Evaluation of different power plant concepts for geothermal heat and power production

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Keywords: Geothermal combined heat and power, Organic Rankine Cycle, Dynamic simulation.

ABSTRACT

The efficiency and the profitability of geothermal power plants can be improved by an additional heat generation. In this study, potential plant concepts for geothermal heat and power generation are investigated. Annual simulations are conducted based on a dynamic model of a double-stage Organic Rankine Cycle. The concepts are evaluated by thermodynamic as well as economic aspects and compared to the reference case of pure power generation.

In general, the results show that the annual return of geothermal power plants can be increased by an additional heat supply. In terms of second law efficiency, it depends on the applied concept, if there is an increase or a decrease. For a district heating network with a supply temperature of 110 °C and a return temperature of 70 °C (110/70) the second law efficiency of the parallel concept is 51.5 %, which is an increase of 3.2 % compared to power generation. For a 60/35 district heating network the most efficient concept is the parallel-LT configuration. In addition, the combined heat and power generation leads to an increase of the annual revenue between 12.8 and 13.0 million €.

1. INTRODUCTION

Heating and cooling represent almost half of the global energy consumption. The market volume for heating and cooling is 164 billion $ in 2017 and expected to grow up to 298 billion $ in 2026 (Richter, 2019). For that reason, flexible heating, cooling and power systems will gain more interest in the future. In this context, geothermal combined heat and power generation offers a high potential to improve the efficiency and profitability of geothermal power plants (Eller et al., 2019b). Due to the fluctuating heat demand, the power plant is driven more often in part load and therefore a dynamic simulation model of an Organic Rankine Cycle (ORC) is required.

In the literature, dynamic models are often developed in the context of fluctuating heat sources like waste heat of combustion engines or industrial processes. Huster et al. (2018) developed a such a model for exhaust gas of diesel trucks. Bin Xu et al (2017) built-up a dynamic ORC for waste heat recovery from a diesel engine. In addition, Baccioli et al (2017) developed a dynamic model of a solar ORC.

Regarding geothermal cogeneration systems, van Erdeweghe et al. (2018) investigated different geothermal heat and power plant concepts. In addition, different temperature levels of the district heating network (DHN) are considered. The investigations are based on stationary simulation for a one-stage ORC assuming a constant heat demand of the DHN. Next to combined heat and power, Seyfouri et al. (2018) investigate different configurations for geothermal combined cooling and power. The results show that the parallel-series system shows a better performance than the parallel configuration. Mahmoudi and Akbari Kordlar (2018) also consider a geothermal cooling and power cogeneration system. However, a Kalina cycle is used instead of an ORC. The maximum second law efficiency at lowest production unit cost is 34.8 %.

In this study, different concepts for geothermal heat and power generation are investigated based on annual simulations of the combined heat and power system. In this context, a dynamic model of a double-stage ORC is built up related to an existing power plant. In addition, heat demand profiles are developed based on a real geothermal fed DHN. In section 2 the simulation model is described including the power plant model and the heat demand profiles. The results are presented in section 3.

2. METHODOLOGY

The evaluation of geothermal combined heat and power plant concepts is based on annual simulations inspired by the method according to VDI 4655 (Gesellschaft Energietechnik and Verein Deutscher Ingenieure, 2008). Therefore, a dynamic simulation model is built-up and heat demand profiles for the DHN are developed.

2.1 Annual simulations based on VDI 4655

In the VDI 4655 different typical day categories are defined based on three criterions: the season, the user behavior and the sky conditions. For the season, the summer (S), winter (W) and transition period (Ü) are distinguished. To take into account the user behaviour, the days are differentiated between workdays "W" (including Saturdays) and Sundays "S" (including all national holidays). Regarding the sky conditions, cloudy (B) and fine (H) days are distinguished. In the summer, this distinction between fine and cloudy days is negligible. Therefore, ten typical day categories are defined according to VDI 4655 (Table 1).

Germany is divided in 15 different climate zones. Depending on the climate zone, the frequency of the typical days varies for one year. For example, in TRY12 104 summer workdays occur during the year, while there are only 73 in TRY13. For an annual simulation, the ten typical days are simulated. Annual results are obtained by weighting the results of the typical days according to their frequency (*n*).

