Thermoeconomic evaluation of one- and double-stage ORC for geothermal combined heat and power production

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Keywords: Geothermal power generation, CHP, thermoeconomic analysis, ORC.

ABSTRACT

We present a thermoeconomic analysis of potential concepts for a combined heat and power generation (CHP) in case of a geothermal heat source. Based on the double-stage Organic Rankine Cycle (ORC) power plant in Kirchstockach (Germany) various strategies for an additional heat generation are examined. For the calculation of the ORC part load behaviour, real power plant data are analysed. Alternatively, a one-stage ORC is considered as a power unit. Regarding the heat demand, a reference load profile for a residential area consisting of single-family and multi-family houses underlies the case study. The results show a higher efficiency for pure electrical power generation as well as for CHP based on the double-stage ORC. In particular, for low supply temperatures of the heating network, CHP could lead to additional revenues up to 1.1 Mio€/a for the examined scenario compared to pure electrical power generation.

1. INTRODUCTION

The Southern German Molasse Basin near Munich (Germany) is dominated by aquifers with temperatures up to 140 °C. In this context, binary power plants like the Organic Rankine Cycle (ORC) or the Kalina Cycle (KC) are favourable for power generation (Tchanche et al., 2011; Vélez et al., 2012). In urban areas, combined heat and power generation (CHP) is a promising approach to improve economic conditions of geothermal projects. In Kirchstockach (Germany) an innovative double-stage ORC power plant operates successfully and provides potential retrofitting opportunities for an additional heat generation. Double-stage power plants for geothermal applications, alternatively named dual-pressure or dual-level ORC, consist of two separate ORC modules with different upper process pressure. In general, the same ORC working fluid is used in both systems due to aspects of storage and legal requirements. In current literature, double-stage ORC systems are mainly investigated under thermodynamic criteria (Bombarda et al., 2015; Guzović et al., 2014; Heberle et al., 2015; Shokati et al., 2014). In this context, it is necessary to differentiate from alternative two-stage cycle configurations (Kosmadakis et al., 2009; Meinel et al., 2014; Preißinger et al., 2012; Smolen, 2011; Walraven et al., 2013). Moreover, thermoeconomic analyses can provide a profound evaluation of different power plant concepts and their economic sense (Astolfi et al., 2014; Heberle et al., 2012; Heberle and Brüggemann, 2015, 2014; Le et al., 2014; Quoilin et al., 2011; Tempesti and Fiaschi, 2013).

This paper evaluates potential CHP concepts and pure electrical power generation under thermodynamic and economic criteria by a case study based on geothermal characteristics of Kirchstockach (Germany). Beside the double-stage ORC, a one-stage ORC is considered as power unit. In addition, sensitivity analyses concerning the supply temperature of the heating network as well as the ORC working fluid are performed.

2. DOUBLE-STAGE ORC KIRCHSTOCKACH

The considered double-stage ORC of Kirchstockach consists of a high-temperature (HT) and a low-temperature (LT) module. Fig. 1 shows an overview of the power plant. The power plant has been in operation since 2013. At the design point, the nominal electric capacity is 5.5 MW, referred to an ambient temperature of 8 °C, a mass flow rate of 120 kg/s and a temperature of 138 °C of the geothermal fluid.

Figure 1: Double-stage ORC power plant in Kirchstockach, Germany (Source: Geothermie Kirchstockach)

Fig. 2 illustrates a scheme of the double-stage power plant. In both modules, R245fa is used as ORC working fluid. The HT-ORC module operates at a higher process pressure compared to the LT-ORC. The thermal energy of the geothermal fluid is coupled to the ORC in the preheater and the evaporator of each module. In case of the HT-ORC, the preheating is divided into two steps, the LHT- and the HHT-preheater. Therefore, the geothermal fluid is separated at the outlet of the LT-evaporator (state points D and E). In both modules (HT and LT), a saturated ORC is realized. The working fluid enters the turbine without superheating. Furthermore, an air-cooled condenser and a feed pump are part of each module.

