V8.8. Fluid properties are calculated according to the Peng-Robinson method, while the Steamnbs-model for the geothermal water (Aspentech-Aspen Technology Inc. 2013), due to the very low salinity of the brine in Molasse Basin, Southern Germany.

2.2 Off-design model

The off-design configuration is developed implementing different part load models for the heat exchangers and the turbine. The off-design behaviour of the heat exchangers is described according to Manente et al. (2013), where the UA is defined as a function of the ORC mass flow. The turbine off-design behaviour is modelled according to the equation proposed by Ghasemi et al. (2013): the isentropic turbine efficiency is a function of the variable enthalpy difference and of the outlet volume flow rate. The pump isentropic efficiency is assumed constant.

2.3 Technical Analysis

The implementation of off-design models allows to describe the annual behaviour of the power plant depending on ambient temperature fluctuations. Since the proposed system is an air-cooled solution, off-design occurs while varying the ambient temperature. Several parameters are calculated in order to perform the technical analysis. The net power output is defined as

$$\dot{W}_{net} = \dot{W}_{turb} - \dot{W}_{pump} - \dot{W}_{acc} \tag{1}$$

where $\dot{W}_{turb}$ and $\dot{W}_{pump}$ represents respectively the turbine power output and the pump power consumption. $\dot{W}_{acc}$ is the air-cooled condenser power consumption, calculated according to Manente et al. (2013). The auxiliary power consumption $\dot{W}_{aux}$ is defined as the sum of the pump and air-cooled condenser power consumption. The power plant thermal efficiency is calculated as

$$\eta_{th} = \frac{\dot{W}_{turbine} - \dot{W}_{pump} - \dot{W}_{acc}}{\dot{Q}_{inlet}}, \tag{2}$$

where $\dot{Q}_{inlet}$ is the available thermal power provided by the geothermal source. The second law efficiency is calculated according to

$$\eta_{II} = \frac{\dot{W}_{turbine} - \dot{W}_{pump} - \dot{W}_{acc}}{\dot{m}_{geo}(h_{geo} - h_0 + T_0(s_{geo} - s_0))}, \tag{3}$$

where the dead state *0* is chosen at 1 bar and 283.15 K. The thermal and second law efficiency, Equation (2) and Equation (3), are both calculated at on-design and as annual average value.

2.4 Economic Analysis

In this work, some economic results are calculated to provide a more extended comparison of the proposed examples. Some economic assumptions are presented in Table 3.

Table 3: Economic boundary conditions according to Heberle and Brüggemann (2014).

Parameter	**Value**
Time availability	90 %
Geothermal feed-in tariff	25.0 €ct/kWh
Auxiliary power consumption cost	12.0 €ct/kWh
ORC unit cost (isobutane example)	2500 €/kWel
Drilling cost	12,5 k€
Insurance cost	1,25 k€

In addition, the cost of operation and maintenance $C_{O\&M}$ is assumed as 3 % of the total investment. Net revenues are defined as

$$\text{Net Revenue} = \text{Revenue} - C_{O\&M} - C_{auxiliary} \tag{4}$$

where the Revenue represents the annual income. The levelized cost of electricity (LCOE) is calculated according to

$$\text{LCOE} = \frac{C_{tot} + \sum_{n=1}^{t} \dfrac{C_{O\&M} + C_{auxiliary}}{(1+i)^n}}{\sum_{n=1}^{t} \dfrac{\dot{W}_{turb}}{(1+i)^n}}, \tag{5}$$

where i, the interest rate, is equal to 7 % and the investment duration n is equal to 30 years. C_{tot} represents the total investment cost, defined as the sum of the ORC cost, insurance and drilling cost. The first two years are considered for the power plant construction. The break-even point BEP is defined as

$$0 = -C_{tot} + \sum_{t=0}^{T} \left(\text{Revenue} - C_{O\&M} - C_{auxiliary}\right)(1+i)^{-t}. \tag{6}$$

The unavailability of detailed information regarding the cost per unit in ORC applications with isobutane/isopentane mixtures represents a crucial step. Consequently, once the BEP and LCOE are calculated for the most cost-efficient pure working fluid (isobutane) case study, economic results for each mixture composition are found varying the cost per unit in order to match first the BEP and second the LCOE provided by the pure isobutane example. This procedure enables conclusions regarding the acceptable increase of the specific costs in order to still obtain a feasible ORC system based on fluid mixtures.

