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Assessing the contribution of simultaneous heat and power generation from geothermal plants in off-grid municipalities

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Abstract

A growing number of German municipalities are striving for energy autonomy. Geothermal plants are increasingly constructed in municipalities in order to exploit the high hydrothermal potential. This paper analyses the potential contribution of simultaneous geothermal power and heat generation in German municipalities to achieving energy autonomy. A linear regression estimates the achievable hydrothermal temperatures and the required drilling depths. Technical restrictions and cost estimations for geothermal plants are implemented within an existing linear optimisation model for municipal energy systems. Novel modelling approaches, such as optimisation with variable drilling depths, are developed. The new approach is validated with data from existing geothermal plants in Germany, demonstrating a Root Mean Squared Error of about 15%. Eleven scenarios show that achieving energy autonomy is associated with at least 4% additional costs, compared to scenarios without it. The crucial role of geothermal plants in providing base load heat and power to achieve energy autonomy is demonstrated. The importance of simultaneous modelling of electricity and heat generation in geothermal plants is also evident, as district heating plants reduce the costs, especially in municipalities with high hydrothermal potential. Further work should focus on the optimal spatial scale of the system boundaries and the impact of the temporal resolution of the analysis on the costs for achieving energy autonomy.

Highlights

- Analysis of hydrothermal potential in German municipalities
- Optimisation of simultaneous geothermal heat and electricity generation
- Drilling depth and hydrothermal temperature are implemented endogenously
- Integration of geothermal plants in a holistic energy system optimisation
- Geothermal plants reveal a potential for cost reduction in off-grid municipalities

Keywords: mixed-integer linear optimisation, geothermal plant, hydrothermal potential, variable drilling depth, energy autonomy

Nomenclature

Variable / Parameter	Description	Unit
A_D	Area for the well site	m ²
A_{el}	Area for the ORC plant	m ²
A_S	Area for the 3D seismology	m ²
A_{th}	Area for the district heating plant	m ²
$b_{D,1900}$	w hether the drilling depth is betw een 0 m and 1900 m (binary)	-
$b_{D,3250}$	w hether the drilling depth is betw een 1900 m and 3250 m (binary)	-
$b_{D,3850}$	w hether the drilling depth is larger than 3250 m (binary)	-
$b_{D,i}$	w hether the drilling depth is betw een $(i-1) \cdot 1000$ m and $i \cdot 1000$ m (binary)	-
b_{DHP}	w hether the district heating plant is built (binary)	-
$b_{DHP,op}$	w hether the district heating plant is in operation or not (binary)	-
$b_{DH,S,i}$	w hether district heating should cover up to $i \cdot 10\%$ of the heat demand of the municipality (binary)	-
b_{GP}	w hether the geothermal plant is built (binary)	-
b_{PP}	w hether the ORC plant is built (binary)	-
C_1	Investment for feasibility study and preliminary planning	€
C_2	Investment for properties and infrastructure	€
C_3	Investment for exploration of the reservoir	€
C_4	Investment for production well pump	€
C_5	Investment for thermal water system (above-ground)	€
C_6	Investment for power generation plant	€
C_7	Investment for district heating system	€
C_8	Investment for project management, control and finance planning as well as other investments	€
C_D	Costs for the drilling work and the construction and recultivation of the well site	€
C_{DR}	Annual costs for working fluid and other demand related-resources	€/a
C_{DW}	Costs for the drilling work	€
C_{FS}	Costs for the feasibility study	€
C_{GI}	Costs for geochemical investigations	€
C_{HT}	Costs for hydraulic tests	€
C_L	Annual labour costs	€/a
C_{OP}	Annual other operating costs, e.g. costs for operating of seismic monitoring	€/a
C_{OV}	Annual variable costs for insurance and legal assistance	€/a
C_P	Cost for properties in German municipalities	€
C_{PP}	Costs for the preliminary planning of the power generation plant and the above-ground plant components	€
$C_{p,w}$	Mean heat capacity of the geothermal water	$\frac{\text{kJ}}{\text{kg} \cdot \text{K}}$
C_{ST}	Costs for stimulation	€
C_{UP}	Costs for the underground planning	€
d_D	Distance betw een the production and the injection well	m
Del	Electricity demand in the municipality	kW
Del_{total}	Sum of electricity demand in the municipality and electricity consumption of the feed pump	kW
$D_{heat,total}$	Total heat demand of the municipality in a time step	kW
D_p	Percentage of electricity consumption of the feed pump in geothermal power plants	%
D_{pump}	Electricity consumption of the feed pump	kW
M	Large number	-
P_{el}	Power generation of the geothermal ORC plant in a time step	kW
$P_{el,max}$	Nominal power of the ORC plant	kW
P_{pump}	Nominal power of the feed pump	
$\dot{Q}_{th}$	Heat generation of the geothermal district heating plant in a time step	kW
$\dot{Q}_{th,max}$	Nominal power of the district heating plant	kW
r_z	Range of a section for the drilling depth	m
ΔT	Temperature gradient	°C/m
T_a	Annual mean ambient temperature	°C
$T_{DHP,return}$	Temperature of the geothermal water after the heat transfer to the district heating system	°C
$T_{DH,return,min}$	Minimum return temperature of the district heating system	°C
$T_{DH,min}$	Minimum forward temperature of the district heating system	°C
$T_{DH,pinch}$	Pinch temperature of the heat exchange to the district heating system	°C

$T_{ORC,min}$	Minimum temperature of the geothermal water after the heat transfer to the ORC plant	°C
$T_{ORC,out}$	Temperature of the geothermal water after the heat transfer to the ORC plant and before the heat transfer to the district heating system	°C
T_{PW}	Hydrothermal temperature in the production well in a time step	°C
$T_{PW,max}$	Maximum hydrothermal temperature in the production well (wellhead temperature)	°C
$\dot{V}_B$	Mean volumetric flow rate in the production well	l/s
Z_D	Drilling depth	m
$Z_{D,1900}$	Drilling depth, if drilling is up to 1900 m at maximum	m
$Z_{D,3250}$	Drilling depth, if drilling is up to 3250 m at maximum	m
$Z_{D,3850}$	Drilling depth, if drilling is above 3250 m	m
$Z_{D,1}$	Drilling depth, if drilling is up to 1000 m at maximum	m
$Z_{D,2}$	Drilling depth, if drilling is up to 2000 m at maximum	m
$Z_{D,3}$	Drilling depth, if drilling is up to 3000 m at maximum	m
$Z_{D,4}$	Drilling depth, if drilling is up to 4000 m at maximum	m
$Z_{D,5}$	Drilling depth, if drilling is up to 5000 m at maximum	m
ρ_w	Mean density of the geothermal water	kg/l
η_{el}	Efficiency of the ORC plant	-
η_{pump}	Efficiency of the feed pump	-
η_{th}	Efficiency of the geothermal district heating plant	-

1. Introduction

The radical change in the energy sector due to ambitious national targets in energy policy is characterised in particular by the expansion of renewable energies. Renewable energies are mainly utilised decentrally due to their characteristics. Therefore, municipalities are often referred to as the driving force behind the energy transition. This particularly applies to Germany, where the decentralised structure also applies to the owners and operators of energy plants: private individuals increasingly invest in renewable energy systems or form so-called citizen-energy cooperatives (McKenna 2018). The majority of regenerative plants in Germany are actually owned and operated by private individuals, farmers and communities (trend:research 2017). This development is due to various motivations: among other things, citizens intend to play an active role in energy supply and to be less dependent on central markets and structures (e.g. Boon & Dieperink 2014). For homeowners, energy autonomy is one of the main factors that drives them to install renewable energies (Engelken et al. 2018).

Besides energy autonomy for homeowners, the concept of municipal energy autonomy (McKenna et al. 2017) has become established, which is employed here to also include energy autarky (Müller et al. 2011), self-sufficiency (Balcombe et al. 2015) and integrated community energy systems (Koirala et al. 2016). Alone the number of terms for this concept illustrates the diversity within the literature, which also extends to its definition. Three rough distinctions are made between complete energy autonomy (i.e. off-grid), net or balanced energy autonomy, whereby local supply equals or exceeds demand on an annual basis, and a tendency towards higher energy autonomy through decentralised renewables (McKenna et al. 2015). The extensive survey of Engelken et al. (2016) shows that the majority of municipalities with energy autonomy aspirations strive for balanced energy autonomy and the focus is usually on electrical energy. This can also be observed by analysing the energy project “100%-Renewable-Energy-Communities”, in which the participating municipalities strive for energy autonomy¹. The exponential development of those projects since 1995 indicates that an increasing number of German municipalities is striving for energy autonomy. The 1,300 municipalities of the project correspond to 12% of all municipalities in Germany and account for 15% of the population.

According to the authors' knowledge, only one entire municipality in Germany strives for complete energy autonomy, namely Bordelum in Schleswig Holstein (Alt 2017). Another example for complete energy autonomy is the village Feldheim, which is a part of the municipality Treuenbrietzen. A study of the impacts of autonomy in this village showed that, after the energy system transition every inhabitant was in an “economically more favourable situation” than before (Mundaca et al. 2018). However, balanced energy autonomy could make network expansion even more essential and also make new allocation systems for grid fees necessary (McKenna 2018). This could result in economic inefficiencies compared to the established system of centralised generation, transmission and distribution (Jägemann et al. 2013). The present study therefore considers complete energy autonomy, as this state could be advantageous for the energy system. In other words, no imports are possible and the electricity and heat demand must be covered by local renewable energies.

These renewable energies already account for 33% of electricity generation in Germany in 2017 (Statistisches Bundesamt 2017a). In contrast, the proportion of renewable heat supply is much lower at around 13% (UBA 2018a). The renewable energies include around 55 GW of wind energy (on- and offshore), 42 GW photovoltaic (PV) systems, about 7 GW of bioenergy (BMWi 2017) and 39 MW of deep geothermal energy (UBA 2018a). In comparison to the other renewable energies, relatively little electricity is generated by geothermal plants (GTPs) despite the fact that deep geothermal energy could make a major contribution to reducing greenhouse gas emissions. However, the relative growth from 7 MW_{el} to 39 MW_{el} (+450%) in geothermal power generation in Germany between 2010 and 2017 is one

¹ Own determination with data from the websites of the municipalities as well as the following websites, among others: <http://www.kommunal-erneuerbar.de/startseite.html> and <http://www.100-ee.de/>.

of the highest in the world (Bertani 2016). The currently (2017) installed 30 GTPs in Germany generate about 155 GWh of electricity (UBA 2018a) and 1.3 TWh of heat (Agemar et al. 2018) annually, which is generally used for district heating (DH) applications (Weber et al. 2016). The locations of the 30 GTPs are shown in Figure 2. The electricity generation is still very low compared to the available resources with a technical potential of 4,155 TWh per year (Jain et al. 2015). This potential is significantly higher than the 654 TWh of gross electricity generated in 2017 in Germany (UBA 2018b).

The use of GTPs could be relevant for municipal energy autonomy efforts due to the following advantages: on the one hand, in contrast to many alternative renewable energy plants, the plants are able to provide heat and electricity as base load. As the Literature Review in section 2 demonstrates, the costs of energy autonomy are very high due to the volatile generation of electricity by PV and wind and the resulting need for high storage capacities. In addition, resources for the use of biomass or gas networks are not available in every municipality. In this case, the use of the DH generated by the GTPs would be particularly important. Furthermore, GTPs emit the lowest amount of pollutants during the life cycle of the plant after hydropower (Purkus & Barth 2011).

The objective of this study is to answer the following research questions, developed from an analysis of existing literature (cf. section 2):

- Could the high costs for off-grid municipal energy systems be reduced through the use of geothermal plants?
- Is it sufficient to consider only the electricity generation of the geothermal plant or would the use of the geothermal heat in district heating networks create an additional benefit?