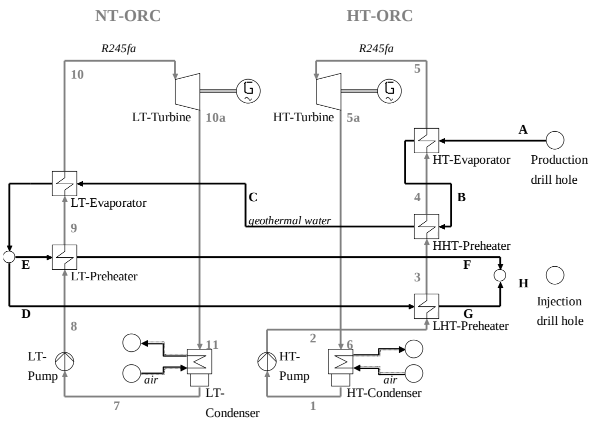

Figure 2: Scheme of the double-stage ORC power plant in Kirchstockach, Germany

3. SIMULATION AND ANALYSES

In order to evaluate potential geothermal CHP-concepts, we perform quasi-steady-state simulations of the ORC in full and part load under variable ambient temperature. For the relevant operating parameters of the ORC in part load, fit functions based on real power plant data were used as an input. For the additional heat supply, various plant configurations are examined based on the double-stage and the one-stage ORC. In this context, a reference scenario of the heating network is applied to the process simulations. In the following, the methodology is described in detail.

3.1 Process simulations

The process simulations are performed by using the software CYCLE TEMPO (Woudstra, N. and van der Stelt, T.P., 2002) whereby fluid properties of R245fa are calculated by STANMIX (Angelino and Colonna di Paliano, 1998). For the double-stage ORC at full load and design conditions, a detailed description, boundary conditions and a validation of the simulation model can be seen in a previous publication (Heberle et al., 2015). In average, the relative deviation for the simulation compared to the real power plant data is 1.3 %. In this context, it should be noted that data obtained from the plant operation and utilized for the present paper do not necessarily reflect the maximum performance that can be obtained by the ORC plant as a number of adverse factors decreasing the performance could have been present (like heat exchangers fouling, presence of non-condensable gases, etc) and have not been verified.

3.2 Examined power systems and CHP-concepts

This study is focussed on the double-stage ORC described in chapter 2. Next to pure electrical power generation, different CHP concepts are investigated. The following configurations are considered:

Concept A: This concept is a parallel circuit of heat extraction and the electrical power unit. For this purpose, the geothermal mass flow is splitted in state point A (see Figure 2) to provide the required thermal energy to the heating network.

Concept C: Here, a split stream of the geothermal fluid at state point C is used to cover the heat demand. This configuration is taken into consideration for low supply temperatures (standard case) of the heating network.

Concept A/C: This concept is a combination of concept A and concept C. The operational premise of concept C/A is a maximum heat extraction at state point C. As required the heat demand could be additionally covered by the geothermal fluid at state point A. The heat extraction at both state points is mainly relevant for high thermal energy demands or high supply temperatures of the heating network.

Finally, a standard one-stage ORC is analysed using the working fluids R245fa and isobutane. The boundary conditions for the geothermal fluid, the cooling circuit and the ORC unit are set according to the considered double-stage ORC system. The upper process pressure of the one-stage ORC is chosen in order to maximise the power output of the power system. As CHP concept, a parallel circuit (analogous to concept A) is examined for a one-stage ORC.

3.3 Heating network

The considered heating network is designed for a residual area with 8000 inhabitants. A distribution of 30 % single-family houses and 70 % multi-family houses is assumed. The heat demand for each housing unit is calculated according to VDI 4655 (Verein Deutscher Ingenieure e.V., 2008) as a function of ambient temperature. The total heat demand of settlement is calculated according to typical climate patterns and their annual rate (see Table 1).

