THERMODYNAMIC AND ECONOMIC ANALYSIS OF GEOTHERMAL COMBINED HEAT AND POWER BASED ON A DOUBLE-STAGE ORGANIC RANKINE CYCLE

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ABSTRACT

For low-enthalpy resources, geothermal energy is usually converted to electricity by Organic Rankine Cycles (ORC). The efficiency and the profitability of these ORC power plants can be improved by an additional heat supply. In this study, several combined heat and power (CHP) plant configurations are investigated and evaluated in terms of thermodynamics and economics. For the evaluation, annual simulations are performed based on a dynamic model of a double-stage ORC system and the results are compared to pure power generation. For the heat supply, a district heating network (DHN) with a supply temperature of 90 °C and a return temperature of 60 °C is considered. The characteristics of the DHN are varied in respect to the peak load in the range of 5 MW to 20 MW.

The results show that, in general, the additional heat supply leads to significant improvements in the efficiency and the profitability of the plant. The sensitivity analysis of the peak load shows that the advantage of the CHP over the reference case increases with a higher peak load and a corresponding increase in heat demand. For a DHN with a peak load of 5 MW the mean exergetic efficiency can be increased by 5.4 % up to 45.0 %. Considering a peak load of 20 MW, the mean exergetic efficiency is 50.2 %, which corresponds to a relative increase of 17.8 %. In terms of economics, for a 5 MW peak load the annual revenues can be increased by 9.8 % up to 12.5 million EUR. For a peak load of 20 MW the revenues can be further increased by 2.9 million EUR. This corresponds to an increase of 35.6 % compared to the power generation.

1. INTRODUCTION

Geothermal energy is a renewable resource for low-carbon power generation. For low-enthalpy reservoirs, the thermal energy of the brine is usually converted to electricity by binary cycles like the Organic Rankine cycle (ORC). Former investigations show that the efficiency and profitability of these power plants can be increased by an additional heat supply (Eller et al., 2019c; Heberle et al., 2016; van Erdeweghe et al., 2018). Due to the fluctuating heat demand, the power plant is driven more often in part-load conditions. Therefore, in this study a dynamic ORC model is developed.

In the literature, dynamic models of ORC are usually developed for waste heat recovery. Marchionni et al. (2017) considered a dynamic model of a one-stage ORC to investigate the off-design behavior. The results show that the power output can be optimized by varying the speed of the pump and the turbine. Shan Lin et al. (2019) investigate a dynamic ORC model for waste heat recovery from an internal combustion engine to improve the overall system efficiency. Therefore, a dynamic model is developed in Dymola/Modelica and two different concepts are considered: a pure ORC and an ORC combined with an oil storage system. The ORC in combination with the oil storage shows a better heat recovery performance than the pure ORC. In addition, fluctuations of the heat source can be damped by the oil storage system. Next to waste heat recovery applications, Baccioli et al. (2017) investigate a solar driven ORC power plant. A dynamic model is developed to analyze a year-long operation of the plant at different sites. The study shows that the specific production can be increased by the concentration ratio and with the decrease of latitude. In addition, a control strategy is identified to drive the system without the need of a storage system.

In the field of geothermal cogeneration systems, van Erdeweghe et al. (2018) investigated different configurations for geothermal combined heat and power generation. The study is based on a stationary simulation model of a one-stage ORC system and different temperature levels of the district heating network are considered. The heat demand of the district heating network is assumed to be constant. In the context of geothermal combined heat and power generation, Dawo et al. (2019) investigate the part load behavior of a Kalina cycle and present suitable correlations for off-design cycle simulation. Seyfouri et al. (2018) conduct an exergo-economic analysis of different concepts for geothermal combined cooling and power based on an ORC. The results show that the parallel-series concept shows a better performance in terms of second law efficiency and leads to the lowest production unit costs. Chauhan et al. (2019) investigate an ammonia-water based cycle for a variable refrigeration and power load fed by a geothermal source. The system is optimized in terms of the second law efficiency and the authors show that by the variable generation of cooling and electricity the geothermal source can be fully utilized all through the year.

