

Thermoeconomic evaluation of combined heat and power generation for geothermal applications

Florian Heberle*, Markus Preißinger, Dieter Brüggemann

University of Bayreuth, Germany

* Corresponding author. Tel: +49 921 557163, Fax: +49 921 557165, E-mail: lttt@uni-bayreuth.de

Abstract: In this study a thermoeconomic analysis of combined heat and power generation (CHP) for geothermal applications is presented. Different working fluids and power plant concepts are investigated for power generation by Organic Rankine Cycle and additional heat generation. For geothermal conditions in Germany, process simulations of series, parallel and hybrid circuits compared to sole power generation are performed. The results show that for power generation fluids with low critical temperature, like R227ea or isobutane, are suitable. In general, an additional heat generation decreases the averaged costs of electricity generation. In case of a source temperature of 120 °C the costs can be reduced from 25 ct/kWh to 16 ct/kWh compared to power generation. For CHP applications fluids with higher critical temperature and series or hybrid circuits are the most efficient concepts. With increasing temperature of the geothermal water an increase of supply temperature of the heating system has less influence on the costs of electricity generation. A doubling of mass flow of the geothermal water decreases the averaged costs of electricity generation in the range of 28 % and 43 % depending on power plant concept and boundary conditions.

Keywords: Geothermal energy, Organic Rankine Cycle, cogeneration, thermoeconomic analysis

Nomenclature

c	cost of electricity generation	ct/kWh	n	contract period.....	a
C	costs	€	N	produced amount of electricity.....	kWh
e	specific exergy	kJ/kg	p	pressure	Pa
\dot{E}	exergy flow rate	kW	P	mechanical power	kW
h	enthalpy	J/kg	s	entropy.....	J/(kgK)
i	interest rate.....	%	T	temperature	°C
\dot{m}	mass flow rate.....	kg/s	η	efficiency.....	%

1. Introduction

Regarding base load capacity, geothermal resources play an important role for renewable energy generation. For temperatures of the geothermal water below 180 °C direct expansion or flash processes are not suitable under thermodynamic and economical aspects [1]. Instead binary power plants like the Organic Rankine Cycle (ORC) or the Kalina Cycle are used. Therefore thermal energy of the geothermal water is coupled with the secondary thermodynamic cycle. Concerning the ORC, there are different possibilities, like selection of the working fluid, supercritical cycle or multi-stage expansion, to raise the electric efficiency [2-5]. Another interesting strategy to improve the second law efficiency and economic aspects is combined heat and power generation (CHP). In case of geothermal applications, previous exergoeconomic and thermoeconomic investigations are restricted to sole power generation or district heating [6-8]. In this study potential ORC fluids, isobutane, isopentane, R227ea and R245fa are investigated for power generation. In case of additional heat generation, parallel, series and hybrid circuit are considered. Second law efficiency and costs of electricity generation are calculated for an assumed heat demand and typical geothermal conditions in Germany. Detailed simulations are performed for variations of mass flow of the geothermal water and supply temperature of the heating system. The results provide basic criteria for fluid selection under thermoeconomic aspects in case of power generation by ORC and CHP.

2. Methodology

2.1. Simulation

Process simulations are done by the software tool Cylce Tempo and fluid properties are calculated by REFPROP Version 8.0 [9,10]. The process scheme of the ORC for sole power generation (SPG) and the corresponding T,s -diagram for isopentane at standard conditions are shown in Fig.1.

