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Thermoeconomic comparison of designs for geothermal combined heat and power generation

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ABSTRACT

In this paper different power plant designs for geothermal power and heat generation are examined under thermodynamic and economic aspects. For quasi steady-state simulations the heat demand is calculated according to reference load profiles of single-family and multi-family houses, which are approximated by discrete load steps. Based on standard conditions sensitivity analyses concerning heat demand, supply temperature, ORC working fluid and geothermal water temperatures are performed. The results show that the hybrid power plant is the most efficient concept for combined heat and power generation. The choice of ORC working fluid is important for geothermal water temperatures higher than 120 °C. Regarding economic aspects the cumulated cashflow obtained by the hybrid power plant is 77 % higher compared to single power generation. The supply temperature of the heating network has a significant influence on thermodynamic and economic efficiency.

1. INTRODUCTION

Combined heat and power generation (CHP) is a promising approach to improve economic conditions in the case of low-temperature geothermal resources. In Germany geothermal water temperatures up to 200 °C can be utilized for energy generation. In case of power generation mainly binary power plants like the Organic Rankine Cycle (ORC) or the Kalina Cycle (KC) are suitable (Tchanche et al., 2011; Vélez et al., 2012). Regarding additional heat generation different concepts can be taken into account. In general, serial or parallel circuit of power and heat generation are considered (Heberle and Brüggemann, 2010). In addition innovative concepts like hybrid power plants can lead to decreasing electricity generation costs. For this purpose the geothermal heat source is coupled with an alternative energy source like a biogas cogeneration unit, solar thermal panels or fossil fuels (Heberle and Brüggemann, 2012; Janczik and Kaltschmitt, 2010; Kohl and Speck, 2004; Tempesti et al., 2012). Focussing on renewable energy sources and regarding boundary conditions for Germany a hybrid power plant of a geothermal heat source and a biogas cogeneration unit is examined in this paper. The described hybrid power plant is compared under thermodynamic and economic aspects to single power generation and parallel circuit for CHP. Based on selected standard conditions sensitivity analyses are performed concerning heat demand and supply temperature of the heating network as well as geothermal water temperature and ORC working fluid.

2. SIMULATION AND ANALYSES

The process simulations are performed by the software Cycle Tempo (Woudstra, N. and Van der Stelt, T.P., 2002) and fluid properties are calculated by REFPROP (Lemmon, E.W. et al., 2002). For power generation an ORC power plant according to Fig. 1 is assumed. The ORC working fluid is forced by the pump to a higher pressure level (7→1) followed by an internal heat exchanger (1→2) and coupling with the geothermal heat source, in the preheater (2→3) first, and then in the evaporator (3→4). In case of so-called dry fluids, which show a positive slope of the dew line in the *T,s*-diagram, no superheating in state point 4 is necessary. In the next step the working fluid is expanded in the turbine (4→5). The internal heat recovery (5→6) and the condensation (6→7) close the cycle.

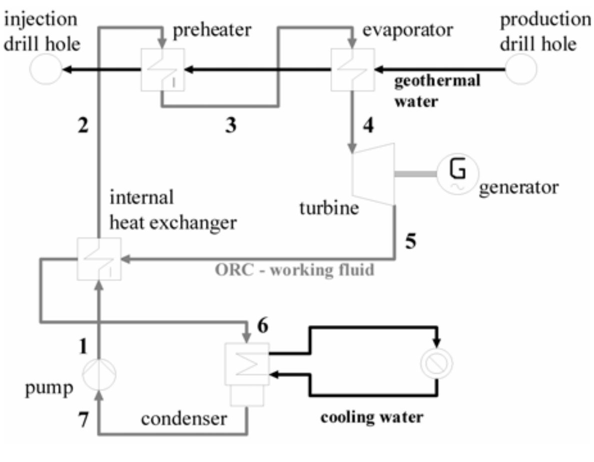

Figure 1: Schematic scheme of an ORC power plant for geothermal application

In Fig. 2 the corresponding *T,s*-diagram of the ORC in case of the working fluid isopentane is shown.

