

Energy/Exergy Conversion Factors of Low Enthalpy Geothermal Plants

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Research Article

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Energy/exergy conversion factors of low enthalpy geothermal plants

Henning Francke, GFZ German Research Centre for Geosciences

Keywords: Geothermal, energy, exergy, efficiency, COP, heat pump

Abstract

A geothermal heat plant is not only a source of heat, but, in general, also a sink for relevant amounts of electricity, consumed mainly by the pump(s). This electricity demand is usually not given much attention although being decisive for operation costs, but also offering chances for demand side management as a variable consumer. From the perspective of an integrated energy system, geothermal installations basically move energy from the electricity sector into the heat sector, similar to compression heat pumps. The main heat pump performance indicator is the ratio between invested energy and useful heat, the COP. This paper transfers the COP concept to geothermal sites, by defining and determining the quantity for a selection of mostly German geothermal sites.

Keywords: COP, Power-to-heat, geothermal, energy, conversion, efficiency, system, auxiliary energy

Introduction

The integration of renewable energies into our energy system poses various challenges, as fluctuating demand and weather dependent production have to be matched. Possible solutions are storage, adaptive production by conventional plants, demand-side load management and energy transport over long distances. Another approach is to leave the electric sector and make use of other energies. Power-to-X is the catchy name for the transformation of surplus electric energy^a into another energy form which can be stored better or consumed directly. Power-to-Heat is the most promising option¹, which can be implemented by basically dissipating the electric energy in an electric resistor. This is very simple technology that scales well and converts nearly 100 % of the input at any voltage, DC or AC, to

^a In Germany 2019 6.4 TWh (2.8 % of the electricity from renewables or 1.2 % of total) were throttled^{39,40}

1 useful heat at virtually any temperature, right where it is needed without residuals, byproducts or
2 exhaust fumes.

3 The valuable electric energy can, however, be used much more efficiently for heat provision by
4 deploying complex technologies, such as compression heat pumps extracting heat from ambient air,
5 sewage water, soil and/or ground water using closed borehole heat exchangers or open groundwater
6 circuits. Heat pumps are designed to provide a heat output power of multiples of 100 % of the input
7 power by adding heat from a low temperature heat source. Their key performance indicator is the
8 coefficient of performance (COP) defined as heat output \dot{Q}_{out} per electrical input \dot{W}_{in} . It is limited by
9 the theoretical maximum, which is defined by the reversed Carnot's law. Hence, for a given heat pump
10 technology, the COP increases with source temperature and decreases with falling output.

$$COP = \frac{\dot{Q}_{\text{out}}}{\dot{W}_{\text{in}}} \leq \left(1 - \frac{T_c}{T_h}\right)^{-1} \quad (1)$$

11 Ambient air as a heat source (ASHP) has low requirements, but also the inherent disadvantage of a
12 low COP especially when air temperature is low and heat demand consequentially high. Manufacturers
13 promise $COP = 3...5^2$, but, often installed in sub-optimal conditions, ASHP often cannot keep that
14 promise, reaching $COP < 2$. Therefore, the German environmental NGO BUND demands to limit grants
15 to more efficient heat pumps with a $COP \geq 5$, which would effectively exclude ASHP³. This requirement
16 could be fulfilled better by ground source heat pumps (GSHP), which operate with a more stable heat
17 source, but require the installation of heat exchangers in the underground. However, they, too, often
18 fail to reach their theoretical COPs in practice with average values below 3.5^4 .

19 Ground temperature and hence the COP generally increase with depth, but so do the technical effort
20 and requirements. At a given depth the ground is warm enough to use the harvested heat directly
21 without enhancing it by a heat pump. This reduces the electrical input approximately to the power
22 consumption of circulation pumps. A closed-circuit heat exchanger relies on heat transport by
23 conduction⁵ and therefore does not allow as much heat extraction as an open circuit, which is based

on convective heat transport. The closed circuit does, however, avoid the problems caused by reservoir hydraulics and precipitation of solutes from the brine.

Generally speaking, increasing the technical effort for a technology, such as increasing the depth of a geothermal well can increase the heat output, absolute and relative to the electrical input, but obviously also the financial cost (see Fig. 2).

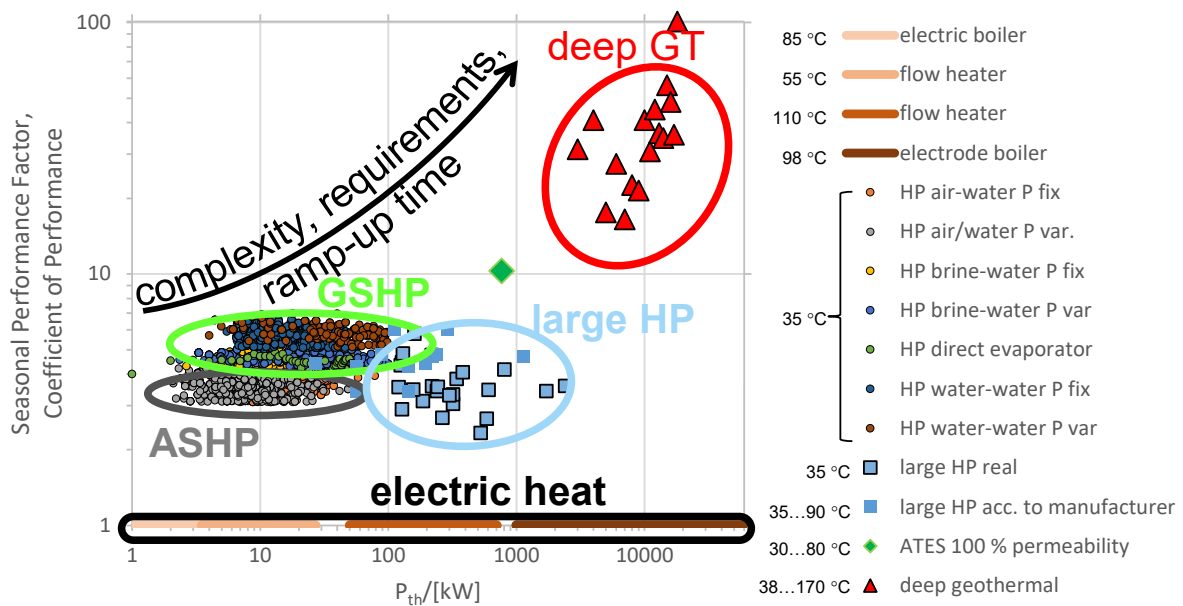


Fig. 1 Common thermal output and energetic conversion efficiencies of different heat provision technologies based on manufacturer info of available and installed devices in Germany/Switzerland² and on the energy conversion efficiencies of low-enthalpy geothermal plants from this publication

Fig. 2 also shows that while electric resistors can easily be scaled up or down, compression heat pumps are commonly available only up to a few dozen kW² as usually installed in single-family houses. A few large-scale heat pumps are in operation with thermal outputs up to a few MW. Beyond their range of thermal power are, however, geothermal wells, having an output of up to hundreds of MW at a relatively smaller electrical expense, as will be shown in herein.

A geothermal plant, sketched in Fig. 2 with open loop and hydrothermal reservoir, comprises one or more production wells and usually one or more injection wells. Hot (geo)fluid is produced from the underground by a production pump. At the surface, heat is extracted from the geofluid, which is then reinjected via the injection well, driven by an injection pump, if required.

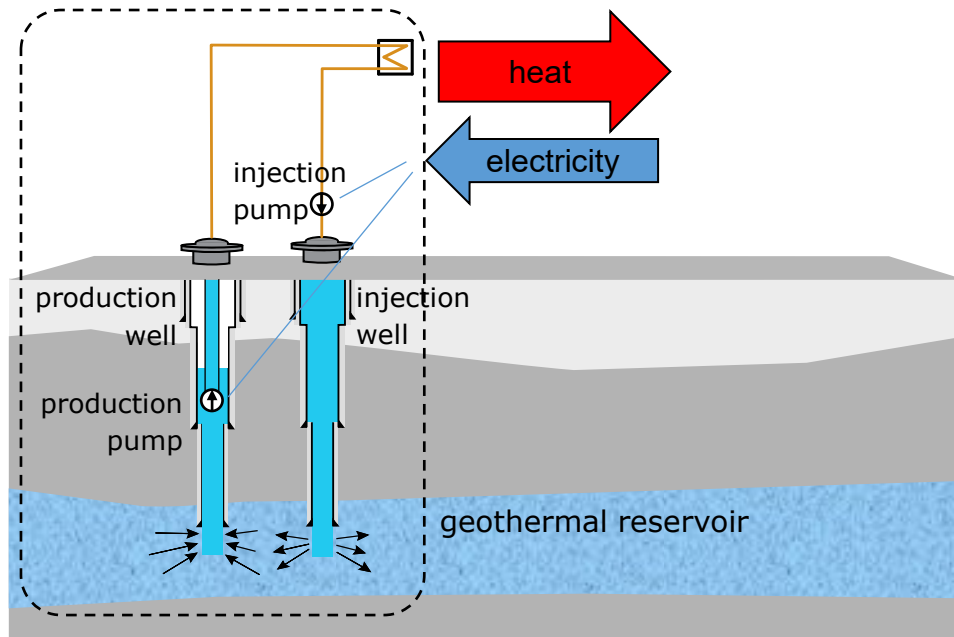


Fig. 2: Principle of a geothermal plant

Heat extraction rate obviously depends on production rate and reinjection temperature. The latter is thermodynamically limited by the temperature of the heat sink, usually the return temperature of the secondary loop. The lower the temperature required by the heat use technology, the more heat can be extracted. Fluid chemistry, however, adds another limitation. Temperature reduction may trigger precipitation, which, at the high mass flow rates realized in geothermal sites, can produce a considerable mass of solids, that at best ends up in filters and at worst clogs pipes, heat exchangers or the pores of the reservoir rock⁶⁻⁹.

Production rate is subject to friction, in the porous rock matrix of the reservoir as well as in the pipes of the wells and the surface installations. The complex hydraulic rock properties with respect to flow into/from a well determine the productivity/injectivity. It is quantified by the productivity/injectivity index (PI/II), defined as the ratio between flow rate and the pressure drop/increase in the well during production/injection.

The pumps have to overcome not only said friction, but also the level difference between static water table and surface plus the production well-head-pressure. Consequently, unless the production well is

artesian^b and the injection well is absorbing (creates no relevant back pressure), considerable energy is required to circulate the fluid in the geothermal circuit. This is independent of the installed pump technology, be it an ESP^c, a LSP^d or a piston pump.