2.5 Working fluid selection and temperature glide matching

In case of zeotropic mixtures, a non-isothermal phase change is observed. In this study, the temperature difference of the cooling medium air is chosen in order to provide the best possible match of the temperature profiles in the condenser.

In this context, the temperature glide of isobutane/isopentane and temperature difference of the cooling medium as function of mixture composition are shown in Figure 2: temperature glides are justifiable between 3 and maximum 12.5 K. For pure fluid application, the cooling fluid temperature variation is set equal to 5 K.

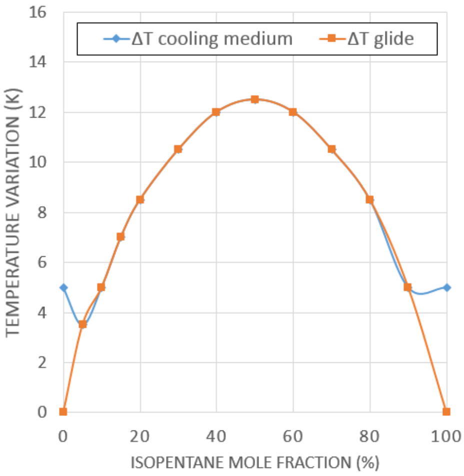


Figure 2: ΔT cooling medium and ΔT glide as a function of isopentane mole fraction.

2.6 Modelling procedure

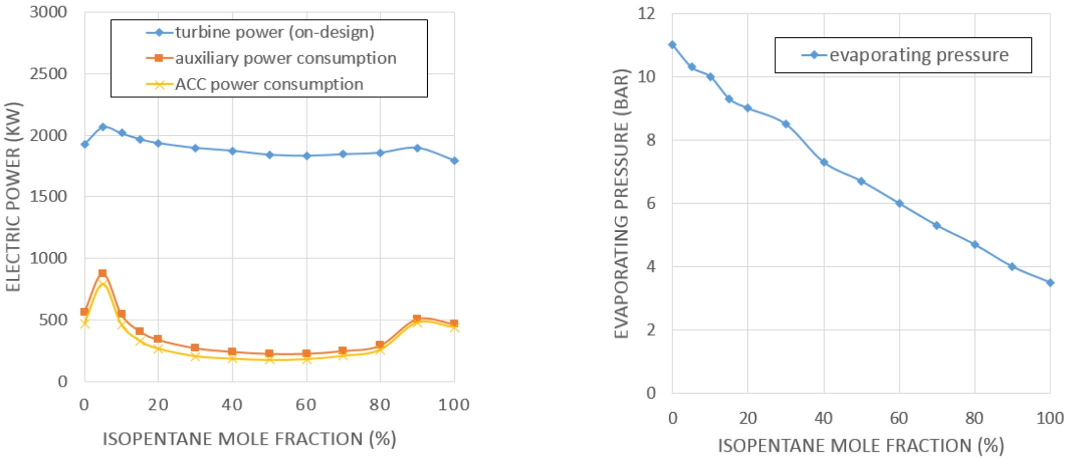
This work is developed according to the following procedure:

- First, the on-design point for each example is defined. The percentage in fluid variation for each mixture case study is set to 10 %, even though an only 5 % variation is applied in proximity of the best on-design composition (90/10), as suggested by Heberle and Brüggemann (2015). In each example, the turbine power output is maximized varying the evaporating pressure. Several on-design parameters are calculated, such as Equation (1), Equation (2) and Equation (3).
- Then, real ambient temperature hourly data in Southern Germany from 2015 (Eller et al. 2019) are implemented in each model. Corresponding equations are necessary in order to describe the off-design behaviour of the systems. Selected technical results are proposed also as annual average value (Equation (1), Equation (2) and Equation (3)). Therefore, a comparison between on-design and annual average values is proposed.
- Finally, economic results (Equation (4), Equation (5) and Equation (6)) are calculated for each example and a general comparison is shown.