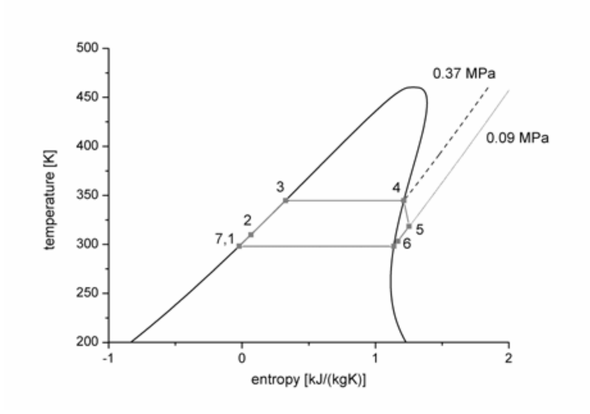

Figure 2: *T,s*-diagram of an ORC with the working fluid isopentane

Process simulations for single power generation are compared to a CHP concept with parallel circuit of power and heat generation, which is shown in Fig. 3. According to heat demand the geothermal water mass flow is splited and the ORC operates in part load.

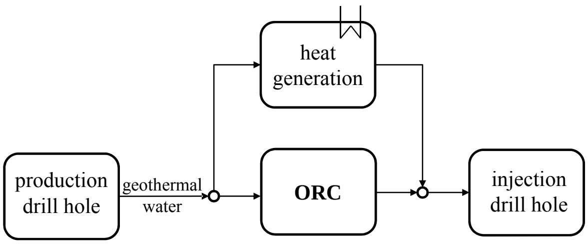

Figure 3: Schematic scheme of the parallel circuit in case of CHP

In addition a hybrid power plant for CHP is investigated (see Fig. 4). The geothermal resource is coupled with a biogas cogeneration unit. A higher geothermal water temperature at the ORC inlet is obtained by utilizing the exhaust gases of the gas engine. The engine coolant provides heat for the heating network in a first step. If necessary a higher amount of heat or higher supply temperatures are obtained by the geothermal water in a second heat exchanger.

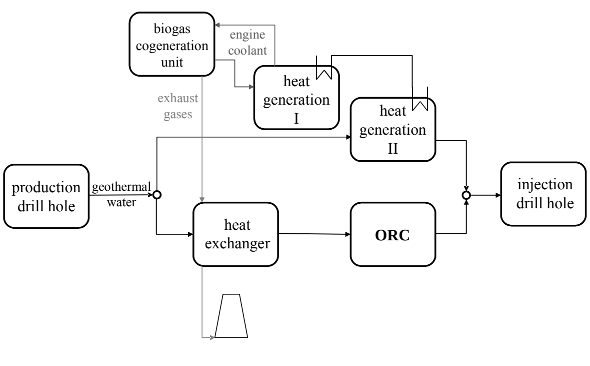

Figure 4: Schematic scheme of the considered hybrid power plant

In case of heat generation different scenarios are examined. The standard case describes a heating network, which supplies a settlement of 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). The resulting annual duration curve is shown in Fig. 5. For a thermal power higher than 6000 kW a peak load boiler is considered. In total a thermal energy of 23.87 GWh is coupled to the heating net. The annual power and heat generation is calculated by quasi steady-state consideration. For this purpose the annual duration is approximated by 10 load steps, which corresponds to ambient temperature of typical climate patterns in accordance to VDI 4655. In addition the dependence of supply and return temperature of the heating net on ambient temperature is taken into account. Simulations for a high-temperature case, with supply temperatures up to 130 °C and a low-temperature case with supply temperatures up to 90 °C are carried out (see Fig. 6).

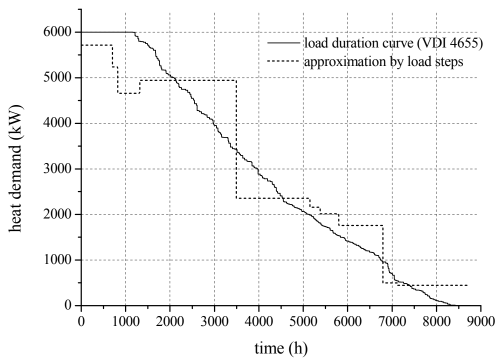

Figure 5: Annual duration curve of the heating net and approximation by load steps for quasi steady-state simulations