Hence, the electrical consumption of the pumps is considerable, albeit controllable by ramping up and down the production rate and with it the heat production. Technically, this is feasible at a given maximum ramp-up speed within the boundaries of minimal partial load and maximum flow-rate. Economically it may make sense to do so given the necessary capacities in storage and/or backup heat production as well as the right economic boundary conditions which gratify electric grid stabilizing operation strategies. This upgrades geothermal energy from being a renewable energy not causing fluctuations to one rather compensating them, thus increasing its benefit as a component of an energy system. Accordingly, Schlagermann predicts the shift in the operation of geothermal power plants from baseload to market oriented or even operating reserve optimized¹⁰. Whether an individual geothermal plant should be operated this way, is a complex question and out of the scope of this work, which is intended rather to quantify the potential service geothermal plants can render to the grid.

The presented approach is applicable irrespective of useful heat application, pump technology, whether there are one or several production/injection wells, the reservoir is petrothermal, or the geothermal is closed. The geothermal plant is simply considered as a system receiving electric energy and returning thermal energy.

This paper gives an overview about the ratio of these two quantities, i.e. the harvested heat \dot{Q}_{out} relative to the auxiliary power demand \dot{W}_{in} for a selection of existing geothermal sites:

$$\varepsilon = \frac{\dot{Q}_{out}}{\dot{W}_{in}} \quad (2)$$

^b Flowing artesian well: the reservoir fluid pressure is high enough to make the fluid rise to the well-head, resulting in flow without pumping.

^c Electrical submersible pump –centrifugal pump installed together with the motor in the production well.

^d Line shaft pump - centrifugal pump installed in the production well driven by a motor at the surface via a shaft.

This quantity is herein referred to as the “energy conversion efficiency/factor”. In contrast to common efficiencies, ε is not limited to $\varepsilon \leq 1$ by energy conservation, but rather nominally exceeds 1. If it is below 1, i.e. if more energy is invested than is harvested, there is no benefit over the much simpler direct transformation to heat in an electric resistor/heater.

The analogy to the COP of heat pumps is obvious. Using a given amount of electrical/mechanical energy to provide a larger amount of energy as heat is what compression heat pumps (CHP) are made for. While their efficiency has the aforementioned theoretical maximum, the ε of a geothermal plant however, is not subject to this limitation derived from the fundamental laws of thermodynamics. That is due to the fact that a geothermal plant is an open system. Given an artesian well, i.e. $\dot{W}_{in} = 0$, ε even goes to infinity.

This key value ε combines the thermal and the hydraulic reservoir properties, but also site-specific boundary conditions and design and operating parameters, primarily reinjection temperature as well as production rate. It can be used to assess the systemic potential of geothermal plants in general or to compare the energetic performance of single sites, but also, with limitations, for comparison with other heat provision technologies in a multimodal energy system.

A fair comparison of heat provision technologies, however, requires taking into account the temperature of the delivered useful heat. One way to do it is to look at the exergies driving and leaving the plant. In analogy to ε , the exergetic conversion efficiency is calculated as the ratio of thermal exergy \dot{E}^*_{out} output to driving electric energy \dot{W}_{in} , which is pure exergy.

$$\zeta = \frac{\dot{E}^*_{out}}{\dot{W}_{in}} = \frac{\dot{Q}_{out}}{\dot{W}_{in}} \cdot \left(1 - \frac{T_{amb}}{T_{out}}\right) \quad (3)$$

The exergy contained in \dot{Q}_{out} is calculated by applying the Carnot or quality factor^{e,11}. It depends on the temperature of heat provision T_{amb} and of the environment T_{out} .

^e Here, the Carnot factor describes the amount of work achievable by a Carnot cycle operating between the brine and the ambient temperature T_{amb} .

While the energy conversion factor ε can be compared to COPs of ideal or real heat pumps, the reference for this exergy ratio is a reversible process with $\zeta = 1$ (ideal heat pump). Everything below 1 indicates an irreversible loss of exergy, while $\zeta < 1$ marks a gain of exergy, possible here because the definition (3) intentionally leaves out the inflow of heat in to the system, as it is not invested in the sense that electric energy is.

Another obvious reference is the heat provision by an electric resistor. There, the electric energy is converted completely to heat, i.e. $\dot{W}_{\text{in}} = \dot{Q}_{\text{out}}$, yet only a fraction of \dot{Q}_{out} being exergy. This fraction, depends on temperature and is directly given by the Carnot factor^f. The resistor could be operated at a higher temperature, thus destroying less exergy, but nothing is gained if the heat is used eventually at a lower temperature anyway. The sink temperature T_{out} eventually determines the system exergy loss, no matter if the loss happens by dissipation in the resistor or during transfer to the heat sink.

Even though eventually the economic profitability of a site usually is pivotal, the conversion factors give a first evaluation from the energetic/exergetic perspective how reasonable the operation of a geothermal plant can be with a systemic perspective.

State of the Art

Thoroughly characterizing geothermal sites is complex as several key parameters must be considered⁷, primarily obviously thermal output power and production temperature. They result from technical installations (well setup, pump configuration, etc.), design and operating decisions (production rate, reinjection temperature), the hydrogeological conditions (rock permeability and porosity) and, last not least, the geochemistry.

The aquifer geometry is often simplified to a homogenous horizontal layer of rock with a given thickness. The hydraulic behavior aquifer is usually linearized and described with the coefficients productivity and injectivity relating drawdown and production rate. The brine composition is thermodynamically relevant as a high salinity affects density, heat capacity and viscosity.

^f For example, electric heating to $T_{\text{out}} = 100\text{ °C}$ at $T_{\text{amb}} = 0\text{ °C}$, has an exergetic efficiency of 0.27.

One way to reduce the multitude of parameters to a single value is to determine the heat generation cost in terms of money^{12–14} or CO₂ emissions¹⁴. This requires a usually rather extensive profitability calculation considering geological, technical and economical boundary conditions. This value can be compared against alternative heat provision technologies.

Schlagermann¹⁰ conducted a comprehensive exergo-economic analysis for the geothermal power plant in Bruchsal, Germany, focusing on the electricity production costs.

While an economic calculation is certainly indispensable for the decision about the realization of a project, it is often too complex and requires too much economic input for purely energetic considerations. For this purpose, the ratio proposed here is more suitable, as it represents a relatively inexpensive and universal evaluation method.

Several publications investigate the energy conversion efficiency of the power cycle or the total power plant efficiencies^{7,15,16}.

Wolfgram et al.¹⁷ compiled data about thickness, depth, localization and hydraulic properties of aquifers to generate a productivity maps of the North German Basin. Together with temperature maps they can help to identify the geothermal potential.

Kastner et al.¹⁸ took this method a step further and combined predictions of productivity and temperature to determine the energetic efficiencies (COP therein) of idealized virtual geothermal doublets in two aquifers below Berlin, Germany. They assume $T_{\text{prod}} = T_{\text{res}}$, an ideal pump, disregarding pressure loss, thermal and limitations on the consumer side.

Their COP is the maximum theoretically possible energetic efficiency. It also depends on the injection temperature T_{inj} and on the flow rate \dot{V} . Kastner et al. generally assume $T_{\text{inj}} = 45\text{ °C}$ (based on the return temperature of a connected heating network) and determine the flow rate assuming an absorbing well without injection pump as:

$$\dot{V}_{\text{max}} = \Pi \rho g (-z_{\text{wt}}) . \quad (4)$$

This in turn requires the knowledge/assumption of the hydraulic properties of the assumed homogenous horizontal aquifer, namely the natural water table depth z_{wt} and the injectivity which they estimate via a porosity-permeability correlation. Kastner's approach yields rather low production rates and consequentially high conversion factors. With large uncertainties mostly due to the porosity data, they estimate the average COP, the ratio of electricity input and thermal output, to be 16.2 for the more productive one of the aquifers (Middle Buntsandstein).

Bugai¹⁹ assessed a geothermal heat supply system and defined an "annual exergy efficiency factor" as the exergy of the useful heat divided by the exergy input by geothermal fluid, peak reheater and pump power supply. Yet no values are given.

Method

In order to be able to include also geothermal power plants, they are considered herein as heat plants with an attached separate power cycle, such that the energy conversion efficiency can be determined in the same way as for heat plants. The additional consumers which are present in a geothermal power plant such as cooling facility and feed pumps are not of interest here.

The energy input into a geothermal heat plant is mainly consumed by the electrical consumption of the pumps P_{el} , where the lion's share is consumed by the production pump.

$$\dot{W}_{in} = P_{el}^{prod} + P_{el}^{inj} \quad (5)$$

Data of pump power consumption in geothermal sites is scarce and often considered company secret. For some sites information about net and gross electricity generation is available. The difference between the two values is a hint to the pump power consumption, but potentially also includes cooling effort for the power cycle and other auxiliary consumers.

P_{el} comprises the pumps' actual hydraulic work as well as mechanical and electrical losses in the pump, motor, cable and power electronics (VSD^g):

^g Variable speed drive

$$P_{el} = \frac{\Delta p_{\text{pump}} \cdot \dot{V}}{\eta_{\text{pump}} \eta_{\text{motor}} \eta_{\text{cable}} \eta_{\text{VSD}}} \quad (6)$$

1 If unavailable, the electrical consumption of the pumps can be estimated with equ. (6) from
2 production rate and differential pump pressure Δp_{pump} and assumed efficiencies.

3 If unknown, Δp_{pump} can be estimated from the hydraulic work, using the productivity/injectivity
4 index PI / II of the well, production rate \dot{V} , the static water table $z_{wt} < 0$ and brine density ρ :

$$\Delta p_{\text{pump}}^{\text{prod}} \approx \text{PI} \cdot \dot{V} - g z_{wt} \quad (7)$$

5 For the injection well, this equation is limited to $\Delta p_{\text{pump}} > 0$ to avoid falsely calculating electricity
6 gain in absorbing wells:

$$\Delta p_{\text{pump}}^{\text{inj}} \approx \max(0, \text{II} \cdot \dot{V} + \rho g z_{wt}). \quad (8)$$

7 If data about the electrical consumption of the injection pump is not available, it is assumed to be
8 insignificant in relation to the production pump consumption. If the static water table is unknown, it is
9 assumed to be 0.

10 The harvested heat \dot{Q}_{out} can be calculated as the difference of the fluid's enthalpy at both wellheads.
11 Disregarding any heat losses possibly occurring in the well or between heat extraction and delivery
12 and assuming one-phase flow (no gas phase), \dot{Q}_{out} can be approximated by the product of production
13 rate \dot{m} , a constant specific heat capacity c_p and the temperature difference between the well heads.
14 If the well head temperature is not available, it is assumed to equal the reservoir temperature:

$$\dot{Q}_{\text{out}} = \dot{m}(h_{\text{prod}} - h_{\text{inj}}) \approx \dot{m}c_p(T_{\text{prod}} - T_{\text{inj}}). \quad (9)$$

15 The production rate \dot{m} is assumed to equal the injection rate, i.e. there is no relevant fluid loss
16 between production and injection, i.e. none of the produced geofluid is diverted without being
17 reinjected and, in the case of HDR^h reservoirs, all of the injected fluid volume is produced again.