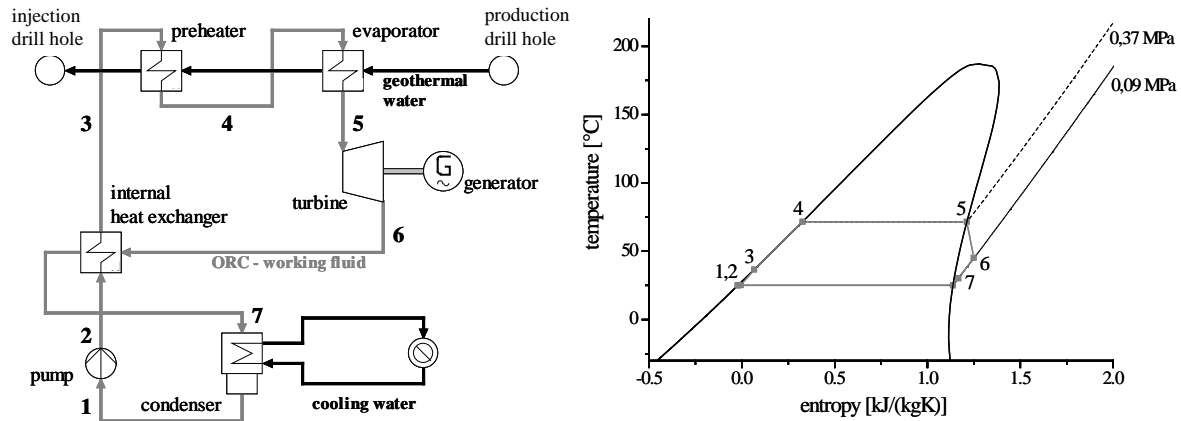


Fig. 1. Scheme of a geothermal ORC-power plant and corresponding T,s -diagram of isopentane.

The liquid fluid is compressed by the pump to maximum process pressure. The heat supply takes place in three steps. First the internal heat recovery, followed by the coupling with the geothermal heat source in the preheater and finally in the evaporator. As the analyzed fluids show a negative slope of the dew line in the T,s -diagram, so-called dry fluids, superheating is not necessary [11]. After the expansion the fluid is cooled down in the internal heat exchanger and condensed in the condenser. For the standard case, process parameters and boundary conditions of the heat source and sink are listed in table 1.

Table 1. Standard parameters of the ORC process simulation

parameter	
temperature of geothermal water	120 °C
mass flow of geothermal water	65.5 kg/s
ΔT -pinch-point (evaporation / condensation)	5 K
ΔT of the cooling water	5 K
cooling temperature	15 °C
maximum pressure ORC	$0.8 \cdot p_c$
isentropic efficiency (turbine / feed pump)	0.75

Regarding the additional heat generation, three concepts are investigated. Fig. 2 shows the series (SC), parallel (PC) and hybrid circuit (HC). As standard parameters of the heating system a supply temperature of 75 °C and a return temperature of 50 °C are assumed. The minimum temperature difference between heating system and geothermal water is 5 K. The supposed annual demand of thermal power is simulated in four steps: 10 MW for 1000 operating hours, 7.5 MW for 1500 operating hours, 5 MW for 2500 operating hours and 2.5 MW for another 3500 operating hours.

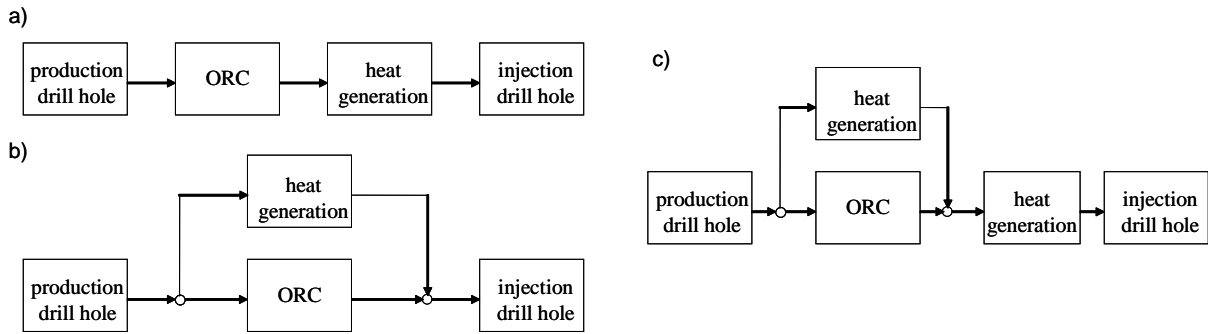


Fig. 2. Series circuit (a), parallel circuit (b) and hybrid circuit (c) as concepts for CHP

In case of series circuit the temperature of the geothermal water at the outlet of the ORC must be adapted to the peak load of the heat demand. For parallel circuit fluctuations in heat demand can be adjusted by varying the ratio of mass flow of the geothermal water. The hybrid circuit describes a coupling of series and parallel circuit.

