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Economic Analysis of Geothermal Combined Heat and Power Processes

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Abstract

Despite huge potentials of geothermal energy the share on worldwide electricity and heat provision is small, which is mainly caused by unfavorable economic boundary conditions. In this study, combinations of combined heat and power systems and working fluids, which perform best from a thermodynamic point of view, are evaluated by means of economic parameters based on VDI standard 2067. The objective is the evaluation of levelized cost of electricity and heat respectively. In detail, effects of electricity and heat price factors, thermal water temperatures and drilling costs on economic efficiency are focused. A trade-off between economic and thermodynamic goals is discussed. Based on a realistic cost structure of geothermal energy systems economic operations are feasible within typical life spans of projects. Annual energy sales are strongly influenced by the applied drilling cost correlation and are calculated to three to five Mio. Euro. In order to generate heat and electricity sales the heat generation represents the limiting process.

Keywords

Combined heat and power processes, Economic analysis, Geothermal heat utilization, Levelized cost of energy, Organic rankine cycle.

1. Introduction

In order to ensure security of supply and sustainable operations, base-load capable and environmental-friendly energy sources are of great interest for future energy provision. In particular, federal regulations have significantly pushed the utilization of renewable energy sources such as geothermal energy. Geothermal heat is outstanding due to base-load capability, low CO_2 emissions and the potential to satisfy the world energy demand. Depending on the drilling depth, the technical potential of deep geothermal energy ranges between $1.78 \cdot 10^{11}$ GJ and $11.1 \cdot 10^{11}$ GJ [1]. A comparison with predicted worldwide installed capacities in 2015 (12.6 GW_{el}) shows a huge gap between potential and current utilization. Low utilization efficiencies of the heat source, high investment costs prior to generating revenues in conjunction with drilling insecurities in terms of expected mass flow rates and brine temperatures represent major drawbacks. The performance of combined heat and power (CHP) plants depends strongly on sale prices for electricity and the scope of financial, federal and network support. Financial support is mainly provided by state-funded subsidies and subventions for investments, low interest rates for credits and concession/environmental taxes. Currently 252 Euro/MWh_e are granted for electricity from hydrothermal and petrothermal reservoirs based on the Renewable Energies Act in Germany.

The interest in economic low-temperature energy systems has increased steadily due to decreasing federal subsidies. A great diversity and number of articles related to the economic evaluation of geothermal heat projects can be found in literature [2-23]. A comprehensive overview of exergoeconomic methods is provided by Abusoglu et al. [2]. Several cost accounting approaches and algebraic models with several sub-groups are described. The field of application for exergoeconomic analyses is versatile and articles related to waste heat recovery in gas turbines [3], reciprocate operating Otto engines [4] and fossil-fired steam power plants [5-6] can be found. Furthermore a combined heat and power plant which is fired by natural gas [7] and a geothermal district heating system [8] are investigated based on an exergoeconomic approach. Heberle et al. carry out an exergoeconomic analysis of a standard geothermal power plant operated by isobutane and isopentane [9]. Lecompte et al. investigate a heat-driven combined heat and power system with a serial-connected Organic Rankine Cycle (ORC) in part load from an exergoeconomic point of view [10]. Schlagermann considers exergoeconomic parameters of geothermal CHP plants in the Upper Rhine Rift in Germany. The author provides a comprehensive overview of costs related to geothermal energy systems during project development [11].