^h Hot Dry Rock method, applied to petrothermal reservoirs

- 1 The flow rate, given as a volume flow rate \dot{V} , is converted to mass flow rate \dot{m} with the fluid density
 2 ρ at production temperature:

$$\dot{m} = \frac{\dot{V}}{\rho(T_{\text{prod}}, X)}. \quad (10)$$

- 3 Both ρ and c_p of the geofluid depend on temperature and salinity X . In this study, their values were
 4 estimated using the brine property model BrineProp²⁰ considering the respective salinity X . Unless
 5 indicated otherwise, the mean specific heat capacity c_p for each site was calculated from the specific
 6 enthalpies at wellhead conditions as follows:

$$c_p = \frac{h(p_{\text{prod}}, T_{\text{prod}}, X) - h(T_{\text{prod}}, T_{\text{inj}}, X)}{T_{\text{prod}} - T_{\text{inj}}}. \quad (11)$$

- 7 The energetic conversion factor of a geothermal plant is hence calculated by equ. (2) as

$$\varepsilon = \frac{\dot{Q}_{\text{out}}}{\dot{W}_{\text{in}}} = \frac{\dot{m}(h_{\text{prod}} - h_{\text{inj}})}{P_{\text{el}}^{\text{prod}} + P_{\text{el}}^{\text{inj}}} = \frac{\dot{m}c_p(T_{\text{prod}} - T_{\text{inj}})}{P_{\text{el}}^{\text{prod}} + P_{\text{el}}^{\text{inj}}}. \quad (12)$$

- 8 Equ. (12) does not directly consider the production temperature T_{prod} , the quality of the heat \dot{Q}_{out}
 9 provided by the geothermal plant. Hence, in the next step, equ. (12). This is again divided by the
 10 electrical consumption \dot{W}_{in} , which is pure exergy, to obtain the exergy ratio between output and input:

- 11 The exergetic conversion factor is calculated by equ. (3)

$$\zeta = \frac{\dot{E}_{\text{out}}^*}{\dot{W}_{\text{in}}} = \frac{\dot{Q}_{\text{out}}}{\dot{W}_{\text{in}}} \cdot \left(1 - \frac{T_{\text{amb}}}{T_{\text{m}}}\right). \quad (13)$$

- 12 Assuming a perfect storage, exergy depends on the minimum of the periodically varying ambient
 13 temperature²¹. The average minimum air temperature in Germany is about -0.4°C ²². This matches
 14 closely the conventional choice of $T_{\text{amb}} = 0^\circ\text{C}$ which is also assumed herein.

- 15 T_{m} is used as the upper temperature, as the brine flow is a sensible heat source. T_{m} is the logarithmic
 16 mean temperature of the heat transfer from the brine:

$$T_m = \frac{T_{inj} - T_{prod}}{\ln\left(\frac{T_{inj}}{T_{prod}}\right)} . \quad (14)$$

Another way of taking into account the temperature level is to set ε into relation to the theoretical maximum COP of a heat pump, i.e. a reversible heat pump, working between these two temperatures. This results in the same equation as equ. (13), with T_{prod} replacing T_m , as the useful heat is non-sensitive here. This is how heat pump performance is assessed independently of temperatures. The quotient is called “exergetic efficiency”^{11,23} or “Gütegrad”⁴ in German.

The net exergy output is defined as the difference of exergy output \dot{E}^*_{out} and the electric input \dot{W}_{in} .

Sites

Motivated by a project dealing with the German energy system, this study focuses on German deep geothermal sites and European sites with comparable conditions. All German sites were included where enough data could be acquired to calculate the efficiencies. All sites have in common that their wells are deeper than 1000 m and that they have at least one production and one injection well.

The source data are very heterogeneous in quality and in what quantities are disclosed. It was acquired from publications, the GeotIS database²⁴, personal communication with operators, but also from project and news websites. While numbers about the thermal power of geothermal sites are easily found, pump consumption data is rarely disclosed by commercial operators. In general, operational parameters are varying due to a multitude of reasons. Hence, picking a number requires some kind of averaging or an educated guess.

This study aims at characterizing the potential of geothermal heat. Hence, typical operational or are used, if available. For some sites, however, only design values or snapshot measured values were available.

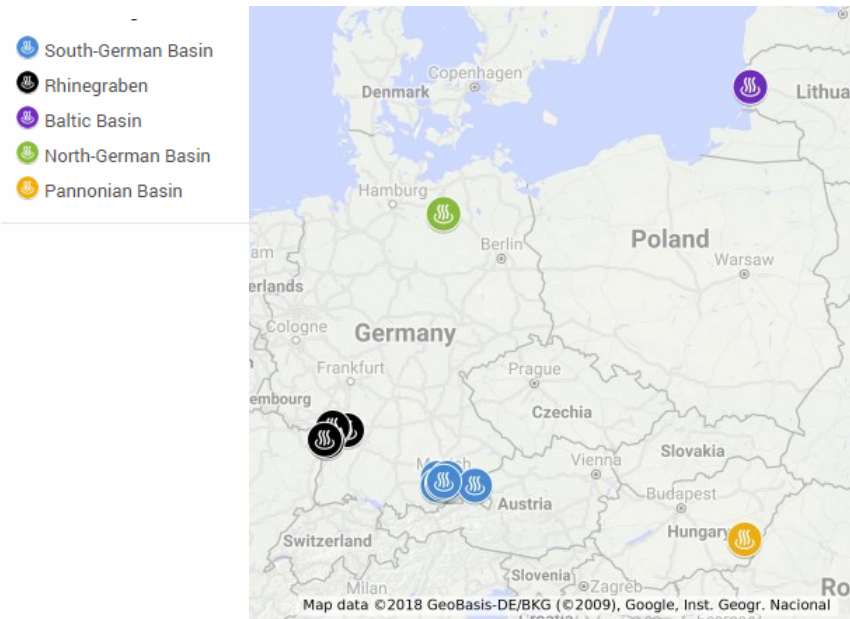


Fig. 3 Locations of the geothermal sites covered in this study

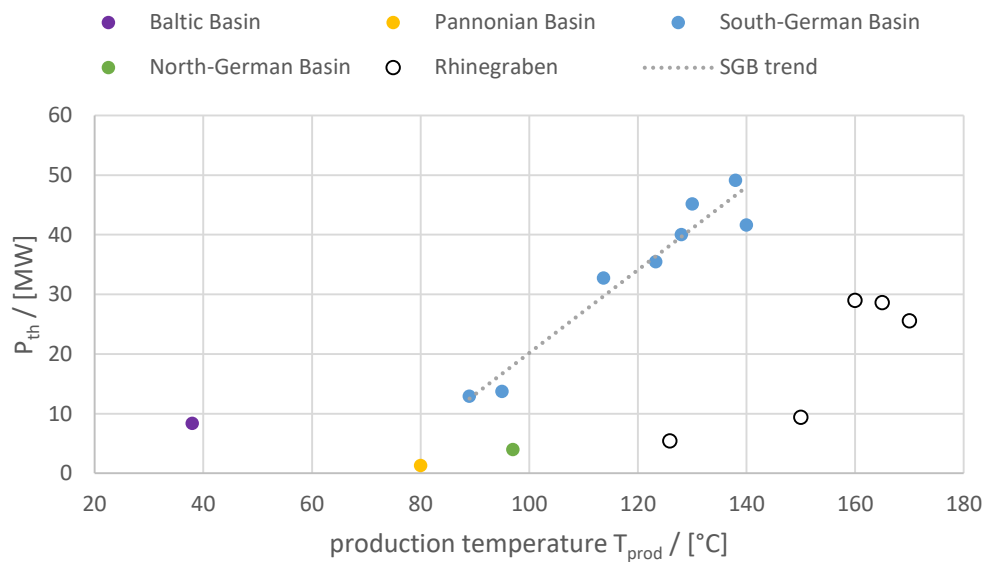


Fig. 4: Thermal output vs. production temperature. Linear trend only for the sites in the South-German Basin

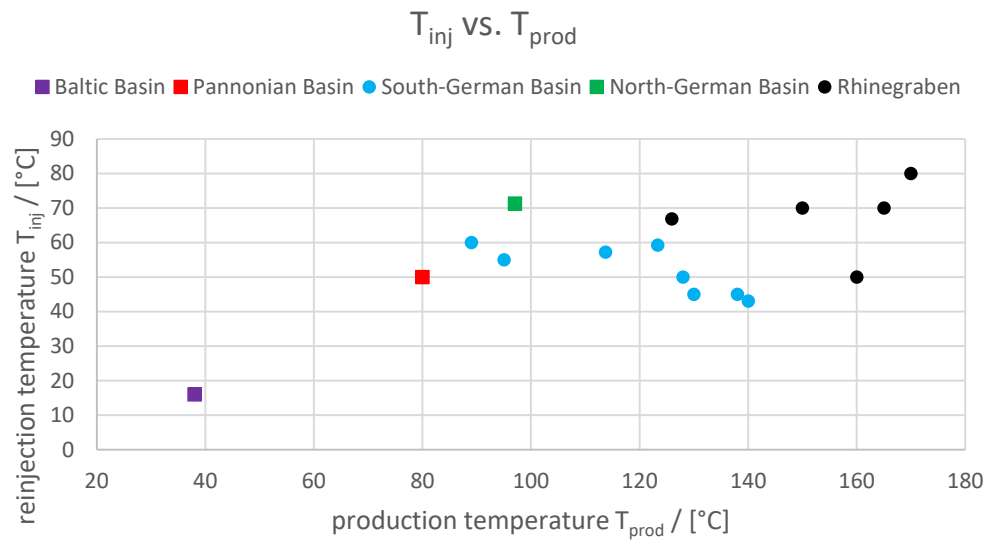


Fig. 5: Injection temperatures vs. production temperatures

Results

Table 1: operational parameters used to calculate the geothermal sites, (ρ/c_p – geofluid density/specific heat capacity calculated with BrineProp²⁰, \dot{V} – production rate, P_{th} – thermal power extracted from the geofluid, $P_{ESP,el}$ – electric consumption of the production pump, $P_{inj,el}$ – electric consumption of the injection pump), NGB – North-German Basin, SGB – South-German Basin, RG – Rhinegraben, BB – Baltic Basin, PB – Pannonian Basin)