2.2. Second law analysis

The simulations of the power plant are performed by solving a system of equations, consisting of energy balances of the heat exchangers units. Pressure and heat losses are not considered in the process components and pipes. As an example the energy balance of the preheater is given by

$$\dot{m}_{GW}(h_{GW,in} - h_{GW,out})_{PH} = \dot{m}_{ORC}(h_4 - h_3) \quad (1)$$

where \dot{m}_{GW} corresponds to the mass flow of the geothermal water, $h_{GW,in}$ and $h_{GW,out}$ to the enthalpy of the geothermal water at the inlet and outlet of the preheater. The mass flow of the ORC is described as \dot{m}_{ORC} , h_3 and h_4 correspond to the enthalpies of the working fluid at the inlet and outlet of the preheater. A detailed formulation of the simulation model can be seen in Heberle and Brüggemann [12]. By using a user subroutine the outlet temperature of geothermal water is adapted to the maximum power output of the ORC in case of power generation. The second law efficiency for sole power generation is calculated by

$$\eta_{II,el} = \frac{|P_T + P_P|}{\dot{E}_{GW}} \quad (2)$$

where P_T is the power of the turbine and P_P corresponds to the power of the pump. The maximum power output of geothermal source, the exergy flow \dot{E}_{GW} , is obtained by multiplying the specific exergy e with the mass flow of the geothermal water:

$$\dot{E}_{GW} = \dot{m}_{GW}e \quad (3)$$

The specific exergy is calculated by:

$$e = h - h_0 - T_0(s - s_0) \quad (4)$$

The state variables T_0 , p_0 and s_0 are related to ambient conditions. In the case of additional heat generation, the numerator from Equation 2 is extended with the exergetic value \dot{E}_Q

$$\eta_{II,tot} = \frac{|P_T + P_P| + \dot{E}_Q}{\dot{E}_{GW}} \quad (5)$$

where the exergy flow of the thermal energy coupled to the heating system \dot{E}_Q can be calculated by

$$\dot{E}_Q = \dot{m}_{HS}(e_{out} - e_{in})_{HS} \quad (6)$$

where \dot{m}_{HS} is the mass flow of the heating system. The specific exergy at the inlet and outlet of the heat transfer unit of the heating system are e_{in} and e_{out} .

2.3. Economic analysis

The assumed parameters for the economic analysis, like exploration costs or specific costs for the ORC module and heating system, are listed in table 2 [13]. PRIVATE EQUITY AND STATE FUNDING ARE NOT CONSIDERED FOR THE CALCULATIONS.

Table 2. Economic boundary conditions for geothermal CHP

parameter	
exploration costs	18 000 000 €
other (building, insurance, etc.)	4 000 000 €
power plant (ORC)	4 000 €kW
heating system	150 €kW
costs of heating pipeline	150 €m
heating price	40 €MWh
rise in price rate (heating price)	1,5 %/a
operating and maintenance (O&M) costs	750 000 €/a
rise in price rate (O&M)	2 %
interest rate i	7 %
contract period n for consumption of fixed capital costs	20 a

The annual costs C_A of the power plant consist of capital consumption C_C , imputed interest C_I , and O&M costs $C_{O\&M}$. The imputed interest $C_{I,t}$ for the year t is calculated by

$$C_{I,t} = \frac{R_{t-1} + R_t}{2} \cdot i \quad \text{with } t = 1, \dots, n \quad (7)$$

where R_t is the residual value and R_0 corresponds to the initial investment costs. The costs of electricity generation c_t at year t are calculated by

$$c_t = \frac{C_{A,t}}{N} = \frac{C_{C,t} + C_{I,t} + C_{O\&M}}{N} \quad (8)$$

where N is the annual produced amount of electricity. In the following the averaged costs of electricity generation c are calculated for the economic analysis by:

$$c = \frac{\sum_{t=1}^n c_t}{n} \quad (9)$$

3. Results

3.1. Second law efficiency for power generation

The second law efficiency for sole power generation as a function of inlet temperature of the geothermal water is shown in Fig. 3 for the investigated working fluids.

