Energy system analysis of energy autonomous municipalities

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Vorwort

Diese Dissertation ist zwischen September 2016 und Juli 2020 während meiner Arbeit am Lehrstuhl für Energiewirtschaft (Institut für Industriebetriebslehre und Industrielle Produktion (IIP) des Karlsruher Instituts für Technologie) entstanden Während dieser Zeit habe ich Unterstützung von vielen Seiten erhalten, für die ich mich an dieser Stelle herzlich bedanken möchte.

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Abstract

Attention on decentralised autonomous energy systems has increased exponentially in the past three decades, as demonstrated by the absolute number of real-world projects and the share of publications in the corpus of scientific literature. This is due to the energy transition and the related environmental awareness as well as the desire of citizens to play an active role in energy supply and to be less dependent on central markets and structures. However, local decision-makers, who often lack the necessary expertise, need decision support in energy system planning. To this end, this thesis follows the objective to develop novel methods for the technical, economic and environmental assessment of a large number of completely energy autonomous municipalities and their impacts on the overall energy system. Completely energy autonomous municipalities are disconnected from the gas and electricity grid and supply themselves with energy from plants owned and operated by the municipality.

Novel methods of energy system analysis were developed in this thesis as part of seven original research articles. Germany is used as a case study, but the general approach, methods and results are transferable to other contexts. First of all, the 11,131 German municipalities were clustered with regard to their suitability for decentralised energy systems. Based on this municipality typology, representative municipalities were selected to be investigated in an already existing holistic municipal energy system optimisation model (RE³ASON). This model was extended by novel and transferable approaches to design deep geothermal plants and district heating networks. These base-load capable technologies were selected to reduce the storage costs in energy autonomous municipalities. The technical feasibility and economic expenditures of energy autonomy could finally be determined in all 11,131 German municipalities by combining the extended energy system optimisation model with a stepwise linear regression.

The energy system optimisations showed that in the case of complete energy autonomy, deep geothermal plants in combination with district heating networks could reduce the total costs by up to 50%. On average, the energy system costs until 2030 in German municipalities increase by about 0.41 €/kWh in the energy autonomous case compared to the optimised reference case with grid connection. While a technical potential to achieve energy autonomy is present in 56% of the German municipalities, there seem to be no economic advantages through energy autonomy compared to the optimised reference energy system. The novel methodological approach of this thesis enabled to obtain optimisation results for a high number of energy systems (6,314 municipalities) with practicable computational expenses. In addition to the original data and planning tools published alongside the articles, the findings of this thesis can also support local decision makers in determining suitable municipal energy systems.

In order to increase the realizability of the case study results, some methodological extensions should be investigated in future studies such as other perspectives than that of a central planner, higher temporal model resolutions or social aspects like consumer acceptance of specific technologies or a security of supply below 100%.

List of appended papers

1) Weinand, J. M.; Scheller, F.; McKenna, R. (2020b): Reviewing energy system modelling of decentralized energy autonomy. In *Energy* 203, 117817. DOI: 10.1016/j.energy.2020.117817. © 2020 Elsevier. Reprinted with permission.

2) Weinand, J. M.; McKenna, R.; Fichtner, W. (2019a): Developing a municipality typology for modelling decentralised energy systems. In *Utilities Policy* 57, pp. 75–96. DOI: 10.1016/j.jup.2019.02.003. © 2019 Elsevier. Reprinted with permission.

3) Weinand, J. M.; McKenna, R.; Mainzer, K. (2019b): Spatial high-resolution socio-energetic data for municipal energy system analyses. In *Scientific data* 6 (1), 243. DOI: 10.1038/s41597-019-0233-0.

4) Weinand, J. M.; McKenna, R.; Karner, K.; Braun, L.; Herbes, C. (2019c): Assessing the potential contribution of excess heat from biogas plants towards decarbonising residential heating. In *Journal of Cleaner Production* 238, 117756. DOI: 10.1016/j.jclepro.2019.117756. © 2019 Elsevier. Reprinted with permission.

5) Weinand, J. M.; Kleinebrahm, M.; McKenna, R.; Mainzer, K.; Fichtner, W. (2019d): Developing a combinatorial optimisation approach to design district heating networks based on deep geothermal energy. In *Applied Energy* 251, 113367. DOI: 10.1016/j.apenergy.2019.113367. © 2019 Elsevier. Reprinted with permission.