To answer these research questions, a generic approach for the modelling of GTPs in municipalities is developed, which is included in a holistic² energy system optimisation. In order to ensure the transferability of the method, a novel modelling approach for the simultaneous generation of electricity and heat as well as the calculation of costs for GTPs is demonstrated. Furthermore, a basis for the assessment of the hydrothermal potential in each German municipality is provided, which also serves as input for the optimisation model. The hydrothermal potential is determined by the achievable temperature of the water in aquifers at depths of up to 5 km. The hydrothermal potential therefore also determines the geothermal potential (i.e. electricity or heat generation potential), since the temperature of the hydrothermal fluid serves as a heat source for the geothermal plants in the present study. The approach is not intended to replace the detailed assessment of the hydrothermal potential on site, but is suitable to demonstrate a possible utilisation of this potential. In addition to the transferability of the approach, the effect of GTPs on the costs and emissions of energy autonomous municipal energy systems is investigated in several municipalities by energy system optimisations. Thereby the focus is on the residential sector. On the one hand, the focus of the energy projects mentioned above is on this sector. On the other hand, this sector can be implemented most precisely due to the comprehensive data availability.

The paper is structured as follows. Section 2 provides an overview of the literature and clarifies the context of this paper. Section 3 then explains the methodology, before sections 4 and 5 present and discuss the results. The paper concludes with a summary and conclusions in section 6.

2. Literature review

In this section, the novelty of the study is demonstrated by discussing peer-reviewed literature on energy autonomy in municipalities (section 2.1) and on the optimisation of GTPs (section 2.2).

² We mean by "holistic" that not only the geothermal plant itself is optimised. Instead, the geothermal plant is only a small part of the overall optimisation, in which the costs for energy supply in municipalities are minimised and other technologies and measures can be applied alongside / instead of the geothermal plant.

2.1. Municipal energy autonomy

Several case studies have already examined the feasibility of municipal energy autonomy (cf. Table 1). In this context, only studies in which at least balanced autonomy is investigated are referred to. Balanced autonomy of a region is examined in Scheffer (2008), Schmidt et al. (2012), Peura et al. (2018) and Burgess et al. (2012). Scheffer (2008) focuses on a rural model region with 10,000 inhabitants and agriculture as well as trade and commerce, but without large-scale industry. High investments are necessary for the balanced energy autonomy and storable biomass is highlighted as the most important energy source for achieving this status. Schmidt et al. (2012) investigate the advantages and disadvantages of energy autonomy compared to conventional energy supply in Sauwald, a rural region with 21,000 inhabitants in Austria. The study comes to the conclusion that attaining energy autonomy implies a decline in local production of food and feed as well as high costs for consumers. Peura et al. (2018) investigate the potential economic effects of balanced energy autonomy in the municipalities of Perho and Jepua in Finland and take into account the consumption sectors of households, industry, transport and commerce. The study finds that energy autonomy can be technically feasible and economically advantageous in rural areas. Finally, the study by Burgess et al. (2012) explores the Marston Vale region in the UK, which in particular would have to import heat energy and fuels, while a large proportion of its electricity needs could be covered by energy from the region itself.

Complete municipal energy autonomy, on the other hand, is investigated in Peter (2013), Jenssen et al. (2014) and Woyke & Forero (2014). The suitability of a rural settlement structure for complete energy autonomy is analysed in Peter (2013), who demonstrates that renewable energies could cover the electricity demand of an "example village" with 3,850 inhabitants but with tremendous storage costs. Jenssen et al. (2014) conclude that complete energy autonomy is technically achievable in an "average" German municipality through the "Bioenergy Village" approach, albeit at high costs. Woyke & Forero (2014) assess complete energy autonomy in Pellworm, an island municipality in Germany with 1,100 inhabitants, which has been regarded as a model location for the construction of renewable energies. Despite the fact that energy supply exceeds demand, complete energy autonomy is not possible with the current energy system in Pellworm due to grid restrictions.

Overall, it appears that energy autonomy can only be achieved at high cost. In the case of complete energy autonomy, this is related to high storage costs. The present study considers all energy supply technologies applied in the presented literature except for solar thermal (cf. Table 1). So far, none of the studies on municipal energy autonomy includes a possible contribution from GTPs, which could reduce the high storage costs through base load capacity.

Table 1: Municipal energy autonomy studies and the considered energy supply technologies (BE = Bioenergy, WE = Wind energy, PV = Photovoltaics, ST = Solar thermal energy, GE = Geothermal energy, AHP = Air-source heat pump, GHP = Ground-source heat pump).

Study	Considered energy supply technologies					Type of energy autonomy	Context
	BE	WE	PV	ST	GE		
Burgess et al. (2012)	✓	✓	✓	✓	GHP	Balanced	Region in UK
Jenssen et al. (2014)	✓	×	×	×	×	Complete	German "Bioenergy village"
Peter (2013)	×	✓	✓	✓	GHP	Balanced and complete	German village
Peura et al. (2018)	✓	✓	×	×	×	Balanced	Finnish municipalities
Scheffer (2008)	✓	✓	✓	✓	×	Balanced	Rural German region
Schmidt et al. (2012)	✓	×	✓	✓	GHP	Balanced	Rural Austrian region
Woyke & Forero (2014)	✓	✓	✓	×	×	Balanced and complete	German Island
This study	✓	✓	✓	×	AHP/GHP and GTPs	Complete	German municipalities

2.2. Geothermal plant optimisation

In most studies on GTPs, process parameters are optimised, such as power output or various efficiencies of the plant (cf. 43 summarised studies in Table A1³ in the Appendix). Usually only electricity generation is considered. Van Erdeweghe et al. (2018) and Marty et al. (2018) alone consider a combined power and heat production, whereby in Van Erdeweghe et al. (2018) the focus is on the optimisation of the power generation as well. Furthermore, in most cases low brine temperatures are investigated, which are also present in Germany. Only in very few cases the investigated energy system includes not only the GTP but a more extensive system with other energy supply technologies. These cases of interest are examined in more detail in the following.

Østergaard et al. (2010) investigate the feasibility of supplying the municipality of Aalborg in Denmark with renewable energy through a combination of deep geothermal heat, wind power plants and biomass. GTPs are used for heat generation only. The results of the simulations show that these technologies cannot cover the demand of Aalborg in every hour and that energy has to be imported instead. The study of Østergaard & Lund (2011) on Frederikshavn in Denmark, in which the city's energy demand should be 100% renewable, also takes deep geothermal energy into account as a heat generation plant with a district heating network (DHN). The simulation includes wind turbines to cover the electricity demand, therefore a balanced electricity autonomy is considered. The study shows that the operation of the GTP and the DHN reduces the energy imports of Frederikshavn. In the study of Sveinbjörnsson et al. (2017), the municipality of Sønderberg in Denmark is considered, which is aiming for zero net CO₂ emissions by 2029. Exactly as in Østergaard & Lund (2011), the GTP is combined with an absorption heat pump. The mixed-integer linear optimisation shows that by supplementing combustion with modern energy conversion technologies, the climate targets can be achieved in a cost- and energy-efficient manner. The most relevant paper for the analysis carried out in the present study is Marty et al. (2018). They highlight the relevance of a simultaneous optimisation of the DHN and the organic rankine cycle (ORC) of a GTP. However, the model in their study is not automatically applicable to any location, as hydrothermal temperatures as well as distances to heat consumers have to be specified manually and geographical conditions are not considered. Furthermore, only parts of the GTP are optimised and not the entire plant. For example, fixed drilling costs are specified in the optimisation and it is not possible to optimise the depth of the boreholes. Beyond that, the greatest need for improvement lies in the fact that the GTP is optimised without being in an energy system context with competition from other technologies such as PV, wind turbines and biomass plants.

Table 2 summarises the main characteristics of the discussed studies. In the 39 other studies on GTP energy systems from Table A1, only those properties are given for which a clear statement was possible. More detailed information can be found in Table A1. As a summary, the evaluation of the studies demonstrates that GTPs are usually optimised with regard to power generation. This is justified as most studies are technical analyses to optimise parameters of the ORC plant. On the other hand, the ORC system is neglected and only the DH supply is considered when optimising municipal energy systems. Furthermore, only specific municipalities were examined and no attempt was made to generate transferable methods. The following gaps were identified in the review of the literature, which the authors fill with the present study:

- 1) Development of a generic optimisation model for the optimisation of a GTP, which simultaneously generates electricity and heat. The model also optimises the drilling depth and the related hydrothermal temperature (cf. section 3).

³ Tables, figures and sections in the Appendix are marked with an A before the numbering.

- 2) Integration of the GTP model in a holistic and transferable⁴ energy system optimisation model applicable to every German municipality (cf. section 3.5).
- 3) Investigation of the economic feasibility of complete municipal energy autonomy including GTPs (cf. section 4).

Table 2: Main characteristics of the geothermal plant optimisation studies.

Study	Methodology	Focus on DH and / or power	Variable temperature and drilling depth	Optimisation of the district heating network	Easily transferable? ⁴	Investigated energy system
39 other studies (section A1)	Mainly optimisation	Power	×	×	-	GTP
Østergaard et al. (2010)	Simulation	DH	×	×	×	Municipality
Østergaard & Lund (2011)	Simulation	DH	×	×	×	Municipality
Sveinbjörnsson et al. (2017)	Optimisation	DH	×	×	×	Municipality
Marty et al. (2018)	Optimisation	Both	×	✓	×	GTP and few consumers
This study	Optimisation	Both	✓	✓	✓	Municipality

3. Methodology

Energy system analyses in municipalities usually require a lot of data. In addition, the possible measures have to be adapted to the individual municipality. The methodology in this study aims to be transferable and applicable to each municipality without further effort⁴. This means that no data needs to be collected. Instead, only the name of the municipality needs to be provided and all required input data are determined automatically. This approach enables the investigation of several municipalities and the identification of the impacts of different prerequisites in the municipalities on the optimal energy systems. First of all, this methodological section gives an overview of the general approach (section 3.1). In section 3.2 the achievable hydrothermal temperatures at certain locations in Germany as well as the varying depths at which these temperatures can be found, depending on the location, are demonstrated. Afterwards, the most important model equations for representing a GTP are presented in section 3.3 before the economic assessment of a GTP is considered in section 3.4. Finally, section 3.5 explains the integration of the developed GTP model into the holistic energy system model. An overview of the existing methodology and the extensions presented in this study are given in Figure 1.

3.1. General approach

For the determination of the optimal municipal energy system design in this study, the “Renewable Energies and Energy Efficiency Analysis and System Optimisation” (RE³ASON) model is used and further extended (Mainzer 2019, cf. Figure 1). In the first step of the model ("Input data determination") the required input data are calculated with the use of a Java model (Eclipse). The input data are applied in the second step, the actual optimisation model, which is implemented by using the General Algebraic Modeling System (GAMS). The RE³ASON model consists of several parts, which provide transferable methods for determining the existing technologies, infrastructure, the heat and electricity demand of residential buildings as well as the potential and associated costs for energy supply from photovoltaic (PV), wind and biomass in an arbitrary location. Due to the transferability, this model is applied in the

⁴ This refers to the developed methods. Some assumptions, especially about certain parameter values, are not necessarily transferable to every municipality (cf. section 5).

present study, as various municipalities in different locations are investigated. RE³ASON further provides a deterministic model of optimal investment and dispatch for new energy conversion technologies at the community level. In the mixed integer linear program (MILP), the optimal technology investment and unit commitment of all technologies as well as energy flows between districts is identified. The model serves to cope with the complexity resulting from the number and combinations of the individual measures and their dependencies that would otherwise not be feasible. Included in the model are the above-mentioned energy supply technologies as well as measures such as insulation, heating technologies or appliances. The municipality under consideration is divided into districts, in which buildings are grouped into building types according to the TABULA building typology (IWU 2015). The spatial resolution consists of these districts as nodes to which the input, like heat and power demand, is assigned. In addition, the existing infrastructure such as gas and electricity grids are identified. However, no DHNs could be built in the old version of the model. Therefore, it is extended for the utilisation of district heat from the GTP (cf. section 3.5). In the present study, the model is used to perform a long-term energy system optimisation (from 2015 to 2030), whereby each 5th year is modelled explicitly and divided into 108 time slices (4 seasons, 3 day types, 9 time slices within each day). An energy system must ensure security of supply even under extreme conditions of energy demand and climatic conditions (Petrakopoulou et al. 2016). Therefore, one extreme day is designed for every season. In the extreme days, the energy demands in the residential buildings reach the maximum values of the originally determined demand load profiles for the respective season and no solar radiation or wind is present.