In this study, different concepts for geothermal combined heat and power generation are investigated and evaluated based on annual simulations. For the power system, a double-stage ORC is considered related to an existing power plant. For the simulation, a dynamic model of the ORC system is built-up to take into account the fluctuating heat demand and ambient temperature over the day. Regarding the heat demand, load profiles are developed based on a real geothermal fed district heating network. The simulation model, the heat load profiles and the considered configurations are described in section 2. In section 3 the results are presented.

2. METHODOLOGY

For the evaluation of the different plant configurations, annual simulations are performed inspired by VDI 6455 (Gesellschaft Energietechnik and Verein Deutscher Ingenieure, 2008). Therefore, a dynamic simulation model is developed and heat load profiles are implemented to model the heat demand of the district heating network.

2.1 Annual simulations according to VDI 4655

In the VDI 4655 ten typical days are defined based on the time of the year, the weekday and the cloudiness. For the time of the year, it is differentiated between summer (S), transition (Ü) and winter (W). For the weekdays, there are workdays “W” (including Saturdays) and Sundays “S” (including all national holidays) to account for the different user behavior. Regarding the cloudiness, fine and cloudy days are distinguished. In the summer time the distinction between cloudy and fine days can be neglected (X). The typical days defined by these criterions are summarized in Table 1.

Table 1: Typical-day categories according to VDI 4655 (Gesellschaft Energietechnik and Verein Deutscher Ingenieure, 2008)

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	WSH	WSB

According to VDI 4655, Germany is divided in 15 climate zones. For each climate zone a test reference year (TRY) is defined. An excerpt of the TRY per climate zone is shown in Table 2. Depending on the climate zone, the frequency (*n*) of the typical days per year varies. For example, in TRY14 there are 115 winter working days (WWB) per year while there are only 57 of them in TRY12.

Table 2: Test reference years according to VDI 4655 (excerpt) (Gesellschaft Energietechnik and Verein Deutscher Ingenieure, 2008)

climate zone	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
…										

For annual simulations, the ten typical days are simulated and the results are scaled up to one year according to the corresponding TRY. In this study TRY13 is used, because this region belongs to the Southern German Molasse Basin.

2.2 Heat demand profiles

To model the heat demand of the district heating network (DHN), heat load profiles for the typical day categories are developed based on operational data of a real geothermal fed DHN inspired by Dubielzig et al. (2007).

At first, the real operational data of the heat plant is assigned to the typical day categories. The heat load profiles are standardized and outliers are removed. A detailed description of the identification of outliers can be found in Eller et al. (2019a). In the next step, the squared error from the mean value is calculated for each measurement time. The heat load profile with the lowest mean value of the squared error is the reference load profile for the corresponding typical day category. Finally, the standardization is cancelled and the reference load profiles are adjusted for weather variations. A detailed explanation of the weather adjustment method based on degree days can also be found in Eller et al. (2019a).

Next to the heat demand, ambient temperature profiles are needed for the typical day categories. For the heat demand based on the method above a reference profile for each category is identified. This is the load profile, which is the most characteristic one for the corresponding typical day category. For that reason, the ambient temperature profile of this day is used as data set for each typical day category.

2.3 Simulation model

For the simulation, a dynamic model of a double-stage ORC is developed related to an existing power plant in the Southern German Molasse Basin. For modelling the software Dymola (Dassault Systèmes, 2014) is used in combination with the ThermoCycle (Quoilin et al., 2014) library. The fluid properties are calculated by CoolProp (Bell et al., 2014).

In Figure 1 the scheme of the double-stage ORC is presented. The plant consists of two ORC units: a high temperature (HT) module and a low temperature (LT) module. In both units R245fa is used as working fluid. The geothermal water (brine) feeds the HT-evaporator followed by the HHT-preheater. After that, the brine enters the LT-evaporator. At the LT-evaporator outlet, the brine mass flow rate is split to supply the LT- and the LHT-preheater before the geothermal water is reinjected. For the condensation of the working fluid in both ORC modules air-cooled condensers are used. Fundamental design data of the power plant can be found in Table 3.

Table 3: Nominal parameters of the considered ORC power plant

parameter	value
Geothermal water temperature	138 °C
Geothermal 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

A detailed description and validation of the simulation model can be found in (Eller et al., 2019b).