A study which has been carried out at the Fraunhofer institute for solar energy gives an overview of levelized cost of electricity of different renewable (photovoltaic, wind power (onshore, offshore), biomass) and conventional (coal, combined cycles) technologies based on the year 2013 [12]. Weimann summarizes the current state of geothermal energy utilization in Germany on behalf of the federal ministry for the environment, nature conservation and building and nuclear safety. The study is based on ten geothermal heat and/or power plants. Specific costs of 3000 to 4400 $\text{Euro}_{2008}/\text{kW}_e$ and levelized cost of electricity of 176 - 279 $\text{Euro}_{2008}/\text{MWh}_e$ are published based on the year 2008 [13]. Another overview is given by Sanyal for large scale power plants with specific costs of 2100 to 4200 $\text{USD}_{2004}/\text{kW}_e$ [14]. Depending on the geothermal technology (binary, flash, dry steam) between 50 and 110 $\text{USD}_{2004}/\text{MWh}_e$ are stated. Kanoglu et al. carry out an economic analysis of a binary geothermal energy system. The authors state specific costs of 2000 to 6000 $\text{USD}_{1999}/\text{kW}_e$, levelized cost of electricity in the range of 30 to 120 $\text{USD}_{1999}/\text{MWh}_e$, levelized cost of heat of about 80.5 $\text{USD}_{1999}/\text{MWh}_t$ and drilling costs between 500 and 4000 $\text{USD}_{1999}/\text{kW}_e$ [15]. Electricity costs utilizing geothermal heat, fossil fuels, nuclear power and hydropower respectively are compared. Vatopoulos et al. present four major operation modes of combined heat and power plants: (a) Matching the electrical base-load by meeting the minimum electricity demand while additional power is purchased from the grid; (b) Matching the thermal base-load by meeting the minimal thermal energy requirement in conjunction with a peak load boiler; (c) Matching the electrical load. For heat decoupling an additional boiler is used; (d) Matching thermal loads. The authors provide mean values of about 1000 to 4000 $\text{Euro}_{2012}/\text{kW}_e$ and 65 $\text{Euro}_{2012}/\text{MWh}_e$ [16]. Hettiarachchi et al. derive a cost effective design criterion for a standard Organic Rankine Cycle considering low-temperature geothermal heat between 70 °C and 90 °C. The objective is to minimize the ratio of heat exchanger area and power output subject to a maximal electricity generation [17]. Toffolo et al. focus on a multi-criteria approach for the optimal selection of working fluids and design parameters in several ORC configurations. Geothermal water temperatures of 130 °C to 180 °C are investigated. The economic analysis is carried out using the bare module costing technique, which is comprehensively used for preliminary cost estimations in the chemical industry. The used technique is validated against cost data of a 30 MW ORC power plant. While specific costs cover a range between 4600 and 7000 $\text{USD}_{2014}/\text{kW}_e$, levelized cost of electricity of 82.3 to 84.0 $\text{USD}_{2014}/\text{MWh}_e$ are obtained [18]. Vélez et al. carry out an economic analysis of different technologies utilizing low-temperature systems such as solar heat, desalination, biomass and combined plants. Specific costs of 1000 to 4000 $\text{Euro}_{2010}/\text{kW}_e$ and 40 to 100 $\text{Euro}_{2010}/\text{MWh}_e$ are obtained [19]. Further comprehensive studies concerning financial aspects of geothermal heat projects in general can be found in [20-23].

In the present study effects of opposing economic and thermodynamic goals related to low-grade geothermal energy are discussed. Benchmark is the evaluation and calculation of levelized cost of electricity and heat respectively of parallel- and serial-connected CHP systems, which represent the state of the art, and of an advanced CHP process. The influence of price factors for electricity and heat as well as different drilling cost correlations are taken into account. In section one the results of a comprehensive literature review on specific costs of geothermal energy processes is presented. In section two the methodology and assumptions are described. The investigated CHP designs and optimized power generation processes are presented and the underlying thermodynamic simulations are explained. Finally, the economic investigation according to VDI standard 2067 is depicted. Section three contains the results of the thermodynamic and economic analyses and the obtained levelized costs of electricity and heat respectively are discussed. In section four the main results are summarized and concluded.

2. Methodology and Assumptions

The present economic considerations are based on preliminary thermodynamic simulations. The main focus has been on heat exchanger configurations for decoupling heat. Based on a heat source scale of 50 MW_t, the objective has been maximal power generation in the heat-driven CHP systems as a function of the thermal water temperature (100 °C to 140 °C) and heat demand. In the considered range optimal combinations of CHP systems and working fluids are highlighted. Figure 1 shows the flow sheets and qualitative TQ-diagrams of the investigated CHP configurations. In addition, two regenerative pre-heating ORC processes, which are shown in Figure 2, are compared to the performance of the standard concepts in Figure 1 from a thermodynamic point of view. Furthermore economic considerations in terms of levelized costs of electricity and heat are focused on in the present work.

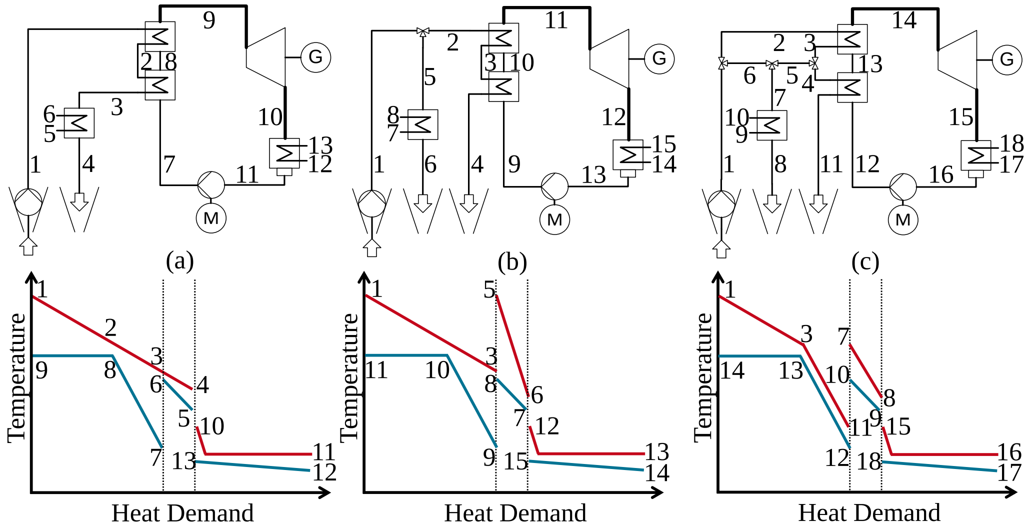

Fig. 1. CHP configurations in the preliminary study: (a) Serial-connected CHP system; (b) Parallel-connected CHP system; (c) CHP-Split system