Figure 1: Overview of RE³ASON and the extensions developed in the present study.

The model can be used to minimise total discounted system costs, CO₂ emissions or energy imports of the municipal energy system. The calculation of the potential of PV, wind and biomass is briefly explained in the following, for further information about the model including the mathematical model formulation the reader is referred to McKenna et al. (2018) and Mainzer (2019). In order to determine the PV potential, OpenStreetMap is used to identify building data and roof areas (OpenStreetMap contributors 2018). Satellite data is used to detect roof type and orientation. In addition, a methodology based on neural networks detects already installed PV modules. More information about the PV potential calculation can be found in Mainzer et al. (2017). The potential calculation of wind turbines uses minimum distance specifications to, for example, settlements or airports to determine the number of wind turbines that can be placed in the municipality. Based on the minimum leveled cost of electricity

(LCOE), the wind turbine type is selected. For wind and PV potential determination, different local climates are also included in the calculation. In the case of biomass plants, the maximum amount of substrates that can be produced on the agricultural and forest areas of the municipality is determined for different types of plants. Implemented plants are waste-to-energy plants, woody biomass combustion plants and biogas plants. The LCOE calculation includes investments as well as transport costs. The amount of energy that can be supplied using the substrates can be divided arbitrarily over the year. The biomass plants, therefore, can be used flexible and can serve peak loads as well as base loads. Results of the input determination for photovoltaics, wind power and biomass as well as for the district heating network for an exemplary municipality can be found in the electronic Appendix. The RE³ASON model extensions shown in Figure 1 are explained hereafter. The extensions are implemented within the program environment of the existing RE³ASON model.

3.2. Achievable hydrothermal temperature and required drilling depth

The achievable hydrothermal temperature $T_{PW,max}$ (wellhead temperature) is based on the values of the Geothermal Information System GeotIS (Agemar et al. 2014). For the present study, the data from the geographical map of Germany in GeotIS were transferred to a CSV file in 8.5 km² resolution and the vertices of the grid now serve as input for the optimisation model. Figure 2 shows the geographical map of the 11,100 German municipalities with achievable temperatures at a depth of up to 5 km resulting from the data transfer. The achievable temperatures reach up to 190°C and the prevailing pressure conditions in the brine are assumed to be high enough, so that the water does not boil below this temperature. If more than one point of the 8.5 km² grid is located in the municipality, the mean value of the achievable temperatures is employed. Since the transfer of the data to create the grid with the hydrothermal temperatures required a substantial amount of work, the CSV is provided as supplementary material.

Figure 2: Achievable average hydrothermal temperature (°C) at a depth of up to 5 km in German municipalities according to Agemar et al. (2014) and locations of GTPs in Germany (blue circles). The background map in this figure and in all of the following figures with background maps is from OpenStreetMap contributors (2018). For a better analysis of the colours in this figure, please refer to the online version of the paper.

As soon as the hydrothermal temperature is known, the required drilling depth z_D can be determined. For this purpose, according to Bauer et al. (2014), the mean German temperature gradient of 32 °C/km

is assumed for the South German Molasse Basin (MB) and 35 °C/km for the North German Basin (NGB). In the Upper Rhine Graben (URG), on the other hand, the temperature gradients are much higher with 43 °C/km on average (locally up to 110 °C/km, Bauer et al. (2014)), especially in the area up to 3 km (Agemar et al. 2012). MB, NGB and URG are shown in Figure 2. In order to be able to determine the temperature gradient more precisely, the temperature gradient resulting from the drillings for the GTP in Landau are taken over for the entire URG (Frey & Milles 2007), but adjusted in such a way that the mean value is 43 °C/km. This results in the three temperature sections in Figure 3. The temperature gradient ΔT decreases with depth and adapts to the German average. Above 3,250 m, a constant temperature gradient is assumed.

Figure 3: Assumed temperature sections as a function of the drilling depth in the Upper Rhine Graben.

3.3. GTP model for simultaneous heat and electricity generation

This section describes the equations used to implement the GTP model. In the equations, variables are shown in bold, the other terms are parameters. Thereby the most important model equations will be described. The authors could provide the complete modeling equations upon request. The schematic illustration of the GTP in Figure 4 is intended to help identify the most important variables and parameters of the model, which are introduced in this section. Since existing DHNs in Germany cannot be identified without further research, it is assumed that no DHN already exists in the municipalities (green field approach).

Figure 4: Schematic illustration of the GTP considered in this study. The heatflow in the condenser of the ORC process could be water or air. For a better analysis of the colours in this figure, please refer to the online version of the paper.

The power generation P_{el} of the ORC plant and heat generation $\dot{Q}_{th}$ of the district heating plant (DHP) per time step t can be determined using Eqs. 1-2.

$$\dot{V}_B \cdot \rho_w \cdot c_{p,w} \cdot (T_{PW}(t) - T_{ORC,out}(t)) = P_{el}(t)/\eta_{el} \quad \forall t \quad 1$$

$$\dot{V}_B \cdot \rho_w \cdot c_{p,w} \cdot (T_{ORC,out}(t) - T_{DHP,return}(t)) = \dot{Q}_{th}(t)/\eta_{th} \quad \forall t \quad 2$$

The maximum possible volumetric flow rate depends on the local geological conditions. Furthermore, in most GTPs the economically and energetically optimal volumetric flow rate is significantly below the maximum possible flow rate, since the installation depth and design of the feed pump depend on the flow rate (Rohloff & Kather 2011). Therefore, the mean flow rate of the existing deep geothermal projects in Germany of 75 l/s is used as the volumetric flow rate $\dot{V}_B$ in the model (cf. Table A2). The heat capacity $c_{p,w}$ of geothermal water increases from approximately $4.18 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ at 20°C to about $4.45 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ at 190°C . In the same temperature interval the water density ρ_w decreases from approximately 1 kg/l to about 0.9 kg/l (Schröder et al. 2015). In this temperature interval, the product of these two coefficients differ by 4%. Therefore, a constant mean heat capacity of $4.31 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ and a mean density of 0.95 kg/l are assumed in the following. The GTP is assumed to operate in base load, therefore P_{el} and $\dot{Q}_{th}$ are limited in such a way that these take constant values in a season, i.e. four different values per year.

The injection temperatures are known for the power plants Insheim, Dürnhaar and Kirchstockach. No heat is generated in these plants (cf. Table A2). Thus, the efficiency of the ORC plants could be determined with the help of Eq. 1. The resulting mean value 13% is assumed for the electrical efficiency η_{el} in the following, which is a relatively high value for binary ORC plants and almost corresponds to the typical efficiency of ORC plants of 16% (Quoilin et al. 2013). In accordance with Ozgener & Ozgener (2009), 65% is assumed for the efficiency η_{th} of the geothermal DH system, including heat exchange and heat losses in the DHN. Thus, the power and heat generation depends only on the temperature in the production well T_{PW} and the temperature after the heat transfer to the ORC process $T_{ORC,out}$, as well as the temperature after the heat transfer to the DH system $T_{DHP,return}$, which are further constrained in the following. Based on the values from Zarrouk & Moon (2014), a minimum output temperature $T_{ORC,min}$ of 50°C is assumed after the heat transfer to the binary power plant. To avoid that the ORC plant is necessarily built, this condition only applies if the binary variable b_{PP} equals 1 (cf. Eq. 3).

$$b_{PP} \cdot T_{ORC,min} \leq T_{ORC,out}(t) \quad \forall t \quad 3$$

The same applies to heat extraction for DH purposes. A conventional DHN is assumed here with a minimum forward temperature $T_{DH,min}$ of 65°C (Lindenberger et al. 2000), a pinch temperature $T_{DH,pinch}$ of 5°C at the heat exchanger and a return temperature $T_{DHP,return}$ of $T_{DH,return,min} = 55^\circ\text{C}$ (Elmegaard et al. 2016). This condition also only applies if the DHP is built ($b_{DHP} = 1$). In order to ensure that $T_{ORC,out}$ is not always at least $T_{DH,min} + T_{DH,pinch} = 70^\circ\text{C}$ in this case, the time-dependent variable $b_{DHP,op}$ is introduced, which indicates whether heat is generated in a time step or not (cf. Eqs. 4 and 5).

$$(T_{DH,return,min} + T_{DH,pinch}) \cdot b_{DHP,op}(t) \leq T_{DHP,return}(t) \quad \forall t \quad 4$$

$$b_{DHP,op}(t) \cdot (T_{DH,min} + T_{DH,pinch}) \leq T_{ORC,out}(t) \quad \forall t \quad 5$$

$$b_{DHP,op}(t) \cdot M \geq T_{DHP,return}(t) \quad \forall t \quad 6$$

Eq. 6 is introduced to ensure that the temperature $T_{DH,return,min}$ is maintained. M is a large number which should be as small as possible and at least as large as the maximum value of the restricted variable (Griva et al. 2009), in this case 190°C . The injection temperature is at least 50°C if no energy is used for DH purposes and 60°C otherwise. As described in more detail in section 3.4, the drilling cost function

is divided into five sections, to obtain a linear function. Only one of the sections may be selected with the binary variable $b_{D,i}$ (cf. Eq. 7):

$$\sum_{i=1}^5 b_{D,i} \leq 1 \quad 7$$

The selected range then determines the possible minimum and maximum value of the drilling depth $z_{D,i}$. The range of a section r_z in Eqs. 8-10 is set to 1,000 m.

$$b_{D,i} \cdot (i - 1) \cdot r_z \leq z_{D,i} \quad \forall i \quad 8$$

$$b_{D,i} \cdot i \cdot r_z \geq z_{D,i} \quad \forall i \quad 9$$

$$z_D \leq 5 \cdot r_z \quad 10$$

For example, if $b_{D,2}$ is set to 1, then the drilling depth is in the range of 1,000 m to 2,000 m. However, since there are now five cost functions for the different sections of the drilling depth z_D , only the cost function that has been selected may be used. Therefore, the drilling depth $z_{D,i}$ is determined for each section, which is zero if the section is not selected (cf. Eq. 11).

$$z_{D,i} = z_D \cdot b_{D,i} \quad \forall i \quad 11$$

In the following, the costs can be assigned to the variables $z_{D,i}$ and $b_{D,i}$ (see section 3.4). The achievable temperature is in turn determined via z_D . To avoid that all $b_{D,i}$ and $z_{D,i}$ are set to zero, the following equation must be added:

$$z_D = \sum_{i=1}^5 z_{D,i} \quad 12$$

The equation and the defined temperature sections from section 3.2 are used to determine the temperature $T_{PW,max}$ of the water in the production well if the investigated municipality is located in the Upper Rhine Graben (cf. Eq. 13).

$$\begin{aligned} & \left(\frac{z_{D,1900}}{1,900 \text{ m}} \right) \cdot (100 \text{ °C} - T_a) + T_a \cdot b_{D,1900} + \left(\frac{z_{D,3250} - 1,900 \text{ m} \cdot b_{D,3250}}{1,350 \text{ m}} \right) \cdot 55 \text{ °C} + 100 \text{ °C} \cdot b_{D,3250} \\ & + \left(\frac{z_{D,3850} - 3,250 \text{ m} \cdot b_{D,3850}}{600 \text{ m}} \right) \cdot 20 \text{ °C} + 155 \text{ °C} \cdot b_{D,3850} \geq T_{PW,max} \end{aligned} \quad 13$$

The sections of the drilling depth $z_{D,1900}$, $z_{D,3250}$ and $z_{D,3850}$ to determine the temperature do not correspond to the sections of the drilling depths $z_{D,i}$ to determine the drilling costs. Therefore, the Eqs. 7-12 from above have to be replicated for these drilling depth sections as well. To limit the temperature $T_{PW,max}$ to the maximum values of the ranges from Eq. 13, Eq. 14 must be implemented:

$$T_{PW,max} \leq 100 \text{ °C} \cdot b_{D,1900} + 155 \text{ °C} \cdot b_{D,3250} + 190 \text{ °C} \cdot b_{D,3850} \quad 14$$

For the North German Basin and the South German Molasse Basin, the temperature linear depends on the drilling depth (cf. section 3.2). In addition, equations are needed to ensure that the GTP has to be built ($b_{GP} = 1$) if a power plant ($b_{PP} = 1$) or DHP is built and to limit the nominal power of ORC and DH plant, $P_{el,max}$ and $\dot{Q}_{th,max}$, to zero if not. The operating life of the plant is assumed to be 30 years based on Budisulistyo et al. (2017).

