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Article

Thermoeconomic Analysis of Hybrid Power Plant Concepts for Geothermal Combined Heat and Power Generation

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Abstract: We present a thermo-economic analysis for a low-temperature Organic Rankine Cycle (ORC) in a combined heat and power generation (CHP) case. For the hybrid power plant, thermal energy input is provided by a geothermal resource coupled with the exhaust gases of a biogas engine. A comparison to alternative geothermal CHP concepts is performed by considering variable parameters like ORC working fluid, supply temperature of the heating network or geothermal water temperature. Second law efficiency as well as economic parameters show that hybrid power plants are more efficient compared to conventional CHP concepts or separate use of the energy sources.

Keywords: geothermal; Organic Rankine Cycle; CHP; hybrid power plant

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1. Introduction

For low-enthalpy geothermal resources binary power plants like the Organic Rankine Cycle (ORC) or the Kalina Cycle (KC) are suitable [1,2]. Combined heat and power generation (CHP) is a promising approach to improve the economic conditions for geothermal energy generation. An additional heat supply could be realized in various types of power plant configurations. In general, serial or parallel circuit of power and heat generation are considered [3]. Furthermore, innovative concepts like hybrid power plants are a promising approach to increase the thermodynamic and economic efficiency. For this purpose, geothermal power plants are typically coupled with an alternative energy source like a biogas cogeneration unit, solar thermal panels, solid biomass or fossil fuels [4–11]. In climatic zones where solar thermal systems are not practical, but renewable CHP is still favoured, a hybrid power plant consisting of a geothermal heat source and a biogas engine seems to be a suitable concept. In this paper different configurations for hybrid power plants based on ORC-technology are compared to conventional geothermal CHP and separate use of the energy sources. For geothermal water temperatures of 120 °C, the electricity produced annually, second law efficiency and economic parameters are calculated. Sensitivity analyses are performed concerning ORC working fluid, supply temperature of the heating network and geothermal conditions.

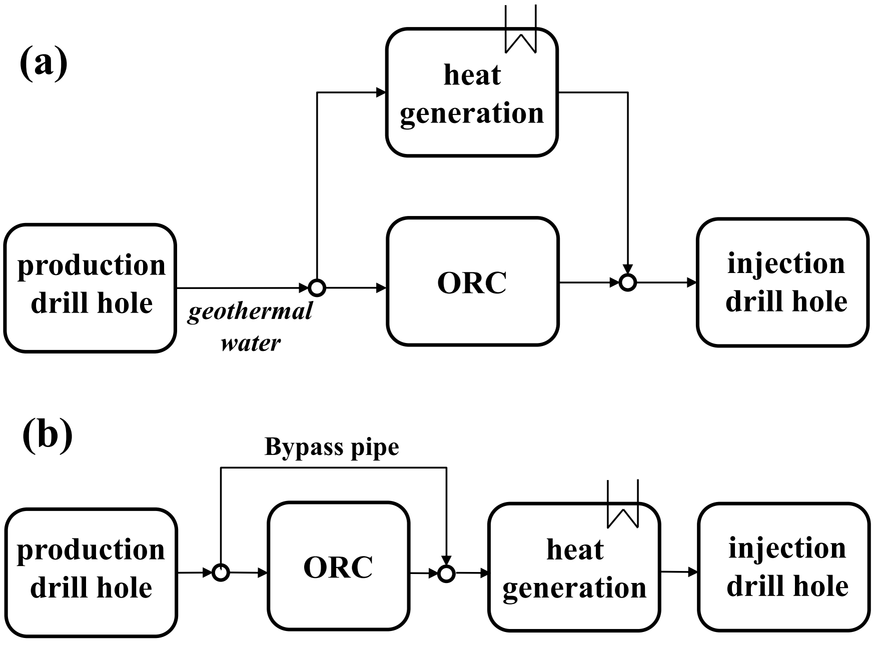
2. Methodology

The annual power output for the considered CHP concepts is calculated using quasi-steady-state considerations, consisting of ORC process simulations and approximation of the annual duration curve of the heat demand. The most efficient power plant configurations are identified based on second law efficiency, internal rate of return and cumulative cashflow. Therefore, thermodynamic and economic boundary conditions are defined.

2.1. Process Simulations

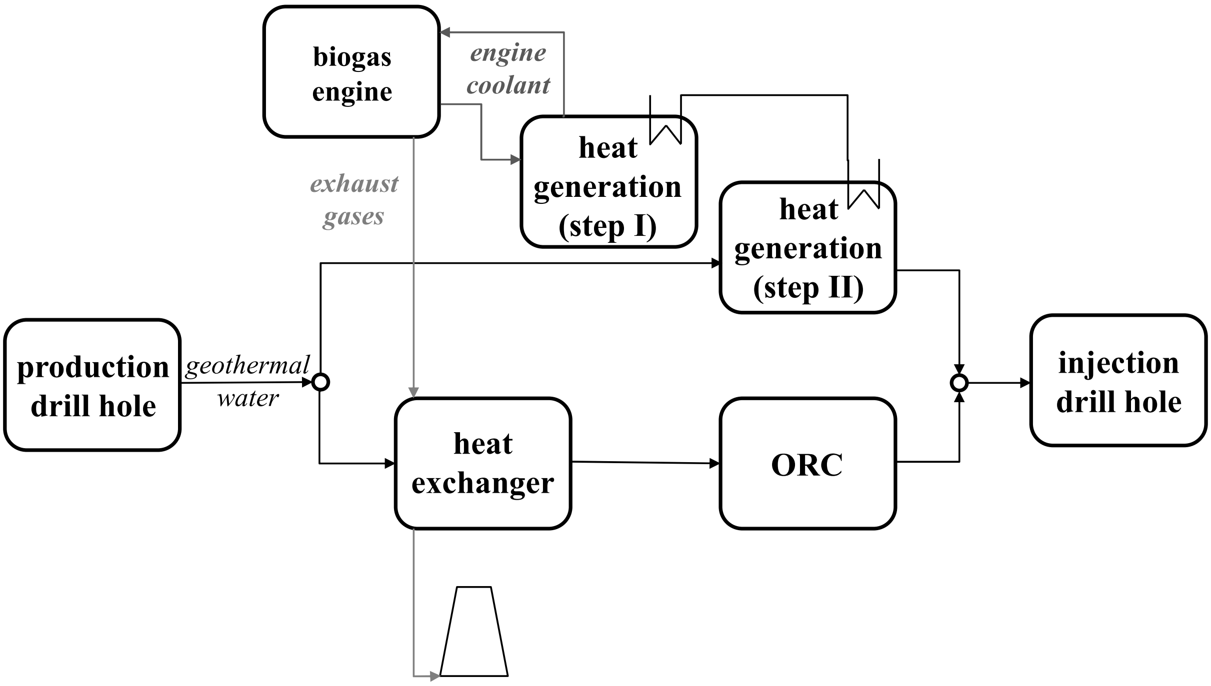
Geothermal CHP for low-enthalpy resources is investigated in parallel or serial configuration of power unit and heat generation. A scheme of both power plant concepts is shown in Figure 1. For serial circuit, a bypass pipe provides sufficient geothermal water temperatures in case of high supply temperatures of the heating network and low ambient temperatures, respectively.