Figure 2 (a) presents a two-stage turbine bleeding ORC process. A defined amount of working fluid is extracted at an intermediate pressure level in order to meet the saturated outlet condition of the direct-contact heater. In Figure 2 (b) a recuperator process is shown in which the super-heated turbine exhaust is used to heat the working fluid prior to the pre-heater. Both systems increase the mean temperature of heat input and thus decrease exergy destruction.

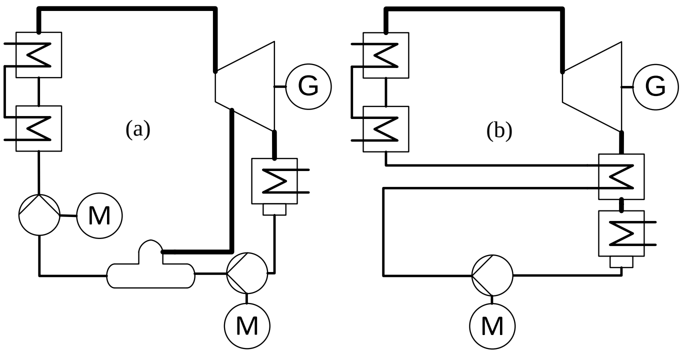

Fig. 2. Investigated regenerative pre-heating ORC systems: (a) Two-stage turbine bleeding process; (b) Process with recuperator

Note that the recuperator design in Figure 2 (b) is only evaluated for isopentane due to the dry character of the fluid. With isopentane the fluid temperature prior to the pre-heater can be increased by 12.37 K. Isobutane and isobutene can be heated by 2.29 K and 4.68 K while R245fa, R1234ze and R227ea don’t meet the defined pinch point specification of 10 K in the recuperator.

The economic analysis is based on a normalized heat load duration curve [24].

$$\frac{\Delta\dot{H}_{DH}\left(\frac{t}{\tau}\right)}{\Delta\dot{H}_{DH,\max}}=1-\left(\left(1-\frac{\Delta\dot{H}_{DH,\min}}{\Delta\dot{H}_{DH,\max}}\right)\cdot\left(\frac{t}{\tau}\right)^{\frac{\frac{t_b}{\tau}-\frac{\Delta\dot{H}_{DH,\min}}{\Delta\dot{H}_{DH,\max}}}{1-\frac{t_b}{\tau}}}\right) \tag{1}$$

with the heat demand at time t $\Delta\dot{H}_{DH}$, maximum heat demand $\Delta\dot{H}_{DH,\max}$, minimum heat demand $\Delta\dot{H}_{DH,\min}$, operational hours τ and full load hours t_b per year.

Component costs are estimated by the bare module costing technique [24]. Based on characteristic parameters of the equipment (area, power, volume) a logarithmic correlation is evaluated at standard conditions (carbon steel, ambient pressure). The correlation is adapted by pressure and material factors. The heat exchanger area is calculated using the logarithmic mean temperature difference (LMDT) method. The assumed heat transfer coefficients U are taken from literature and are shown in Table 1 [24-26].

Table 1. Assumed heat transfer coefficients U

Heat exchanger	U [W / m^2·K]	Heat exchanger	U [W / m^2·K]
Evaporator	2000	District heating	1500
Pre-heater	900	Recuperator	900
Condenser	1000		

In order to correlate reference purchase equipment costs (PEC) to the present value, the chemical engineering plant cost index (CEPCI) is used.

$$PEC_{present}=PEC_{reference}\cdot\frac{CEPCI_{present}}{CEPCI_{reference}} \tag{2}$$

According to Turdon et al. additional expenses for assembly, piping, insulation, fundaments etc. (50 % of component material cost), planning and other administrative costs (18 % of component material cost) and instrumentation, controlling and automation (8 % of component material cost) are taken into account. Furthermore 12 % of component material costs represent expenses for balancing the plant [24]. The mean exchange rate in 2014 is used to convert US dollars to Euro.

Direct and indirect costs are categorized in capital-related and demand-related payments. Furthermore operation-related costs, miscellaneous costs and sales are distinguished. Economic parameters are mainly taken from Schlagermann and Lukawski [11,23]. The annuity of all costs and sales are calculated according to VDI standard 2067 [27]. The annuity factor a discounts the total investment of a component during the period of consideration T to equally sized annual payment.

$$a=\frac{i}{1-(1+i)^{-T}} \tag{3}$$

with interest factor i.