3.4. Economic assessment

In GTP projects, four main phases occur to which costs can be allocated. The four phases are resource identification, resource exploration, drilling and energy production (Clauser & Ewert 2018). The costs for GTPs are subject to uncertainties. As an extreme example, investments in the Sauerlach project have

increased from the original estimate of 25 M€ to 90 M€ (cf. Table A2, Zeitungsverlag tz 2014). The cost-functions in this section are mainly based on Schlagermann (2014). Three of the eight components of the investment in Table 3 that are particularly relevant for this study are explained in this section. An explanation of the remaining cost functions can be found in section A4.

Table 3: Components of the investment for the GTP and their dependence on variables of the GTP model.

Variable of the component	Description of component	Depending on the following variables
C_1	Feasibility study and preliminary planning	b_{GP}, z_D
C_2	Properties and infrastructure	$b_{GP}, b_{PP}, b_{DHP}, P_{el,max}, \dot{Q}_{th,max}$
C_3	Exploration of the reservoir	$b_{GP}, b_{W,1}, b_{W,2}, z_D$
C_4	Production well pump	$b_{W,1}, P_{el}, \dot{Q}_{th}$
C_5	Thermal water system (above-ground)	b_{GP}
C_6	Power generation plant	$P_{el,max}, b_{PP}$
C_7	District heating system	$b_{DH,S,i}$
C_8	Project management, control and finance planning as well as other investments	All variables from C_1 - C_7

The costs C_1 are divided into the costs for the feasibility study C_{FS} , the preliminary underground planning C_{UP} as well as the preliminary planning of the power generation plant and the above-ground plant components C_{PP} (Schlagermann 2014):

$$C_1 = C_{FS} + C_{UP} + C_{PP} = (180,000 \text{ €} \cdot b_{GP}) + (100,000 \text{ €} \cdot b_{GP} + 25,000 \text{ €/km}^2 \cdot A_S) + (150,000 \text{ €} \cdot b_{GP}) \quad 15$$

$$\text{with} \quad A_S = (z_D + 4 \text{ km} + d_D) \cdot (z_D + 4 \text{ km}) = z_D^2 + 9,5 \text{ km} \cdot z_D + 22 \text{ km}^2 \quad 16$$

The preliminary underground planning includes a 3D seismology for which the area A_S must be known. The vertical depth of the drillings z_D and the distance between the two drillings d_D is required to calculate A_S . For d_D , deflections of the drillings are also taken into account. According to Stober & Bucher (2014), the distance in the underground, in the area of the working horizon, is usually 1,000-2,000 m. Therefore d_D is assumed to be 1,500 m in the following. In order to use Eq. 15 in the linear optimisation problem, the function must be linearised. This was achieved by dividing the function into five sections in 1,000 m steps. Now the costs can be calculated using the linearised cost functions (cf. Equations in red boxes in Figure 5).

The costs for the exploration of the reservoir C_3 are divided into costs for drilling C_D , stimulation C_{ST} , hydraulic tests C_{HT} and geochemical investigations C_{GI} (Schlagermann 2014). With a share of up to 70% of the capital costs, drilling costs account for the largest share of the investment for a GTP (Leipziger Institut für Energie 2007). The drilling costs are estimated according to the following equation (Eyerer et al. 2017):

$$C_D = 610,000 \text{ €} \cdot b_{GP} + 1.015 \cdot C_{DW} = 610,000 \text{ €} \cdot b_{GP} + 1.015 \cdot \left[1.198 \cdot e^{0.00047894 \cdot \sqrt{z_D^2 + d_D^2}} \cdot 10^6 \text{ €} \right] \quad 17$$

The term in the square brackets covers the costs of the actual drilling work C_{DW} , the rest is for the construction and recultivation of the well site, among other things. This study assumes that all drilling is done at one well site. Therefore, the costs of 610,000 € are only charged for the first well.

The drilling costs are assumed to be subject to economies of scale and the costs of the second well is only 90% of the costs of the first well. The same applies to the hydraulic tests with 67% as well as the geochemical investigations of the wells with 70% for the second well. The costs for the exploration of the reservoir can therefore be calculated using the following equations (Schlagermann 2014):

$$C_3 = C_D + C_{ST} + C_{HT} + C_{GI} \quad 18$$

$$\text{with} \quad C_D = 610,000 \text{ €} \cdot b_{GP} + 1.015 \cdot C_{DW} \cdot (1 + 0.9) \quad 19$$

$$C_{ST} = 450,000 \text{ €} \cdot (1 + 0.67) \cdot b_{GP} \quad 20$$

$$C_{HT} = 500,000 \text{ €} \cdot b_{GP} \quad 21$$

$$C_{GI} = 65 \frac{\text{€}}{\text{m}} \cdot \sqrt{z_D^2 + d_D^2} \cdot (1 + 0.7) \quad 22$$

The investment for exploration of the reservoir C_3 thus depend on the vertical drilling depth according to the function in Figure 5. The deviations of the linearised curves from the actual costs C_1 and C_3 are between -2% and +1%.

Figure 5: The costs for the feasibility study and the preliminary planning C_1 (red) and the costs for exploration of the reservoir C_3 as a function of vertical drilling depth as well as linearization of the functions. The costs C_3 are shown for the first (blue) and second (yellow) drilling. For a better analysis of the colours in this figure, please refer to the online version of the paper.

3.5. Integration in RE³ASON

The entire GTP model presented above is integrated in the optimisation model of the RE³ASON model, as explained in the following using the three model extensions.

1) Determination of the hydrothermal potential in a municipality (cf. section 3.2)

The achievable hydrothermal temperature serves as input for the optimisation model and is determined within the scope of the input calculation. The basin is also transferred to the model in order to determine the required drilling depth.

2) GTP model equations for simultaneous heat and electricity generation (cf. section 3.3) and

3) GTP cost determination (cf. section 3.4)

The technical and economic model equations are integrated into the RE³ASON optimisation model. The total costs for the GTP are determined as the sum of all individual costs C_1 to C_8 . These total costs and the variable costs of the GTP are part of the objective function to calculate the total discounted system costs for the entire energy system (cf. Eqs. A.1-A.2 in the Appendix of McKenna et al. (2018)).

At this point it is necessary to clarify the consideration of the construction of a new DHN for the utilisation of the geothermal heat. The spatial resolution of the model is that of the district as a node (cf. 3.1). The costs for the DHN are calculated in several percentage steps of heat supply based on the heuristic developed in Weinand et al. (2019a). In the following a segmentation into ten steps is chosen, i.e. costs for the supply of 10%, 20%, 30% etc. up to 100% of the municipal heat demand. This also includes determining which buildings should optimally be connected to the DHN in the various steps. Therefore,

the investigated municipality has to be divided into districts to also take account of energy flows in the optimisation process. For this purpose, a Voronoi clustering is performed on the basis of the settlements in the municipality. The resulting Voronoi cluster for an example municipality can be found in the electronic Appendix. For a given number of points in a plane, a Voronoi diagram divides the plane according to the rule of the nearest neighbour: each point is associated to the region closest to it (Aurenhammer 1991). The resulting districts are used to determine which settlements will be connected to the geothermal-based DHN. The investment for the DHN in the different steps serves as input for the optimisation model in RE³ASON. In the optimisation model, the DH connections and costs then depend on the choice of the binary variable $b_{DH,S,i}$ (cf. Eq. 23).

$$\sum_{i=1}^{10} b_{DH,S,i} \leq 1 \quad 23$$

For example, if all buildings/settlements in a municipality should be supplied with DH, then $b_{DH,S,10}$ has to be set to 1. If only 70% of the heat demand should be covered by DH, then $b_{DH,S,7} = 1$ applies. The DHN that results in this latter case can be found in the electronic Appendix for an example municipality. By selecting the binary variables, the output $\dot{Q}_{th}$ of the DH plant is limited by a proportion of the heat demand of the municipality $D_{heat,total}$ (cf. Eq. 24).

$$\dot{Q}_{th}(t) \leq \sum_{i=1}^9 (b_{DH,S,i} \cdot 10\% \cdot i \cdot D_{heat,total}(t)) + (b_{DH,S,10} \cdot M) \quad 24$$

The case with 100% is not included in the sum so that more DH can be generated than required. Therefore, the binary variable is multiplied by a large number M . In addition, the investment for the district heating system C_7 for the DHN can be specified with the binary variable $b_{DH,S,i}$.

4. Results

First, the GTP model is validated in section 4.1. Subsequently, in section 4.2, general information on the energy system optimisations are given and the results are presented in detail.

4.1. Validation

Validations are performed for the achievable hydrothermal temperatures and associated drilling depths as well as for the cost calculations (investment and LCOE). Table A2 shows a list of 31 deep geothermal projects in Germany, with corresponding data. The findings of this section can be analysed in more detail by examining the columns *Temperature deviation*, *Temperature gradient* and *Depth deviation* of Table A2 as well as the figures A1-A3. Since the drilling depths as well as the achieved temperatures are indicated in the projects, the model can be validated with the data from Table A2. For this purpose, the temperatures in the model are calculated on the basis of the actual drilling depths of the projects. The locations show deviations from the real achievable temperatures in the existing geothermal projects. The deviation could occur due to the fact that locations with above-average temperature gradients have been chosen for the geothermal projects realised so far. Furthermore, the hydrothermal temperatures could only be transferred as point coordinates of an 8.5 km² grid. The root-mean-squared-error (RMSE) between the real and calculated temperature values is 27 °C. Actually, the RMSE calculated with the model equations would be only 16 °C, however, the calculated temperatures are limited by the maximum achievable temperatures from Figure 2. At 17 of the 31 locations, the deviations are less than 15%, all deviations are on average 19%. Apart from a few municipalities in the North German Basin, the accuracy of the model is considered sufficient for generic application and identification of municipalities with potential geothermal exploitation. For a detailed planning of a GTP plant, specific measurements have to be performed. Since hydrothermal temperature and drilling depth are directly interdependent in the model, the deviations are the same for both parameters. The validation of the investment for the GTP

can be found in section A4.1 of the Appendix. All in all, the validation shows satisfactory results for the model. Due to the lack of data, however, it is not possible to predict the exact hydrothermal temperature and temperature gradient at a specific location. As already mentioned in the objectives in section 1, the applied methods are sufficient to estimate the geothermal potential for the energy system optimisations, since this study is intended to demonstrate possible utilisation of this potential.

Figure 6: LCOE of geothermal power plants calculated by the model presented in this study using different achievable temperatures for the three large basins in Germany (upper part). The dotted black horizontal lines mark the area in which the LCOE of real deep geothermal projects fall according to IRENA (2018). As a sensitivity analysis, the change in LCOE for the NGB are shown with parameter values deviating from the reference case (lower part). For a better analysis of the colours in this figure, please refer to the online version of the paper.