Figure 1. (**a**) Scheme of geothermal CHP in parallel circuit; (**b**) Scheme of geothermal CHP in serial circuit with bypass pipe.



A hybrid power plant for CHP is also feasible in parallel and serial configuration. Figure 2 shows the parallel power unit and heat generation circuit. According to heat demand the geothermal water mass flow is split and the ORC operates under partial load. A higher geothermal water temperature at the inlet of the ORC-unit 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 in a second heat exchanger. The serial configuration of the hybrid power plant is analogue to the serial geothermal CHP in Figure 1b. Finally, a separate use of geothermal heat source and biogas cogeneration unit is examined. In this case, the exhaust gases of the gas engine are simply used for heat generation instead of coupling with the geothermal water.

Figure 2. Scheme of geothermal hybrid power plant in parallel circuit.



The ORC is calculated using the software Cycle Tempo [12] and fluid properties are based on REFPROP 9.1 [13]. According to Figure 3a the ORC working fluid is forced by the pump to a higher pressure level (1→2) followed by the coupling with the geothermal heat source, in the preheater (2→3) first, and then in the evaporator (3→4). A saturated cycle is assumed, so in state point 4 no superheating arises. For the considered working fluids R245fa (1,1,1,3,3-pentafluoropropane), isopentane and isobutane, all so-called dry fluids, there is no danger of turbine erosion due to the positive slope of the dew line in the *T*,*s*-diagram. In the next step the working fluid is expanded in the turbine (4→5). The condensation (5→1) closes the cycle. Figure 3b shows exemplarily the changes of states in a *T*,*s*-diagram for an ORC using the working fluid isopentane. In Table 1 the boundary conditions of the ORC like isentropic efficiency of the rotating equipment η_i, temperature difference at the pinch point ΔT_{PP} in the condenser and evaporator, cooling temperature at the inlet $T_{CW,in}$ and temperature difference of the cooling water ΔT_{CW} are outlined. Due to a high content of dissolved salts in the geothermal fluid, mineral deposits could occur for low temperatures. To avoid such scalings in the heat exchangers, in particular the preheater, the reinjection temperature of geothermal water is set to 60 °C. Regarding the hybrid power plant, the biogas cogeneration unit (a 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 $\dot{Q}$, outlet temperature of cooling water $T_{CW,out}$, mass flow of cooling water $\dot{m}_{CW}$ or outlet temperature of the exhaust gases $T_{EG,out}$ are shown in Table 2.

Figure 3. Scheme of ORC-unit (**a**) and corresponding *T,s*-diagram for ORC with the working fluid isopentane (**b**).

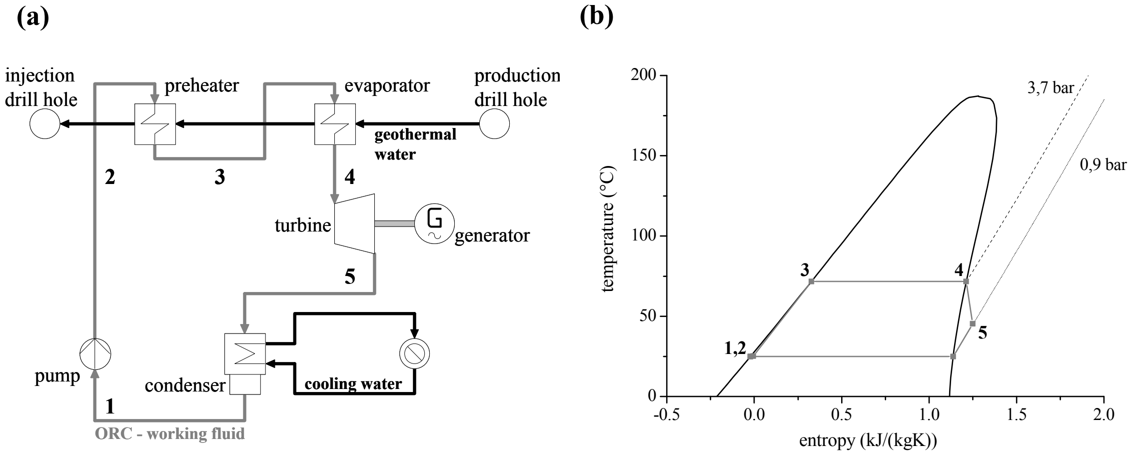


Table 1. Boundary conditions for the ORC power plant.