In addition, the dependence of supply and return temperature of the heating net on ambient temperature is taken into account. For the standard boundary conditions, a supply temperature up to 90 °C is assumed. The resulting heat demand and supply temperature of the heating network depending on ambient conditions are listed in Table 2. Furthermore, a scenario with higher supply temperatures (up to 110 °C) is examined.

Table 1: Average ambient temperature and annual rate of typical climate patterns near Munich according to VDI 4655

Typical climate patterns	Average ambient temperature (°C)	Annual rate (days/a)
1	-2.8	29
2	0.3	6
3	0.8	19
4	1.3	91
5	10.2	72
6	10.7	10
7	11.8	15
8	12.3	37
9	16.8	13
10	17.4	73

Table 2: Total heat demand and supply temperature of the considered heating network at standard conditions

Typical climate patterns	Heat demand (kW)	Supply temperature (°C)
1	5715	78.8
2	5235	75.7
3	4658	75.2
4	4941	74.7
5	2355	65.8
6	2158	65.3
7	2015	64.2
8	1757	63.7
9	499	59.2
10	445	58.6

3.4 Analysis of real power plant data for the prediction of part load behaviour

For the process simulations, part load curves for relevant parameters are developed based on real power plant data. In this context, Table 3 provides an overview of the available data taking into account the load condition and the temperature range. For the load condition, the mass flow rate of the geothermal fluid is divided by the value at design conditions ($\dot{m}_{GF,design}$ = 119,7 kg/s).

Part load curves for the upper and lower ORC process pressure, pressure losses and pinch points of the heat exchangers as well as subcooling of the ORC working fluid at the condenser outlet are derived from the real power plant data. In order to minimize the relative deviations between fit function and plant data, either linear or exponential fit functions were applied. The subcooling at the HT condenser outlet is shown exemplarily in Fig. 3.

Table 3: Load condition of the ORC power plant and corresponding ambient temperature range of the real power plant data

Load condition (%)	Temperature range (°C)
75	4 – 15
80	4 – 13
85	-2 – 7
89	-7 – 7
90	9 – 19
93	0 – 20
96	8 – 15
100	4 – 15

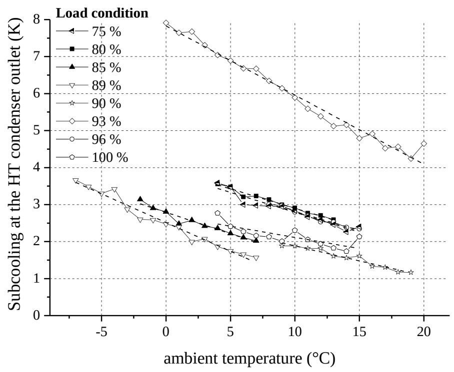

Figure 3: Subcooling of the ORC working fluid at the HT condenser outlet depending on load condition and ambient temperature

For this specific process parameter, Table 4 summarizes the mean and maximum deviation of the selected fit curves. The applied linear fit functions lead to a mean relative deviation below 4.4 % in relation to the power plant data. A maximum deviation of 12.1 % is obtained at 93 % load condition and 20 °C ambient temperature. For values beyond the ensured data range concerning the ambient temperature, the identified fit curves are extrapolated. For an adaption of the load condition, a linear interpolation of the corresponding load curves is performed.

For the rotating equipment, characteristic part load curves were applied to the simulation model. Exemplarily, Fig. 4 illustrates the efficiency of the ORC pumps and the generator depending on load condition.

3.5 Thermo-economic evaluation of the considered power plant concepts

For the performed process simulations, the same heat demand characteristics (see chapter 3.3) are considered. Therefore, the annual amount of generated electrical power is the crucial criterion regarding the evaluation of the considered CHP concepts. For an economic analysis, the additional revenues based on the remuneration for electricity supplied to the public grid and heat sales are compared to pure electrical power generation. In this context, the current German feed in tariff for geothermal projects (25 ct/kWh$_e$) and a typical heating price for Bavaria (7 ct/kWh$_{th}$) are assumed.