The present value factor b_k of a specific cost type k takes future price developments into account.

$$b_k = \frac{1-\left(\frac{1+r_k}{1+i}\right)^T}{i-r_k} \tag{4}$$

with price factor r_k.

Capital-related (Cap) costs are taking the investment costs at the beginning A_0, the present value of replacements A_n and the salvage value A_S into account.

$$A_{N,Cap} = \sum_c \left(A_0 + A_1 + A_2 + \cdots + A_n - A_S\right)\cdot a \tag{5}$$

A_n of replacement 1, 2,…, n is the present value of a future investment for a component.

$$A_n = A_0 \cdot \frac{(1+r)^{n\cdot T_N}}{(1+i)^{n\cdot T_N}} \tag{6}$$

with the lifetime of a component T_N.

The salvage value A_S of a component which is purchased in the future is linear depreciated and discounted to present value.

$$A_S = A_0 \cdot (1+r)^{n\cdot T_N} \cdot \frac{(n+1)\cdot T_N - T}{T_N} \cdot \frac{1}{(1+r)^T} \tag{7}$$

Demand-related (Dem), operation-related (Ope) and miscellaneous costs (Misc) as well as sales (Sal) are calculated by taking the corresponding costs and sales after the first year of operation $A_{N,k,1st\ year}$ into account.

$$A_{N,k} = \sum_{k\in\{Dem,Ope,Misc,Sal\}} A_{N,k,1^{st}\ year} \cdot a \cdot b_k \tag{8}$$

Levelized costs of electricity (LCOE) and heat (LCOH) are obtained by relating the total annuity costs either to the electric power output P_{el} or to the amount of decoupled heat $\Delta\dot{H}_{DH}$.

$$\frac{A_{N,Cap} + A_{N,Dem} + A_{N,Ope} + A_{N,Misc} + A_{N,Sal}}{\Delta\dot{H}} = \left\{\begin{array}{c} LCOE\ if\ A_{N,Sal} = Heat\ sales; \Delta\dot{H} = \sum_\tau P_{el} \\ LCOH\ if\ A_{N,Sal} = Power\ sales; \Delta\dot{H} = \sum_\tau \Delta\dot{H}_{DH} \end{array}\right\} \tag{9}$$

3. Results and Discussion

Taking regenerative pre-heating processes into account the system performance can be improved. Up to 28.72 % more power can be generated in the heat-driven processes compared to the reference design in particular at high heat demands. Figure 3 presents a surface plot relating the generated power to the thermal water temperature range and heat demand. Selected isolines of power outputs are included in the figure. Furthermore areas are highlighted which define optimal combinations of CHP systems and working fluids in terms of maximal power generation. Note that in the thermodynamic analysis on-site power of the production/reinjection pumps and air ventilation is neglected.

The required annual heat of the assumed heat network is 75 GWh_{th} with a minimum and maximum demand of 1 MW_t and 30 MW_t respectively and 2500 full load hours. The availability corresponds to 92 % based on 8760 hours per year. Heat for the heat network is completely provided by the geothermal CHP systems.