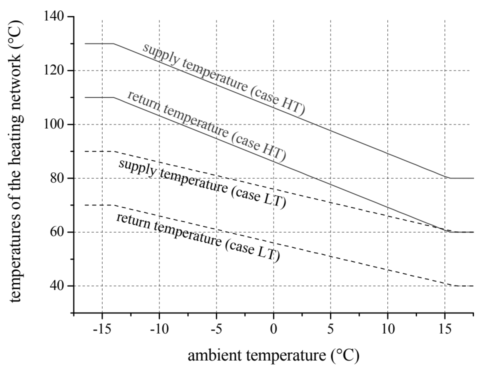

Figure 6: Supply temperature and return temperature of the heating network depending on ambient temperature

Regarding the geothermal heat source two regions in Germany are compared. As standard case the Upper Rhine Rift Valley (URRV) is chosen. In addition the

Southern German Molasse Basin (SGMB) near Munich is also considered. In Tab. 1 typical parameters for the geothermal resources are listed.

Table 1: Parameters for typical geothermal resources in Germany

	URRV	SGMB
T_{GW} (°C)	160	120
$T_{inj,min}$ (°C)	60	30
$\dot{m}_{GW}$ (kg/s)	65	100

Furthermore two different ORC working fluids are considered in the simulations. Fluid properties like critical pressure p_{crit} and temperature T_{crit}, Global Warming Potential GWP and acute toxicity exposure limit ATEL of the chosen 1,1,1,2,2-pentafluoropropane (R245fa) and isopentane are listed in Tab. 2.

Table 2: Fluid properties of R245fa and isopentane

	R245fa	isopentane
T_{crit} (°C)	154.0	187.2
p_{crit} (bar)	36.5	33.8
GWP (4^{th} AS)	1030	3
Safety Group	B1	A3
ATEL/ODL (kg/m^3)	0.19	0.003

In Tab. 3 the boundary conditions of the ORC like isentropic efficiency of the rotating equipment η_i, temperature difference at the pinch point ΔT_{PP} and cooling temperature at the inlet $T_{CW,in}$ are outlined. These parameters are valid in case of single power generation, CHP and hybrid concept.

Table 3: Boundary conditions for the ORC power plant

parameter	
$\eta_{i,T}$ (%)	80
η_G (%)	95
$\eta_{i,P}$ (%)	75
$\Delta T_{PP,EVP}$ (K)	5
$\Delta T_{PP,C}$ (°K)	5
$T_{CW,in}$ (°C)	15
dT_{CW} (K)	5

Regarding the hybrid power plant a biogas cogeneration unit of GE Jenbacher JMS 620 GS-B.L. is coupled with the geothermal heat source. All relevant parameters of the gas engine like electric power P_{el}, thermal power P_{th}, outlet temperature of cooling water $T_{CW,out}$, massflow of cooling water $\dot{m}_{CW}$ or outlet temperature of the exhaust gases $T_{EG,out}$ are shown in Tab. 4. For all simulations the geothermal water temperature at the outlet of the ORC is adapted according to the maximum of power output of the ORC unit. As a fixed criterion for the process simulations the heat demand is fully covered in case of CHP applications. Hence the annual amount of produced electricity is suitable to compare the considered concepts under thermodynamic aspects.

Table 4: Parameters of the selected biogas cogeneration unit (JMS 620 GS-B.L.)

parameter	
P_{el} (kW)	2717
P_{th} (kW)	1315
$T_{CW,out}$ (°C)	87.8
$T_{CW,in}$ (°C)	65.5
$\dot{m}_{CW}$ (kg/s)	19.9
$T_{EG,out}$ (°C)	463.9
$\dot{m}_{EG}$ (kg/s)	4.35

Regarding economic criteria the cumulated cashflow and the averaged electricity generation costs are calculated. According to equation [1] the cashflow Cf for a period is calculated by the difference between revenues R and total costs T:

$$Cf = R + T. \qquad [1]$$

Equation [2] shows the cumulated cashflow Cf_{cum} for a certain time t.

$$Cf_{cum} = \sum_{t=0}^{t} Cf_t \qquad [2]$$

For the economic evaluation of the power plant concepts the specific costs of Table 5 are estimated. In addition drilling costs are assumed with 18 million €, insurance with 2 million € and costs for operation and maintenance are 2 % of the total investment costs. The lifetime of the power plant is 30 years and the interest rate is 6.5 %. For the biogas cogeneration, maize silage is assumed as energy source and the length of the heating network is 10 km. In addition an annual price increase by 2 % for electricity and heat supply is assumed. The heating costs are 5 ct/kWh.