Table 4: Mean and maximum relative deviation of the selected fit curves for the subcooling of the ORC working fluid at HT condenser outlet

Load condition (%)	Mean deviation (%)	Maximum deviation (%)
75	2.7	-7.6
80	0.5	-3.5
85	1.3	-7.9
89	1.6	-10.3
90	1.4	8.3
93	1.0	12.1
96	0.2	1.9
100	4.4	-7.2

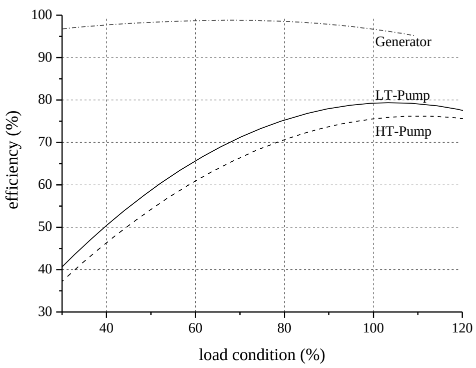

Figure 4: Part load efficiency of the ORC pumps and the generator depending on load condition

4. RESULTS

4.1 Pure electrical power generation

For pure electrical power generation, the gross and net power output of the considered ORC power systems are shown in Fig. 5 depending on ambient temperature. Regarding ambient temperature, the simulated values are chosen in respect to the typical climate patterns listed in Table 1. In general, the results for pure electrical power generation correspond to a load condition of 100 % according to Table 4.

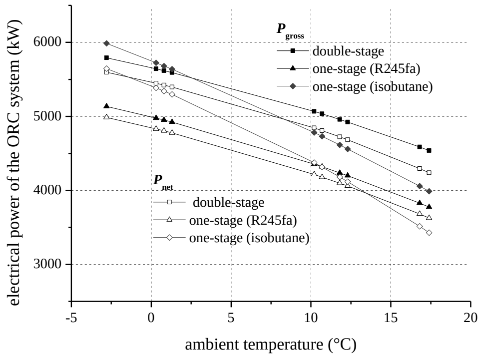

Figure 5: Gross and net power of the considered ORC power systems as a function of ambient temperature for pure electrical power generation

It is obvious that the power output decreases with increasing ambient temperature for all considered power systems. This effect is based on the increase of the condensation pressure of the ORC with rising ambient temperature (air-cooled condensers). For the double-stage ORC a reduction of gross power output of 62 KW/K is obtained. In order to optimize the power output of the one-stage ORC using R245fa as a working fluid, an upper pressure of 10.1 bar is chosen. This leads to a 10 K higher reinjection temperature of the geothermal fluid compared to the double-stage system, which could be favourable in respect of a reduction of scaling in the heat exchangers. In addition, the power consumption of the ORC pump is 47.9 % lower at the design point (8 °C ambient temperature). However, the one-stage ORC leads to a significant lower power output compared to the double-stage ORC.

In the following, the discussion is focussed on the electrical gross power output of the ORC system due to the fact that the German feed in tariff is based on this parameter. In general, auxiliary power requirements are covered by electricity purchased from the grid.

4.2 CHP concepts

In this chapter, the results for the potential CHP-concepts and different supply temperatures of the heating network are discussed. First, Fig. 6 illustrates the electrical gross power of the double-stage ORC for concept A and in case of a one-stage-concept for a parallel circuit. For each CHP concept, the thermal energy coupled to the heating network is considered according to Table 1. In addition, Fig. 6 compares the power output for a low- and high-temperature heating network. In this context, the double-stage ORC and the one-stage ORC using R245fa are analysed.