Site	Geology	T_{prod} °C	T_{inj} °C	c_p J/kg/K	ρ kg/m ³	\dot{V} l/s	\dot{Q}_{out} MW	P_{el}^{prod} MW	P_{el}^{inj} MW	ε	ζ_0 $T_{amb} = 0\text{ °C}$	ζ_{20} $= 20\text{ °C}$
Neustadt-Glewe ²⁵	NGB	96	71.3	3361	1122	28.8	2.7	0.16	?	16	3.9	2.9
Dürrnhaar ²⁶	SGB	138	40...50	4211...4214	928	135	46...52	1.35	0	34...38	8.7...9.2	6.8...7.1
Freiham ²⁶	SGB	89	60	4190	966	110	12.9	0.73	0	18	3.8	2.7
Grünwald/Laufzorn	SGB	127 ²⁷	(60) ²⁸ⁱ			90 ²⁷	40.0 ²⁷	(0.76) ^{29j}	0	53	13.3	10.4
Kirchstockach ²⁶	SGB	130	40...50	4205...4209	935	135	43...48	1.00	0	43...48	10.4...11.1	8.1...8.5
Riem ²⁶	SGB	95	55	4191	962	85	13.7	0.50	0	27	5.9	4.3
Sauerlach ²⁶	SGB	140	38...48	4211...4215	926	110	40...44	1.20	0	33...36	8.3...8.8	6.5...8.8
Traunreut ³⁰	SGB	113.7	57.2			146	34.4	1.31	0.142	24	5.3	4.1
Oberhaching ¹⁶	SGB	128	50	4209	935	140	43.0	1.30	0	33	8.0	6.2
Unterhaching	SGB	123.3 ³¹	59 ^k	4206	941	140 ³¹	35.5 ^{32l}	1.65 ^{32m}	0 ³²	21	5.3	4.2
Bruchsal ¹⁰	RG	126	66.8			24	5.4	0.13	0	41	10.6	8.4
Insheim ¹⁶	RG	165	70	3837	982	80	28.6	(0.80) ⁿ	0	36	10.6	8.8
Landau ¹⁶	RG	160	50	3837	982	70	29.0	(0.60) ⁿ	0	48	13.2	10.6
Rittershoffen ⁶	RG	170	80	3915	968	72...77	25...26	(0.21...0.31) ^{33o}	0	86...116	26.8...36.0	22.5...30.1
Soultz-sous-Forêts ⁶	RG	150	70	3907	983	31	9.4	(0.17) ^{34o}	0	56	16.0	13.1
Klaipeda ⁹	BB	36	11	3844 ⁸	1054 ⁸	168	17	0.055 ^p	0.55	28	2.2	0.31
Mezőberény ³⁵	PB	80	50	4177	975	8.3...12.8 ^q	1.0...1.6 ^r	0.013...0.03	0.005...0.012 ^s	36...48	6.9...9.2	4.8...6.4

ⁱ Assumption based on heating network return temperature of 55 °C

^j Linear interpolation for indicated flow rate from nominal values 1.350 MW at 160 l/s⁶

^k Calculated with equ. (9)

^l 38 MW is valid at 150 l/s, here scaled to actual production rate

^m Including losses in motor, cable and variable-frequency drive

ⁿ Assumption made in the data source

^o Calculated as $P_{el}^{prod} = \dot{V}^2 / PI / \eta$, where $\eta_{prod} = 0.7$ and $PI = 0.8$ l/s (Soultz) or 2.8 ... 3.5 l/s²³ (Rittershofen)

^p $PI = II \cdot 10 = 73$ according to ³², natural water level = sea level, surface at 9 m

^q Nominal volume flow rate of the two main circulation pumps vs. design flow rate of the plant.

^r Nominal power of main heat exchanger is given as 533 kW, while thermal power calculated from temperature difference and flow rate amounts to 1018 kW

^s No injection pump, includes compressor, pressure boosting pump block and heat exchanger circulation pump

Table 1 lists the key parameters of the included geothermal sites as well as the calculated energy and exergy conversion factors. Where the input parameters were available as ranges or in several variants, they are listed as a value range of the resulting conversion factors.

Fig. 6 plots the energy conversion factors ε , whereas Fig. 7 plots the exergy conversion factors ζ for all included sites. The value range is indicated by the respective mean value with error bars. Fig. 8 shows the conversion factors plotted against the production temperature.

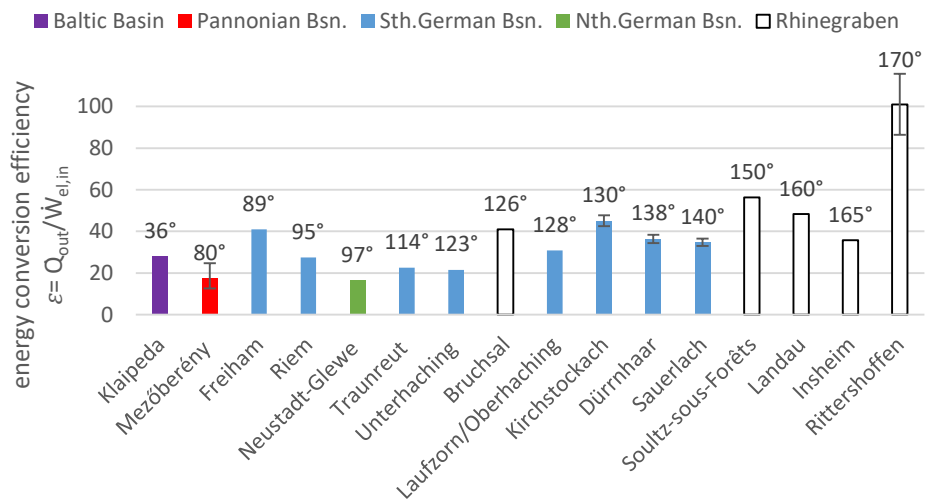


Fig. 6: Energy conversion factors (mean values with error bars indicating the value range) for selected geothermal sites, sorted and annotated by production temperature

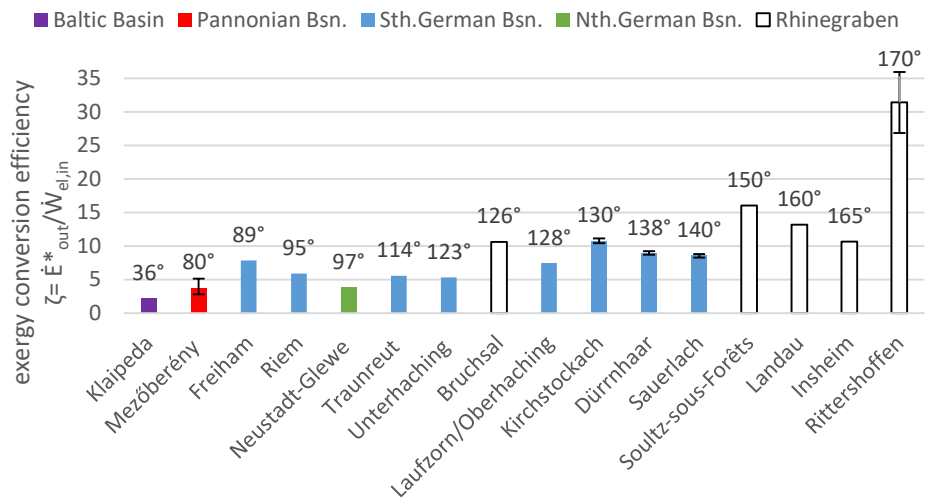


Fig. 7: Exergy conversion factors (mean values with error bars indicating the value range) for selected geothermal sites at an ambient temperature of 0 °C, sorted by and annotated with production temperature.

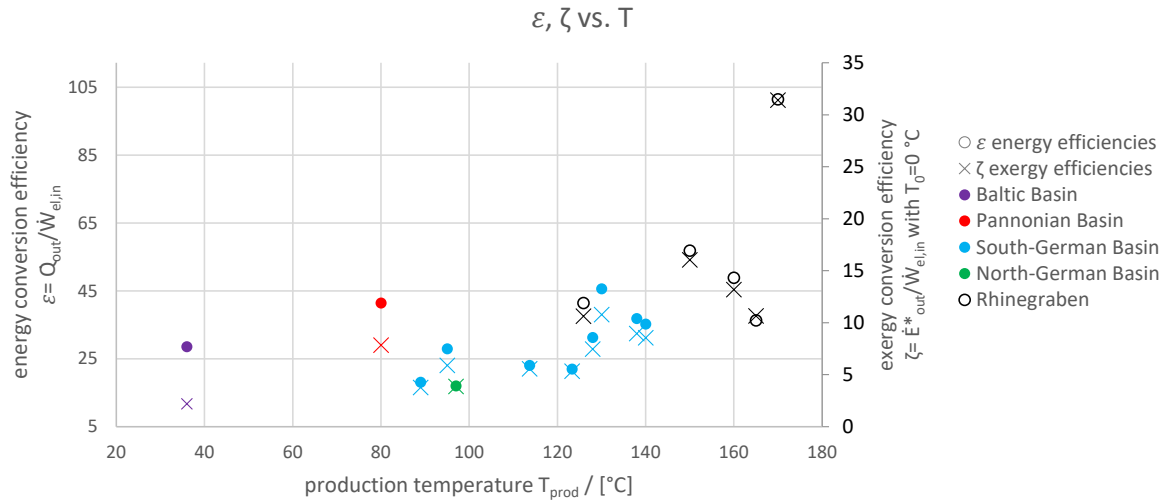


Fig. 8: Conversion factors vs. production temperature (exergy reference temperature $T_0 = 0^{\circ}\text{C}$, axis scaled to make ε plot match ζ plot for sites with min/max ε).

For the Soultz site, the calculation of electricity consumption is based on the specific parameters and the simple model defined by equations (5) till (14). This allows an exemplary study of the sensitivity of the efficiency on the production rate (Fig. 9).