3. RESULTS

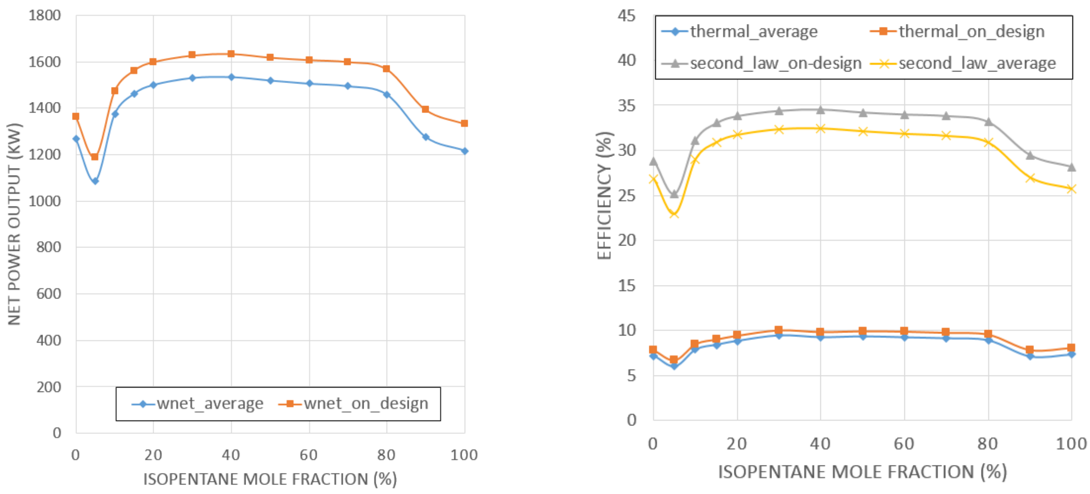
3.1 On-design results

Using pure isobutane as ORC working fluid provides a turbine power output of 1926 kW$_{el}$, while pure isopentane only 1796 kW$_{el}$ (Figure 3a). The application of mixtures allows a maximum improvement up to 2066 kW$_{el}$ in the 95/5 case study, which corresponds to an increase of 7.27 % compared to the 100/0 example. The mixture 95/5 provides the highest turbine power output, + 48 kW$_{el}$ than 90/10 one, which is considered as the most promising one by Heberle and Brüggemann (2015). Furthermore, the compositions 95/5 and 80/20 still provide turbine power outputs higher than the pure isobutane, while other examples show lower values. The air-cooled condenser power consumption is strictly related to the temperature glide of the working fluid: the lower the temperature glide, the higher the power consumption. In addition, also the different and optimized evaporating pressure affects the auxiliary power consumption (Figure 3b). The highest auxiliary electric power consumption occurs at 95/5 (Figure 3a), determining also the lowest net power production (1118 kW$_{el}$, Figure 4a). The auxiliary power consumption tends to decrease while augmenting the percentage of isopentane mole fraction, providing the highest net power production at 60/40, even though remarkable results occurs at even lower isobutane percentage (1567 kW$_{el}$ at 20/80).



(a) (b)

Figure 3: Turbine power output and auxiliary power consumption as a function of isopentane mole fraction in mixtures (a). Evaporating pressure as a function of the isopentane mole fraction in mixtures (b).



(a)

(b)

Figure 4: Net power production as a function of the isopentane mole fraction in mixtures (a). Efficiency parameters as a function of the isopentane mole fraction in mixtures (b).

The thermal and second law efficiency results (Figure 4b) tend to increase with isopentane mole fraction between 20 % and 80 %. The 95/5 mixture provides the lowest thermal efficiency, only 6.68 %, and also the lowest second law efficiency, which is equal to 25.13 %. These results are strictly related to the very high auxiliary electric power consumption. Due to a higher temperature glide, the other examples provide lower auxiliary electric power consumptions and, as a consequence, also higher thermal and second law efficiency values. The increase in turbine power output in case 95/5 is not able to counter balance the rising auxiliary power consumption. Example 70/30 shows the highest thermal efficiency, equal to 10.04 %. The highest second law efficiency is provided by 60/40, with 34.54 %, slightly better than the one provided by 70/30.

3.2 Yearly part load results

Real ambient temperature fluctuations during the year (Eller et al. 2019) are implemented in the models. The highest annual energy production is equal to 15,453 MWh and it is provided by the 95/5 case study. The 95/5 mixture demonstrates an increase of 7.18 % compared to pure isobutane. Pure isopentane shows the lowest value, equal to 13,263 MWh. The annual energy production trend (Figure 5) reasonably follows the turbine power output one (Figure 3a). In Figure 5, also the net annual energy production is shown. The average net power production is calculated and shown in Figure 4a. The average value is always lower than the on-design one; deviations vary between 5.94 % (for 70/30) and 8.68 % (in case of 95/5).