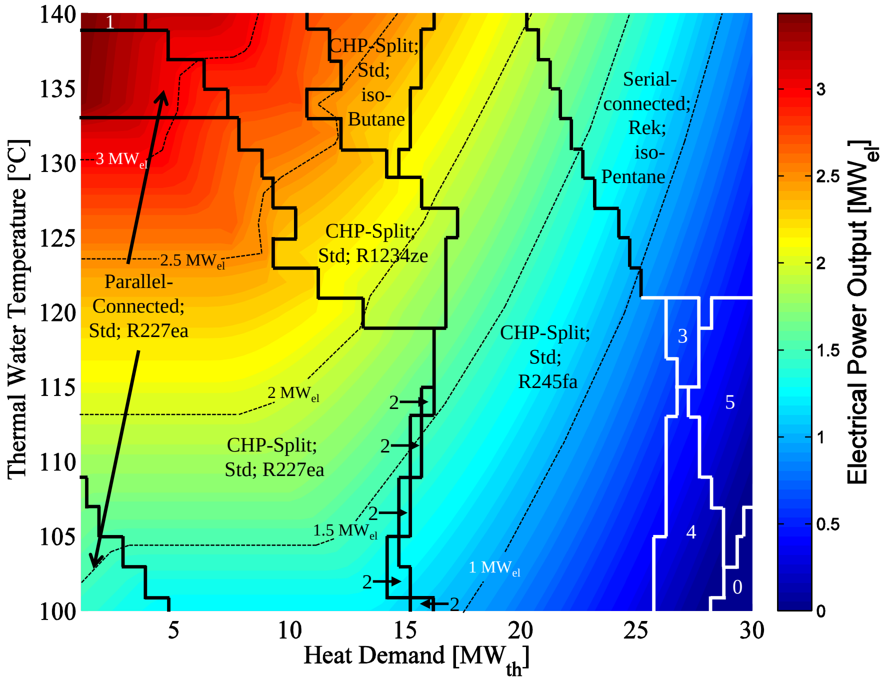

Fig. 3. Optimal CHP system/working fluid combinations: (0) not possible; (1) CHP-Split; Standard (Std) cycle; R227ea; (2) CHP-Split; Standard cycle; R1234ze; (3) Serial-connected; Two-stage (Sat) cycle; R245fa; (4) CHP-Split; Recuperator (Rec) cycle; isopentane; (5) Serial-connected; Two-stage cycle; isopentane)

The interest rate i is set to 9 % which represents a typical value based on debt and equity in geothermal energy projects [11]. Price changes for general payments and investment goods are considered by factors 1.015 and 1.02 [11]. Electricity factors are negative due to the decrease of the guaranteed electricity sale prices according to the Renewable Energies Act. Sensitivity analyses varying electricity (r_{Power} = 0 %, -2.5 %, -5 %) and heat (r_{Heat} = 3 %, 5 %) price factors are carried out. The on-site power for air ventilation in the condenser is determined by multiplying 0.15 $kW_e/(kg/s)$ and the air mass flow rate [11,18]. Due to the lack of data for the power requirement of the production pump data of an existing geothermal heat plant in Germany are adapted and interpolated. In general, equipment lifetimes are taken from VDI standard 2067. Due to the highly corrosive conditions as well as temperature and pressure levels, the lifetime of the production pump is reduced to four years [11]. The length of the heat network is assumed to eight kilometers with costs of 0.6 Mio. Euro/km. One production and one reinjection well, each with a length of 3500 m, are considered in the economic analysis. In order to evaluate the effect of drilling costs three correlations are applied. The highest costs are obtained with the correlation according to [13]. Based on the boundary conditions drilling costs of 23.73 Mio. Euro are calculated. Further correlations are taken from [11] and [23] with drilling costs of 12.65 Mio. Euro and 7.45 Mio. Euro respectively.

Capital-related costs contain expenses for a feasibility analysis, scheduling, land, infrastructure, reservoir development, sub-surface and above ground plant components and connections as well as capital-related insurances. Demand-related costs contain expenses for additional on-site power and other costs such as disposal and fresh water. Costs for labor, operation and maintenance are summarized in operation-related costs. Miscellaneous costs mainly encompass additional insurances, public relation and legal consulting [11]. Electricity is sold according to the state-regulated price of 252 Euro/MWh_e for utilizing hydrothermal and petrothermal reservoirs. Heat sale prices in Germany vary significantly depending on the supplier and the area. A comparison of district heating prices in 2013, which was carried out by the chamber of Commerce and Industry in

Schleswig-Holstein [28], quantify prices between 62.74 Euro/MWh_t and 104.07 Euro/MWh_t. Taking 92 networks with different full load hours and network lengths into account, a mean value of 73.69 Euro/MWh_t is obtained.

In order to find the best CHP system/working fluid combination from an economic point of view, LCOH are calculated for all combinations which are crossed by a horizontal line at the considered thermal water temperature in Figure 3. For example, considering a thermal water temperature of 125 °C, a parallel-connected standard system operated by R227ea, the CHP-Split concept operated by R1234ze and R245fa respectively and a serial-connected recuperated CHP system with isopentane as the working fluid are analysed. Among these systems the one with the lowest levelized costs are further analyzed. For the majority of investigated thermal water temperatures and within the feasible temperature range the serial-connected, regenerative pre-heating CHP system with a recuperator (compare Figures 1 (a) and 2 (b)) and isopentane as the working fluid performs best from an economic point of view. Only a small dependency of the thermal water temperature, price factors and drilling costs on the optimal combination is observed: (a) a CHP-Split standard system (compare Figure 1 (c)) with R245fa as the working fluid is preferred at a thermal water temperature of 118 °C and drilling costs of 23.73 Mio. Euro and 12.65 Mio. Euro respectively independent of the electricity price factor; (b) the same system is beneficial at 120 °C and an electricity price factor of 0 %; (c) a serial-connected two-stage process (compare Figures 1 (a) and 2 (a)) with isopentane as the working fluid is favorable at a thermal water temperature of 118 °C, drilling costs of 7.45 Mio. Euro and electricity price factors of 0 % and -2 %.