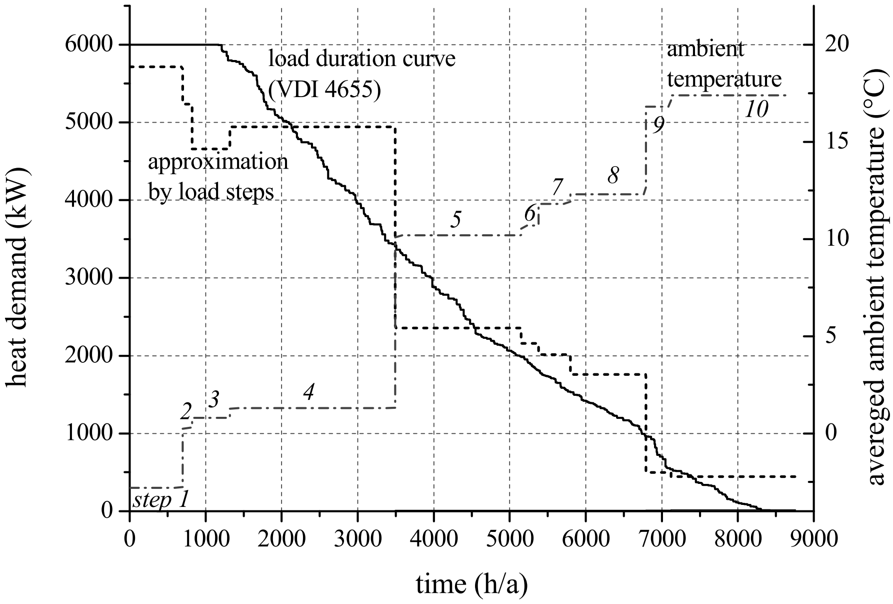
Parameter	Unit	
Isentropic efficiency of the ORC-turbine $\eta_{i,T}$	%	80
Generator efficiency η_G	%	95
Isentropic efficiency of the ORC-pump $\eta_{i,P}$	%	75
$\Delta T_{PP,EVP}$	K	5
$T_{CW,in}$	°C	15
ΔT_{CW}	K	5

Table 2. Operational parameters of the biogas cogeneration unit (JMS 620 GS-B.L.).

Parameter	Unit	
Electrical power output P_{el}	kW	2717
Thermal power output $\dot{Q}$	kW	1315
Engine coolant outlet temperature $T_{CW,out}$	°C	87.8
Engine coolant inlet temperature $T_{CW,in}$	°C	65.5
Engine coolant mass flow rate $\dot{m}_{CW}$	kg/s	19.9
Exhaust gas outlet temperature $T_{EG,out}$	°C	463.9
Exhaust gas mass flow rate $\dot{m}_{EG}$	kg/s	4.35

In the case of heat generation, a heating network which supplies a settlement of 8000 inhabitants is considered. A distribution of 30% single-family houses and 70% multi-family houses is assumed. The heat demand for each housing unit is calculated based on load profiles for typical climatic patterns (zone 13) according to VDI 4655 [14]. For a thermal power higher than 6000 kW a peak load boiler is considered. In total a thermal energy of 23.9 GWh is coupled to the heating network. For a quasi-steady-state calculation of power and heat generation, the annual duration curve is approximated by 10 load steps, which correspond to the averaged ambient temperature of the typical climate patterns (see Figure 4). In addition, a linear dependence of supply and return temperature of the heating network on ambient temperature between −14 °C and 16 °C is taken into account. The maximum supply temperature is 90 °C and the minimal value is 60 °C. The temperature difference between supply and return temperature is set constant to 20 K.

Figure 4. Annual duration curve of the heating network and approximation by load steps corresponding to the averaged ambient temperature of the considered climatic patterns.



As a fixed criterion for the process simulations, the heat demand is fully covered by all CHP concepts. Hence the annual amount of produced electricity is suitable to compare the considered concepts under thermodynamic aspects.

2.2. Second Law Analyses

Next to the annual amount of produced electricity, the second law efficiency η_{II} is calculated. In case of single power generation or consideration of the ORC-unit in a CHP-system, the net power output P_{Net} is divided by the exergy flow rate of the geothermal water $\dot{E}_{GW}$:

$$\eta_{II} = \frac{P_{Net}}{\dot{E}_{GW}} \tag{1}$$

The exergy flow rate of the geothermal source is obtained by multiplying the specific exergy e with the mass flow rate of geothermal water $\dot{m}_{GW}$. For the analysis, the specific exergy e is based on:

$$e = h - h_0 - T_0(s - s_0) \tag{2}$$

$$\dot{E}_{GW} = \dot{m}_{GW} e \tag{3}$$

The state variables T_0, p_0 and s_0 are related to ambient conditions. In case of CHP the numerator of Equation (1) is extended by the exergy flow rate of the heating network $\dot{E}_{HN}$ and in case of a hybrid power plant the exergy flow rate of the biogas $\dot{E}_{BG}$ has to be considered in the denominator according to Equation (4):

$$\eta_{II} = \frac{P_{Net} + \dot{E}_{HN}}{\dot{E}_{GW} + \dot{E}_{BG}} \tag{4}$$

To calculate the exergy flow rate of the biogas $\dot{E}_{BG}$, the molar exergy of the biogas $E_{m,BG}$ is defined as:

$$E_{m,BG} = \sum_{i=1}^{N} \tilde{x}_i E_{m,i} + R_m T_0 \sum_{i=1}^{N} \tilde{x}_i \ln(\tilde{x}_i) \tag{5}$$

Here R_m is the universal molar gas constant, $\tilde{x}_i$ describes the molar fraction for each component and $E_{m,i}$ is the molar exergy of each component according to Baehr and Kabelac [15]. A gas mixture of 65% methane and 35% carbon dioxide is assumed. In the following, second law efficiency for a certain power plant concept is calculated by evaluating each load step and finally rating according to the annual contribution.