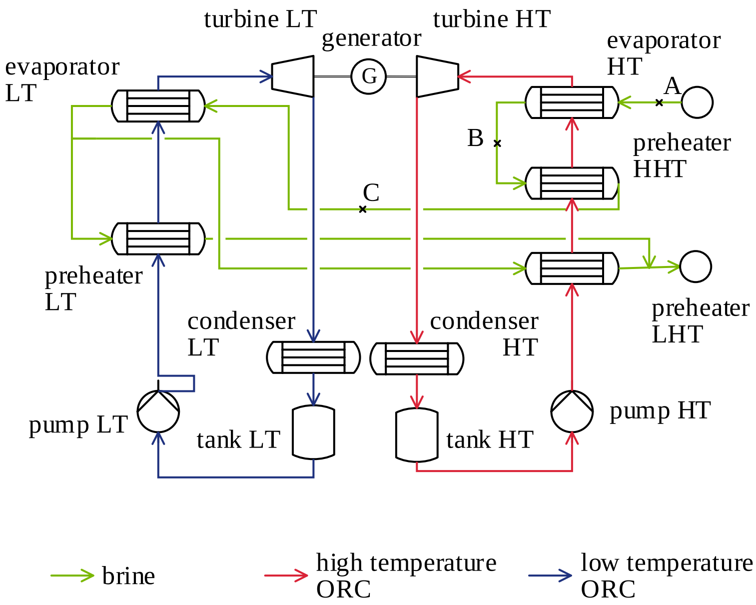


Figure 1: scheme of the double-stage Organic Rankine Cycle

2.3 Combined heat and power plant concepts

In this study, the operational strategy of the combined heat and power (CHP) plant is heat driven, i.e. the whole heat demand of the DHN must be covered by the geothermal source at any time. The remaining mass flow rate is used in the ORC plant for power generation. In this study, three different concepts for geothermal CHP generation are considered: the parallel-concept, the HHT-concept and the LT-concept.

For the parallel plant configuration, the geothermal water is split to the DHN depending on the current heat demand before entering the double-stage ORC (point A in Figure 1). For the HHT concept the geothermal water is split to the DHN before entering the HHT-preheater (point B in Figure 1). For the LT concept, the brine is coupled to the DHN between the HT- and the LT-module (point C in Figure 1). For all considered CHP-concepts, the geothermal water is coupled back to the ORC after feeding the DHN between the HT- and the LT-cycle (point C in Figure 1).

For the DHN a supply temperature of 90 °C and a return temperature of 60 °C is assumed. The peak load is varied in the range of 5 MW to 20 MW. This leads to a variation in the thermal energy demand between 21.5 MWh/a and 86 MWh/a.

Depending on the peak load and the supply temperature of the DHN, for the HHT and the LT CHP-configuration, there is the possibility that the thermal energy at the decoupling point is not sufficient to cover the peak load and/or to reach the supply temperature of the DHN. In this case, geothermal water directly from the well (point A in Figure 2) is additionally coupled to the DHN and mixed with the geothermal water at point B (for HHT) and point C (for LT) to meet the heat demand.

2.4 Thermodynamic and economic evaluation parameters

The CHP-plant concepts are evaluated by thermodynamic and economic parameters. The results are compared to the reference case pure power generation. The thermodynamic evaluation is based on the second law efficiency according to equation (1):

$$\eta_{II} = \frac{P_{el,net} + \dot{E}_{DHN}}{\dot{E}_{HS}} = \frac{P_{el,gross} - P_{el,pump} - P_{el,fans} - P_{el,aux} + \dot{E}_{DHN}}{\dot{E}_{HS}} \quad (1)$$

For each typical day, the mean value of the second law efficiency is calculated and weighted by the frequency *n* of the corresponding typical day category to obtain a mean annual second law efficiency. The exergy flow rate $\dot{E}$ is calculated by

$$\dot{E} = \dot{m}\left[h - h_0 - T_0\left(s - s_0\right)\right]. \tag{2}$$

$P_{el,net}$ is the net power output of the double-stage ORC. It is the difference between the gross power output of the generator and the electrical power consumption of the cycle components. In the double-stage ORC electrical power is needed for the feed pumps $P_{el,pump}$ and for the fans of the air-cooled condensers $P_{el,fans}$. In addition, electrical power is consumed by auxiliary equipment like control or lubrications equipment ($P_{el,aux}$). The electricity demand for the geothermal water pump is not considered. For the fans of the air-cooled condensers and the auxiliary equipment a constant value of 788 kW is assumed according to the 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 for calculating the exergy is assumed to be at 15 °C and 1 bar.