6) Weinand, J. M.; McKenna, R.; Kleinebrahm, M.; Mainzer, K. (2019e): Assessing the contribution of simultaneous heat and power generation from geothermal plants in off-grid municipalities. In *Applied Energy* 255, 113824. DOI: 10.1016/j.apenergy.2019.113824. © 2019 Elsevier. Reprinted with permission.

7) Weinand, J. M.; Ried, S.; Kleinebrahm, M.; McKenna, R.; Fichtner, W. (2020a): Identification of Potential Off-Grid Municipalities with 100% Renewable Energy Supply. In *Working Paper Series in Production and Energy*. DOI: 10.5445/IR/1000118013.

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Part A: Overview

1. Introduction

In 2015, 197 countries agreed on the Paris Climate Convention, which includes limiting global warming to below 2 °C and reducing greenhouse gas emissions (BMWi 2019a). Germany, which is examined as case study in this thesis, aims to reduce its greenhouse gas emissions until 2050 by at least 80% below the 1990 level (BMWi 2019b). To achieve this objective, a decarbonisation of the energy sector is necessary, since this sector is responsible for about 80% of the greenhouse gas emissions (eurostat 2020). Increasing the share of low-emission renewable energy in the energy mix and increasing energy efficiency would contribute to this decarbonisation. In fact, the share of renewable energies in Germany has increased steadily in the past years: in 2019, renewable energies already accounted for 17.1% of gross energy consumption in Germany (UBA 2020). This expansion of renewable energy sources is mainly decentralised due to their characteristics. Thus, about 95% of the installed capacity of renewable energy plants in Germany are connected to the distribution grid (BDEW 2017) and the owner structure of energy plants in Germany has changed (trend:research 2017): the majority of renewable energy plants are actually owned and operated by private individuals, farmers and communities.

In this context of local renewable energy expansion, the concept of energy autonomy (cf. section 2) has become established especially for municipalities (McKenna et al. 2015; Rae and Bradley 2012). Many municipalities claim energy autonomy as their central motivation for investing in local renewable energies (McKenna 2018). Section 2 divides energy autonomy into balanced energy autonomy (i.e. annual energy supply by local renewable energy plants is at least as high as local demand) and complete energy autonomy (i.e. disconnection from the gas and electricity grid). Due to the possible impacts of balanced autonomous municipalities on the energy sector mentioned in section 2, the present thesis focuses on complete municipal energy autonomy, as this state could be more advantageous for the national energy system. Furthermore, in contrast to balanced energy autonomy, this state is less dependent on political framework conditions and thus more generally applicable conclusions can be drawn. In addition, novel methodological developments on this topic are also relevant for many other applications, for example in case studies of islands or communities that are not connected to the national transmission grid.

The associated questions to be answered in this thesis would include for which German municipalities complete energy autonomous systems would make economic sense and what the consequences would be for the overarching, mainly centralised energy system. For example, the necessary expansion of the transmission grid could be reduced by many completely energy autonomous municipalities. To analyse this in detail, it would first be necessary to examine the energy systems of a large number (> 1,000) of German municipalities, in order to identify municipalities in which complete energy autonomy based on renewable energies is feasible from a techno-economic perspective. To meet this central objective, it is necessary to develop an approach that allows to analyse a multitude of energy systems with practicable computational expenses. First of all, therefore, a typology of the energy systems to be investigated is needed. Subsequently, selected energy systems that represent this typology have to be optimised from a techno-economic perspective. In the final step, the results of the optimisations must then be transferred to all energy systems. This approach is generally transferable to other case studies, in the case of this thesis it is applied to energy system analyses of completely autonomous municipalities. Thereby, this thesis also addresses the following research questions:

1) What must be improved in energy system analyses of autonomous systems (Weinand et al. 2020b)?
2) How can municipalities be grouped using socio-energetic indicators for the purposes of energy system analysis (Weinand et al. 2019a; 2019b)?
3) How do additional measures such as exploitation of excess heat potentials of the German biogas stock or technologies like district heating and base-load capable deep geothermal energy affect the technical feasibility and economic expenditure for municipal energy autonomy (Weinand et al. 2019c; 2019d; 2019e)?
4) In which municipalities is complete energy autonomy of all consumption sectors (industry, commercial, residential and private transport) technically feasible, and what are the associated costs of each of these municipal energy systems (Weinand et al. 2020a)?