Table 5: Specific costs for power plant components or modules

ORC power plant (€/kW)	3500
Table-top cooler (€/kW)	14.8
Heating network (€/km)	500000
Peak load boiler (€/kW)	200
Cogeneration unit (€/kW)	225
Heat exchanger hybrid power plant (€/m^2)	125

3. RESULTS

3.1 Standard conditions

The standard conditions are defined as UPPV for the geothermal resource, R245fa as ORC working fluid, high-temperature case for supply temperature, and

8000 inhabitants. Concerning a hybrid power plant Fig. 7 shows the electric power of the ORC and the gas engine as well as the total thermal power of the heating network depending on the assumed load steps (see Fig. 5). In addition the parts of thermal power supplied by geothermal water and engine coolant are pointed out.

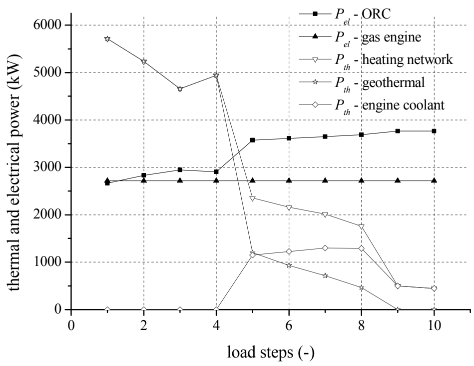

Figure 7: Electrical and thermal power of the power plant units (hybrid power plant)

The biogas engine operates 8000 h/a with a maximum electrical power of 2717 kW. In case of the ORC the electrical power increases for higher load steps which corresponds to higher ambient temperatures and less heat demand. In addition the engine coolant supplies the heating network increasingly for higher load steps. Finally for 2064 h/a, load steps 9 to 10, the heating network is supplied fully by the engine coolant. In this period the geothermal water is not needed for heat generation. However in case of load steps 1 to 4 the engine coolant cannot be used, due to the high supply temperatures required by heating network.

Regarding geothermal CHP in parallel circuit the heating network has to be supplied fully by the geothermal water. Hence, compared to the hybrid power plant the electrical power of the ORC is decreased due to a lower amount of geothermal heat which is coupled to the cycle. In addition in case of a hybrid power plant the cycle efficiency is about 4 % higher because of the exhaust gases of the biogas engine coupled to the geothermal water. Fig. 8 shows the electric power of the ORC and the thermal power of the heating network depending on the assumed load steps in case of CHP.

To summarize the results for the considered power plant designs at standard conditions the annual amount of generated electricity is shown in Fig. 9. In case of the hybrid power plant a distinction is made between ORC unit and gas engine. Beside the hybrid power plant a separate use of geothermal heat source and cogeneration unit is examined. In this case the exhaust gases of the engine are used for heat generation instead of coupling with the geothermal water.

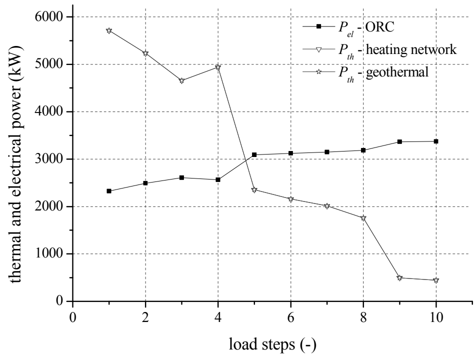

Figure 8: Electrical and thermal power of the power plant units (CHP – parallel circuit)

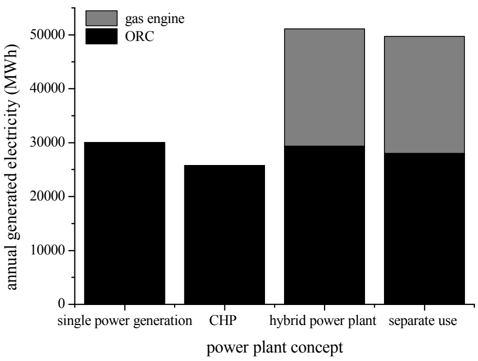

Figure 9: Annual amount of generated electricity for the investigated power plant concepts

The comparison shows that a single power generation leads to the highest amount of generated electricity of the ORC unit per year. Due to the additional heat supply the electricity generation decreases by 14 % in case of CHP. Regarding the hybrid power plant the power generation of the ORC unit is only 2 % lower compared to single power generation. A separate use of geothermal water and biogas engine leads to 4.8 % lower amount of generated electricity compared to the hybrid concept.