For the economic evaluation, the annual revenue of the CHP-plant is calculated. It consists of the remuneration for power and heat supply and is calculated according to

$$E = \sum_{typical\ days} (P_{el,gross} \cdot p_{el} + \dot{Q}_{DHN} \cdot p_{HE}) \cdot n \tag{3}$$

For the power, the remuneration for 1 MWh electrical power generated by geothermal resource is fixed by the German law to 25.2 c€/kWh. For the heat supply, the mean price of 72.16 €/MWh for district heating of Germany in 2018 is assumed (AGFW - Der Effizienzverband für Wärme, Kälte und KWK e. V., 2019).

The basis for all CHP-concepts considered in this study is the double-stage ORC. Therefore, the investment costs can be neglected. In the future, a detailed economic model is developed to take into account the investment costs for the additional heat supply.

3. RESULTS

The exergetic efficiencies of the different configurations for a peak load of the DHN of 5 MW are shown in Figure 2 (a). For all considered concepts, the additional heat supply leads to an increasing exergetic efficiency of at least 3.6 %. The HHT-concept shows the highest exergetic efficiency of 45.0 %, which corresponds to a relative increase of 5.4 %.

The heat demand of the DHN is 21.5 GWh per year. It is covered by the geothermal resource for all configurations. The remaining thermal energy of the brine is converted to electricity. The LT-concept delivers nearly the same amount of electricity per year than the parallel-concept. For the HHT-configuration almost 1 GWh more electrical energy is produced than for the other concepts. Usually, the LT-concept is expected to produce the highest electrical power output. However, for the considered DHN geothermal water directly from the well (point A in Figure 1) has to be coupled to the DHN to observe the DHN supply temperature of 90 °C. Therefore, the LT-concept is quite similar to the parallel concept. For the parallel concept, the whole heat demand is covered by geothermal water on a high temperature level (directly from the well). For the LT configuration, a part of the heat demand can be covered by the geothermal water at a lower temperature level (point C in Figure 1). Therefore, a lower amount of geothermal water must be coupled to the DHN at point A and more thermal energy is fed to the HT-cycle. Since the HT is more efficient than the LT-cycle, the LT-concept is expected to produce more electrical energy than the parallel-concept. However, due to the small DHN with a peak load of 5 MW, there is no significant advantage of the LT-concept recognizable.

For the economic analysis, the annual revenues are shown in Figure 2 (b). In general, the revenues are at least 8.1 % higher than for power generation, which corresponds to an absolute growth of 0.9 million (M) € per year. This is the case for the parallel-concept, since it leads to the lowest increase in exergetic efficiency. For that configuration 2.5 GWh lower electrical energy is generated than for the power generation. This corresponds to lost revenues of 0.6 M€. On the other hand, there are higher revenues due to the additional heat supply of 1.5 M€. For the other concepts, the increase in revenues due to the heat supply is equal, but the lost revenues are lower since more electricity can be generated. The highest growth in revenues is for the HHT-concept. It is 12.5 M€ and therefore 9.8 % higher than for power generation.