Figure 6 shows the calculated LCOE for geothermal power plants using the model equations developed in this study (upper part). The temperature $T_{ORC,out}$ is set to 50°C for the calculation of the reference cases. Based on the achievable temperature, the LCOE are given for all three large basins in Germany. Values between 0.05 €/kWh and 0.5 €/kWh are reached. In 2017 the LCOE of selected international geothermal projects ranged between 0.03 €/kWh and 0.14 €/kWh (cf. area between black dotted lines in Figure 6, IRENA 2018). The range is given in general, not depending on the hydrothermal temperature. Since only projects with achievable temperatures of over 80°C are usually realised, the model can be assessed as plausible in this respect. For the NGB, four scenarios with changed

parameter values compared to the reference case are also shown as sensitivities in the lower part of Figure 6. If the ORC efficiency η_{el} is reduced or $T_{ORC,out}$ is increased, the LCOE increase. Thereby the deviation of the LCOE in comparison to the reference case decreases the higher the achievable hydrothermal temperature is. Furthermore, the deviation for parameter changes that reduce electricity production ($\eta_{el} = 5\%$ and $T_{ORC,out} = 80\text{ °C}$) is higher due to the high fixed costs of GTP. Since the LCOE deviation is largest in the scenario with an efficiency of 5% (in the relevant temperature range above 100 °C), this sensitivity is also investigated in the optimisations in section 4.2.2. A validation of the RE³ASON model can be found in Mainzer (2019).

4.2. Results of the energy system optimisation case studies

Three German municipalities are selected as case studies. These municipalities are taken from three different municipality clusters (Weinand et al. 2019b), so that they differ considerably in terms of relevant indicators. The indicators of the municipalities important for the analyses are listed in Table 4. Westheim is selected to examine a densely populated municipality in the URG in which the maximum hydrothermal temperature of 190 °C can be reached. The case of Prinzenmoor, on the other hand, should show how the energy system changes, if a sparsely populated municipality is investigated. Furthermore, Groß Kreutz is chosen to investigate whether geothermal plants are also installed in municipalities with a large population and widely dispersed settlements in various districts as well as low hydrothermal potential.

Table 4: Characteristics of the municipalities Westheim, Prinzenmoor and Groß Kreutz examined in this study.

Municipality	Westheim (Pfalz)	Prinzenmoor	Groß Kreutz (Havel)
Cluster (Weinand et al. 2019b)	3	4	8
Basin (Agemar et al. 2014)	URG	NGB	NGB
Area [km ²]	7	6	99
Population	1,731	179	8,133
Population density in municipality [1/km ²]	243	32	82
Number of districts	1	1	12
Maximum hydrothermal temperature [°C]	190	175	80

The objective value of the optimisations are the total discounted system costs (TDSC). The energy systems are optimised for the period between 2015 and 2030. In addition, the majority of the optimisations consider complete municipal energy autonomy (CMEA), i.e. the demand must be met by local regenerative energy and no energy imports are allowed. In all optimisations, the MIP-Gap, the relative tolerance on the gap between the best integer objective and the objective of the best node remaining, is set to 5%. The maximum capacity for the electricity storage per district is given as 20 MWh. Optimisation times depend largely on the number of districts in a municipality, as more energy flows need to be optimised in cases with many districts. In addition, the optimisations for Westheim lasted longer than for Prinzenmoor since Westheim is located in the Upper Rhine Graben and therefore Eqs. 13-14 become relevant. The calculation times ranged from a few hours to seven days. More information about the optimisation problem and the computation is given in Table 5. The number of variables and equations depends on the number of districts, therefore the optimisation problem for Groß-Kreutz is considerably larger. In addition, more equations and variables are contained for Westheim than for Prinzenmoor, due to the different modelling of the drilling depth (cf. Eq. 13).

Table 5: Structure of the optimisation problem as well as properties and hardware for solving the model.

Case study	Westheim (Pfalz)	Prinzenmoor	Groß Kreutz (Havel)
Number of variables	602,619	573,177	5,945,481
Number of binary variables	3,235	3,180	6,724
Number of equations	1,074,006	1,031,469	8,484,842
Programming language	General Algebraic Modeling System (GAMS)		
Solver	CPLEX (branch & cut)		
Hardware properties	Intel Xeon E-1650 v2; 3.5 GHz; 12 Threads; 128 GB RAM		

Further input data, including energy carrier price developments and techno-economic assumptions, can be found in the electronic Appendix.

Whilst scenario specifications and the optimisation results concerning the geothermal plant can be found in Table 6, the resulting TDSC and their development are shown in Figure 7. Before presenting specific results in detail in sections 4.2.1 and 4.2.2, the following list gives an overview of the most important results, as well as in which section and by which scenarios these results can be explained:

- Achieving CMEA is associated with a significant increase in TDSC and is never achieved unless it is enforced (all scenarios).
- The construction of a GTP is not worthwhile, if CMEA does not have to be achieved (W1, P1, GK1 in sections 4.2.1 - 4.2.2).
- The construction and operation of a GTP can significantly reduce the TDSC, if CMEA has to be achieved (W2 and GK2 in comparison with W5 and GK3 in section 4.2.1).
- The previous statement also applies to the case with significantly lower ORC efficiency (W3 in section 4.2.2).
- Neglecting the district heating option of a GTP by only considering the ORC could lead to higher TDSC (W2 in comparison with W4 in section 4.2.2).
- In municipalities with low population, the installation of a GTP is not worthwhile due to high fixed costs (P2 in comparison with P3 in section 4.2.2).
- In contrast, the TDSC can be significantly reduced, even at low hydrothermal potential, if the fixed costs of the GTP are distributed over a large population (GK2 in comparison with GK3 in section 4.2.2).

In the description of the results, the focus is on the GTP and electricity.

4.2.1. Impact of geothermal plants on complete municipal energy autonomy

Scenario W2 demonstrates on the one hand the importance of a GTP in achieving CMEA and on the other hand the importance of considering the heat side and the electricity side of the GTP. In comparison to scenario W5, in which the installation of a GTP is prohibited (cf. Table 6), the use of the GTP saves 1.6 k€ per inhabitant for the energy supply system until 2030 (cf. Figure 7). Thus, the use of a GTP can significantly reduce the cost of achieving CMEA. In scenario W2, only one biomass plant with a capacity of 225 kW_{el} is built in addition to the GTP to cover the demand. Due to the base-load operation of the 1.1 MW_{el} ORC plant, the electricity demand is exceeded in some time steps (cf. Figure 8). In these cases, the excess energy is temporarily stored in a 1.3 MWh battery storage and reused as required. Scenario W5, on the other hand, requires an 18.2 MWh storage capacity in order to achieve CMEA using biomass and the volatile energy supply technologies PV and wind. This clarifies the high increase of the costs for CMEA through the use of large storage capacities which was already found in the literature in section 2.1. By the use of the GTP in scenario W2, these costs can be lowered, however, the TDSC increase by 70% in comparison to the reference scenario W1 without CMEA.

Table 6: Scenarios including specifications as well as the results for the geothermal plant in the individual scenarios.

Scenario	Scenario specifications				GTP results				
	CMEA forced?	ORC allowed?	DH allowed?	Special characteristics	Drilling depth [m]	Temperature [°C]	ORC capacity [kW]	DH capacity [kW]	GTP investment [M€]
Westheim 1 (W1)	×	✓	✓		-	-	-	-	-
Westheim 2 (W2)	✓	✓	✓		1,850	98	1,100	1,970	22
Westheim 3 (W3)	✓	✓	✓	5% ORC efficiency	2,130	109	610	1,920	22
Westheim 4 (W4)	✓	✓	×	ORC forced	1,580	85	1,390	-	18
Westheim 5 (W5)	✓	×	×		-	-	-	-	-
Prinzenmoor 1 (P1)	×	✓	✓		-	-	-	-	-
Prinzenmoor 2 (P2)	✓	✓	✓		-	-	-	-	-
Prinzenmoor 3 (P3)	✓	✓	✓	ORC forced	1,590	56	230	-	15
Groß Kreutz 1 (GK1)	×	✓	✓		-	-	-	-	-
Groß Kreutz 2 (GK2)	✓	✓	✓		2,290	80	1,200	-	20
Groß Kreutz 3 (GK3)	✓	×	×		-	-	-	-	-

Since almost all heat demand is covered by the GTP via DH in scenario W2, only a few power-operated heat generators (e.g. electric storage heaters) are operated. The electric storage heaters are only needed for peak loads, which cannot be covered by the DH base load. A large part of the municipal power consumption is caused by the pump in the production well of the GTP. For further information on the distribution of the consumption patterns, please refer to the electronic Appendix.

Figure 7: TDSC per inhabitant for the energy supply between 2015 and 2030 in various scenarios for the municipalities Westheim, Prinzenmoor and Groß Kreutz.

The preference for biomass plants and the GTP in scenario W2 over the volatile energy from wind and PV can be explained by the base load capability of the plants. However, it is not so obvious why the GTP is preferred instead of biomass plants, which can be operated flexibly in addition to the base load. On the one hand this is due to the low technical biomass potential in Westheim. On the other hand, the average LCOE of the potential biomass plants of 0.25 €/kWh is significantly higher than that of the GTP amounting to (at least) 0.07 €/kWh with a hydrothermal temperature of 98 °C. Even with assumptions that would reduce the performance of the GTP, the LCOE would still be below 0.25 €/kWh (cf. section 4.1).

Figure 8: Optimised energy supply patterns (upper part) - divided into energy supply technologies - on a typical weekday for all seasons in 2015 for the municipalities of Westheim (upper part) and Prinzenmoor (lower part). For a better analysis of the colours in this figure, please refer to the online version of the paper.

4.2.2. Sensitivity analysis

A particularly critical assumption in the modelling of the GTP in section 3.3 is the assumption of a constant ORC efficiency of 13%. For this reason, scenario W2 is changed in scenario W3 in such a way that the efficiency is only 5%. As shown in Table 6, even in this case, an ORC plant and a DH system are built. The 1.5 k€ higher TDSC per inhabitant result primarily from the larger biomass plant and battery storage. An ORC plant is therefore constructed even with very low efficiency. The TDSC with the real efficiency would most likely be between the TDSC of scenarios W2 and W3.

The literature review in section 2.2 shows that GTPs are usually investigated with regard to electricity generation and not with regard to simultaneous electricity and heat generation. The results of scenario W4 demonstrate that simultaneous electricity and heat optimisation could create added value. The TDSC in scenario W4, in which no DH system may be installed, are 2.1 k€ higher per inhabitant than in scenario W2 (cf. Figure 7). The ORC system in scenario W4 has a higher capacity than in scenario W2, since more of the generated electricity has to be used for heat supply with heat pumps and electric storage heaters. Furthermore, the different drilling depths and the resulting hydrothermal

temperatures in scenarios W2, W3 and W4 show the added value which results from the novel modelling of the drilling depth as a variable.

For the municipality Prinzenmoor, the costs in the scenarios with CMEA show a significant increase compared to the reference scenario P1 without CMEA (cf. Figure 7). This indicates that the small rural municipalities which are mainly examined in the literature are not necessarily more suitable for achieving CMEA than larger municipalities (cf. section 2.1), as will be clarified further below using scenario P3.