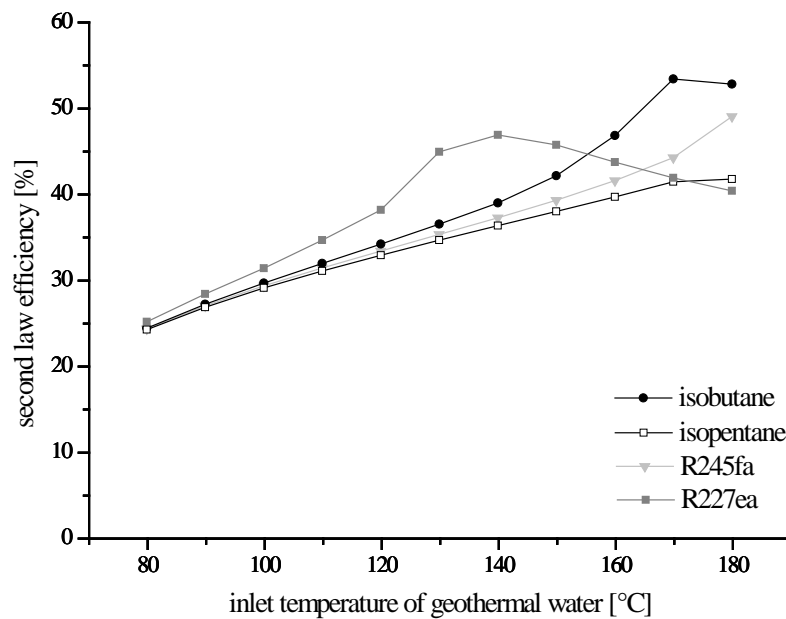


Fig. 3. Second law efficiency for the investigated working fluids as a function of temperature of the geothermal water

The results show obvious differences in efficiency depending on inlet temperatures. For low temperatures R227ea is a suitable working fluid, for temperatures higher than 150 °C isobutane should be favored. The local maxima for R227ea and isobutane are due to the shift of the pinch point from the inlet of the evaporator, state point 4, to the inlet of preheater, state point 3. The effect occurs, because the maximum process pressure of the ORC fluid is reached, which leads to a high amount of thermal energy coupled to the cycle. As a result the outlet temperature of the geothermal water decreases significantly. In case of the less efficient fluids, like R245fa and isopentane, the second law efficiency increases linear with inlet temperatures. For these fluids the outlet temperatures of the geothermal water are higher compared to R227ea or isobutane. At 120 °C inlet temperature isopentane leads to an outlet temperature of 64.3 °C compared to R227ea with 59.7 °C. The difference becomes apparent for 160 °C with outlet temperatures of 73.2 °C and 36.5 °C. A detailed explanation and graphical description of these correlations can be found in Heberle and Brüggemann [12].

3.2. Second law efficiency for CHP

Fig. 4 shows the second law efficiency for CHP as a function of thermal power of the heating system compared to sole power generation at standard conditions for isopentane and R227ea.

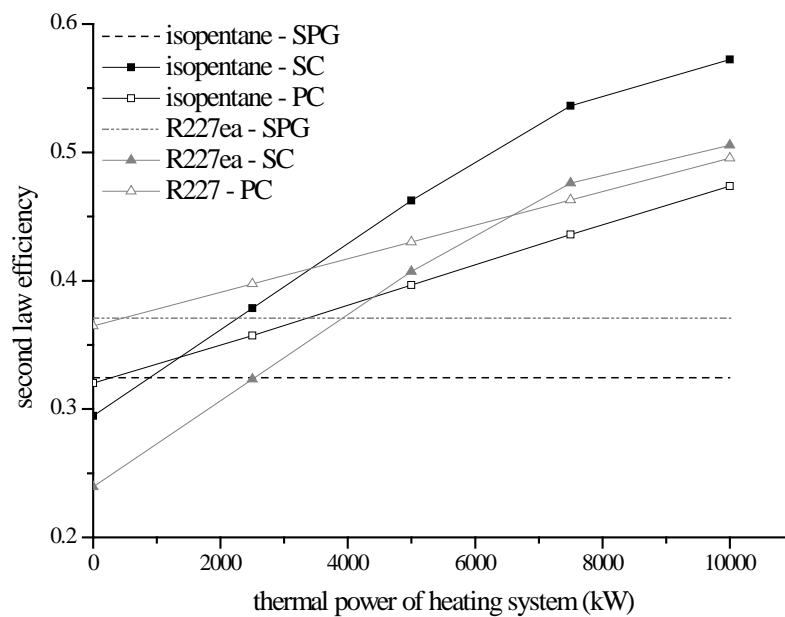


Fig. 4. Second law efficiency depending on thermal power coupled to the heating system