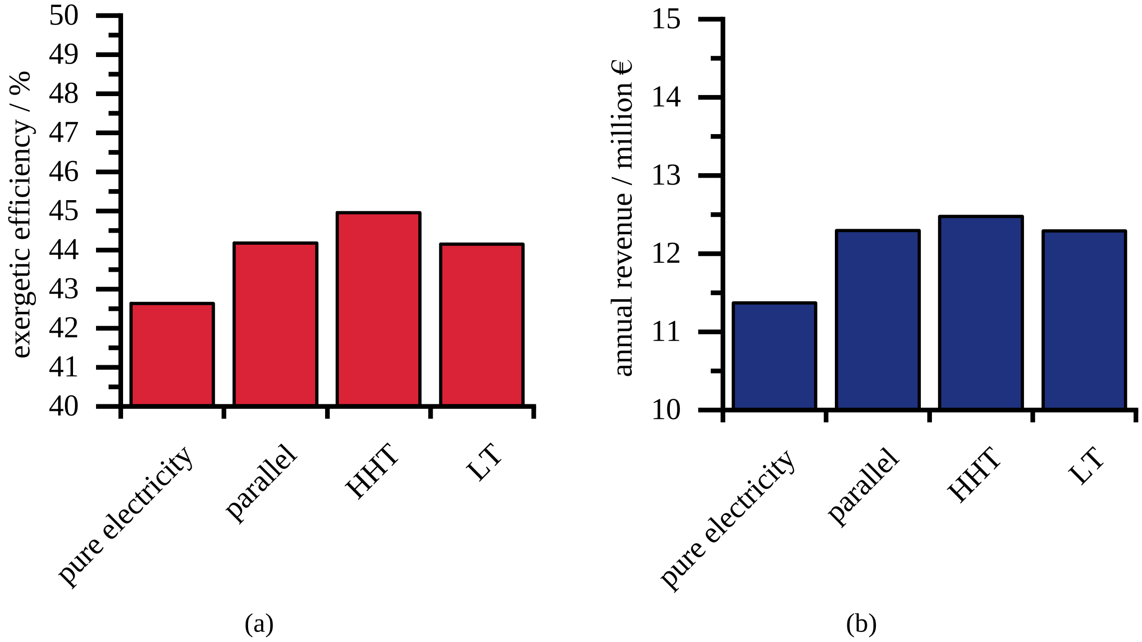


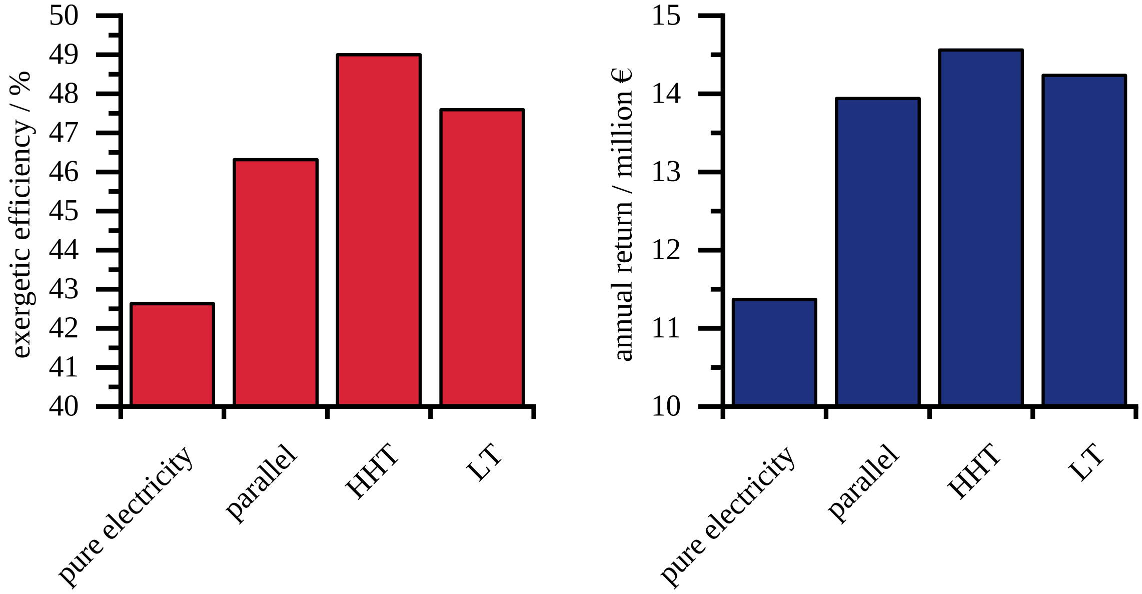
Figure 2: Exergetic efficiency (a) and annual revenues (b) for the different CHP plant concepts for a DHN with a peak load of 5 MW

For a peak load of 10 MW, the parallel concept leads to the lowest efficiency increase of 6.3 %. Analogous to a 5 MW DHN, the HHT-concept shows the highest exergetic efficiency of 47 %. This corresponds to an increase of 10.3 % compared to power generation. The LT-concept has an exergetic efficiency of 46.0 %. Because of the higher heat demand, the electrical power generation decreases. For the parallel-concept and the LT-concept, the reduction is 11.8 % and 10.3 %, respectively. The highest amount of electricity is generated by the HHT-concept: 41.4 GWh are generated per year, which corresponds to a reduction of 8.3 %.