As Table 6 shows, no GTP is built to achieve CMEA in scenario P2. The energy demand is covered by PV rooftop modules, biomass plants and a battery storage. The largest peak loads, which are mainly caused by heat pumps, are covered by biomass and the battery (cf. Figure 8). If the construction of a GTP is forced (scenario P3), the TDSC increase by 472% compared to the reference scenario P1. This is due to the high fixed costs of the GTP, whose investment is not much lower than in the other scenarios despite significantly lower capacity (cf. Table 6). The two drillings alone account for 10 M€, corresponding to 66% of the total investment, which is distributed among significantly fewer inhabitants than in Westheim. This demonstrates that in smaller municipalities the fixed costs of the energy plants in particular lead to high TDSC per inhabitant. Therefore, economies of scale lead to lower TDSC in larger municipalities. Furthermore, the disadvantage of the lower temperature gradient in the NGB is evident, since the depth of the drillings in the URG would have to be only 970 m in order to reach the 56 °C, instead of 1,590 m in the NGB.

The dependence of the TDSC per inhabitant on the number of inhabitants is further confirmed in Groß Kreutz. Since the costs of the GTP are distributed among significantly more inhabitants than in the other two municipalities, CMEA only leads to a 4% increase in costs in scenario GK2 compared to reference scenario GK1. The increase in TDSC per inhabitant is significantly lower than in Prinzenmoor and Westheim (cf. Figure 7). Thus, in the case of CMEA, the construction of a geothermal plant is worthwhile even with a low hydrothermal potential. However, the construction of a DH plant is probably prevented by the low achievable temperature. A comparison of scenario GK2 with scenario GK3, in which no GTP may be installed, shows this again. The cost to achieve CMEA without GTP almost doubles in GK3 (cf. Figure 7). In GK3, wind turbines, PV modules, biomass plants and battery storages are installed.

5. Critical appraisal

This study is not without weaknesses which should be addressed in future work. While the developed model provides transferability to any German municipality⁴, the geological conditions on site must always be considered when planning a GTP. As shown in the previous sections, the model cannot guarantee 100% accuracy in the calculation of achievable hydrothermal temperatures, drilling depths and associated costs. This probably results from the average temperature gradients assumed for the different basins. The geothermal projects with which the model was compared were probably realised at sites with exceptionally high temperature gradients.

In addition, GTPs are sensitive to various types of scaling, including carbonate minerals, amorphous silicates, metal oxides and sulphides. Silica (SiO₂), and calcite (CaCO₃) are the most common. One result of the scaling is the degradation of plant components, which requires their premature replacement (Gunnlaugsson et al. 2014). In addition, the scaling reduces the diameter of the pipes and thus increases the total pressure drop and the friction factor in the pipe (Zarrouk et al. 2014). In the water of low-temperature GTPs (T<150 °C at 1 km depth) there is no silica saturation even when cooling to approximately 20 °C in DH systems (Gunnlaugsson et al. 2014). This would therefore be applicable to all locations in Germany. Problems caused by the high salt content in the water of the North German

Basin are avoided by the relatively high injection temperature of at least 50 °C, which is applied in this study (Magri et al. 2009).

Furthermore, some assumptions about parameters like constant efficiencies, temperatures and flow rates were necessary to represent the GTP in a linear optimisation model. The temperature dependent ORC efficiency is one of the most critical assumptions and has been investigated in the sensitivity analysis (cf. section 4.2.2). The ORC efficiency did not have a significant impact: although the TDSC have increased while the efficiency was considerably lower (+7%), the GTP has been built nevertheless to achieve CMEA. For the other parameters, the assumptions are rather conservative, but the impacts should also be further examined in the future. Due to the employed assumptions, the statement that a simultaneous optimisation of heat and electricity of the geothermal plant is recommended has to be critically evaluated. The fact that the installation and operation of the district heating system in scenarios W2 and W3 leads to lower TDSC could be explained by the uncertainties of the model. On the other hand, the efficiency of the competing ORC plant is overestimated. Since the district heating option is applied nevertheless, district heating should also be considered in future modelling of geothermal plants.

In addition, the GTP is assumed to operate without outages. This leads to a moderate underestimation of the LCOE of the GTP. A possible improvement of this weakness could be to create redundancy, which still allows the operation of the plant in the case of a pump outage. To this end, the model could be extended by the option to build a triplet instead of a doublet (Baasch 2011), which consists of an injection well and two production wells (Majorowicz & Grasby 2010). The heat from the reservoir could be used for up to ten years longer with a triplet well layout in comparison to a doublet well layout due to improved system performance (Jiang et al. 2014).

Another important issue for future studies is the investigation of the influence of the time series structure on the results. In the RE³ASON model an hourly resolution is used. A higher resolution would involve higher peak loads, which could make CMEA no longer achievable in municipalities, or with greater effort. Furthermore, only extreme days were considered in this study. In future analyses longer extreme periods could be considered to take periods of very low solar and wind production into account. However, even with only one extreme day per season, geothermal plants were built in the cases considered in this study.

Furthermore, the fact already mentioned in the literature was confirmed: the total costs to achieve CMEA increase very much, if large battery storage capacities are required (cf. section 4.2.2). Besides battery storages for short-term purposes, it would also be sensible to include seasonal storages, such as hydrogen storages, in upcoming analyses.

Finally, the choice of the system boundaries must also be considered. The analysis of the municipality of Prinzenmoor showed that CMEA in small municipalities is associated with high additional costs due to the high fixed costs of the energy supply technologies. These municipalities could therefore be analysed together with smaller neighbouring municipalities. Since the municipality Groß Kreutz with the least TDSC in a CMEA scenario is the largest of the investigated municipalities with regard to the population, the conclusion is obvious that there could be an optimal municipality scale for CMEA. All of the aspects mentioned in this section will be the focus of forthcoming contributions.

6. Conclusions

The objective of this paper is the investigation of the economic feasibility of complete municipal energy autonomy in an energy system including geothermal plants. Therefore, a generic optimisation model of a geothermal plant, which simultaneously generates electricity and heat, is developed and integrated into an existing holistic energy system optimisation model. Variable drilling depths and thus hydrothermal temperatures represent one of the novel modelling approaches. As input for the optimisation, a linear regression estimates the achievable hydrothermal temperatures and the required

drilling depths in the municipalities. Some cost estimations for the geothermal plant, such as drilling costs, had to be linearised for this purpose. A validation of the cost and the input determination with data from actual plants shows that the model presented in this work can reasonably be applied to any municipality in Germany without additional efforts⁴.

Related to the above objective, the specific research questions addressed in this paper are as follows. Could the high costs for off-grid municipal energy systems be reduced through the use of geothermal plants? Is it sufficient to consider only the electricity generation of the geothermal plant or would the use of the geothermal heat in district heating networks create an additional benefit? In order to answer these questions, the developed optimisation model was applied to three different municipalities from different municipal clusters. Eleven scenarios demonstrated that achieving energy autonomy is associated with high additional costs. Compared to the scenarios without energy autonomy, total discounted system costs for the period between 2015 and 2030 have increased by at least 4%. Thereby, the utilisation of geothermal plants can significantly reduce the costs for achieving energy autonomy, which answers the first research question above. The electricity generation is preferred to heat generation in geothermal plants, which is related to the high costs for the district heating network. However, the importance of simultaneous modelling of electricity and heat generation in geothermal plants is evident, as district heating plants reduce the costs, especially in municipalities with high hydrothermal potential. This provides an answer to the second research question, i.e. that in the context of municipal energy system planning it is not sufficient to only consider the electricity side of the plant. Therefore, the installation of geothermal plants could help to decarbonise the energy system through energy autonomy.

This paper has developed a generally-applicable method for the optimal setup of a GTP within or near a residential area and considering both heat and electricity generation. Together with the related contribution for optimally locating the GTP plant within an existing or new district heating network (Weinand et al. 2019a), the consideration of the heat side represents a significant step forward. Compared to previous studies that focussed on a detailed GTP system setup, typically optimised for power generation, the present paper adopts a more holistic approach. The current and the above cited paper together provide a methodological framework for the economically effective and energetically efficient integration of GTPs into local energy systems. In the context of renewable energy system planning this therefore represents an invaluable tool in the context of the energy transition. Furthermore, the employed method is intended to be highly transferable, both within Germany and, by employing additional data sources, beyond. It can provide decision support to local energy planners and other relevant stakeholders when considering the renewable energy options at their disposal.

Due to the fact that the employed methodology is intended as an early-stage planning tool, it has several uncertainties, however. Hence the authors emphasize the need for a more detailed energy system planning, especially but not only relating to the GTP, before entering the implementation phase. Most importantly, the costs of geothermal plants are very uncertain and depend on local geological conditions. Whilst the model presented provides a good estimate of the hydrothermal temperatures, the investment can rise due to uncertain incidents. Further work should also include the investigation of the impact of a higher temporal resolution as well as the identification of the optimal spatial scale for energy autonomy.

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Appendix

A1. Literature review table

Table A1: Literature review on energy system analyses with geothermal plants.

Study	Methodology	Assessment area/region or plant site	Objective function	Energy system	Plant type	Energy Generation	Brine temperature
Aali et al. (2017)	Exergoeconomic analysis and multi-objective optimisation	Site: Sablan geothermal field (Iran)	Specific cost of output power and exergy efficiency	Geothermal plant	Combined flash-binary ORC	Power	165-183
Astolfi et al. (2014)	Optimisation	-	Thermodynamic efficiency	Geothermal plant	Binary ORC	Power	120-180
Budisulistyo et al. (2017)	Thermo-economic analysis	Taupo Volcanic Zone (New Zealand)	Plant performance and lifetime	Geothermal plant	Binary ORC	Power	131
Chagnon-Lessard et al. (2016)	Thermodynamic numerical simulation and optimisation	-	Specific power output	Geothermal plant	ORC	Power	80-180
Clarke et al. (2014)	Comparison of genetic algorithm with particle swarm optimisation for the constrained, non-linear, simulation-based optimisation	-	Plant performance (power output)	Geothermal plant	Double flash	Power	-
Clarke & McLeskey (2015)	Multi-objective particle swarm optimisation (MOPSO)	-	Pareto-optimal set of designs depending on brine temperature and dry-bulb temperature	Geothermal plant	Binary ORC	Power	80-180
Ghaebi et al. (2018)	Exergoeconomic analysis & single- and multi-objective optimisations (using genetic algorithm (GA))	-	Total levelized cost of energy system products; thermal efficiency along with the exergy efficiency.	Geothermal plant	Cascade cycle (CKC) Kalina	Heat	170
Ghasemi et al. (2013)	Parametric optimisation	-	Net power output	Geothermal plant	Binary ORC	Power	135
Guzović et al. (2012)	Optimisation of the main parameters of ORC and Kalina cycle.	Lunjkovec-Kutnajak, Croatia	Power output, by optimising the main cycle parameters: ORC: upper cycle pressure Kalina: concentration of ammonia	Geothermal plant	ORC and Kalina cycle	Power	140
Huster et al. (2017)	Deterministic global optimisation of component size and operating conditions (Non Linear Program)	-	Net power; LCOE	Geothermal plant	ORC	Power	135.85
Karimi & Mansouri (2018)	Exergoeconomic analysis and optimisation of different ORC configurations	20 countries (e.g. Australia, Brazil, Jordan)	Exergy efficiency, specific investment cost (SIC) and a combination of exergy and SIC	Geothermal plant	Organic Rankine Cycle (ORC), Regenerative Rankine Cycle (RORC) and Two-Stage Evaporation Organic Rankine Cycle (TSEORC)	Power	61.85 - 211.85