Figure 4 shows levelized cost of heat (LCOH) and minimal periods of consideration (PoC) of the optimal CHP systems as a function of the thermal water temperature and electricity price factors based on drilling costs of 23.73 Mio. Euro. In order to reach LCOH equal to the mean heat sale price of 73.69 Euro/MWh_t, the minimal periods of consideration of the heat-driven systems are determined. Thus, when the operational time exceeds the shown minimal necessary period of consideration at a specific thermal water temperature LCOH decreases and heat sales are generated. Figure 4 is divided in three zones. Zone A covers high thermal water temperatures ranging from 124 °C/126 °C/128 °C (depending on the electricity price factor) to 140 °C. In this area, levelized cost of heat can be kept constant accompanied by increasing minimal necessary operational years. The exponential increase is based on the decreased annuity of electricity sales at lower thermal water temperatures. Depending on the electricity price factor and thermal water temperature zone B covers the range between 118 °C and 124 °C/126 °C/128 °C. The period of consideration is capped at about 31.5 years. This upper bound represents a typical life span of a geothermal energy project [11]. The bound is determined by analyzing the minimal necessary operational years which are obtained with an electricity price factor of -5 % and a thermal water temperature of 130 °C. With the defined boundary in conjunction with the medium-temperature heat source, LCOH of 73.69 Euro/MWh_t cannot be maintained anymore. Thus depending on the thermal water temperature and electricity price factor, the minimal heat sale price must be increased to 83.03 Euro/MWh_t (r_{Power} = 0 %) and 83.28 Euro/MWh_t (r_{Power} = -5 %) respectively. In zone C, which covers thermal water temperatures lower than 118 °C, the on-site power demand of the production pump, reinjection pump and air ventilation exceeds the generated power in the CHP process. Thus, with the defined boundary conditions no economic generation of heat and power is possible. In order to utilize such low-temperature hydrothermal reservoirs several approaches can be investigated. Among others (a) electricity is purchased from the power grid; (b) the power generation unit is further optimized; (c) pure heat generation systems including peak load boilers are applied. Note that these investigations are not part of the present study.

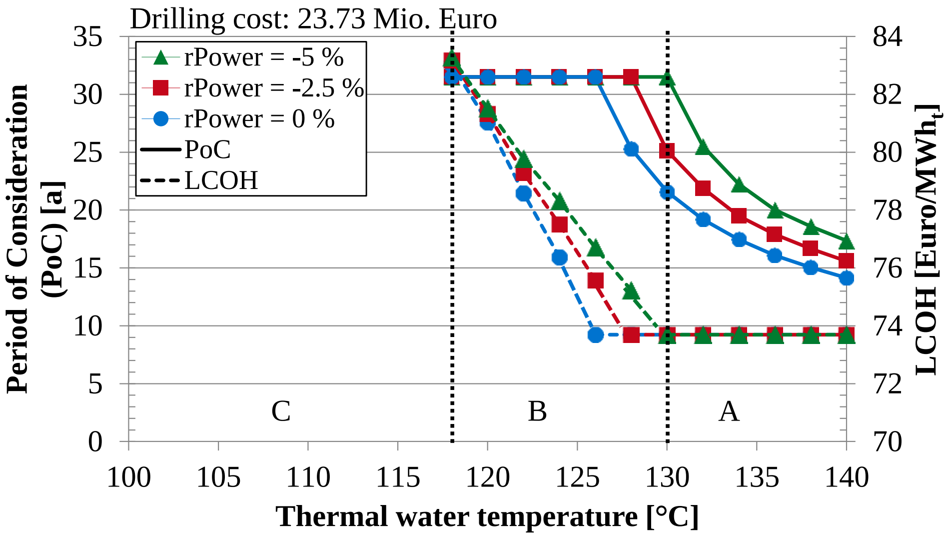

Fig. 4. Period of consideration and LCOH as a function of the thermal water temperature and electricity price factor for drilling costs of 23.73 Mio. Euro

In Figure 5 the influence of drilling costs on the minimal operational years are analyzed. The performance for drilling costs of 23.73 Mio. Euro has already been discussed in Figure 4. A further adaption of the heat sale prices considering the correlations in [11] and [23] are not necessary. The target of 73.69 Euro/MWh$_t$ for levelized cost of heat is reached within the defined upper bound for the period of consideration.