Table 1: Typical-day categories according to VDI 4655

Time of the year	**Workday W**		**Sunday S**	
	fine H	cloudy B	fine H	cloudy B
Transition Ü	ÜWH	ÜWB	ÜSH	ÜSB
Summer S	SWX		SSX	
Winter W	WWH	WWB	WS H	WSB

Table 2. Frequency of the typical day per year in dependence of the region according to VDI 4655

	ÜWH	**ÜWB**	**ÜSH**	**ÜSB**	**SWX**	**SSX**	**WWH**	**WWB**	**WSH**	**WSB**
…										
TRY12	27	91	8	18	104	19	23	57	2	16
TRY13	37	72	15	10	73	13	29	91	6	19
TRY14	42	81	11	15	42	7	22	115	5	25
…										

2.2 Heat demand profiles

To model the DHN, heat demand profiles are implemented in the simulation model. For every typical day category (see Table 1), a heat demand profile is developed based on operational data of a real geothermal heat plant in the southern of Germany.

The development of the heat demand profiles is inspired by the VDI report "reference load profiles" (Dubielzig, 2007) and adapted to the analysis of real operational data. In addition, a method for a systematic identification of outlying load profiles is applied. Furthermore, the degree day method according to VDI 3807 (Gesellschaft Technische Gebäudeausrüstung and Verein Deutscher Ingenieure, 1994) is used to account for the weather adjustment.

In general, the procedure for the development of the reference load profiles is described in Eller et al. (2019). At first, the operational data of the heat plant is assigned to the typical day categories. For every typical day category outlying heat demand profiles are identified and excluded from the analysis. After that, the squared error from the mean value is calculated and the heat demand profile with the lowest squared error becomes the reference load profile for the corresponding typical day category. In addition, the reference load profile is adjusted for weather variations. In this paper, the method for identifying outliers and the weather adjustment is explained in detail.

For the outlier analysis, a box-whisker plot (Tukey, 1977) is used. The principle is illustrated in Figure 1.

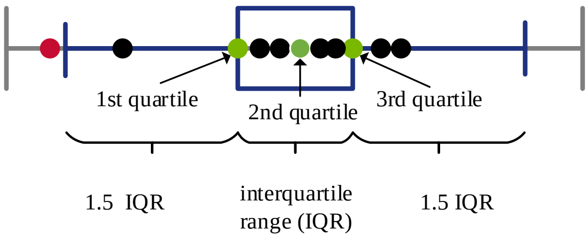

Figure 1: Example of a box-whisker-plot

In the first step, all data points are placed on a number line and the median is determined (2nd quartile). The median divides the data points in two intervals containing the same number of points. Subsequently, the first and the third quartile are calculated, so that the data points are divided in four intervals with the same number of data points. The distance between the first and the third quartile is called the interquartile range. This range includes per definition 50 % of all measurement points. The whisker limits are defined by 1.5 times of the interquartile range. They are added on both sides of the interquartile box. Measurements which are beyond the whisker limits (red point) are declared as outlying measurements.

For every time of measurement a box-whisker-plot is applied to the measurement data and the outlying points are determined. Heat demand profiles with more than

15 % outlying measurements are declared as outliers and excluded from the analysis.

For the weather adjustment, the degree day method according to VDI 3807 is used. The heating energy consumption is adjusted by equation [1]

$$E_v = E_{v_s} \frac{G_{15m}}{G_{15}} . \qquad [1]$$

E_{vs} is the unadjusted heating energy demand and E_v the adjusted one. The degree days are defined according to

$$G_{15} = \sum_{n=1}^{z} (15 - t_{m,n}) , \qquad [2]$$

where t is the 7-days-mean ambient temperature. The method of VDI 3807 is adapted to the typical day categories as follows: All days of the last ten years are allocated to the typical day categories according to VDI 4655. For each typical day category the mean value is calculated for the last 10 years (G_{15m}). Furthermore, the degree days for the considered year are calculated (G_{15}).

Next to the heat demand, ambient temperature profiles are needed for every typical day category. The identified reference load profile of a typical day category is the profile, which is the most characteristic one for the corresponding typical day category. Therefore, the ambient temperature of this day is used as the ambient temperature profile.