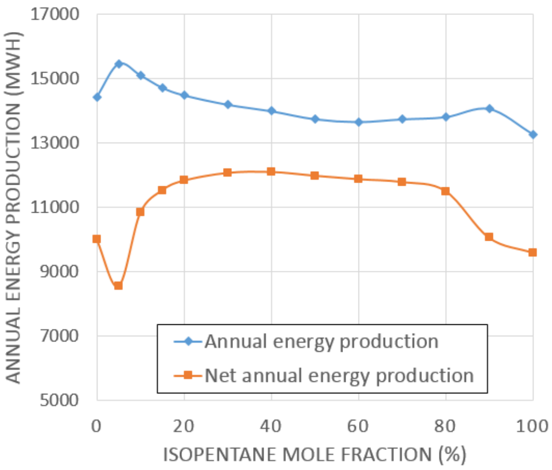


Figure 5: Annual energy production as a function of the isopentane mole fraction in mixtures.

Average values also regarding thermal and second law efficiency are shown in Figure 4b. Average results always remain lower than on-design ones. With regards to thermal efficiency, the highest absolute deviation occurs in the pure isobutane, where the average value is 0.78 % lower than the on-design one. On the contrary, the lowest absolute deviation is found at 100/0, with 0.59 % decrease. Absolute deviations in second law efficiency are slightly higher: the lowest decrease is equal to 1.94 % and it occurs at 100/0. On the other hand, the highest deviation is found at 5/95 composition and it is equal to 2.46 %.

3.3 Economic results

In this work, the total cost of the power plant is estimated according to a fixed cost per unit. This value is assumed equal to 2,500 €/kW$_{el}$ for the isobutane example. The BEP found in pure isobutane (15.22 years) is fixed also in the mixtures considerations and the costs per unit are consequently varied. The lowest cost per unit occurs at 0/100, equal to 2010 €/kW$_{el}$. The 95/5 mixture shows 2217 €/kW$_{el}$ as acceptable cost per unit. According to a fixed BEP equal for all the investigated examples, economic feasibility is shown to be improved while tending to higher costs per unit (Figure 6). The composition 70/30 provides 3225 €/kW$_{el}$, which results as the best scenario. The LCOE provides 20.107 €ct/kWh as highest result at 95/5, while the lowest LCOE, equal to 19.154 €ct/kWh, is found at 50/50 mixture. LCOE results to be quite constant according to different mixtures. The net cash flow reaches a peak of 8,715 k€ at 80/20, 8.73 % more than in the 95/5 example. The lowest value (7,591 k€) occurs at 0/100. The lowest net cash flow is 12.90 % lower than the best case study result. According to Heberle et al. (2015), the 90/10 composition shows +15.40 % in ORC cost per unit respect to pure isobutane, while in this work an increase of 18.0 % is reached. Regarding the 70/30 mixture, Heberle and Brüggemann (2015) shows an increase of 5.45 % on pure isobutane; here it augments up to 29.0 %. Oyewunmi et al. (2016) investigated n-pentane/n-hexane mixtures in low-temperature ORC systems. The 90/10 and 70/30 compositions show respectively +22.0 % and +33.0 % increase in ORC cost per unit on pure n-pentane.

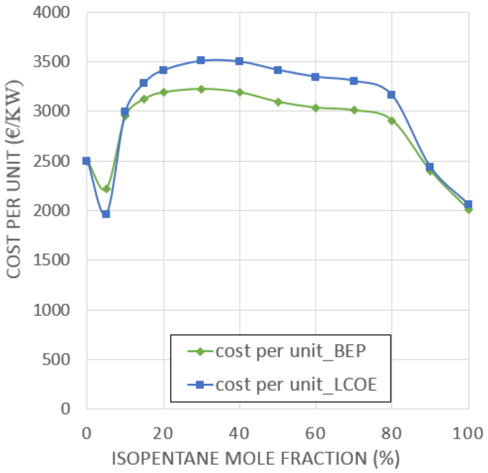


Figure 6: ORC cost per unit per kW$_{el}$ as a function of the isopentane mole fraction in mixtures.