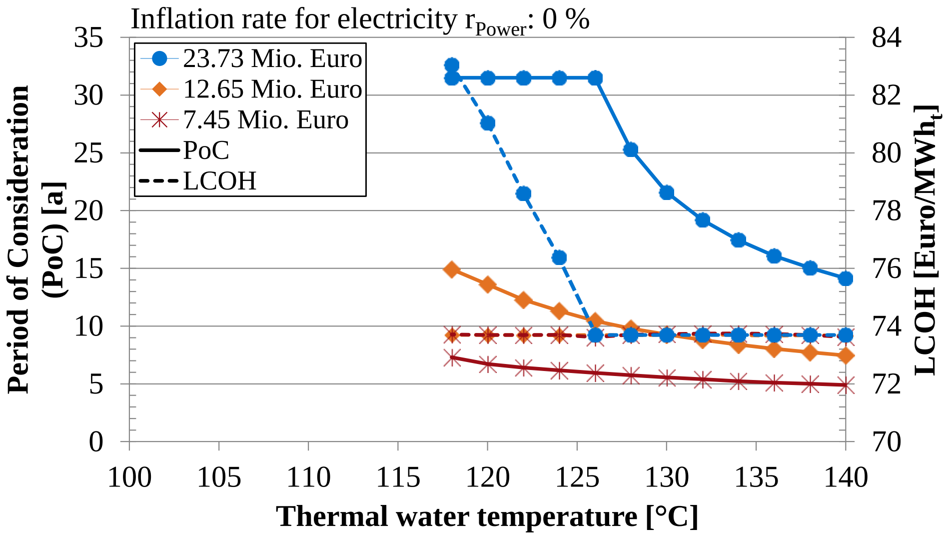

Fig. 5. Period of consideration and LCOH as a function of the thermal water temperature and drilling cost correlation for an electricity price factor of 0 %

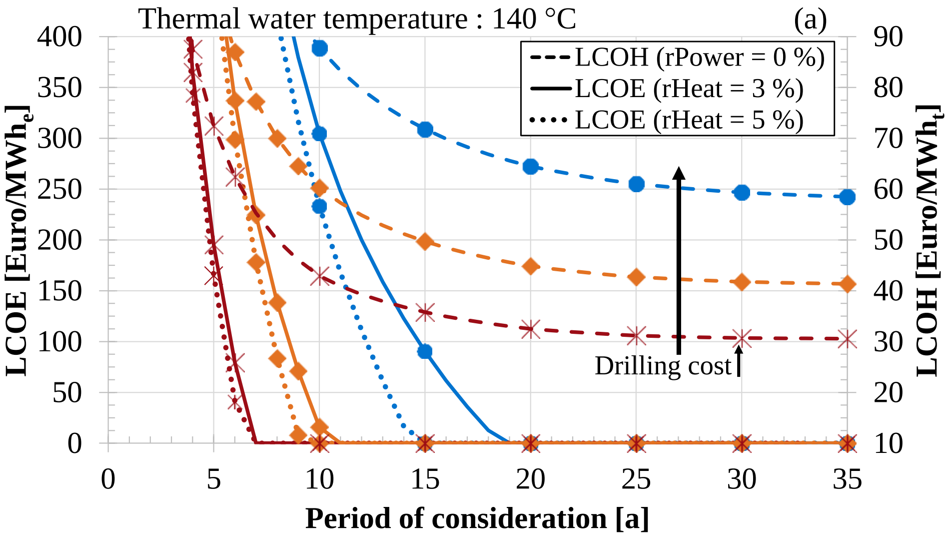

Fig. 6. LCOE and LCOH as a function of the period of consideration and electricity and heat price factors for a thermal temperature of 140 °C

Figures 6 and 7 provide levelized costs of electricity (LCOE) and heat as well as annual energy sales as a function of the expected operational years/period of consideration, drilling costs and price factors. The dashed lines in Figure 6 represent LCOH as a function of the drilling correlation and the period of consideration. Exceeding the minimal necessary operational years, which are obtained in Figure 5, LCOH decrease with a flattening trend. Assuming a heat sale price of 73.69 Euro/MWh$_t$, the difference between the sale price and LCOH presents specific earnings. The solid and dotted lines represent LCOE assuming heat price factors of 3 % and 5 % respectively as a function of the drilling costs. Similar to the heat sales, electricity sales are generated when LCOE are lower than the state-regulated sale price.

Table 2 shows minimal periods of consideration for which LCOE amounts to 252 Euro/MWh$_e$ assuming a heat sale price of 73.69 Euro/MWh and LCOH of 73.69 Euro/MWh$_t$ with an electricity sale price of 252 Euro/MWh$_e$ respectively exemplary for a thermal water temperature of 140 °C.

Table 2. Minimal operational years in order to generate heat and power sales at 140 °C

Price factors for heat and elctricity	Drilling cost = 7.45 Mio. Euro [23]	Drilling cost = 12.65 Mio. Euro [11]	Drilling cost = 23.73 Mio. Euro [13]
Operational years for LCOE = 252 Euro/MWh$_e$ and a heat sale price of 73.69 Euro/MWh$_t$			
r_{Heat} = 3 %	4.67a	6.76a	10.93a
r_{Heat} = 5 %	4.51a	6.39a	9.77a
Operational years for LCOH = 73.69 Euro/MWh$_t$ and an electricity sale price of 252 Euro/MWh$_e$			
r_{Power} = 0 %	4.90 a	7.46 a	14.14 a

Comparing minimal operational years in order to generate heat and power sales the limiting values are obtained for the heat generation processes. The periods of consideration which are necessary to reach LCOH of 73.69 Euro/MWh$_t$ are higher compared to the target of 252 Euro/MWh$_e$ for LCOE.