2.3. Economic Analyses

For a comprehensive analysis of different plant concepts or potential ORC working fluids an additional economic evaluation is of steadily growing importance [7,16–18]. In this study cumulated cashflow and internal rate of return are calculated as economic parameters. According to Equation (6) the cashflow *Cf* for a period is calculated by the difference between revenues *R* and total costs *C*. Therefore *Cf* describes the inflow of available funds within a certain time period *t*:

$$Cf_t = R_t + T_t \tag{6}$$

Equation (7) shows the cumulated cashflow Cf_{cum} at a certain point in time *T*, which is obtained by summarizing *Cf* of previous time periods:

$$Cf_{cum} = \sum_{t=0}^{T} Cf_t \tag{7}$$

In addition, the internal rate of return *IRR* is calculated for the considered power plant concepts. This parameter is the interest rate *r*, at which the net value of the investment is equal zero:

$$0 = -C_0 + \sum_{t=0}^{T} (R_t - C_t) \cdot (1 + r)^{-t} \tag{8}$$

For the economic evaluation of the power plant concepts the specific costs listed in Table 3 are estimated. Drilling costs of 18 million € and insurance of 2 million € are assumed [19]. Costs for operation and maintenance, including personnel costs, are set to 4% of the total investment costs for a separate use of geothermal heat source and biogas engine [7]. In case of a hybrid concept, this value is reduced to 2% due to the cost savings in personnel and administrative costs. The lifetime of the power plant is 30 years and the interest rate is 6.5% [20]. The credit period is 12 years and the rate of borrowed capital is 80%. For the biogas cogeneration, maize silage (30 €/t) is assumed as energy source [21]. The length of the heating network is 8 km. The heating price is 0.05 €/kWh [22]. German feed-in tariffs for geothermal power generation (0.25 €/kWh) and biomass power generation (0.11 €/kWh) are considered [23]. Furthermore, an electricity price of 0.12 €/kWh for auxiliary power requirements, like working fluid pump, downhole pump, condensation system or table-top coolers for the engine coolant in the summer period, is assumed [22]. The annual price increase for electricity and heat supply as well as the considered inflation rate is 2%.

Table 3. Specific costs for power plant units and components.

Parameter	Unit	
ORC power plant [2]	€/kW$_{el}$	3500
Table-top cooler [24]	€/kW$_{th}$	14.8
Heating network [25]	€/km	500,000
Peak load boiler [26]	€/kW$_{th}$	200
Biogas engine [27]	€/kW$_{el}$	225
Heat exchanger hybrid power plant [26]	€/m^2	125

3. Results and Discussion

In the standard case, a mass flow rate of 100 kg/s and a temperature of 120 °C are assumed for geothermal fluid. This corresponds to the characteristic conditions of the Southern German Molasse Basin near Munich. R245fa is chosen as ORC working fluid. In the thermodynamic results, thermal and electric power of the units are present depending on different load steps. In addition, the annual amount of generated electricity and the second law efficiency is shown. The economic results compare the cashflow and *IRR* for the considered power plant concepts. Finally, the economic effects of varying selected boundary conditions are discussed.

3.1. Thermodynamic Results

Regarding a geothermal CHP in parallel circuit, the heating network has to be fully supplied by the geothermal water. For a hybrid power plant the heat demand could partly be covered by the engine coolant. Furthermore, the power generation of the ORC-unit is more efficient due to the temperature increase of the geothermal water by coupling with the exhaust gases of the gas engine. In this context, for a geothermal CHP in parallel circuit, the electric power of the ORC-unit $P_{el,ORC}$ as well as the total thermal power of the heating network $P_{th,HN}$ depending on the assumed load steps are shown in Figure 5a. In addition, the part of thermal power supplied by geothermal water $\dot{Q}_{Geo}$ pointed out. For geothermal CHP the heat demand is supplied completely by the geothermal fluid. Therefore in Figure 5a the values for $P_{th,HN}$ and $\dot{Q}_{Geo}$ are equal. For higher load steps the thermal power of the heating network decreases and a higher amount of thermal energy is coupled to the ORC. As a result the power output of the ORC increases. In Figure 5b these parameters are shown for a hybrid power plant in parallel circuit, extended by electric power of the gas engine $P_{el,GE}$ and part of thermal power supplied by engine coolant $\dot{Q}_{EC}$. In case of the hybrid power plant, the biogas engine operates 8000 h/a with a maximum electrical power of 2717 kW. The electrical power of the ORC-unit increases for higher load steps which correspond to higher ambient temperatures and less heat demand. The engine coolant supplies the heating network partly for all load steps. Finally, for load steps 8 to 10, corresponding to 2952 h/a, the heating network is fully supplied by engine coolant. In this period, the geothermal water is not required for heat generation. Therefore, the complete geothermal mass flow rate can be coupled to the ORC-unit for power generation. In addition, in case of a hybrid power plant, geothermal water temperature is increased. As a result, higher process pressures of the ORC can be reached and the efficiency of the ORC-unit is about 3% higher. In this context, the ORC pressure at condensation and evaporation for the geothermal CHP and the hybrid power plant are listed in Table 4.

Figure 5. Electrical and thermal power of the power plant units (**a**) Geothermal CHP in parallel circuit; (**b**) Hybrid power plant in parallel circuit.

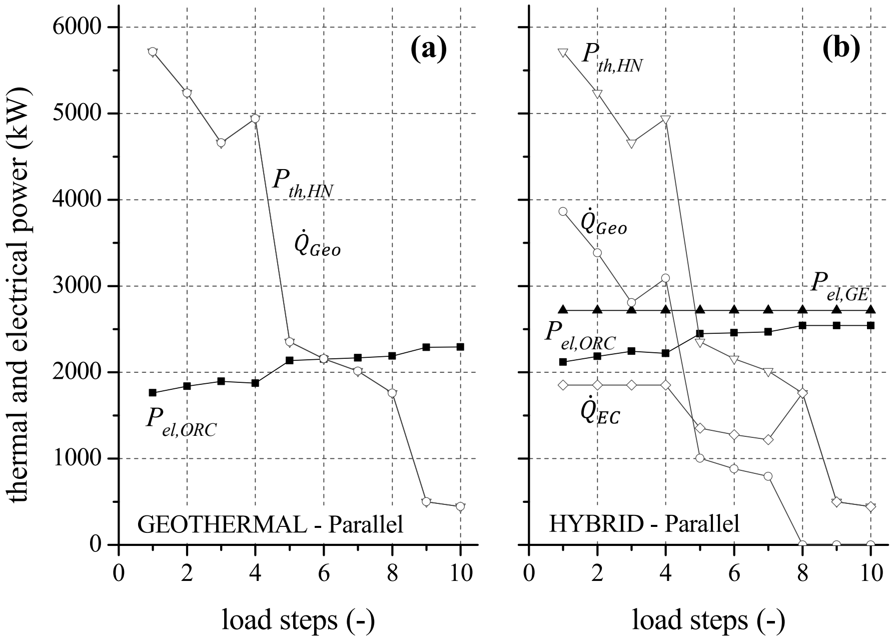


Table 4. Condensation and evaporation pressure.