3.2 Heat demand

In Fig. 10 the electrical and thermal power of hybrid power plant units in case of a heating network supplying 4000 inhabitants is shown. Compared to standard conditions the heat demand is halved. Due to a lower heat demand a higher amount of heat is coupled to the ORC. Therefore the annual power generation is 6% higher in case of the lower heat demand.

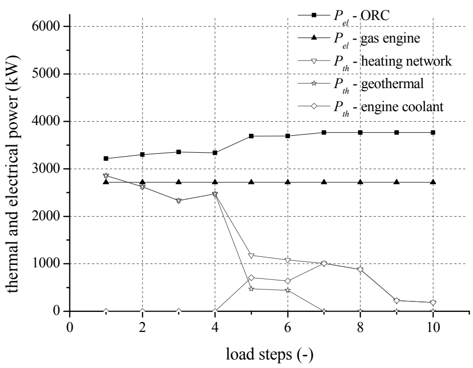

Figure 10: Electrical and thermal power of the power plant units (hybrid power plant)

3.3 ORC working fluid and geothermal water temperature

In the simulations the common ORC working fluids R245fa and isopentane are compared for typical geothermal conditions according to the URRV and the SGMB. Fig. 11 illustrates the electrical power of the ORC unit depending on the considered load steps. In this case for the heating network 4000 inhabitants are assumed.

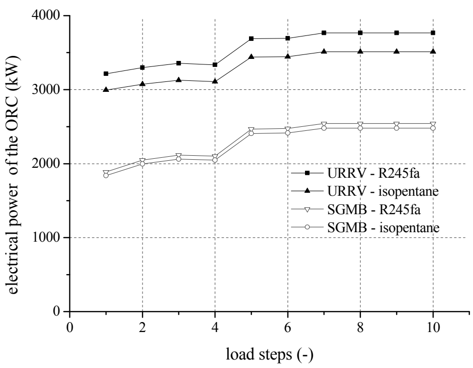

Figure 11: Electrical power of the ORC unit depending on the considered load steps

The results show that R245fa leads to a higher efficiency compared to isopentane. In case of the URRV the difference is more pronounced compared to the lower geothermal water temperature of the SGMB. Regarding the URRV the annual averaged thermal efficiency of the ORC with R245fa as working fluid is 12.43 % while isopentane leads to 11.83 %. However, in case of the SGMB the relative deviation between the working fluids is only 1 %. In general a lower geothermal temperature leads to a decrease in efficiency. For the assumed conditions of the geothermal resources a 48 % lower installed ORC capacity and a 53 % lower amount of generated electricity results in case of SGMB compared to URRV.

3.4 Supply temperature of the heating network

A further important influence on the generated electricity for CHP has the supply temperature of the heating network. Current developments in heating systems lead constantly to lower supply temperatures. The effects of a low-temperature case (according to Fig. 6) for the supply temperature on the thermal and electrical power of hybrid power plants are summarized in Fig. 12.

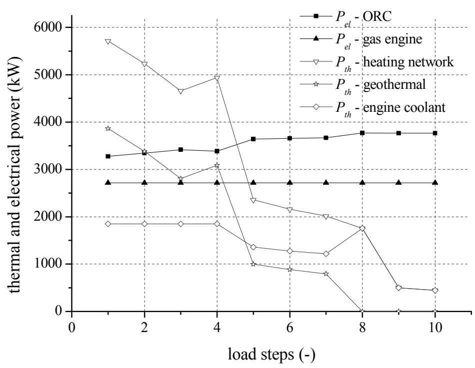

Figure 12: Electrical and thermal power of the power plant units (hybrid power plant)

For the low-temperature case the engine coolant can be used the complete year to supply the heating network. In return the geothermal water plays a smaller role for heat supply and the electrical power of the ORC unit increases.

The positive effect of a lower supply temperature for power plant concepts with additional heat generation can be seen in Fig. 13.