2.3 Dynamic simulation model

In this study, a double-stage ORC is considered for the power generation based on a real geothermal power plant in the Molasse Basin of southern Germany. Figure 2 presents a scheme of the power plant.

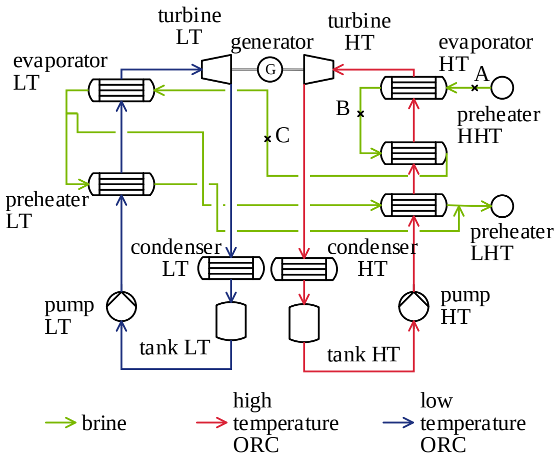

Figure 2: Scheme of the considered double-stage ORC system

The plant consists of two ORC modules: a high-temperature (HT) and a low-temperature (LT) module. In both modules, R245fa is used as working fluid. The thermal water feds the HT-evaporator and then the high-high-temperature (HHT)-preheater first. After that, the thermal water enters the LT-evaporator before it is split and fed to the LT- and LHT-preheater. For cooling, air-cooled condensers are used. Fundamental design data of the power plant is summarized in Table 3.

Table 3: Nominal parameters of the considered ORC-power plant

parameter	value
thermal water temperature	138 °C
thermal water mass flow rate	120 kg/s
ambient temperature	8 °C
power rate	5.5 MW
HT-turbine inlet pressure	13.3 bar
LT-turbine inlet pressure	5.8 bar

The simulation model is built-up in Dymola (Dassault Systèmes, 2014) based on the ThermoCycle library (Quoilin et al., 2014). The fluid properties are calculated by the software Coolprop (Bell et al., 2014). A detailed description and validation of the simulation model is shown by Eller et al. (2019a).

2.4 Combined heat and power plant concepts

In this study, three different plant concepts for geothermal heat and power generation are investigated: parallel, parallel-HHT and parallel-LT. In principle, the parallel concept is shown in Figure 3.

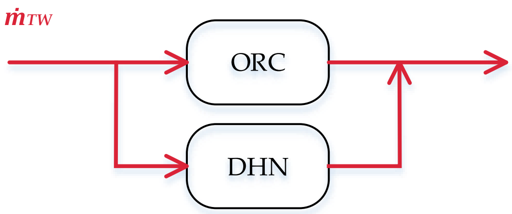

Figure 3: Scheme of the parallel heat extraction concept

For the parallel concept, the thermal water is split to the DHN before entering the ORC (point A in Figure 2). The operational strategy for the combined heat and power generation is heat driven. This means that the heat demand of the DHN must be covered by the geothermal source at any time. The remaining mass flow rate of the thermal water is used for power generation in the ORC plant. Regarding the parallel-HHT-concept, the thermal water is coupled to the DHN after the HT-ORC-evaporator (point B in Figure 2). For the parallel-LT-concept, the brine is split between the HT- and the LT-ORC-module (point C in Figure 2). The temperatures of the brine at the design case are summarized in Table 4.

Table 4: Brine temperatures at the design point

point	brine temperature / °C
A	138.0
B	105.2
C	92.9

Depending on the assumed supply temperature of the DHN, for the parallel-HHT and parallel-LT it is possible, that the thermal water temperature is not sufficient to reach the required supply temperature of the considered DHN. In this case, thermal water directly from the well (point A in Figure 2) is additionally coupled to the DHN and mixed with the brine from point B (for parallel-HHT) and point C (for parallel-LT) to meet the supply temperature.

For the DHN a peak load of 5 MW is considered. Regarding the temperature level three generations are investigated. The first one is a second generation heating network with a supply temperature of 110 °C and a return temperature of 70 °C (110/70). In addition, a third generation 90/60 DHN is considered and a fourth generation 60/35 DHN.