Parameter	R245fa-GeoCHP	R245fa-Hybrid	Isopentane-GeoCHP	Isopentane-Hybrid
p_1 (bar)	1.47	1.47	0.90	0.90
p_2 (bar)	6.53	6.94	3.67	3.85

The annual amount of generated gross electricity for all considered power plant concepts is shown in Figure 6. In case of the hybrid power plant, a distinction is made between ORC-unit and gas engine. The generated electricity of the gas engine is equal for the hybrid concepts and separate use. In case of the hybrid power plant in parallel circuit, the highest amount of generated electricity per year is obtained. In comparison, a separate use of geothermal water and biogas engine leads to a 4.7% lower amount of generated electricity. This difference is due to the efficiency increase of the ORC-unit by increasing the geothermal water temperature within the hybrid concept. The hybrid power plant in serial circuit leads to an 11% lower amount of electricity compared to the parallel circuit. In case of the serial circuit, a higher geothermal mass flow is needed to obtain the required supply temperature and heat load. For the first load step, 39.6% of the geothermal water mass flow are required to supply the heating network, while in parallel circuit only 18.5% are sufficient. This difference occurs up to load step 7 and leads to a significantly lower electricity generation for the serial circuit. In case of geothermal CHP, the electricity generation is up to 23% lower compared to the hybrid power plant in parallel circuit. Due to the heat supply which has to be fully covered by the geothermal heat source, a considerable reduction occurs. CHP in parallel circuit is 11.3% more efficient compared to CHP in serial circuit.

Figure 6. Annual amount of generated electricity for the investigated power plant concepts.

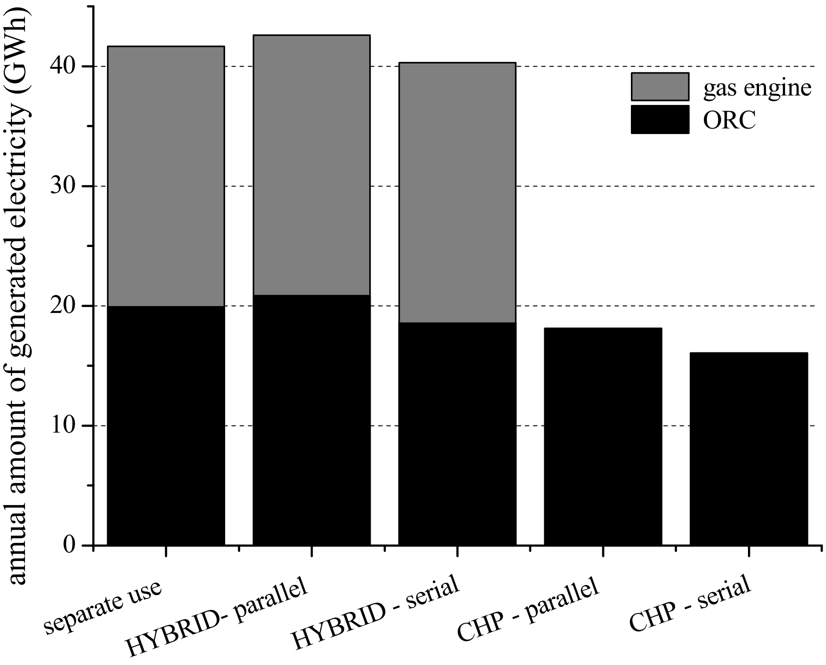
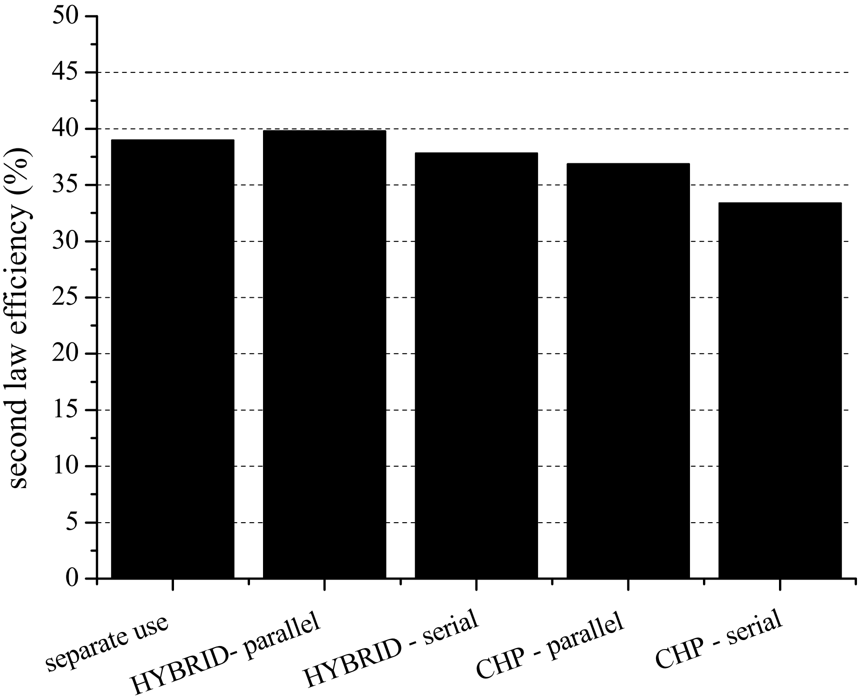


Figure 7 presents the second law efficiency for the analyzed concepts. In general, the results are consistent with the annual amount of generated electricity. The most efficient concept is the hybrid power plant in parallel circuit. A separate use of geothermal heat source and biogas cogeneration unit is 2.1% less efficient. In case of hybrid power plants as well as for geothermal CHP concepts, parallel circuit is more efficient compared to serial circuit. The efficiency increase is between 5.2% and 10.4%. A comparison under thermodynamic aspects based on second law efficiency seems to be more appropriate, since the additional use of biogas as energy resource is considered.