In terms of economic analysis, for the parallel-concept the annual revenues are 15.5 % (13.1 M€) higher than for power generation. Compared to the 5 MW DHN, the revenues can be increased again by 0.8 M€. For the LT-concept, the results are quite similar to the parallel-concept. The highest revenues are obtained by the HHT-concept: The increase is about 19.0 % up to 13.5 M€ per year.

The peak load of the DHN is now further increased to 15 MW. The results for the exergetic efficiency are presented in Figure 3 (a). The thermodynamic analysis shows that the ranking is similar to the 10 MW DHN: The highest efficiency increase is obtained by the HHT-concept. The exergetic efficiency is 49.0 % and increased by 14.9 %. For the LT-concept, the exergetic efficiency is 11.6 % higher than for power generation and the lowest efficiency increase with 8.6 % is for the parallel-configuration.

Concerning the produced amount of electricity due to the further increased heat demand, the power generation decreases. For the parallel-concept, 36.8 GWh can be generated. This is a decrease compared to power generation of 18.3 % and 3 GWh lower than for the 10 MW DHN. For the LT-concept, 38 GWh electricity can be generated, which is 3.2 % higher than for the parallel-concept. Compared to a peak load of 5 MW, for a 15 MW DHN the advantage of the LT-concept over the parallel-concept is more significant.



(a) (b)

Figure 3: Exergetic efficiency and annual revenues for the different CHP plant concepts for a DHN with a peak load of 15 MW

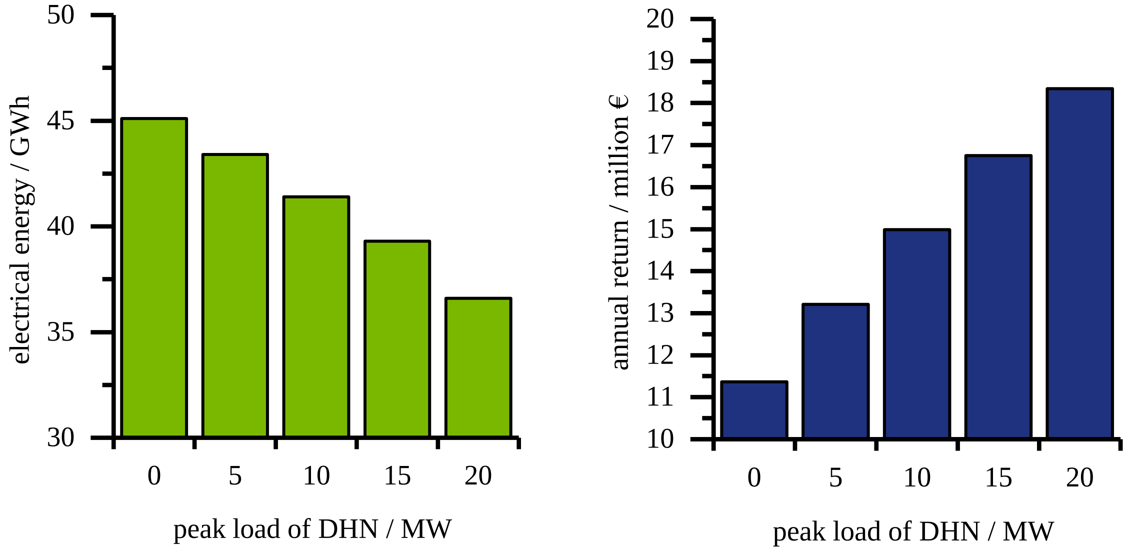
The annual revenues for the combined heat and power (CHP)-plant concepts are shown in Figure 3 (b). The annual return can be further increased by the CHP-generation. The parallel concept leads to the lowest increase of 22.6 %. This corresponds to an absolute increase in revenue of 2.6 M€. For the other concepts, the increase is even higher. The HHT-concept shows the highest revenue of 14.6 M€. This is 28.1 % higher than for power generation.