Study	Methodology	Assessment area/region or plant site	Objective function	Energy system	Plant type	Energy Generation	Brine temperature
Kolahi et al. (2018)	Particle swarm optimisation	Sabalan geothermal power plant (Iran)	Maximum total output power	Geothermal plant	Flash-binary ORC	Power	31- 188
Lazzarin et al. (2017)	Cycle and turbine re-optimisation on geothermal resources	-	Net electrical output	Geothermal plant	-	Power	145
Liu et al. (2015)	Parametric optimisation and performance analysis	-	Net power output	Geothermal plant	ORC	Power	110-150
Liu et al. (2016)	Analysis of the thermodynamic performance of a hybrid geothermal-fossil power generation system for various geothermal resource temperatures	-	-	Plant	Hybrid geothermal-fossil power generation system	Power	100-160
Liu et al. (2017)	Thermo-economic analysis (multi-objective optimisation)	-	Thermal efficiency, exergy efficiency, power output, capital cost	Geothermal plant	Binary ORC	Power	80-95
Lu et al. (2018)	Optimisation	-	Net power output	Geothermal plant	Single-flash system, double-flash system, flash-ORC system, and double-flash-ORC system	Power	170
Makhanlall et al. (2015)	Optimisation by an exergy-topological methodology (cognitive thermodynamic tool)	-	Optimal operating conditions	Geothermal plant	Binary medium grade plant	Power	25-150
Martínez-Gómez et al. (2017)	Multi-objective optimisation	-	Maximise profit from energy sales, minimise risk and minimise environmental impact (CO ₂ emissions)	Geothermal plant	ORC	Power	167.75
Marty et al. (2018)	Simultaneous optimisation	-	Net annual profit	ORC plant, district heating plant and a few consumers	ORC	Heat and Power	185
Mohammadzadeh Bina et al. (2017)	Thermo-economic analysis (EES optimisation (multi-criteria))	Sabalan geothermal power plant (Iran)	Energy efficiency, exergy efficiency, net power output, production cost, total cost rate	Geothermal plant	Basic ORC (B-ORC), Dual fluid ORC, Regenerative ORC (R-ORC), ORC with Internal Heat Exchanger (IHE-ORC)	Power	165
Mohammadzadeh Bina et al. (2018)	Exergoeconomic analysis and optimisation	Sabalan geothermal power plant (Iran)	Net power output	Geothermal plant	Single and Double flash cycles	Power	149-242.96
Mosaffa et al. (2017)	Thermodynamic and economic analysis (optimisation)	-	Maximise energy and exergy efficiency levels, minimise total product unit cost	Geothermal plant	ORC with Internal Heat Exchanger (IHX), Dual fluid ORC, Regenerative ORC	Power	160-180

Study	Methodology	Assessment area/region or plant site	Objective function	Energy system	Plant type	Energy Generation	Brine temperature
Nakomcic-Smaragdakis et al. (2016)	1. Determination of geomorphological, geological, geophysical, hydrogeological and hydrothermal characteristics of the area; 2. Analysis of physicochemical characteristics of geothermal and mineral waters, as well as drill's capacity; 3. Possible applications of the geothermal fluid are considered and recommendations for direct use are given	Indijja (Serbia)	-	Geothermal plant	-	Heat	-
Østergaard et al. (2010)	Analysing scenario for supplying Aalborg through renewable energies on the basis of the EnergyPLAN model	Aalborg (Denmark)	-	Energy system of the municipality Aalborg	-	Heat	-
Østergaard & Lund (2011)	Analysing scenario for supplying Frederikshavn through renewable energies on the basis of the EnergyPLAN model	Frederikshavn (Denmark)	-	Energy system of the municipality Frederikshavn	-	Heat	-
Pambudi et al. (2014)	Optimisation	Dieng Geothermal Power Plant (Indonesia)	Energy exergy flow and efficiency	Geothermal plant	Single flash binary	Power	18-179.9
Pambudi et al. (2018)	Thermodynamic and silica scaling analysis	Dieng Geothermal Power Plant (Indonesia)	Increase capacity, reduce the impact of silica scaling	Geothermal plant	Single flash binary, double flash binary	Power	116.4
Peña-Lamas et al. (2018)	Optimisation	-	Structure of the cycle, operating conditions and best fluid	Geothermal plant	Binary ORC	Power	164.34-170
Pollet et al. (2018)	Optimisation	-	Total energy output	Geothermal plant	ORC	Power	120-150
Shengjun et al. (2011)	Parametric optimisation and performance analysis	-	Thermal efficiency, exergy efficiency, recovery efficiency, heat exchanger area per unit power output and the levelized energy cost	Geothermal plant	Subcritical ORC and transcritical power cycle	Power	80-100
Sigurdardottir et al. (2015)	Lumped parameter modelling (LPM) combined with a mixed integer linear programming (MILP)	Laugarnes geothermal system (South-West Iceland)	Profit	Geothermal reservoir	-	Heat	127.55
Sun et al. (2017)	Thermodynamic optimisation (parametric analysis by means of genetic algorithm)	-	Turbine high-level inlet pressure and temperature, turbine low-level inlet pressure	Geothermal plant	Double-pressure ORC	Power	120
Sun et al. (2018)	Thermodynamic optimisation	-	Evaporation temperature and net power output	Geothermal ORC	ORC	Power	100-150
Sveinbjörnsson et al. (2017)	Energy supply modelling using the Sifre tool	Sonderborg Municipality (Denmark)	Operating expenses of the specified energy demand during all time steps	Energy system of the municipality Sonderborg	-	-	-

Study	Methodology	Assessment area/region or plant site	Objective function	Energy system	Plant type	Energy Generation	Brine temperature
van Erdev eghe et al. (2018)	Thermodynamic optimisation	-	Electrical pow er output	Combined heat-and-pow er (CHP) configurations	ORC	Heat and Pow er	110-150
van Erdev eghe et al. (2019)	Tw o-step optimisation	Balmatt site, Belgium	Design case: Net present value Off-Design case: Net electrical pow er output	Geothermal plant	ORC	Pow er	110-150
Walraven et al. (2015)	Optimisation with different types of cooling systems	Belgium	Levelized cost of electricity	Geothermal plant	ORC	Pow er	100-150
Wu et al. (2017)	Thermodynamic analysis and performance optimisation (parametric optimisation via pattern search algorithm (PSA))	-	Turbine inlet temperature, turbine inlet pressure, pow er output	Geothermal plant	Transcritical Power Cycle (TPC)	Pow er	100-150
Yang & Yeh (2015)	Economic performance optimisation	-	Net pow er output	Geothermal plant	Transcritical Rankine Cycle (TRC)	Pow er	44.13-66.02
Yilmaz (2017)	Thermo-economic optimisation using genetic algorithm method	-	Cost optimal exergetic efficiency	Geothermal plant	Combined flash-binary	Pow er	150-159
Zare (2015)	Thermodynamic and exergoeconomic optimisation with own models & profitability evaluation	-	Optimisation: total capital investment and payback period	Geothermal plant	ORC-based binary pow er plant	Pow er	160-170
Zhao & Wang (2016)	Exergoeconomic analysis and optimisation	-	Exergoeconomic: Minimise levelized cost per unit of exergy; Thermodynamic: maximise exergy efficiency.	Geothermal plant	Flash-binary ORC cycle	Pow er	200

A2. Data tables on deep geothermal projects

Table A2: Data on German deep geothermal projects (Agemar et al. 2014; Enerchange 2018; Eyerer et al. 2017). If more sources than Agemar et al. (2014), Enerchange (2018) and Eyerer et al. (2017) were used, these are indicated in the table column "sources". If the maximum wellhead temperature of the model is less than the calculated temperature, it is coloured red.

Location	Latitude	Longitude	Wellhead temperature reality [°C]	Wellhead temperature model [°C]	Max. Wellhead temperature model [°C]	Temperature deviation	Depth reality [m]	Depth model [m]	Depth Deviation	Temperature gradient [°C/km]
Groß Schönbeck	52.9099	13.5544	150	151	80	-47%	4309	4286	-1%	34.8
Hannover	52.4872	9.9095	169	137	80	-53%	3901	4829	+24%	43.3
Neubrandenburg	53.5547	13.2357	71	44	115	-37%	1268	2029	+60%	56.0
Neuruppin	52.9244	12.8150	64	57	115	-11%	1620	1829	+13%	39.5
Neustadt-Glewe	53.3714	11.5930	97	86	115	-11%	2450	2771	+13%	39.6
Waren	53.5253	12.6548	63	55	115	-13%	1565	1800	+15%	40.3
Average NGB			102	88	103	29%	2519	2924	21%	42.2
Bruchsal	49.1261	8.5669	123	126	96	-22%	2542	2465	-3%	48.4
Brühl	49.3924	8.5352	160	157	150	-6%	3318	3400	+2%	48.2
Insheim	49.1539	8.1534	165	173	171	+3%	3800	3550	-7%	43.4
Landau (Palatinate)	49.1864	8.1228	159	156	121	-24%	3291	3370	+2%	48.3
Average URG			152	153	134	14%	3238	2926	4%	47.1
Aschheim	48.1701	11.7352	85	84	80	-6%	2630	2656	+1%	32.3
Dürnhaar	47.9960	11.7260	135	132	115	-15%	4114	4219	+3%	32.8
Erding	48.3087	11.8828	63	75	57	-10%	2359	1969	-17%	26.7
Garching	48.2571	11.6672	74	71	80	-4%	2226	2313	+4%	33.2
Geretsried	47.8432	11.4903	165	193	145	-12%	6036	5156	-15%	27.3
Grünwald	48.0349	11.5223	130	131	107	-17%	4083	4063	-1%	31.8
Ismaning	48.2310	11.6986	75	88	80	+7%	2738	2344	-14%	27.4
Kirchstockach	48.0274	11.6877	139	124	115	-17%	3881	4344	+12%	35.8
Kirchweidach	48.0991	12.6454	130	121	115	-12%	3800	4063	+7%	34.2
München (Riem)	48.1349	11.7153	95	88	80	-16%	2747	2969	+8%	34.6
Pöing	48.1673	11.7915	76	98	80	+5%	3049	2375	-22%	24.9
Pullach	48.0567	11.5140	104	112	93	-11%	3505	3250	-7%	29.7
Sauerlach	47.9723	11.6686	140	143	127	-9%	4480	4375	-2%	31.3
Simbach-Braunau	48.2571	13.0105	81	62	69	-23%	1941	2531.25	+30%	41.7
Straubing	48.9751	12.5553	37	26	0	-100%	824	1156.25	+40%	44.9
Taufkirchen	48.0237	11.6208	136	136	115	-15%	4258	4250	0%	31.9
Traunreut	47.9732	12.5792	108	149	115	+6%	4645	3375	-27%	23.3
Unterföhring	48.1933	11.6593	86	64	80	-26%	1986	2687.5	+35%	43.3
Unterhaching	48.0660	11.6131	123	115	115	-7%	3590	3843.75	+7%	34.3
Unterschleißheim	48.2725	11.5806	78	63	80	-20%	1960	2437.5	+24%	39.8
Waldkraiburg	48.2024	12.4206	109	87	80	-27%	2718	3406.25	+25%	40.1
Average MB			104	103	92	17%	3242	3262	14%	36.6

Table A2 (continued)

Location	Injection Temperature [°C]	Forward/ return temperature [°C]	Volumetric flow rate [L/s]	Nom inal power (electrical) [MW]	Nom inal Power (thermal) [MW]	Calculated electrical efficiency [%]	Sources
Groß Schönbeck			21	0.07	7		
Hannover			7	0	2		
Neubrandenburg		65 / 35	11-28	0	3.8		Schallenberg (1996)
Neuruppin			14	0	2.1		
Neustadt-Glewe		90 / 60	11-33	0.2	5 / 6.5		Schallenberg (1996)
Waren		70 / 50	17	0	3.6		
Average NGB			14-20				
Bruchsal	60	90 / 65	24	0.55	5.5		Eyerer et al. (2017)
Brühl							
Insheim	70		85	4.8	0	15	
Landau (Palatinate)	50	70 / 40	70	3.8	6		Eyerer et al. (2017)
Average URG			60			15	
Aschheim			75	0	27		
Dürnhaar	45		130	5.5 / 7	0	15	
Erding			48	0	34 / 10.2		
Garching			100	0	15 / 8		
Geretsried							
Grünwald		120 / 65	150	4.5	50		Bauer et al. (2014)
Ismaning			85	0	10		
Kirchstockach	45		145	5.5	0	10	
Kirchweidach			50	0.7	12		
München (Riem)			75	0	10		
Pöing			80	0	9		
Pullach			71	0	15		
Sauerlach	45	90-105 / 60	110	4	5		
Simbach-Braunau			80	0.2	8		
Straubing			45	0	4.1		
Taufkirchen		115 / 70	120	4.3	35		
Traunreut	55	100 / 65	150	5	12		
Unterföhring			75	0	10		
Unterhaching	60	80-110 / 50-60	150	3.4	38		Eyerer et al. (2017)
Unterschleißheim			90	0	28 / 8		
Waldkraiburg			65	4.8	14		
Average MB			95			12.5	