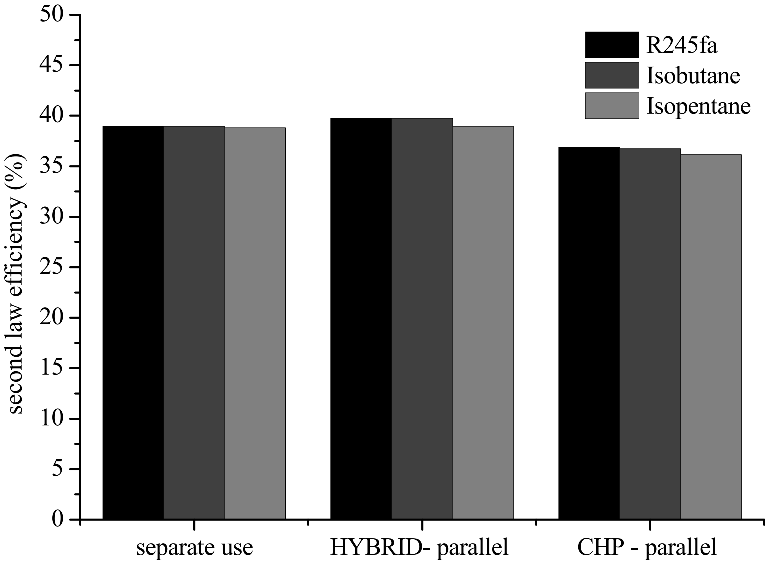
Figure 7. Second law efficiency for the considered power plant concepts.



3.1.1. ORC Working Fluid

Regarding second law efficiency, the choice of working fluid has a minor role in these systems. Exemplarily in Figure 8 second law efficiency for R245fa, isobutane and isopentane are shown for separate use, hybrid power plant and geothermal CHP in parallel circuit.

Figure 8. Second law efficiency for different ORC working fluids and selected power plant concepts.

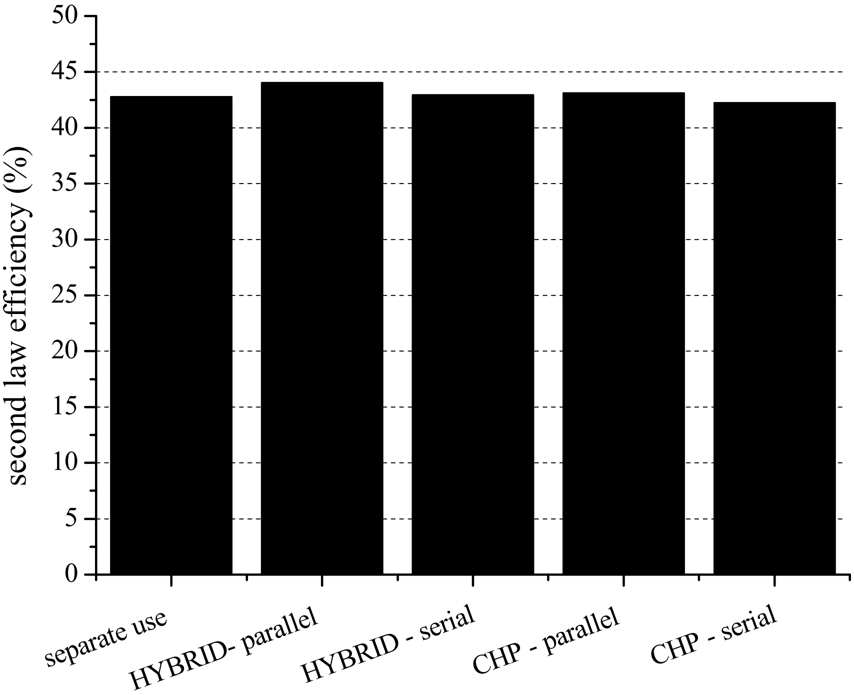


R245fa as ORC working fluid leads to the most efficient power plant concepts. The ORC-unit with isopentane is up to 1.5% less efficient. In case of isobutane the differences are below 0.5%. Therefore the choice of working fluid is more dependent on fluid properties, component design, Global Warming Potential and safety issues than system efficiency.

3.1.2. Geothermal Conditions

In respect to the geothermal resource, the mass flow rate and the temperature are the most important parameters. In case of typical geothermal conditions of the Upper Rhine Rift Valley with a geothermal water temperature of 160 °C and a mass flow rate of 65 kg/s, second law efficiency for the investigated power plant concept is shown in Figure 9. With increasing geothermal temperature, the second law efficiency of the ORC-unit is rising. In the context of a hybrid power plant in parallel circuit, this increase is 10.7% due to the raise of geothermal water temperature from 120 °C to 160 °C. For geothermal CHP the second law efficiency of the ORC-unit increases from 34.4% to 42.3%. A comparison between the different power plant concepts at higher geothermal water temperature shows qualitatively the same results. The hybrid power plant in parallel circuit is the most efficient concept and in general hybrid power plants are favorable compared to geothermal CHP. However, the differences in efficiency of parallel and serial circuit are less pronounced. Due to higher geothermal water temperature a lower partial flow rate is needed to obtain the required supply temperature for the heating network. Comparing again the first load step between the hybrid power plant and the geothermal CHP in parallel circuit, here 24.2% of the geothermal water mass flow are required to supply the heating network in serial circuit, while in parallel circuit 15.6% are sufficient. Therefore, compared to the serial circuit, the parallel configuration is only 2.1% more efficient in case of geothermal CHP and 2.6% for the hybrid concept. Compared to the low-temperature case the efficiency increase for a hybrid power plant in relation to separate use is similar with 2.9%. In both scenarios, an increase of geothermal water temperature due to the coupling with the exhaust gases of the gas engine affects the efficiency of the ORC-unit in a positive manner. In this context, the second law efficiency increases in the range of 2.6% and 3.1%.