2.5 Thermodynamic and economic evaluation parameters

The evaluation of the different heat and power plant concepts is based on annual simulations. Next to thermodynamic, also economic parameters are considered. The CHP concepts are compared to the reference case of pure power generation.

For the thermodynamic evaluation the second law efficiency

$$\eta_{II} = \frac{P_{el,net} + \dot{E}_{DHN}}{\dot{E}_{HS}} = \frac{P_{el,gross} - P_{el,pump} - P_{el,fans} - P_{el,aux} + \dot{E}_{DHN}}{\dot{E}_{HS}} \quad [3]$$

is used. The exergy flow rate $\dot{E}$ is calculated by

$$\dot{E} = \dot{m}\left[h - h_0 - T_0\left(s - s_0\right)\right]. \quad [4]$$

$P_{el,net}$ is the net power output of the plant, which is the difference between the gross power output and the electrical power consumption of the components. The power consumption of the components consists of the consumption of the pump $P_{el,pump}$, the electrical power needed for the fans of the air-cooled condensers $P_{el,fans}$ and for the auxiliary equipment like control or lubrication equipment. The electricity demand for the thermal water pump is not considered. The fans of the condensers are usually operating at constant speed Therefore, a constant power consumption of 788.0 kW is assumed for the auxiliary equipment and the fans according to real operational data of the power plant. $\dot{E}$ is the exergy flow rate of the heat source (HS) and to the DHN. The dead state is assumed to be at 15 °C and 1 bar.

For the economic evaluation, the annual revenues are considered. The revenues are composed of the remuneration for power and heat supply and calculated according to

$$E = \sum_{typical\ days} (P_{el,gross} \cdot p_{el} + \dot{Q}_{DHN} \cdot p_{HE}) \cdot n \quad [5]$$

For the power, the price for 1 kWh generated from geothermal resource is fixed German law to 0.252 €. For the heat supply the average price for district heating (106.1 €/MWh) of Germany in 2017 is assumed (Statistisches Bundesamt, 2019).

The basis for all considered concepts in this study is the double-stage ORC system. So the investment costs for all concepts are the same and can be neglected. In future work, a detailed economic model will be developed to consider the investment costs of the heat supply.

3. RESULTS

In this section, the results for the different DHN generations are presented. For a 110/70 DHN, the second law efficiency for the considered heat and power plant concepts is shown in Figure 4.

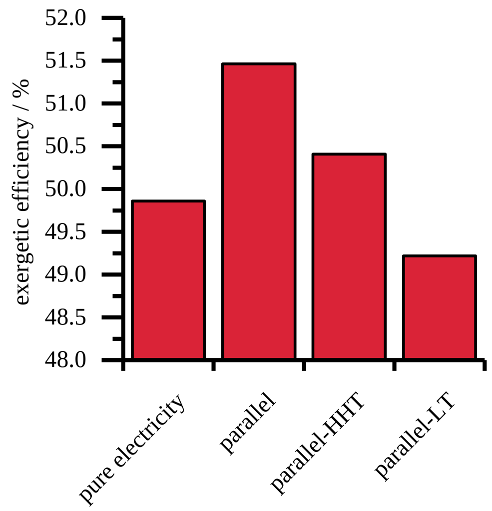

Figure 4: Second law efficiency for considered configurations for a 110/70 district heating network

The second law efficiency can be increased by the parallel concept by 3.2 % up to 51.5 %. Since a part of the thermal water is needed for heat generation, the generated electrical energy by the parallel concept is only 41.5 GWh which corresponds to a decrease of 2.9 GWh compared to single power production. However, about 20 GWh additional thermal energy is delivered to the connected DHN.

As described, for the parallel-HHT concept, the brine temperature is lower than the supply temperature of the DHN of 110 °C (see point B in Table 4). Therefore, also thermal water from the well is connected to the DHN to reach the supply temperature. The second law efficiency of the parallel HHT concept is 50.4 % and also 1.1 % higher than for power production. Since the same heat demand is covered as for the parallel concept, the reason for the lower efficiency is a lower amount of electrical energy produced. In comparison to power production the electrical energy produced by the parallel-HHT concept is 8.6 % lower.