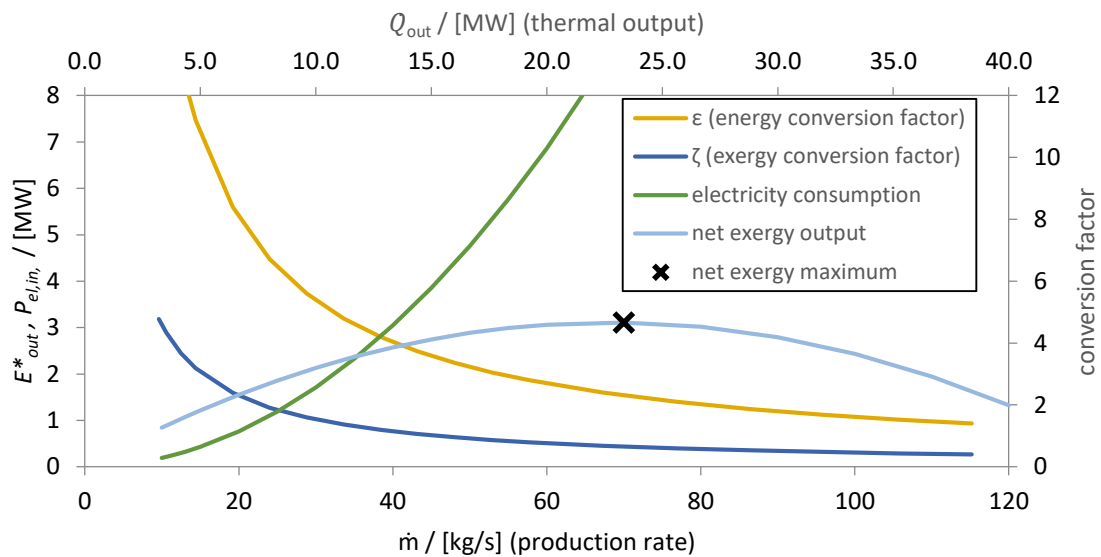


Fig. 9: Conversion factors as a function of production rate for a synthetic site ($WHT=150^{\circ}\text{C}$, $\Delta T=80^{\circ}\text{C}$, $PI = 5.4 \text{ m}^3/\text{h}/\text{MPa}$, $c_p=4 \text{ kJ/kg/K}$, $\rho=1000 \text{ kg/m}^3$)

Discussion

Before elaborating on the numbers, note that this study aims at giving a first overview of the conversion factors realized in actually operating geothermal plants. The heterogeneity of the source data should be kept in mind when comparing the sites, especially when the sources are pretty websites or optimistic press releases. Furthermore, a single datapoint per site can only be a snapshot or an

average of variable quantities. On the other hand, off-design operation can decrease the conversion factor, as pump efficiency will be reduced outside of their design operation range or fluid friction in the well becomes relevant if the diameter is small. Finally, the calculated conversion factors are not meant as a rating of the plant design and construction as they also include the boundary conditions given by thermo-hydraulic aquifer properties as well as limitations imposed by the fluid chemistry.

The small number of sites does not allow conclusions with respect to different regions.

The geothermal sites considered here provide heat at temperatures between 38 and 170 °C. They show a wide range of energy conversion factors ε between 12 and 112 (Fig. 6), Given that the COP of common CHPs are roughly one order of magnitude below ($\text{COP} \approx 2 \dots 6^2$ when providing heat at 35 °C), this suggests that deep geothermal heat exploitation offers a highly efficient way of transforming electricity into heat. This matches roughly the theoretical values determined by Kastner et al.: between 6 and 21 for the Middle Buntsandstein and between 43 and 74 for the Rotliegend¹⁸ formation.

Similarly, the exergy conversion factors ζ show a broad distribution with values ranging from 1 to 36, which makes these geothermal plants more efficient than any real or even ideal heat pump (always $=1$).

Fig. 8 shows an increasing trend w.r.t. production temperature of both ε and ζ . This comes as no surprise given the linear relation between thermal power output \dot{Q}_{out} and the temperature difference between the well-heads ΔT from equ. (9) visualized in Fig. 4.. Hence, exceptions from the positive trend can indicate either a high T_{inj} , a low productivity/injectivity or bad performance for other reasons. The influence of the injection temperature is negative but does not take effect here as it appears to be more or less constant around 60 °C, independently from T_{prod} (see Fig. 5). The Carnot factor in eq. (13) and the logarithmic mean in equ. (14) add positive non-linear temperature dependences, which create the offsets in Fig. 8.

The ζ listed and plotted above have been determined for the common yet arbitrarily chosen $T_{\text{amb}} = 0 \text{ °C}$. Having the lowest production temperature, Klaipeda's ζ is most sensitive to a change of T_{amb} of all sites. Recalculating Klaipeda's ζ with the reference $T_{\text{amb}} = 20 \text{ °C}$ lowers it to 0.31, while all other

1 sites remain “safely” beyond $\zeta = 1$ with values ranging from 2.7 to 30. $\zeta = 0.3$ is in the lower range of
 2 what current CHPs achieve, as the exergetic efficiencies derived from a comprehensive list of CHP of
 3 different technologies available on the German market² show ζ between 0.33 and 0.64 for $T_{\text{amb}} =$
 4 $0\text{ }^{\circ}\text{C}$ or $2\text{ }^{\circ}\text{C}$. Other sources give values between 0.28 and 0.5⁴. This assessment shows that the
 5 operation of the Klaipeda site would be exergetically reasonable if it were operating with the listed
 6 parameters. However, it is not, because productivity has declined due to precipitation in spite of
 7 counter-measures, which is why the plant operation indefinitely ceased operation in March 2017^{9,36}.

8 The remarkably high conversion factors of the Rittershoffen site can obviously be explained with high
 9 production temperature and low pumping demand, but possible also with the fact that it is based on
 10 estimation rather than on operational measurements. Pump power for both this site and the one in
 11 Soultz have been estimated only from the well productivity, thus neglecting additional work caused by
 12 the lower water table level, high well head pressure and friction within the brine circuit. Hence, the
 13 real conversion factors can be expected to be lower. Vice versa, the low factors of Klaipeda, Neustadt-
 14 Glewe and Freiham are a consequence of low production temperature and relatively high electricity
 15 consumption by the pumps. A detailed analysis of the individual reasons is out of the scope of this
 16 work

17 Fig. 9. depicts the non-linear influence of the production rate on the conversion factors as calculated
 18 using a simple model based on constant temperatures and parameters. According to the model
 19 equations, production rate grows proportionally with thermal output (indicated by the second
 20 abscissa), while pump effort increases quadratically, thus reducing the conversion factors. Hence the
 21 best operating point will be a tradeoff between thermal output and the energetic/exergetic conversion
 22 efficiency. As visualized by the broad maximum of the net exergy output, there may be a point within
 23 the feasible operation range beyond which a further increase of production will cost more exergy in
 24 the form of electricity than is gained from additional provided heat. The flat curve, however, indicates
 25 a low sensitivity to a change of production rate around the maximum, which makes the choice less
 26 critical. The same may apply for an economic optimum as both electricity demand and heat production

can be converted into cost and revenue. This optimum may, however, be offset, as it depends on these prices as economic boundary conditions.

Conclusion

Geothermal heat is available independently of weather conditions. It may be considered as free, but its exploitation certainly requires investment, not only of money, but also of energy. From the system perspective, geothermal plants are commonly only considered as heat sources. However, they require pumps to produce and/or reinject the geofluid, unless they operate at very favorable reservoir conditions (i.e. artesian production well, absorbing injection well). These pumps consume considerable amounts of electricity, with their nominal powers often amounting to several of hundreds of kW. This makes GT plants effectively Power-to-Heat converters.

The energetic and exergetic analysis of the gathered production data of a selection of geothermal sites shows that extracting heat from the underground requires considerable amounts of valuable electric energy. Compared to alternative methods of electrically powered heat provision such as electric heating or CHPs, however, this is a very efficient one, as far more heat and exergy is provided than invested as electrical input, even though this ratio output/input varies by one order of magnitude among the sites considered in this study.

The exergetic conversion factor used here can be helpful as a key parameter to characterize geothermal plants in strongly simplified energy system models. For this and other purposes it would be beneficial to include the pump power consumption to overview tables and databases^{7,24,37}, which usually lack it^t, compiling only other key figures such as thermal/electric power, production rate and temperature.

Similarly to the efficiency of a geothermal power cycle, the conversion factors are not the quantities to be maximized by varying mass flows, as this would lead to small thermal output. More reasonable

^t The OpenEI online database³⁷ has a field for „parasitic load“, but no data

is maximizing the net exergy output. Its maximum may help to identify the “sweet spot” with respect to the production rate independent from economic parameters.

Outlook

Including more sites in this assessment would potentially allow to draw further conclusions, e.g. by correlating the conversion factors to plant design or operational parameters or clustering them by geologic setting.

Considering geothermal plants as sinks for surplus electricity raises the question of their part load performance and their part load ability, i.e. how far and how quickly can their output be reduced or increased. This should be quantified and be used as additional key parameters to describe geothermal plants from the perspective of the energy system.

The assessment method presented here could be extended from existing geothermal plants to existing boreholes or even to unexploited geothermal reservoirs, founding on existing data of geothermal potential¹⁷. Following Kastner et al.¹⁸, the energetic/exergetic conversion efficiency could be calculated based on the well productivity/injectivity, the water table and the reservoir temperature. Discarding the limitation in eq. (8). Eq. (12) would then be adapted as follows:

$$\varepsilon = \frac{\rho c_p (T_{\text{prod}} - T_{\text{inj}})}{(\text{PI}^{-1} + \text{II}^{-1}) \dot{V}}. \quad (15)$$

As described in the “state of the art”, this approach would yield rather high efficiencies at a small production rate. Another choice for the mass flow could be on the other end of the range: The maximum production mass flow limited by the maximum drawdown, which is limited by the given production pump installation depth (ignoring NPSH_R^u), which in turn is limited by the reservoir depth:

$$\dot{V}_{\text{max}} = \text{PI} \rho g (z_{\text{wt}} - z_{\text{res}}) \quad (16)$$

^u Required net positive suction head –minimal water column above a pump inlet required for safe operation

Consequently, this approach returns rather high flowrates, low efficiencies, and, assuming $PI = II$, cancels the productivity from the equation only leaving the depths and the temperatures.

The practical optimum for production rate is somewhere between these two values, determined by a variety of boundary conditions, e.g. geologically motivated pressure limits, demand side requirements, financial deliberation or optimal net power output³⁸. With this information being unknown for non-existent plants, an educated guess for the design operating point could be made using the net exergy maximum as discussed before.

The presented conversion efficiencies can be calculated for any electrically driven heat provision technology, including geothermal sites operated as thermal storages (ATES, BTES, MTES^v). Like the storage efficiency, the conversion efficiency could serve as key figure to assess different storage technologies or to compare storage to other heat/cold provision technologies. Eq. (12) should then be changed to include the energy invested for storing the heat/cold.