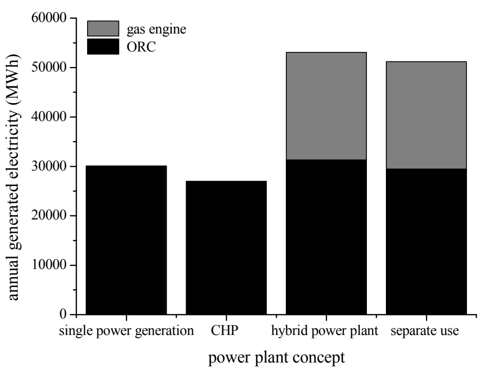

Figure 13: Annual amount of generated electricity for the investigated power plant concepts

The results show that the hybrid concept leads to a higher amount of annual generated electricity compared to single power generation. In case of the CHP concept the annual power generation is 10 % reduced to single power generation while for the high-temperature case the difference is 14 %.

3.5 Economic analyses

For a general evaluation of the CHP concepts compared to single power generation the revenues from heat sales has to be considered. In Fig. 14 the cumulated cashflow for the selected power plant designs at standard conditions is shown.

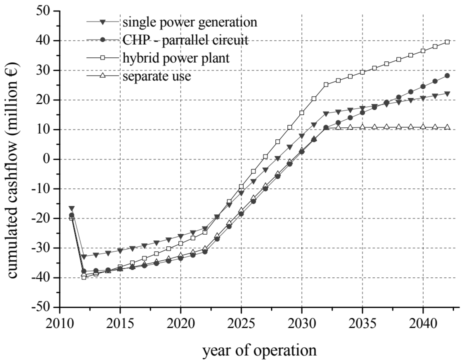

Figure 14: Cumulated cashflow for the considered power plant concepts at standard conditions

In general the unsteadiness of the curves at 10 years and 20 years lifetime are due to the assumed payback period and end of the guaranteed electricity feed-in tariffs. The hybrid power plant leads with 39.5 million € to the highest cumulated cashflow at the end of the lifetime. According to the costs for the heating network and the cogeneration unit the CHP concepts show up to 20 % higher investment cost compared to single power generation. This effect and the lower power generation are compensated by the revenues of heat sales. In this context the CHP in parallel circuit is economically more efficient compared to single power generation. Next to lower efficiency higher personnel costs as well as higher costs for operation and maintenance are reason for a lower cumulated cashflow in case of the separate use compared to the hybrid power plant. The hybrid power plant leads to the lowest electricity generation costs (averaged for 20 years lifetime) of 11.88 ct/kWh, followed by the single power generation with 12.25 ct/kWh and the CHP concept with 15.98 ct/kWh.

The economic effects of parameter variations are shown exemplarily in Fig. 15 for lower supply temperatures of the heating network. The varied parameter has no influence on the economic conditions for single power generation. Regarding CHP concepts the cumulated cashflow increases significantly compared to higher supply temperatures. For both CHP in parallel circuit and hybrid power plant the cumulated cashflow is more than doubled at the end of the lifetime.

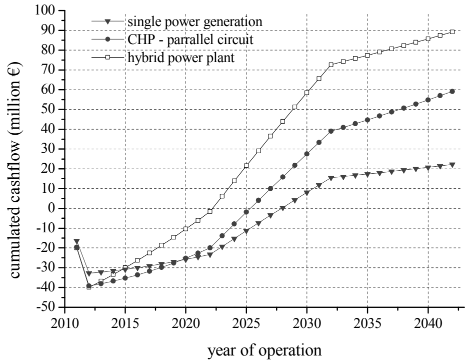

Figure 15: Cumulated cashflow for the considered power plant concepts at low supply temperature of the heating network

3. CONCLUSIONS

Hybrid power plants are promising concepts for geothermal CHP. Comparisons to the separate use prove the advantages of coupling geothermal resource and biogas cogeneration unit. With respect to single power generation the ORC unit generates only 2 % less electricity per year. A reduction of 50 % in heat demand leads to higher annual power generation by 6 %. Concerning different working fluids R245fa is favourable compared to isopentane. The simulations show a higher thermal efficiency of the ORC between 1 % and 5 % for R245fa depending on geothermal conditions. A low-temperature heating network leads to a better implementation of the biogas-cogeneration unit in the hybrid power plant. If realizable CHP applications lead to economic more efficient solutions compared to single power generation. Despite higher investment costs the cumulated cashflow at the end of the lifetime is up to 77 % higher. In case of low supply temperature of the heating network these advantages become even more significant. In the considered case studies the hybrid power plant is always the most efficient power plant concept.

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