For the parallel-LT concept, also thermal water from the well must be coupled to the DHN to reach the supply temperature. The second law efficiency is 49.2 % and in this case even 1.3 % lower than for the power production. The generated electricity is 39.5 GWh, which corresponds to a decrease of 11.1 %.

In terms of economic considerations, the annual revenues are summarized in Table 5. The parallel concept leads to an annual return of 12.6 million (M) €. This is an increase of 12.4 % compared to the power production. Therefore, the additional revenues due to the heat supply can compensate the lower revenues of electricity generation. For the parallel HHT concept, the annual return can also be increased compared to power generation by 10.2 %. Even for the parallel-LT concept, the revenues are 7.8 % higher than for the power production although in this case, the second law efficiency is lower than for power generation. To sum up, for a 110/70 DHN the parallel concept is thermodynamically and economically recommended.

Table 5: Annual return for the considered configurations for a 110/70 district heating network

concept	annual return / M€
pure	11.2
parallel	12.6
parallel-HHT	12.3
parallel-LT	12.1

In the next step, a third generation DHN is considered with a supply temperature of 90 °C and a return temperature of 60 °C. The results for the second law efficiency are presented in Table 6.

Table 6: Second law efficiency for the considered configurations for a 90/60 district heating network

concept	second law efficiency / %
pure	49.9
parallel	51.0
parallel-HHT	51.8
parallel-LT	51.4

For the parallel configuration, the second law efficiency is 51 % and 2.3 % higher than for the power generation concept. The generated electricity per year is 41.8 GWh. This is a decrease of 5.9 % compared to power production. By the additional heat supply, the amount of delivered exergy is higher than for the reference case. Regarding the parallel-HHT concept, the temperature level is now sufficient to reach the supply temperature of 90 °C and therefore no thermal water has to be coupled to the DHN directly from the well. The second law efficiency is 51.8 % and 3.8 % increased by the additional heat supply. The amount of electricity generated is 42.5 GWh. This corresponds to a relative decrease of 4.3 %. However, more electrical energy can be produced compared to the parallel concept.

For the parallel-HHT concept, a lower thermal power for preheating in the HHT is provided. In addition, the thermal water temperature at the LT-evaporator inlet is lower and therefore the power output of the LT-cycle. However, the higher thermal power fed to the HT-evaporator can compensate the lower LT-power output, and the amount of generated electricity is increased.

In case of the parallel-LT concept, the temperature of the thermal water is still not sufficient to reach the supply temperature. Therefore, again thermal brine directly from the well is coupled to the DHN. The second law efficiency for this configuration is 51.3 %. This is an increase of 3.0 % compared to power generation. Despite of the additional heat supply, 42.1 GWh electricity can be generated.

The annual revenues are presented in . The parallel concept leads to an increase of 13.4 % compared to power generation. This corresponds to an annual return of 12.7 M€. In case of the parallel-HHT concept the annual return is increased by 15.0 % up to 12.9 M€. For the parallel-LT concept the revenues are 12.8 M€ and therefore higher than for power generation and the parallel concept, but lower than for the parallel-HHT configuration.

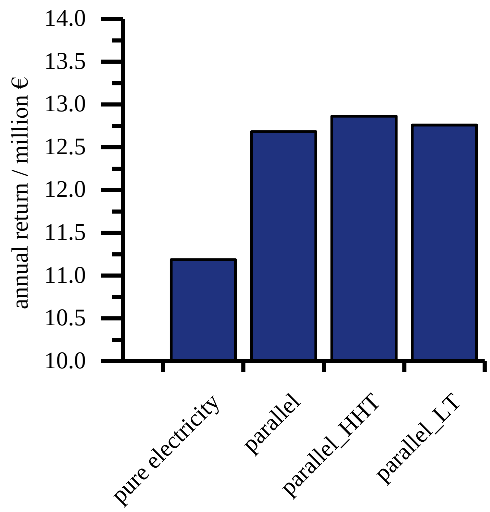

Figure 5: Annual revenues for considered configurations for 90/60 district heating network

The second law efficiency considering a fourth generation DHN with a supply temperature of 60 °C and a return temperature of 35 °C is shown in Figure 6.