An additional heat generation improves the second law efficiency of the analyzed system. In case of isopentane the efficiency increases up to 24.8 % compared to sole power generation. For R227ea the raise is 15.5 % in case of 10 MW thermal power coupled to the heating system. Another interesting aspect is the comparison of the different concepts and working fluids. In the range of 1 MW to 10 MW thermal power the series circuit is the most efficient concept for isopentane as an ORC working fluid. In case of R227ea only for a thermal power higher than 7 MW the series circuit leads to slightly higher efficiencies compared to parallel circuit. The different behaviour of the working fluids corresponds to the outlet temperatures of geothermal water, which has to be adjusted to the temperatures of the heating system in case of series circuit. For R227ea, this adjustment shows higher losses in power generation compared to isopentane.

3.3. Averaged costs for electricity generation depending on power plant concept

In the following sections only the results for R227ea and isopentane are presented, to guarantee well-arranged analyses. The Southern German Molasse Basin and the Upper Rhine Rift Valley with temperatures of 120 °C and 160 °C for the geothermal water are chosen as geothermal reservoirs. In Fig. 5 the averaged costs of electricity generation depending on power plant concept and geothermal conditions are presented. Corresponding to the second law analysis R227ea is more suitable for power generation in comparison to isopentane. In case of 120 °C the costs are 25 ct/kWh, for 160 °C they are reduced to 15 ct/kWh. The difference to isopentane decreases with increasing temperature of the heat source. In general CHP leads to a decrease of averaged costs of electricity generation. In case of R227ea and 120 °C they are reduced to 18 ct/kWh by parallel circuit. The most economic concept for 120 °C is isopentane in conjunction with series circuit. For 160 °C the working fluid isopentane and the hybrid circuit with averaged costs of electricity generation of 9 ct/kWh should be preferred. In general the hybrid circuit only makes sense for working fluids with high outlet temperatures of the geothermal water, like R245fa or isopentane.

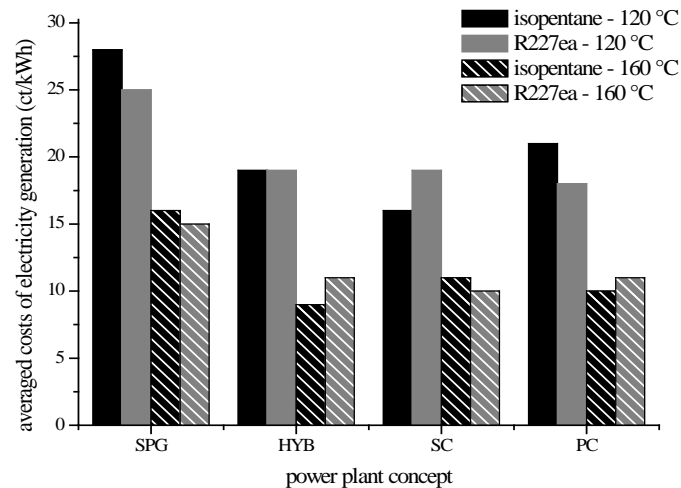


Fig. 5. Averaged costs of electricity generation depending on power plant concept

3.4. Variation of supply temperature of the heating system and mass flow of the geothermal water

Table 3 shows the averaged costs of electricity generation as a function of supply temperature of the heating system and mass flow of the geothermal water for isopentane in case of SPG and SC. In this case the duration curve of heat demand is analyzed more detailed in 11 steps.