Nomenclature

COP	1	Coefficient of Performance
c_p	J/(kg · K)	specific heat capacity
\dot{E}^*_{out}	W	exergy output
g	N/kg	gravitational acceleration
h_{prod}, h_{inj}	J/kg	specific enthalpy at production, injection well-head
II	l/s/MPa	Injectivity index
\dot{m}	kg/s	mass flow rate
Δp_{pump}	Pa	differential pump pressure
P_{el}	W	electrical power consumption
PI	l/s/MPa	productivity index

^v Aquifer/Borehole/Mine Thermal Energy Storage

1	$T_{\text{prod}}, T_{\text{inj}}$	K	well-head temperature production, injection
2	T_{amb}	K	ambient temperature
3	T_{m}	K	mean temperature of heat transfer
4	T_{out}	K	temperature of heat output
5	\dot{W}_{in}	W	input power to the brine circuit
6	\dot{Q}_{out}	W	thermal power extracted from the brine circuit
7	\dot{V}	m ³ /s	Flowrate, production rate
8	X	kg/kg	brine salinity
9	z_{wt}	m	natural water table / hydraulic head
10	ε	1	energetic conversion factor
11	ζ	1	exergetic efficiency / conversion factor
12	η	1	energetic efficiency
13	ρ	kg/m ³	fluid density

14 Declarations

15 Availability of data and material

16 The collected data is provided as supplementary spreadsheet files

17 Competing interests

18 The author is employed by an institution conducting research in and advocating geothermal energy.

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22 Authors' contributions

23 Not applicable.

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3

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10

Figures

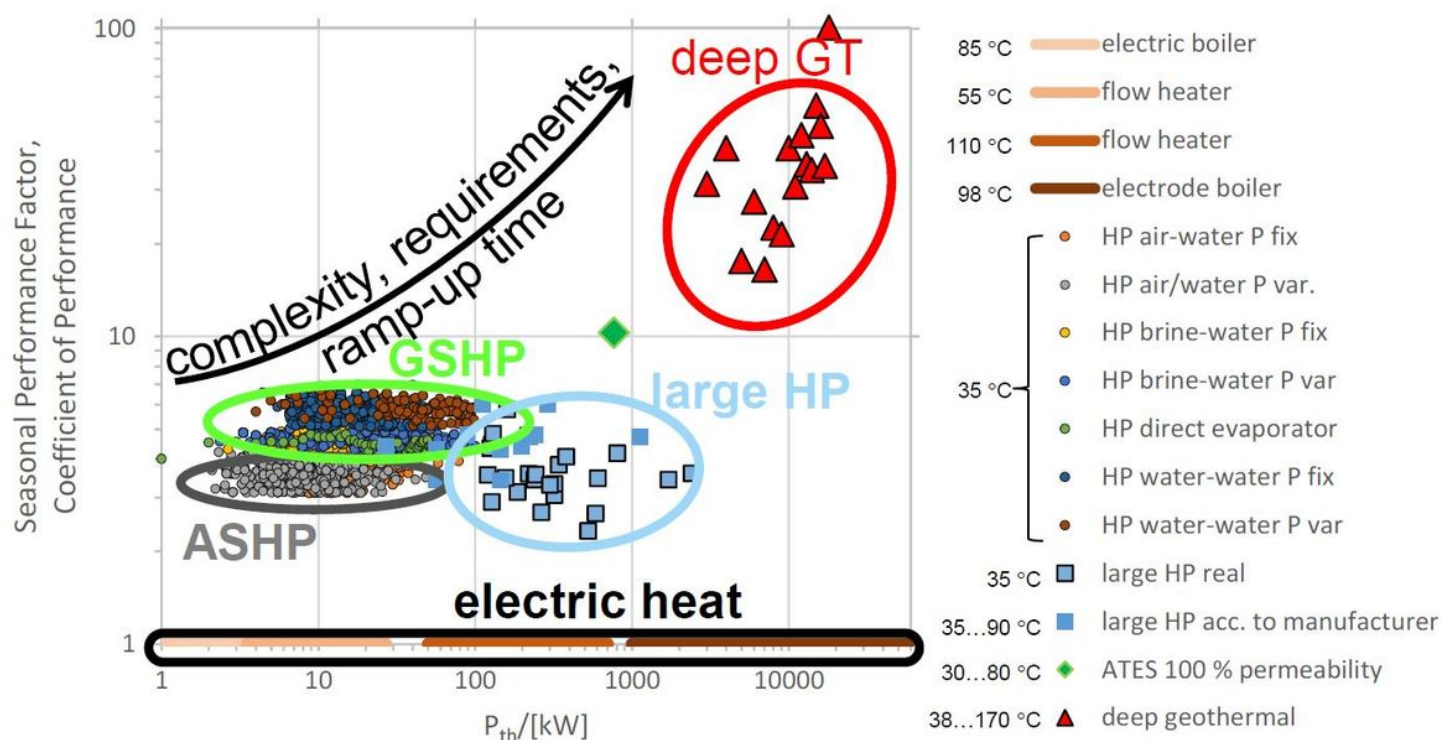


Figure 1

Common thermal output and energetic conversion efficiencies of different heat provision technologies based on manufacturer info of available and installed devices in Germany/Switzerland² and on the energy conversion efficiencies of low-enthalpy geothermal plants from this publication

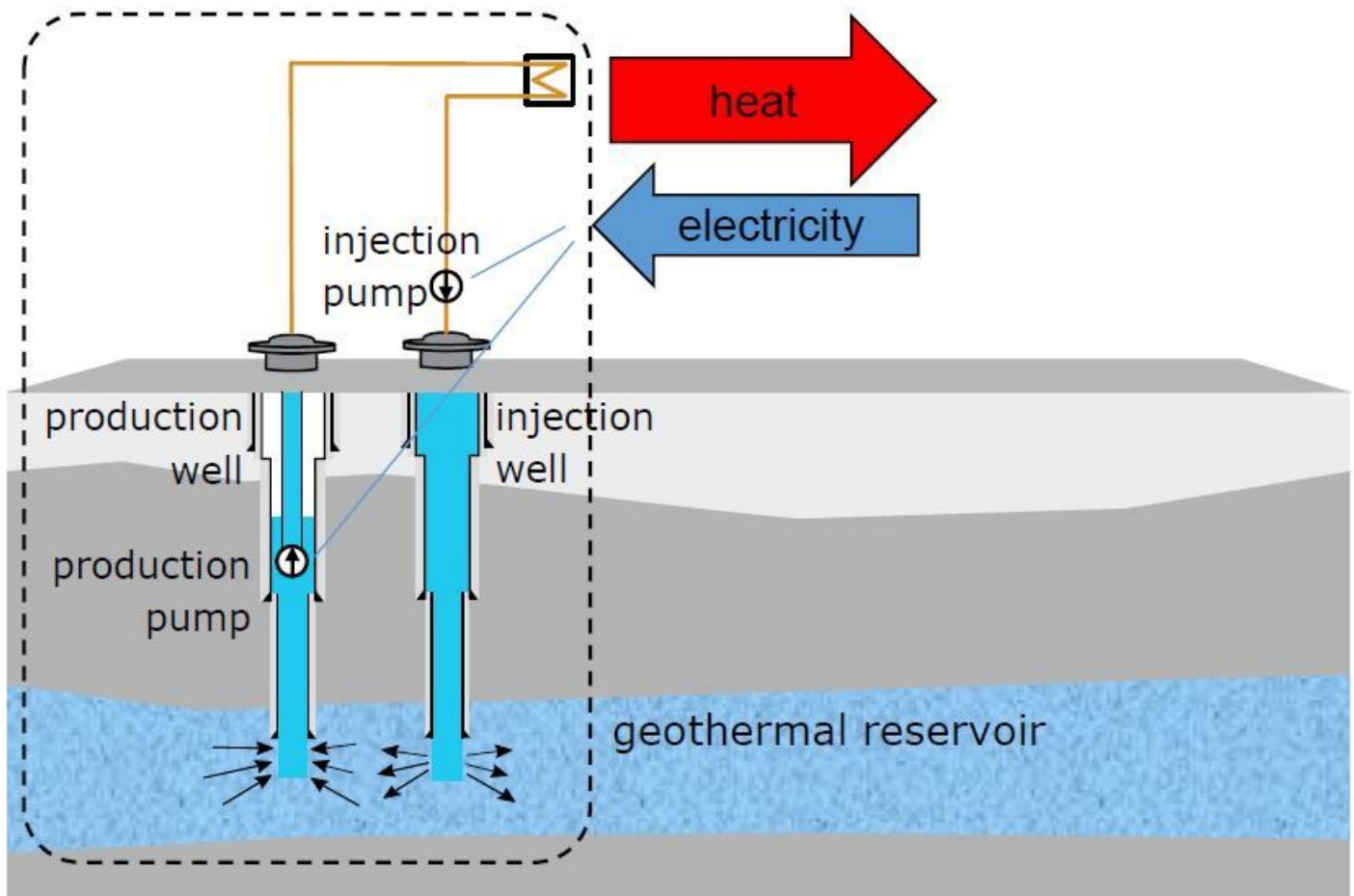


Figure 2

Principle of a geothermal plant

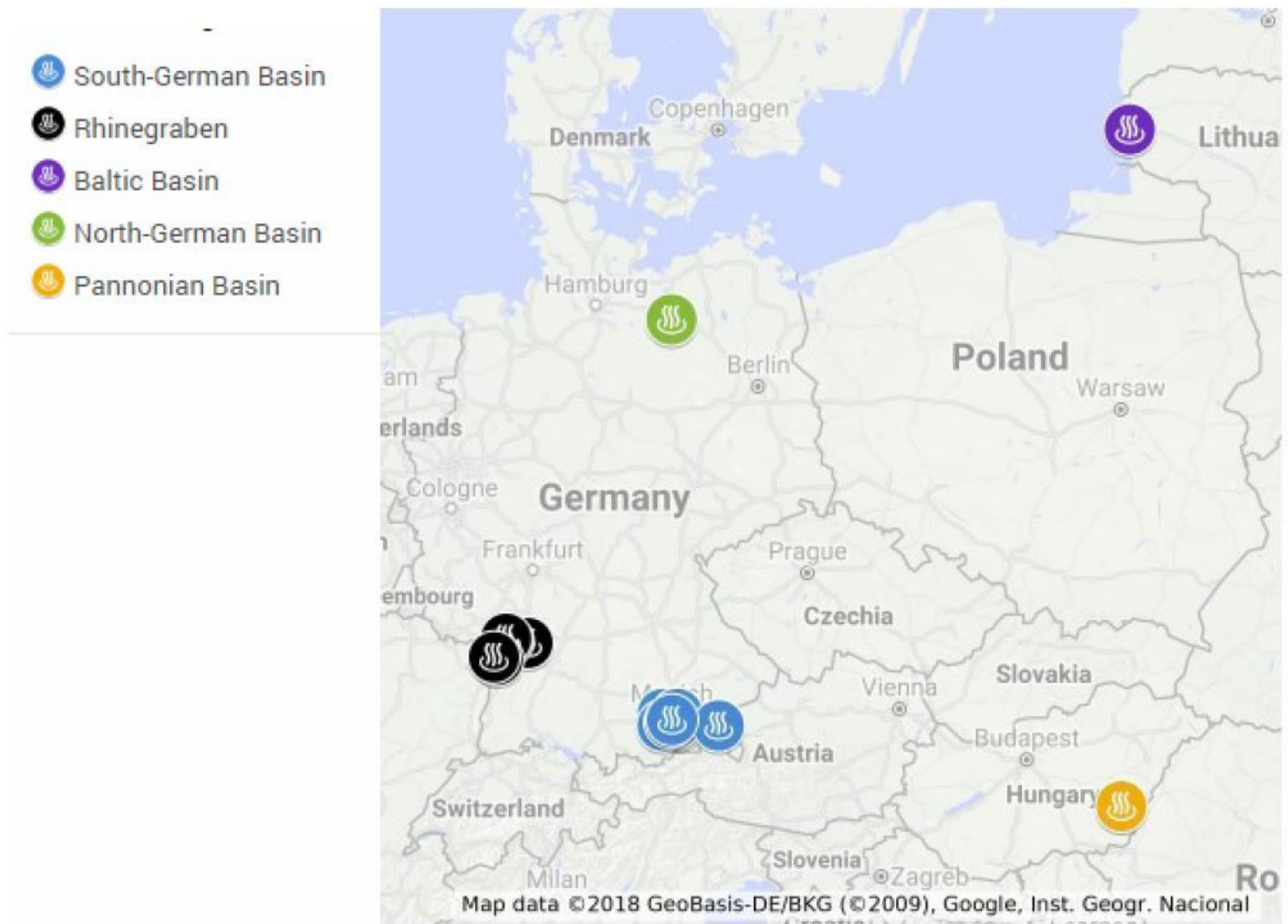


Figure 3

Locations of the geothermal sites covered in this study. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