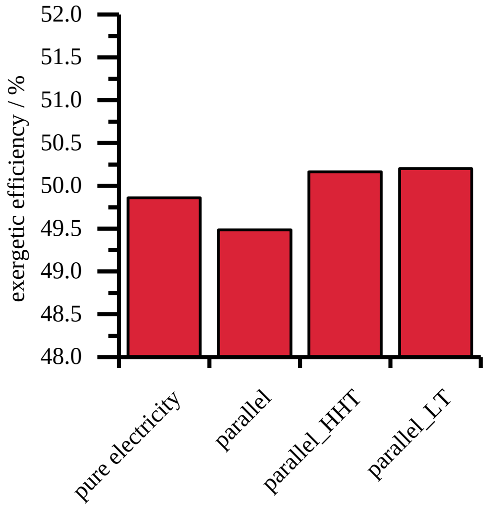

Figure 6: Second law efficiency for considered configurations for 60/35 district heating network

In comparison to power production for the parallel concept the second law efficiency is 0.8 % lower. The decrease in electrical energy delivered is 2.6 GWh. However, round about 20 GWh thermal power is fed into the DHN. Due to the low temperature level of the DHN, the exergy of the heat supply cannot compensate the decrease in power generation. For the parallel-HHT concept, the exergetic efficiency is 0.6 % higher than for power generation. The electrical power produced is 4.3 % lower, but can be compensated by the additional heat supply to the DHN. For the parallel-LT concept there is also a small increase in second law efficiency of 0.7 %. The generated electrical power is 42.5 GWh and approximately similar to the parallel-HHT concept.

Table 7: Annual return for the considered configurations for a 60/35 district heating network

concept	annual return / M€
pure	11.2
parallel	12.8
parallel-HHT	12.9
parallel-LT	13.0

In terms of economic considerations, the revenues can also be increased by the parallel concept by 14.3 % up to 12.8 M€. The second law efficiency is lower than for power generation, but the additional revenues of the heat supply overcome the lost revenues because of the decrease in electrical power generation. For the parallel-HHT concept the annual revenue is 12.9 M€, which corresponds to an increase of 15.7 %. Next to the additional revenues of the heat supply, for the parallel-HHT concept more electrical energy is generated and therefore, the revenues are slightly higher than for the parallel concept. Considering the parallel-LT concept, the increase in revenue compared to electrical power generation is approximately similar to the parallel-HHT concept. For the parallel-LT concept the electrical power generation is slightly higher, because all thermal power of the brine can be supplied to the more efficient HT-cycle.

3. CONCLUSIONS

Based on the simulations of geothermal CHP it is shown, that, in general, the annual return can be increased by an additional heat supply compared to the power generation. For the second law efficiency it depends on the configuration, if there is an increase or a decrease. For all district heating networks considered, there is at least one configuration which shows a higher second law efficiency.

For the 110/70 DHN the highest increase of the second law efficiency is obtained by the parallel concept. Although, the power generation is reduced by 6.4 %, the exergy of the additional heat supply leads in total to a second law efficiency of 51.5 %, which is an increase of 3.2 %. Regarding the economic analysis, the annual return can be increased by 12.2 % up to 12.6 M€.

For the 90/60 DHN the most appropriate concept in terms of thermodynamic and economic considerations is the parallel-HHT concept. The generated power is 4.3 % lower than for the reference case, but the second law efficiency is increased by 3.8 %. In terms of economic considerations, the annual revenues can be increased by up to 13.4 %.

For the 60/35 district heating network the parallel-LT concept is the most appropriate configuration. The second law efficiency can be slightly increased by 0.7 %. The annual revenues of nearly 13 M€ are 15.8 % higher than for power generation.

In summary, a lower temperature level of the district heating network leads to higher annual revenues compared to the power generation. In future work the peak load of the district heating network is varied and an economic model is developed to account for the costs of the district heating network.

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Acknowledgements

The funding from the Bavarian State Ministry for Education, Science and the Arts in the framework of the project ‘‘Geothermie-Allianz Bayern” is gratefully acknowledged.