A second approach is performed, according now to a fixed LCOE, equal to 19.69 €ct/kWh in the 100/0 example. The ORC unit cost ranges between 3508 €/kW$_{el}$ in 70/30 and 1965 €/kW$_{el}$ in 95/5 (Figure 6). The highest BEP (16.04 years) is found at 50/50 composition, while the lowest (14.51 years) occurs at 95/5. As shown in the previous approach, also here a high BEP guarantees better economic feasibility. The highest net cash flow (8,700 k€) occurs at 95/5, while the lowest (7,467 k€) occurs at pure isopentane, showing a 14.17 % decrease in comparison to the best scenario.

4. CONCLUSION

In this work, the mixture isobutane/isopentane and its pure components are investigated as ORC working fluids according to a geothermal air-cooled ORC application. The on-design analysis shows comparable results to the ones proposed by Heberle and Brüggemann (2015), even though the highest turbine power output occurs at 95/5 and not at 90/10. An extended yearly off-design analysis based on hourly data underlines the effect of auxiliary power consumption on thermodynamic and economic parameters, determining the 60/40 and the 70/30 as the examples with the highest annual average net power production (about 1530 kW_{el}), while the 95/5 composition only provides 1085 kW_{el}. Economic results are based on a comparison between the pure isobutane as reference case and the selected mixtures compositions. According to a BEP of 15.22 years, the 80/20 mixture shows the highest net cash flow (8,715 k€) while the 70/30 appears as the most economically feasible one in respect to the acceptable ORC unit cost (3225 €/kW_{el}). In order to provide a LCOE of 19.69 €ct/kWh, the use of 95/5 requires an acceptable ORC unit cost equal to 1965 €/kW_{el}. It is demonstrated how fluid mixtures providing the highest turbine power output actually shows less feasible economic results. On the other hand, the annual performance and economic aspects can be improved by the use of a mixture compared to its pure components. Further works will combine the performed off-design considerations with a more detailed economic analysis on the component level. The investigation of the selected mixtures with a higher geothermal mass flow might also be suggested.

REFERENCES

Andreasen, J.G., Larsen, U., Knudsen, T., Pierobon, L., Haglind, F., 2014. Selection and optimization of pure and mixed working fluids for low grade heat utilization using organic Rankine cycles. Energy 73, 204–213. 10.1016/j.energy.2014.06.012.

Aspentech-Aspen Technology Inc., 2013. Aspen V8.8, USA.

Astolfi, M., Romano, M.C., Bombarda, P., Macchi, E., 2014. Binary ORC (Organic Rankine Cycles) power plants for the exploitation of medium–low temperature geothermal sources – Part B: Techno-economic optimization. Energy 66, 435–446. 10.1016/j.energy.2013.11.057.

Bertani, R., 2015. Geothermal Power Generation in the World 2010-2014 Update Report. WGC, 2015, Melbourne, Australia.

Eller, T., Heberle, F., Brüggemann, D., 2019. Transient simulation of geothermal combined heat and power generation for a resilient energetic and economic evaluation. Energies (12(5),894).

Ghasemi, H., Paci, M., Tizzanini, A., Mitsos, A., 2013. Modeling and optimization of a binary geothermal power plant. Energy 50, 412–428. 10.1016/j.energy.2012.10.039.

Heberle, F., Brüggemann, D., 2014. Thermoeconomic Analysis of Hybrid Power Plant Concepts for Geothermal Combined Heat and Power Generation. Energies 7 (7), 4482–4497. 10.3390/en7074482.

Heberle, F., Brüggemann, D., 2015. Thermo-Economic Evaluation of Organic Rankine Cycles for Geothermal Power Generation Using Zeotropic Mixtures. Energies 8 (3), 2097–2124. 10.3390/en8032097.

Jung, H.C., Krumdieck, S. (Eds.), 2013. Analysis of zeotropic mixture in a geothermal organic rankine cycle power plant with an air-cooled condenser.

Manente, G., Toffolo, A., Lazzaretto, A., Paci, M., 2013. An Organic Rankine Cycle off-design model for the search of the optimal control strategy. Energy 58, 97–106. 10.1016/j.energy.2012.12.035.

Michaelides, E., Michaelides, D., 2011. The effect of ambient temperature fluctuation on the performance of geothermal power plants. IJEX 8 (1), 86. 10.1504/IJEX.2011.037216.

Oyewunmi, O., Markides, C., 2016. Thermo-Economic and Heat Transfer Optimization of Working-Fluid Mixtures in a Low-Temperature Organic Rankine Cycle System. Energies 9 (6), 448. 10.3390/en9060448.

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