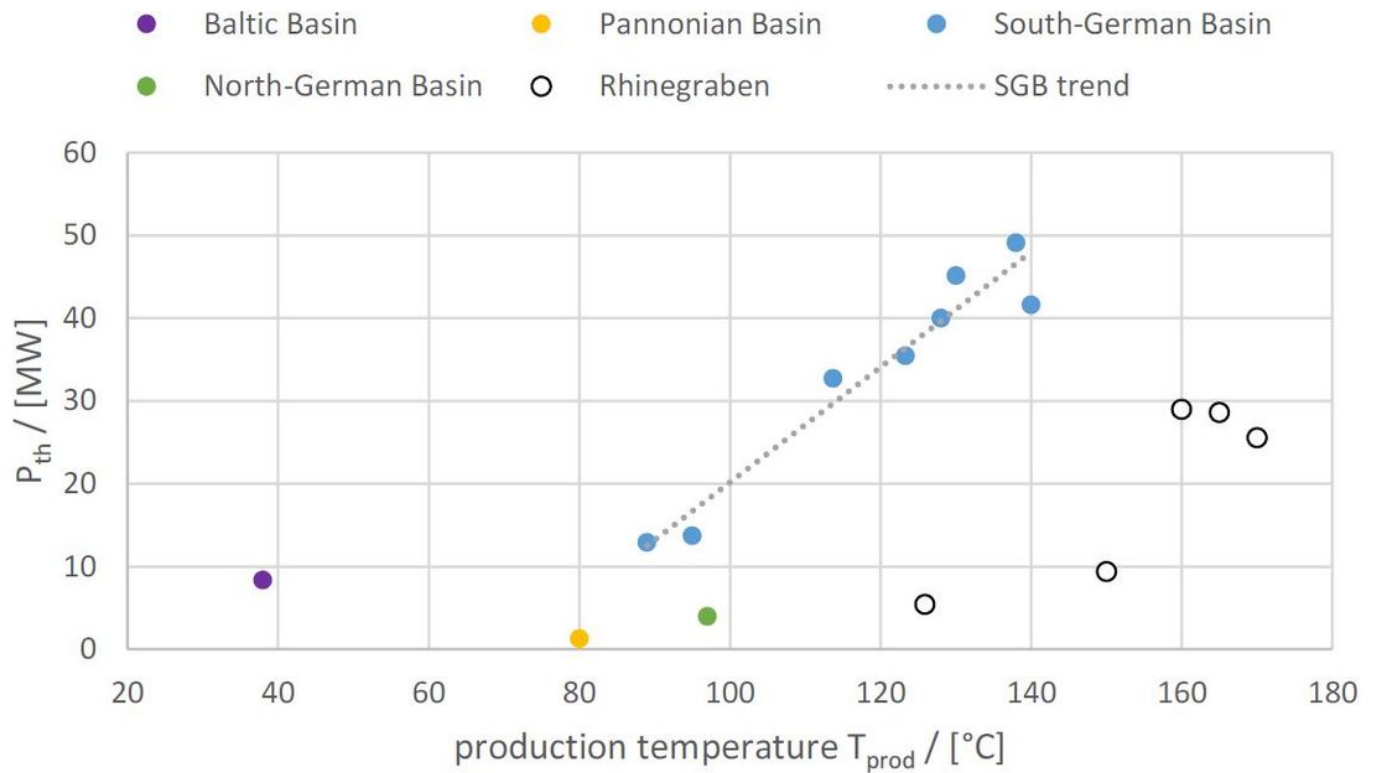


Figure 4

Thermal output vs. production temperature. Linear trend only for the sites in the South-German Basin

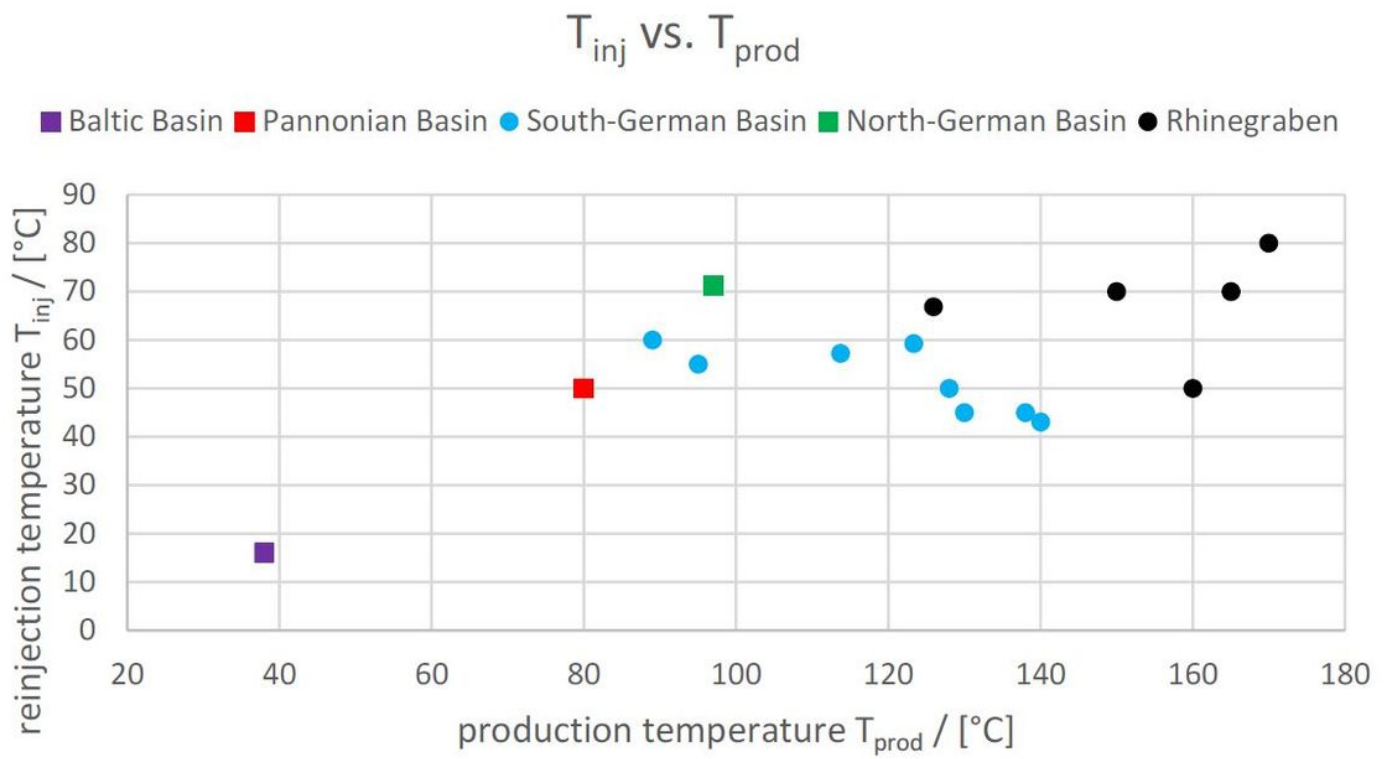


Figure 5

Injection temperatures vs. production temperatures

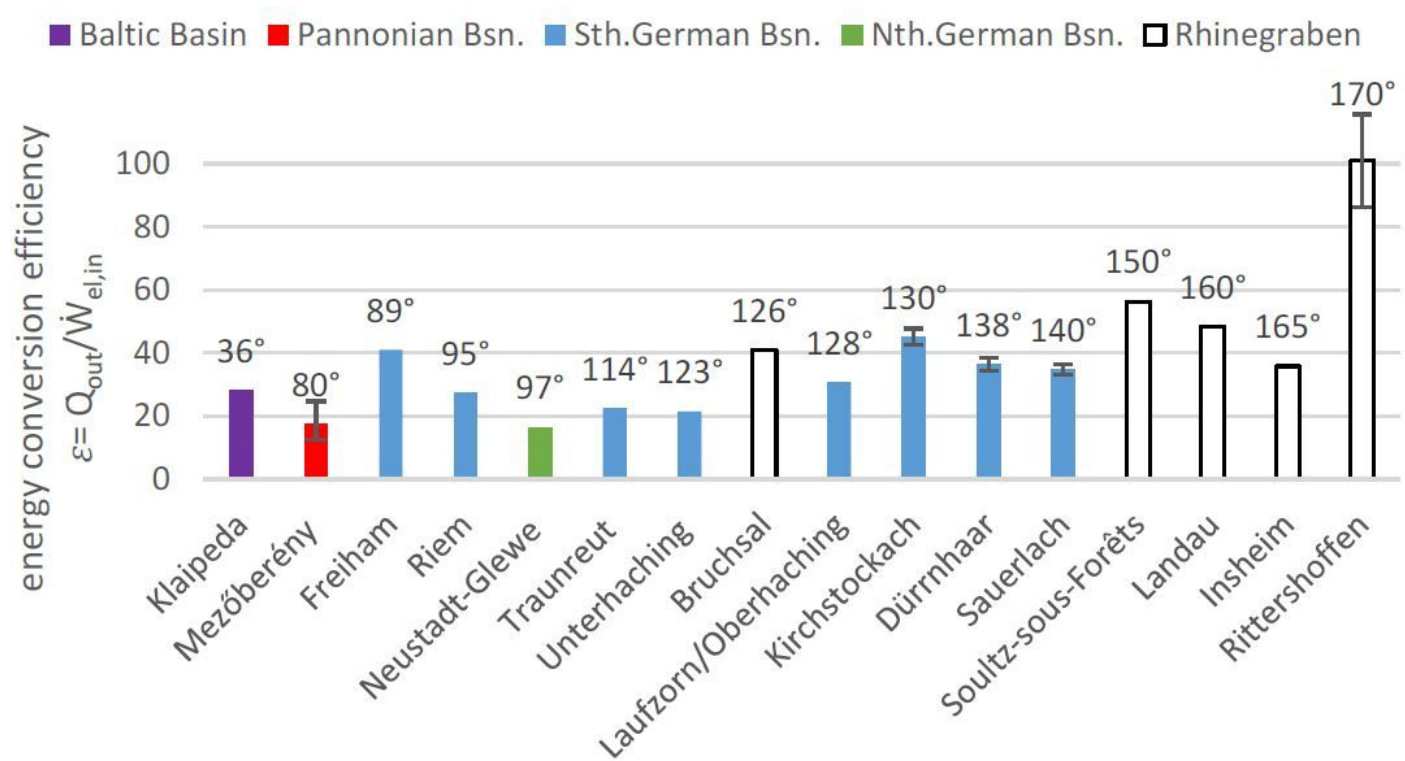


Figure 6

Energy conversion factors (mean values with error bars indicating the value range) for selected geothermal sites, sorted and annotated by production temperature