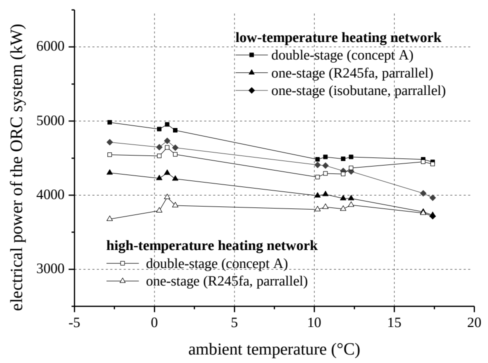

Figure 6: Electrical gross power of the power plant units for different ORC concepts (double- or one-stage) depending on ambient temperature and supply temperature of the heating network

In comparison to Fig. 5, the reduction of gross power output with ambient temperature is weakened due to a decreasing heat demand with increasing ambient temperature. This relation also explains the differences in power output depending on the supply temperature of the heating network. For low heat demand and high ambient temperature, respectively, the differences are negligible (0.6 %). However, for low ambient temperatures, the power output is reduced up to 8.7 %.

In Fig. 7 the electrical gross power of the double-stage ORC is shown for different CHP concepts depending on the ambient temperature and the supply temperature of the heating network

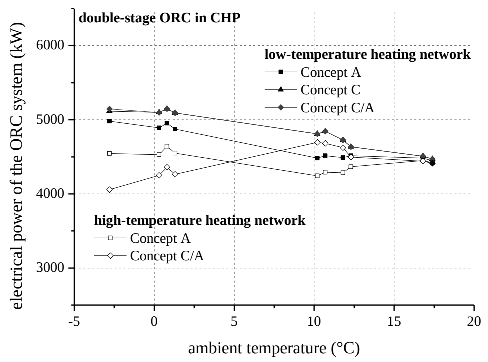

Figure 7: Electrical gross power of the double-stage ORC for different CHP concepts depending on ambient temperature and supply temperature of the heating network

The results show that concept C and concept C/A lead to a nearly identical power output in case of low supply temperatures. Only if the heating network requires a high thermal power, a heat extraction at state point A makes sense under thermodynamic criteria. The differences in gross power output between concept A and C are due to the characteristic part load conditions of the ORC modules (HT and LT). In the considered temperature range the HT-module performs at higher part load conditions in conjunction with concept C/A (96.4 % - 100 %). In case of concept A, the part load condition for the HT-module is only between 94.4 % and 84.1 %. For higher supply temperatures of the heating network, concept C is technically not feasible due to the required minimal temperature difference in the heat exchanger. For concept A, the gross power output is qualitatively similar to the results at lower supply temperatures. Obviously, the power output is reduced due to a higher split stream of the geothermal fluid which is required to provide the thermal power at a higher supply temperature. For high ambient temperatures, these differences are negligible, because only a low thermal power is coupled to the heating network.

4.3 Thermoeconomic evaluation

Fig. 8 shows the generated amount of electricity per year for the considered ORC power systems. A distinction has been made between pure electrical power generation and CHP (concept A and parallel circuit).

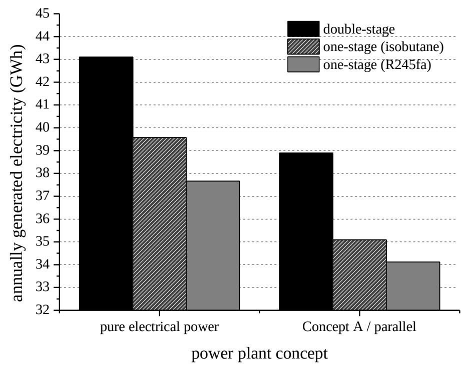

Figure 8: Annually generated amount of electricity for the examined power plant concepts

Based on the annually generated amount of electricity the double-stage ORC is the most suitable power system for pure electrical power generation. Compared to the one-stage ORC using isobutane as a working fluid, the generated amount of electricity is 8.2 % higher. For R245fa as ORC working fluid, a 12.6 % lower electricity generation is obtained. Also for CHP the double-stage concept leads to a significantly higher amount of generated electricity. However, compared to pure electrical power generation the produced electricity is reduced by 9.7 %. This reduction is comparable to the one-stage ORC (9.4 %). The highest reduction of 11.3 % is obtained for the one-stage ORC using isobutane as a working fluid.