Table A2 (continued)

Location	Total investment reality [m. €]	Total investment model [m. €]	Total investment deviation	Investment for drilling [m. €]	Investment district heating network [m. €]	Investment for plant process [m. €]	Plant Process	Commissioning year	Number of wells	Sources
Groß Schönbeck	12.1	38	+212%				ORC	Testing phase	2	GTN (2012a)
Hannover	15	17	+15%					development	1	Bundesverband Geothermie (2018)
Neubrandenburg		21						1987	3	Bundesverband Geothermie (2018)
Neuruppin		16						2007	2	Bundesverband Geothermie (2018)
Neustadt-Glewe	10.8	24	+122%	1.7	1.8	3.2	ORC	2003	2	GTN (2012b); Enerchange (2009)
Waren		27						1984	4	
Average NGB	13	24	116%						2.3	
Bruchsal	17	24	+43%	8.1			Kalina	2001	2	
Brühl								development		
Insheim	50	40	-20%				ORC	2012	2	Eyerer et al. (2017)
Landau (Palatinate)	20	39	+93%				ORC	2007	2	
Average URG	19	34	52%						2	
Aschheim	60	45	-24%					2009	2	Bundesverband Geothermie (2018)
Dürnhaar	60	50	-17%					2012	2	Bundesverband Geothermie (2018); Eyerer et al. (2017)
Erding	18.7	51	+172%					1998	2	Bundesverband Geothermie (2018)
Garching		32		13				2011	2	Bundesverband Geothermie (2018)
Geretsried								development		
Grünwald	150.4	92	-39%		53.8		ORC	2011	2	Erdwärme Grünwald GmbH (2013)
Ismaning	71.6	36	-50%	18	41			2012	3	
Kirchstockach	62	44	-30%	23			ORC	2013	2	Eyerer et al. (2017)
Kirchweidach		40						2012	2	Bundesverband Geothermie (2018)
München (Riem)		31						2004	2	Bundesverband Geothermie (2018)
Pöing		30						2013	2	
Pullach		47		9				2005	3	
Sauerlach	90 (initially 25)	62	-31%				ORC	2014	3	Bundesverband Geothermie (2018); Zeitungsverlag tz (2014)
Simbach-Braunau	21	24	+14%				ORC	2001	2	Bundesverband Geothermie (2018)
Straubing	12	16	+33%					1999	2	Bundesverband Geothermie (2018)
Taufkirchen	65	78	+20%				Kalina	Testing phase (2014)	2	Bundesverband Geothermie (2018); Eyerer et al. (2017)
Traunreut	80	62	-23%				ORC	2014	2	
Unterföhring	37.5	36	-5%	12.5	14.5			2009	4	
Unterhaching	80	73	-9%		48	16	Kalina	2009	2	Geothermie Unterhaching (2017)
Unterschleißheim	22	44	+99%					2013	2	Bundesverband Geothermie (2018)
Waldkraiburg	12	46	+281%					2012	2	OVB24 GmbH (2009); Bundesverband Geothermie (2013)
Average MB	55	47	56%						2.3	

A3. Model deviation compared to reality

Figure A1: Wellhead temperature of geothermal projects in reality compared to the model (cf. columns “Wellhead temperature reality”, “Wellhead temperature model” and “Max. wellhead temperature model” in Table A2 for precise values). For a better analysis of the colours in this figure, please refer to the online version of the paper.

Figure A2: Drilling depth of geothermal projects in reality compared to the model. (cf. columns “Depth reality” and “Depth model” in Table A2 for precise values). For a better analysis of the colours in this figure, please refer to the online version of the paper.

Figure A3: Total investment of geothermal projects in reality compared to the model. (cf. columns “Total investment reality” and “Total investment model” in Table A2 for precise values). For a better analysis of the colours in this figure, please refer to the online version of the paper.

A4. Further economic assessment

The purchase values for properties C_P in German municipalities are given in Statistisches Bundesamt (2016a) divided into municipal size classes, i. e. depending on the population in the municipality. A distinction is made here between *developed building land*, *undeveloped building land* and *other building land*. Other building land can be developed building land and undeveloped building land, but differs from both in its fixed use to date. It includes industrial land, land for transport and open spaces (Statistisches Bundesamt 2016b). As commercial and industrial sites are included in the other building land, it is assumed that the geothermal plants will be built on this kind of land. Figure A4 shows the cost structure of other building land for different municipality sizes (Statistisches Bundesamt 2016a).

Figure A4: Average purchase value for other building land for different municipality sizes (Statistisches Bundesamt 2016a).

The figure shows that the land prices can differ significantly from the 60 €/m² assumed in Schlagermann (2014). With the exception of the outlier in municipalities with between 50,000 and 100,000 inhabitants, property costs increase with the number of inhabitants, probably due to the scarcity of free space in municipalities with many inhabitants. However, as Schmalwasser & Brede (2015) show, land prices depend more on population density. Therefore, the average population densities are determined for the municipal size classes in Table A3 by using the municipality data from Statistisches Bundesamt (2017b) and the prices are set for the resulting population density classes.

Table A3: Costs for other building land depending on the number of inhabitants of the municipality.

Population (in thsd.)	<2	2-5	5-10	10-20	20-50	50-100	100-200	200-500	>500
Mean population density in municipality [Inhabitants/km ²]	80	170	245	380	565	885	1385	1695	2700
Purchase value [€/m ²]	21.5	31.0	42.0	50.5	64.0	37.5	103.0	117.5	449.0

Finally, the cost of land and infrastructure C_2 can be estimated using the following equation:

$$C_2 = C_P \cdot (A_D + A_{el} + A_{th}) \quad A1$$

$$= C_P \cdot \left(2400 \text{ m}^2 \cdot b_{GP} + \left(2000 \text{ m}^2 \cdot b_{PP} + 0.25 \frac{\text{m}^2}{\text{kW}_{el}} \cdot P_{el,max} \right) + \left(100 \text{ m}^2 \cdot b_{DHP} + 0.01 \frac{\text{m}^2}{\text{kW}_{th}} \cdot \dot{Q}_{th,max} \right) \right)$$

A_D is the area required for the well site, A_{el} for the power generation plant and A_{th} for the district heating plant.

The pumps in a low-temperature geothermal plant consume approximately $D_p = 30\%$ of the gross output (Quoilin et al. 2013; Kraml & Walzer 2008). Therefore, the demand D_{pump} has to be added to the electricity demand D_{el} if a geothermal plant is built during the optimisation in order to determine the total electricity demand $D_{el,total}$.

$$D_{el,total}(t) = D_{el}(t) + D_{pump}(t) \quad A2$$

with

$$D_{pump}(t) = D_p \cdot \left(P_{el}(t) + \dot{Q}_{th}(t) \cdot \frac{\eta_{el}}{\eta_{th}} \right) \quad A3$$

As a conservative estimate, the assumption is made that the required amount D_{pump} is not yet included in the calculation to determine η_{th} in Ozgener & Ozgener (2009). The nominal power P_{pump} of the pump is determined via Eq. A4 with a pump efficiency η_{pump} of 0.95.

$$P_{pump} \geq D_{pump}(t) \cdot \eta_{pump} \quad A4$$

Eyerer et al. (2017) specify the installation depth of the pumps in the production wells for eight German power plants. With the help of the average value of 700 m, the costs for the production well pump C_4 can then be calculated according to Eq. A5 (Schlagermann 2014).

$$C_4 = 15.7 \frac{\text{€}}{\text{kW}_{el}} \cdot P_{pump} + 98,500 \text{ €} \cdot b_{GP} \quad A5$$

The costs for the thermal water circuit C_5 are determined as a function of the volumetric flow rate rate $\dot{V}_B$, assuming a constant length of the circuit (Jancik & Kupfermann 2014):

$$C_5 = 5,000 \frac{\text{€} \cdot \text{s}}{\text{l}} \cdot \dot{V}_B + 600,000 \text{ €} \cdot b_{GP} \quad A6$$

For the ORC plant and the grid connection, a linear cost function C_6 is assumed according to the values from Jancik & Kupfermann (2014), Campos Rodríguez et al. (2013) and Rubio-Maya et al. (2016):

$$C_6 = 2,470 \frac{\text{€}}{\text{kW}_{\text{el}}} \cdot P_{el,max} + 14,100 \text{ €} \cdot b_{PP} \quad A7$$

The costs for project management, control and finance planning as well as other capital-related costs such as insurance, seismic monitoring and public relations C_8 are determined according to the following equation (Schlagermann 2014):

$$C_8 = 0.08 \cdot (C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7) + 0.035 \cdot C_3 + 0.005 \cdot (C_4 + C_5 + C_6 + C_7) + 650,000 \text{ €} \cdot b_{GP} \quad A8$$

A4.1. Total investment in model and reality

The total investment is determined for comparison with the real investments for the projects in Table A2. Since the costs for district heating depend on the population density and thus on the individual case of consideration, an equation is derived from (Jancik & Kupfermann 2014) for the calculation of the total investment in Table A2:

$$f(\dot{Q}_{th,max}) = 815 \text{ €}/\text{kW}_{th} \cdot \dot{Q}_{th,max} - 130,000 \text{ €} \quad A9$$

The more accurate investment calculation for the district heating plant from section 3.4.2 cannot be used in this comparison but is used in the optimisations. The total investment was determined only for those geothermal plants for which sufficient information was available. By comparing the total investment calculated in the model and in reality, it is noticeable that the total investment is usually overestimated in the model (40% on average). However, a RMSE of 22 M€ is achieved (cf. Figure A3). This conservative assessment is taken over for the optimisation.

A4.2. Demand-related costs, operating costs and other variable costs

The yearly costs for working fluid and other demand-related resources C_{DR} are applied in accordance with Schlagermann (2014):

$$C_{DR}(a) = 0.01 \cdot (C_4 + C_5 + C_6 + C_7 + 150,000 \text{ €} \cdot b_{GP}) \quad A10$$

The operating costs include yearly labour costs C_L , which are calculated as a function of the thermal output of the thermal water mass flow (Eyerer et al. 2017):

$$C_L(a) = 220,000 \cdot e^{5 \cdot 10^{-6} \cdot \dot{V}_B \cdot \rho_w \cdot c_{p,w} (T_{PW,max} - T_{DHP,return})} \quad A11$$

This equation has to be linearised. However, since it depends on the temperature of the water in the production well $T_{PW,max}$ and the injection temperature T_{IW} , a value must be set for T_{IW} . Since the influence of the injection temperature on the costs is not high, 65°C is set as an estimate for the safe side. This results in the following equation for labour costs:

$$C_L(a) = 380 \text{ €}/^\circ\text{C} \cdot T_{PW,max} + 205,500 \text{ €} \cdot b_{GP} \quad A12$$

Other operating costs C_{OP} include costs for remote monitoring and operation of seismic monitoring as well as maintenance and repair costs and other variable costs C_{OV} include costs for insurance and legal assistance:

$$C_{OP}(a) = 61,000 \text{ €} \cdot b_{GP} + 1.25 \cdot 0.005 \cdot C_D + 0.03 \cdot (C_4 + C_5 + C_6 + C_7) \quad A13$$

$$C_{OV}(a) = 0.006 \cdot (C_4 + C_5 + C_6 + C_7) + 115,900 \text{ €} \cdot b_{GP} \quad A14$$