Table 3. Averaged costs of electricity generation depending on supply temperature of the heating system and mass flow of the geothermal water

heating system supply temperature	SC – 120 °C (ct/kWh)	SPG – 120 °C (ct/kWh)	SC – 160 °C (ct/kWh)	SPG – 160 °C(ct/kWh)
75 °C	20	28	11	14
85 °C	24	28	11	14
95 °C	32	28	12	14
mass flow				
65.5 kg/s	20	28	11	14
100 kg/s	15	19	8	11
120 kg/s	13	16	8	10

In case of 120 °C an increasing supply temperature has a significant influence on the averaged costs of electricity generation. Since the outlet temperature of the geothermal water has to be increased for higher supply temperatures the losses in electrical power generation rise. For 95 °C supply temperature, the CHP concept leads with 32 ct/kWh to higher costs than sole power generation with 28 ct/kWh. For 160 °C the increase in supply temperature has only a marginal influence on economic aspects. A rise in mass flow of the geothermal water leads to a higher power output and lower costs of electricity generation. At a source temperature of 120 °C an increase from 65.5 kg/s to 120 kg/s leads to a reduction of costs from 28 ct/kWh to 16 ct/kWh in case of power generation and for series circuit from 20 ct/kWh to 13 ct/kWh. In case of 160 °C, costs are reduced up to 28 %.

4. Discussion

A thermoeconomic analysis for combined heat and power generation in case of geothermal heat sources below 180 °C was performed. For power generation the ORC with different

working fluids was investigated. The second law efficiency and the costs of electricity generation were calculated for three concepts of heat generation and two typical geothermal conditions in Germany. The following conclusions can be summarized:

- Second law efficiency and economic aspects can be enhanced by CHP.
- For power generation working fluids with low critical temperatures, at the shift of the pinch point, should be selected.
- R227ea leads with 25 ct/kWh and 15 ct/kWh to low costs for sole power generation.
- In case of CHP, working fluids with higher critical temperatures are suitable.
- Isopentane in conjunction with series and hybrid circuit is the most economic concept for CHP. In case of 120 °C and series circuit the costs of electricity generation are 16 ct/kWh and for 160 °C and hybrid circuit the costs are 8 ct/kWh.

References

- [1] R. DiPippo, Small geothermal power plants: design, performance and economics, GHC Bulletin, June 1999.
- [2] B. Saleh, G. Koglbauer, M. Wendland, J. Fischer, Working fluids for low-temperature organic Rankine cycles, *Energy* 32, 2007, pp. 1210-1221.
- [3] U. Drescher, D. Brüggemann, Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants, *Applied Thermal Engineering* 27, 2007, pp. 223-228.
- [4] S. Karellas, A. Schuster, Supercritical fluid parameters in Organic Rankine Applications, *International Journal of Thermodynamics* 11, 2008, pp. 101-108.
- [5] Z. Gnutek, A. Bryszewska-Mazurek, The thermodynamic analysis of multicycle ORC engine, *Energy* 26, 2001, pp. 1075-1082.
- [6] O. Arslan, Exergoeconomic evaluation of electricity generation by the medium temperature geothermal resources, using a Kalina cycle: Simav case study, *International Journal of Thermal Sciences* 49, 2010, pp. 1866-1873.
- [7] O. Arslan et al., Exergoeconomic evaluation on the optimum heating circuit system of Simav geothermal district heating system, *Energy and Buildings* 41, 2009, pp. 1325-1333.
- [8] A. Hepbasli, A review on energetic, exergetic and exergoeconomic aspects of geothermal district heating systems, *Energy Conversion and Management* 51, 2010, pp. 2041-2061.
- [9] N. Woudstra, T.P. van der Stelt. Cycle-Tempo: a program for the thermodynamic analysis. Energy Technology Section, Delft University of Technology, The Netherlands, 2002.
- [10] E.W. Lemmon, M.L. Huber, M.O. McLinden. NIST Standard Reference Database 23 – Version 8.0. Physical and Chemical Properties Division, National Institute of Standards and Technology, Boulder, Colorado, US Department of Commerce, USA, 2002.
- [11] P. Mago, L. Chamra, K. Srinivasan, C. Somayaji, An examination of regenerative organic Rankine cycles using dry fluids, *Applied Thermal Engineering* 28, 2008, pp. 998-1007.
- [12] F. Heberle, D. Brüggemann, Exergy based fluid selection for a geothermal Organic Rankine Cycle for combined heat and power generation, *Applied Thermal Engineering* 30, 2010, pp. 1326-1332.
- [13] B. Görke, A. Sievers, Gewinnbetrachtung von strom- und wärmegeführten Geothermie-Projekten unter Berücksichtigung der aktuellen EEG Novelle, Tagungsband Geothermiekongress, 2008, Karlsruhe (D), pp. 157-156.