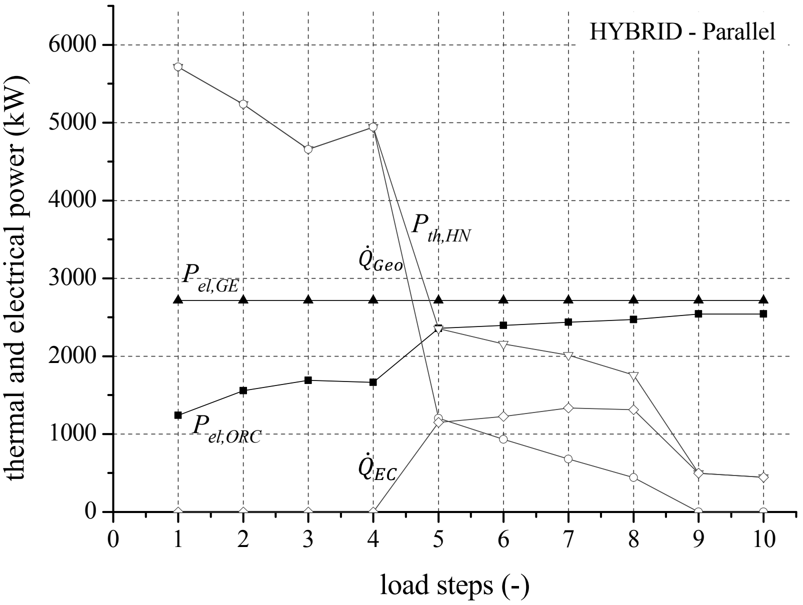
Figure 9. Second law efficiency for the investigated power plant concepts considering geothermal mass flow rate of 65 kg/s and geothermal water temperature of 160 °C.



3.1.3. Supply Temperature of the Heating Network

The supply temperature of the heating network plays an important role in the energy conversion system. Exemplarily, a raise of the maximum supply temperature to 130 °C (at ambient temperature below −14 °C) is examined. The minimum supply temperature for ambient temperatures higher than 16 °C is 80 °C. Again a linear function for supply temperature depending on ambient temperature is assumed. Figure 10 shows the electrical and thermal power for a hybrid power plant in parallel circuit. In comparison to a maximum supply temperature of 90 °C (see Figure 5b) for load steps 1 to 4, the engine coolant cannot be used for heat generation. In addition, a full supply of the heat demand by the engine coolant is only possible for 2064 h/a, in load steps 9 to 10, respectively. As a result, the amount of generated electricity is reduced by 5.3 MWh/a and the second law efficiency decreases by 1.5%.

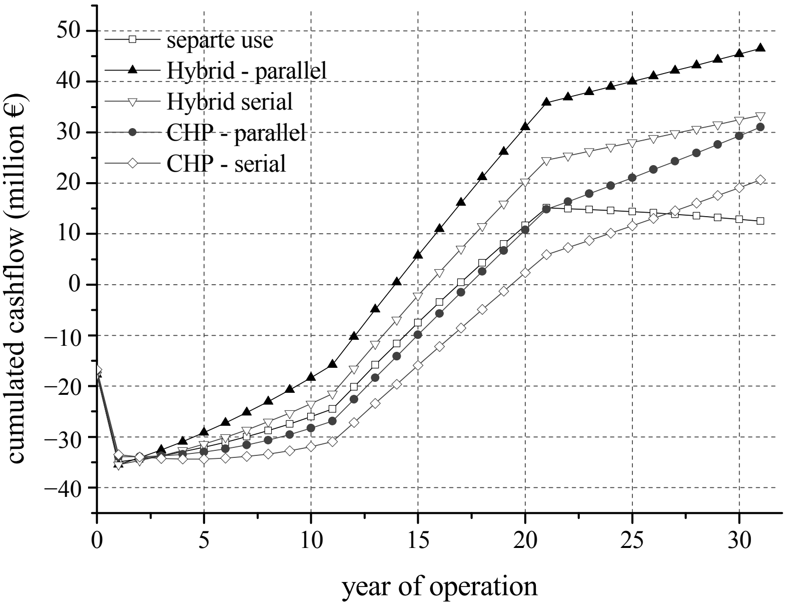
Figure 10. Electrical and thermal power of the power plant units for a maximum supply temperature of the heating network of 130 °C.