A detailed comparison based on the annually generated amount of electricity for the investigated CHP concept in conjunction with double-stage ORC summarizes Fig. 9. In the context of Fig. 7 the differences between concept A and concept C/A are marginal for the standard condition of the heating network. Therefore, concept C/A generates about 30 MWh more electricity per year. Compared to pure electrical power generation this is a reduction of 6.3 %. Concept A, the alternative CHP configuration, is less efficient and leads to a 3.8 % lower annual electricity generation compared to concept C/A.

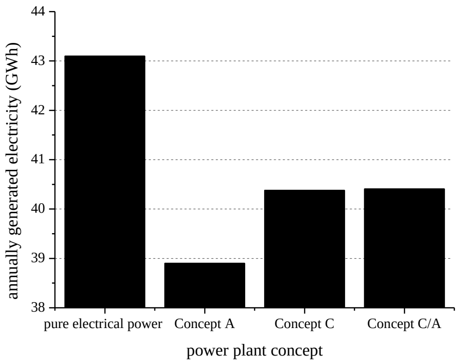

Figure 9: Annually generated amount of electricity for the examined CHP concepts in conjunction with the double-stage ORC

In Fig. 10 the annually generated amount of electricity for selected CHP concepts is illustrated depending on the supply temperature of the heating network.

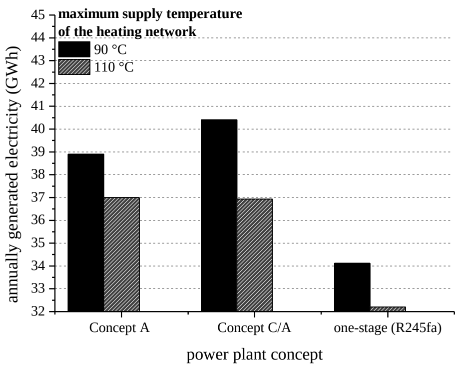

Figure 10: Annually generated amount of electricity for the examined CHP concepts depending on the supply temperature of the heating network

For the considered high-temperature heating network the reduction of the generated amount of electricity is most pronounced by 8.6 % for concept C/A. This is due to a limited heat extraction at state point C in case of high supply temperatures. For concept A and the one-stage ORC in parallel circuit, the reduction of the produced electricity in case of higher supply temperatures is less pronounced (4.9 % and 5.6 %). Therefore, concept A leads to 70 MWh/a higher amount of generated electricity in case of a maximal supply temperature of 110 °C.

Concerning the German economic boundary conditions, a geothermal CHP could lead to additional revenues of 1.1 Mio€/a (concept C/A) compared to pure electrical power generation. In case of higher supply temperatures, the revenues are reduced noticeably. In this context, concept A leads to 0.26 Mio€/a additional revenues in relation to pure electrical power generation.

5. CONCLUSIONS

We present a quasi-stationary model based on real power plant data for geothermal CHP and pure electrical power generation based on a double-stage ORC power system. An evaluation of potential CHP concepts and a comparison to one-stage ORC systems is performed. The results show a higher flexibility and efficiency for CHP concepts based on the double-stage ORC, especially for low supply temperatures of the heating network. In case of high supply temperature, standard plant schemes like the parallel circuit of heat extraction and binary power unit are suitable. For the considered case study, a combined heat and power generation could lead up to 1.1 Mio€/a additional revenues compared to pure power generation.

Future work will focus on a more detailed part load prediction of the ORC power systems based on a dynamic simulation model. In addition, the economic evaluation will be carried out on component level for different case scenarios concerning the required heat demand and supply temperatures.

AKNOWLEDGEMENTS

Funding from the Bavarian State Ministry of Education, Science and the Arts in the framework of the project “Geothermie-Allianz Bayern” is gratefully acknowledged.

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