In the last step, the peak load of the DHN is set to 20 MW. The results are similar to the former investigated peak loads. In general, the combined heat and power generation leads still to an efficiency increase. For the parallel concept, the increase is 10.6 % up to 47.1 %. It is followed by the LT-concept with an exergetic efficiency of 48.8 %. The highest efficiency of 50.2 % is obtained by the HHT-concept. For the peak load of 20 MW, the power generation decreases for the parallel concept by 25.2 % to 33.8 GWh. The LT-concept generates 4.5 % more electrical energy (35.3 GWh). For the HHT-concept the highest amount of electricity is generated (36.6 GWh).

The annual revenues are higher than for power generation. The decrease in electrical energy is therefore overcompensated by the additional thermal energy supplied to the DHN. For the parallel-concept, the revenues are 29.4 % higher than for power generation. The LT-concept leads to even higher revenues of 15.1 M€ (32.7 %). Analogous to lower peak loads of the DHN, the HHT-concept shows the highest increase in revenues of 35.6 % up to 15.4 M€.

For each of the considered configurations, the rising peak load of the DHN leads to higher exergetic efficiencies. For the HHT-concept, the exergetic efficiency is 45.0 % for a 5 MW DHN and it is increased by a 20 MW DHN up to 50.2 %. This is equal to a relative increase of 11.7 %. For the LT- and the parallel concept the relative increase is 10.6 % and 6.7 %, respectively.

The increasing peak load leads to a lower electricity production. Exemplarily, the generated electrical energy per year of the HHT-concept is shown in Figure 4 (a) for the different peak loads, since the HHT-concept is the most efficient CHP-concept. In this context, a peak load of 0 MW corresponds to pure power generation. For a peak load of 5 MW, 43.4 GWh electrical energy is generated per year. This is a decrease of 3.9 % compared to power generation (45.1 GWh). With increasing peak load of the DHN the electrical energy produced continues to decrease. For a 20 MW DHN, the decrease is 19.0 % (36.6 GWh).



(a) (b)

Figure 4: Generated electrical power and annual revenues of the HHT-concept for the considered peak loads of DHN

The increase in peak load of the DHN goes along with higher revenues. For the HHT-concept, the annual revenues over the peak load are presented in Figure 4 (b). For a 5 MW DHN, the annual revenues are 12.5 M€, which corresponds to an increase of 9.8 % compared to the reference case. For a peak load of 20 MW, the annual revenues are increased by 35.6 % up to 15.4 M€. For the considered peak loads, the HHT-concept shows a relative increase of 23.6 % from 12.5 M€ (5 MW) up to 15.4 M€ (20 MW). For the LT- and the parallel-concept the relative increase is slightly lower (22.8 % and 19.7 %, respectively).

4. CONCLUSION

In this study, different concepts for geothermal combined heat and power generation are considered. For the district heating network (DHN) a supply temperature of 90 °C and a return temperature of 60 °C is assumed. The peak load is varied in steps of 5 MW from 5 MW peak load to 20 MW.

The main results are summarized as follows:

- For all considered peak loads the HHT-concept is the most efficient and profitable one. The efficiency increase is in the range of 5.4 % up to 17.8 %. The LT- and the parallel-concepts show lower efficiencies.
- For low peak loads of the DHN, the LT-concept is comparable to the parallel one. For high peak loads, the LT-concept is more favorable than the parallel concept, because geothermal water on a lower temperature level is used to cover the base load of the DHN.
- The higher the peak load of the DHN the higher is the increase in exergetic efficiency and profitability. For the HHT-concept and a 5 MW peak load of the DHN, the annual return can be increased by 9.8 % compared to power generation. For a 20 MW peak load, the relative increase of the annual revenues is 35.6 % up to 15.4 M€.

Regarding the economic analysis, different peak loads of the DHN usually lead to different investment costs. Therefore, in future work a detailed economic model is developed to account for the investment costs of the DHN.

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