3.2. Economic Results

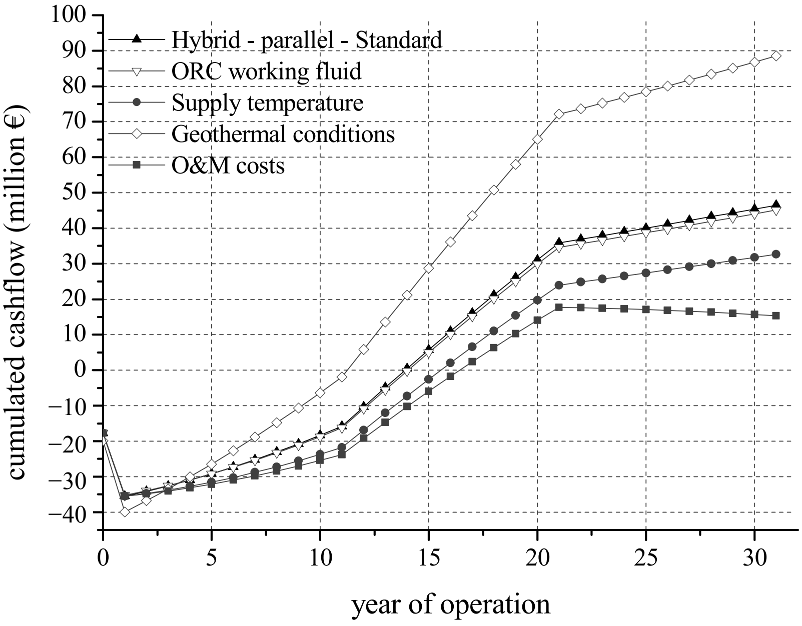
For an economic evaluation of the examined CHP concepts, investment, operation and maintenance as well as fuel costs have to be considered. On the other hand, the revenues from feeding electricity into the grid and heat sales have an effect on the energy cost balance and economic parameters like the cumulated cashflow and *IRR*. The cumulative cashflow for the selected power plant designs is shown in Figure 11. A construction time of 2 years is assumed, the related investment costs are evenly distributed. In general, during operation the curve of the cumulated cashflow shows unsteadiness. The first change occurs 10 years after initial operation of the power plant. This is due to the assumed payback period. A second one is observed for 20 years of operation and is related to the end of the guaranteed electricity feed-in tariffs. Regarding the investment cost, hybrid power plants are the most expensive concept, at 35.5 million €. A separate use leads to cost savings of 0.6 million·€ and a geothermal CHP to cost savings of 1.6 million €. The hybrid power plant in parallel circuit leads with 46.5 million € to the highest accumulated cashflow at the end of the complete lifetime. A significantly lower cumulated cashflow is obtained for separate use, mainly caused by the higher costs for operation and maintenance and lower efficiency. For the last 10 years the total cost balance even shows negative cashflows. At the end of the life time a cumulative cashflow of 12.5 million € is reached. Also in the economic analysis, a serial circuit for hybrid power plants as well as for geothermal CHP leads to lower results compared to parallel circuit. In case of the hybrid circuit a 28.3% lower cashflow is observed and for geothermal CHP the reduction is 33.5%. Geothermal CHP in parallel circuit is almost competitive compared to a hybrid power plant in serial circuit. The accumulated cashflow after 30 years of operation is only 7.5% lower. The described economic relationships are confirmed by the *IRR*. The highest value with 6.3% is obtained for hybrid power plant in parallel circuit, followed by the serial concept with 4.7% and the geothermal CHP in parallel circuit. Lowest *IRR* are calculated for geothermal CHP in serial circuit (2.7%) and separate use (2.4%).

Figure 11. Cumulated cashflow for the considered power plant concepts.



In Figure 12 the cumulated cashflow for an alternative working fluid (isopentane instead of R245fa), a higher maximum supply temperature (130 °C instead of 90 °C), higher operation and maintenance costs for the hybrid power plant (4% of the total investment costs instead of 2%) and different geothermal conditions (T_{GW} = 160 °C; $\dot{m}_{GW}$ = 65 kg/s instead of T_{GW} = 120 °C; $\dot{m}_{GW}$ = 100 kg/s) are shown in addition to the hybrid power plant in parallel circuit.

Figure 12. Cumulated cashflow for the variable boundary conditions.



According to the second law efficiency economic parameters are not affected significantly by the choice of working fluid. Isopentane as ORC working fluid leads to a 3% lower accumulated cashflow at the end of the lifetime compared to the use of R245fa. The *IRR* is 6.2% instead of 6.3%. The supply temperature of the heating network has a more obvious effect on economics. Since a higher rate of heat demand has to be supplied by the geothermal heat source, the electricity generation is decreased by 2.4 GWh/a in case of an increase of the maximum supply temperature range from 90 °C to 130 °C. This leads to a reduction of the cumulated cashflow of 27.6% after 30 years of operation. The *IRR* is 4.6%. For a geothermal water temperature of 160 °C and a mass flow rate of 65 kg/s the cumulated cashflow is almost doubled at the end of the lifetime. Compared to the low-temperature case, a more efficient ORC-unit with higher capacity can be realized. In case of 120 °C and 100 kg/s an ORC-unit of 2.5 MW electrical power output results, while 3.8 MW are obtained for a heat source with 160 °C. Therefore, the reduction of geothermal water mass flow can be overcompensated by the increase in temperature. In case of the hybrid power plant in parallel circuit, 10 GWh/a more electricity are generated and the IRR is increased to 9.97%. An increase of operation and maintenance costs lead to a considerable reduction of the economic parameters for the hybrid power plant. However, for an equal cost rate of 4% regarding operation and maintenance the cumulated cashflow at the end of the lifetime is still 23% higher compared to a separate use of the geothermal resource and the biogas CHP-unit.

4. Conclusions

Hybrid power plants are promising concepts for geothermal CHP. Comparisons to the separate use prove the advantages of coupling a geothermal resource and biogas engine. A higher efficiency of the ORC-unit is obtained due to the increase of geothermal water temperature by the exhaust gases. A parallel circuit of power and heat generation is favourable. Compared to conventional geothermal CHP, the second law efficiency is increased by up to 8.0% and the accumulated cashflow at the end of the lifetime is 50% higher. In relation to separate use, the hybrid power plant is 2.1% more efficient and a higher amount of electricity by 943.3 MWh/a could be generated. In addition, advantages regarding costs for operation and maintenance lead to significant economic differences. The cumulative cashflow at the end of the lifetime is more than tripled. Sensitivity analyses show a small influence on efficiency and economic parameters for the choice of the ORC working fluid. In contrast, a higher supply temperature of the heating network leads to a reduced implementation of the biogas-cogeneration unit in the hybrid power plant and a 27.6% lower cumulated cashflow after 30 years of operation is observed. In case of an increase of the geothermal water temperature from 120 °C to 160 °C, second law efficiency is increased by 22.9% and cumulated cashflow is almost doubled. For further work, dynamic simulations are performed, under consideration of part load behavior of pump and turbine as well as variable pinch points in the heat exchanger.

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Author Contributions

Florian Heberle is the principle investigator of this work. Final review was done by Dieter Brüggemann.

Conflicts of Interest

The authors declare no conflict of interest.

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