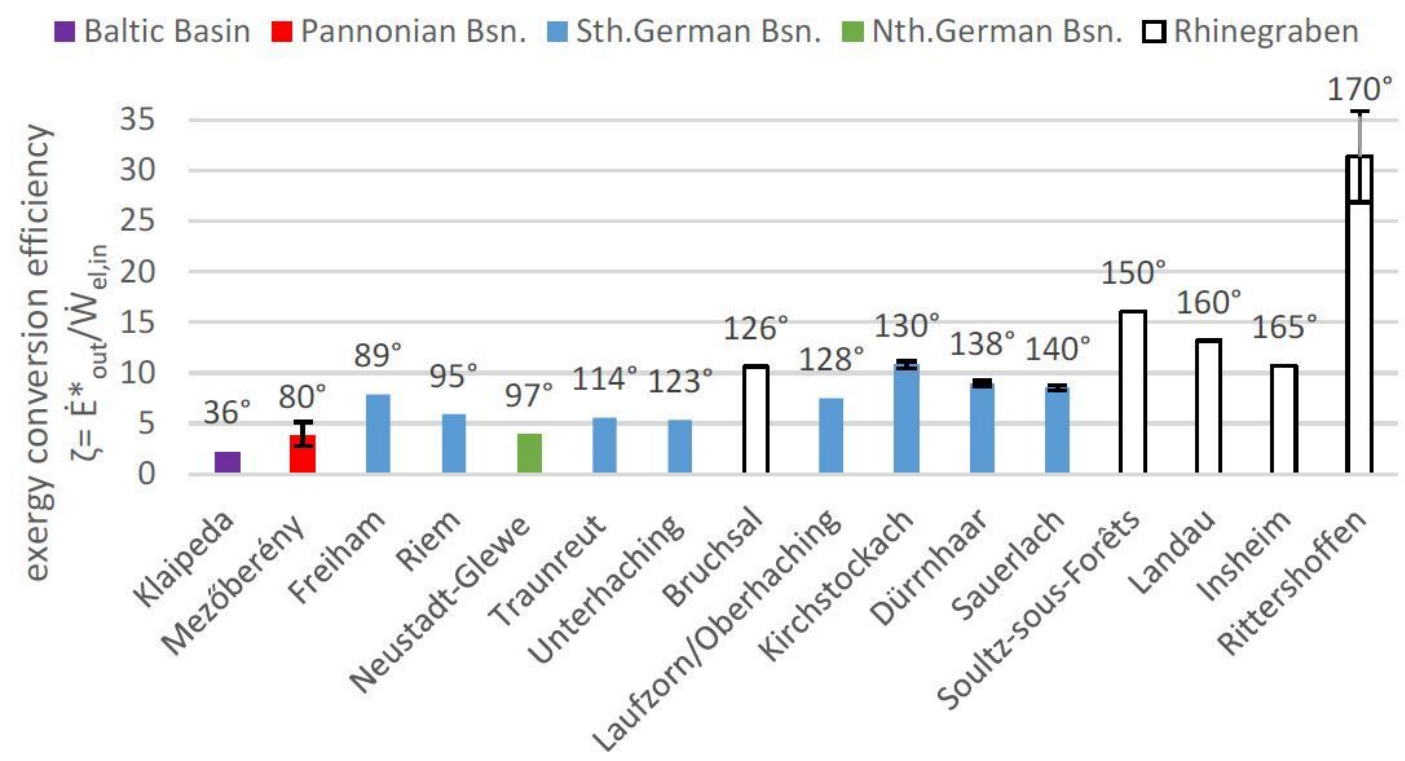


Figure 7

Exergy conversion factors (mean values with error bars indicating the value range) for selected geothermal sites at an ambient temperature of 0 °C., sorted by and annotated with production temperature.

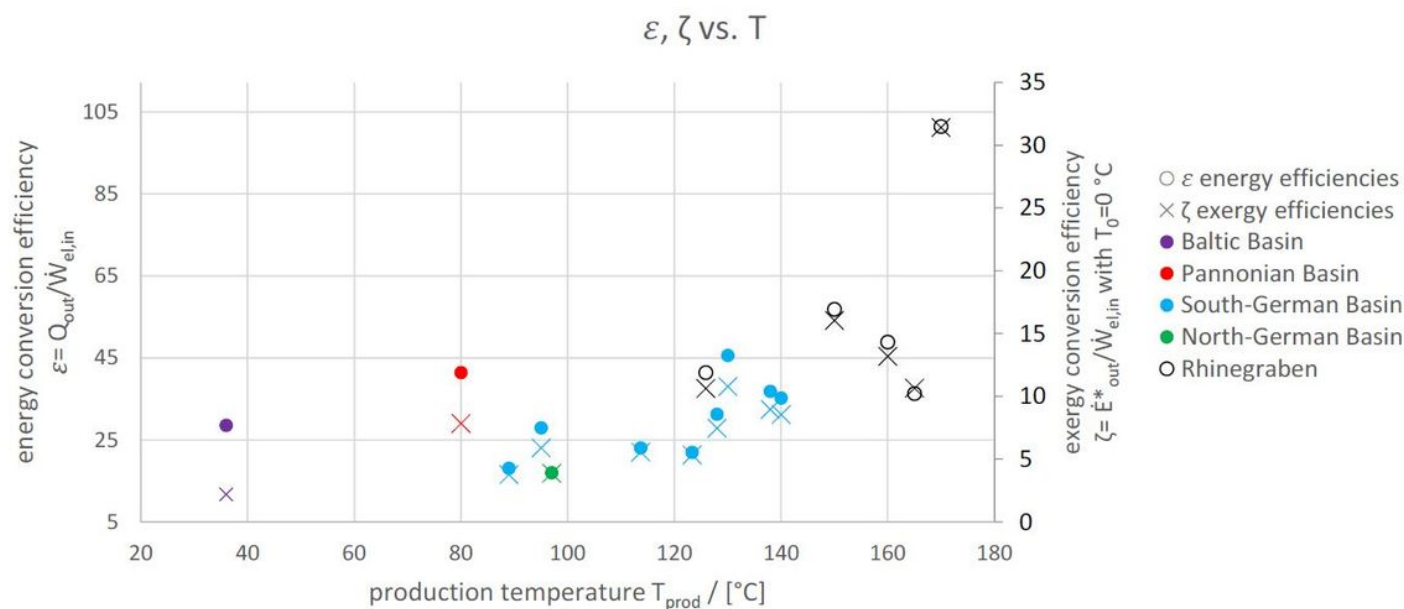


Figure 8

Conversion factors vs. production temperature (exergy reference temperature $T_0 = 0^\circ\text{C}$, axis scaled to make ε plot match ζ plot for sites with min/max ε).

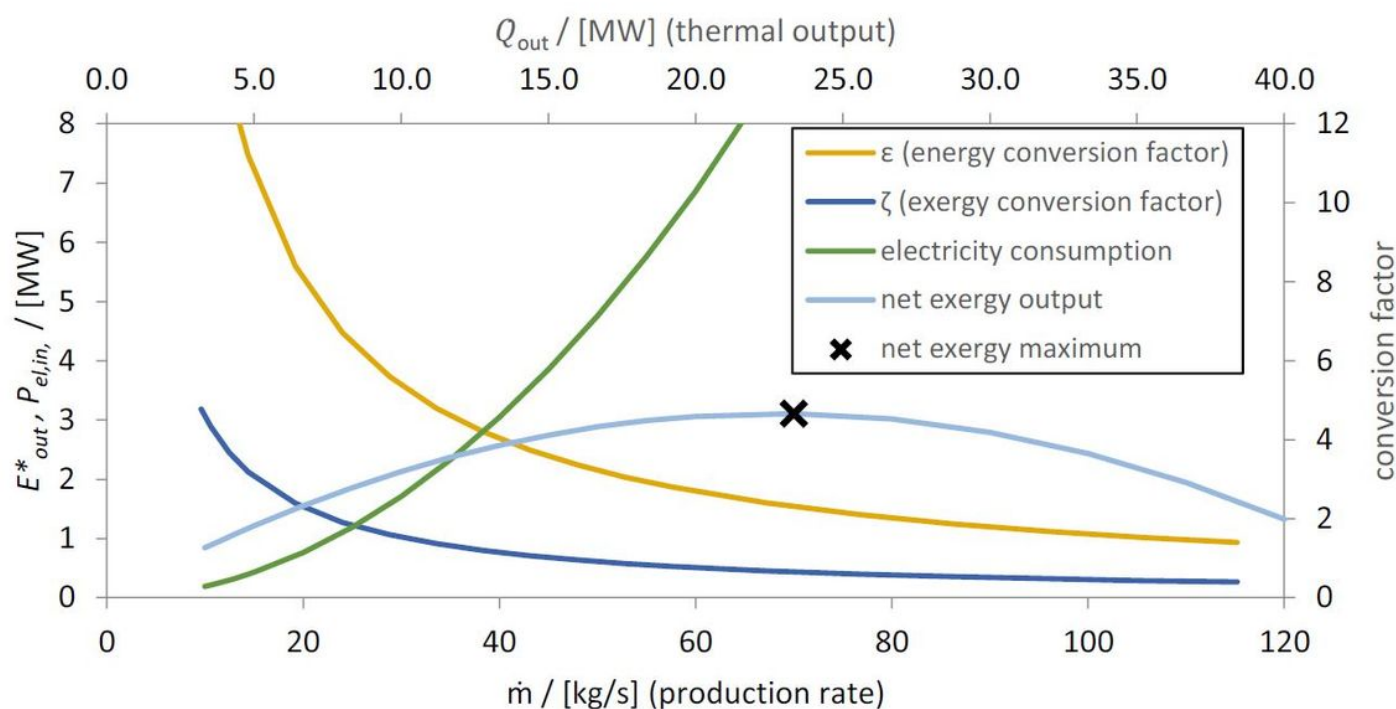


Figure 9

Conversion factors as a function of production rate for a synthetic site (WHT=150 °C, ΔT =80 °C, PI = 5.4 m³/h/MPa, c_p =4 kJ/kg/K, ρ =1000 kg/m³)

Supplementary Files

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