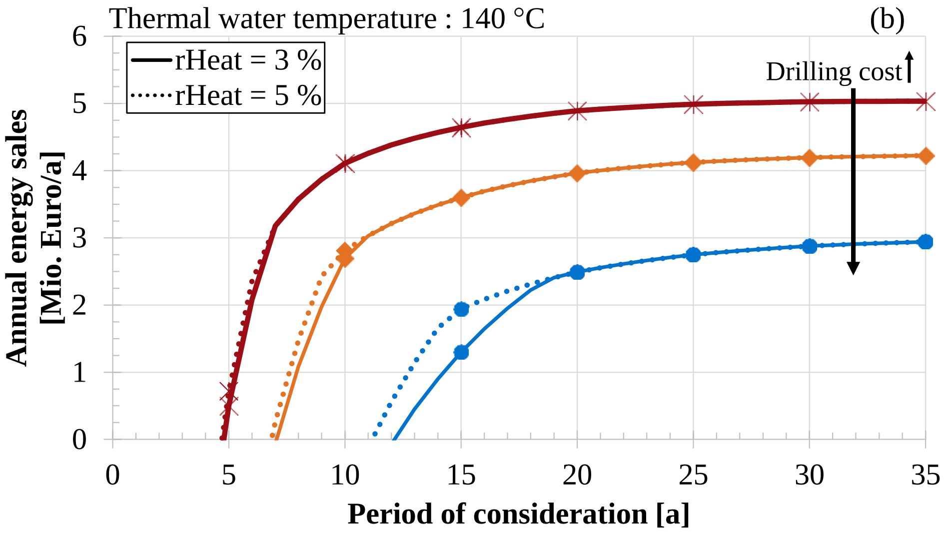

Fig. 7. Annual electricity and heat sales as a function of the period of consideration in dependence of the heat price factor for a thermal temperature of 140 °C

Figure 7 shows the influence of the drilling cost correlations and heat price factors on the total annual energy sales. As expected, drilling costs strongly influence the annual energy sales. The significant impact of the price factors for drilling costs of 23.73 Mio. Euro compared to the other correlations is based on the higher period of consideration. The flattening trend of the curves is caused by the applied annuity method. As a function of the applied correlation between three and five million Euro per year are calculated depending on the expected life span of the project. Considering a plant life of 30 years and comparing drilling costs of 23.73 Mio. Euro and 7.45 Mio. Euro 42 % lower annual energy sales are generated using the correlation of [13].

Conclusion

In this work different standard and regenerative pre-heating CHP designs are considered from a thermodynamic and economic point of view. The main focus of the present study is a comprehensive economic analysis of heat-driven CHP systems according to VDI standard 2067. In detail, the effect of thermal water temperatures, heat and electricity price factors and drilling costs on levelized cost of electricity and heat respectively are investigated. Based on a mean heat sale price of 73.69 Euro/MWh$_t$ in Germany and on the guaranteed sale price for electricity from geothermal reservoirs of 252 Euro/MWh$_e$, annual energy sales of three to five Mio. Euro depending on the drilling cost correlation are calculated. Drilling costs also play a significant role for the minimal period of consideration in order to obtain LCOE and LCOH equal to the mean sale prices. For thermal water temperatures in the range of 126 °C to 140 °C minimal operational years are lower than typical life spans of a geothermal energy project. With the defined boundary conditions and medium reservoir temperatures the upper bound for the period of consideration is reached and thus heat sale prices must be increased up to 82.3 Euro/MWh$_t$. At lower temperatures the on-site power exceeds the power generation in the CHP system and thus no economic operation is possible. The least period of consideration/operational years is defined by the time which is necessary for levelized cost of heat to come below the mean heat sale prices.

Nomenclature

Parameter

a	annuity factor, -
A	present value, Euro
A_N	annuity cost, Euro/a
b	present value factor, -
c	component, -
$\Delta\dot{H}$	enthalpy rate, W
i	interest rate, %
$LCOE$	levelized cost of electricity, Euro/MWh$_e$
$LCOH$	levelized cost of heat, Euro/MWh$_t$
P	power, W
PEC	purchased equipment costs, Euro
r	price change rate, %
t	time, h
t_b	full load hours per year, h
T	period of consideration, a
T_N	lifetime of a component, a
U	heat transfer coefficient, W/(m^2·K)

Greek symbols

τ	operational hours per year, h

Subscripts

Cap	capital-related
Dem	demand-related
DH	district heating
el	electrical
Heat	heat
k	cost type (Cap, Dem, Ope, Oth, Sal)
max	maximum
min	minimum
Misc	miscellaneous
n	running number
Ope	operation-related
Oth	other
Power	electricity
S	salvage
Sal	sales

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