In this thesis, novel methods for techno-economic energy system analysis are developed. The generated planning tools and planning knowledge on municipal energy system analysis can support local planners and decision makers in the design of municipal energy systems. Especially the typically smaller municipalities striving for energy autonomy require support in energy system analyses due to a lack of expertise and resources. In a first step, data on the 11,131 German municipalities are generated and compiled in order to cluster the municipalities with regard to their suitability for decentralised energy systems (Weinand et al. 2019a; 2019b). In addition, a generic model is developed to determine the potential of deep geothermal energy in arbitrary municipalities and to represent the economic and technical restrictions of this technology in an optimisation model (Weinand et al. 2019e). In connection with this, an approach based on combinatorial optimisation is developed for the design of district heating networks in municipalities in order to use the heat from deep geothermal plants in heating networks (Weinand et al. 2019c; 2019d). The combination of the latter two approaches opens the possibility to investigate the heat and electricity side of a deep geothermal plant in an optimisation model for the first time (Weinand et al. 2019e). Furthermore, an existing holistic municipal energy system optimisation model is extended by the above mentioned technologies as well as the consumption sectors industry, commerce, and private transport in the form of electric vehicles to investigate the technical feasibility and economic expenditures of a multitude of energy autonomous German municipalities (Weinand et al. 2020a). The additional consideration of heat grid infrastructure and alternative technologies such as deep geothermal energy provides local decision makers a comprehensive picture of the available resources at their disposal and their economic and technical impacts. Thereby it is important, that the approaches of energy system optimisation in this thesis are all automatically applicable to arbitrary German municipalities in order to be able to analyse a large number of municipalities. The results of the thesis are then to be applied, among other things, to examine scenarios with many energy autonomous municipalities in future national energy system designs and transmission network analyses. Although Germany is used as a case study in the present thesis, the approach and the newly developed methods are also suitable to be transferred to other contexts and countries with similar data availability.

This framework chapter is structured as follows. First, the concept, motives and consequences of energy autonomy are presented in the following section 2. The literature review in section 3 then shows the evolution of the research area of energy autonomy as well as research gaps filled by this thesis. Subsequently, in section 4 the methods of seven studies conducted for this thesis (Weinand et al. 2019a; 2019b; 2019c; 2019d; 2019e; 2020a; 2020b) are summarised before the results of these studies are presented in section 5. Section 6 then shows potential for improvement and possible future research projects. Finally, the thesis is summarised in section 7 and the most important findings are demonstrated.

2. Background on energy autonomy

In the growing body of literature on energy autonomy (cf. section 3), different terms are used to describe this concept: energy autarky (Müller et al. 2011), self-sufficiency (Engelken et al. 2016) or off-grid energy systems (Chmiel and Bhattacharyya 2015) are just a few of those terms. This number of terms alone illustrates the diversity within the literature, which also extends to its definition. Three rough distinctions can be made between complete energy autonomy (i.e. off-grid), balanced energy autonomy and a tendency towards higher energy autonomy through decentralised renewables (McKenna et al. 2015). Whereas in the case of complete energy autonomy no energy imports are permitted, in the case of balanced energy autonomy only the annual energy supply by local energy plants must exceed the annual demand. For the latter, energy imports are therefore permitted to compensate for supply gaps (McKenna et al. 2015).

In particular, autonomous energy systems need to exhibit the basic criteria defined by Rae and Bradley (2012). First, the local system is able to generate at least enough energy to meet the demand. Second, the local system allows energy shifting possibilities for times in which there is a temporal mismatch between demand and supply (i.e. through storage or in the case of balanced autonomy through energy infrastructure). Third, the system is capable of operating independently on a stand-alone or off-grid basis. Thereby, local autonomy efforts are related to active participation of the community or rather the system components are owned by the community members. In general, autonomy efforts are directly related to the notion of self-governance and community ownership (Rae and Bradley 2012). These previously mentioned definitions also apply to this thesis. Figure 1 shows a schematic representation of decentralised (autonomous) energy systems.

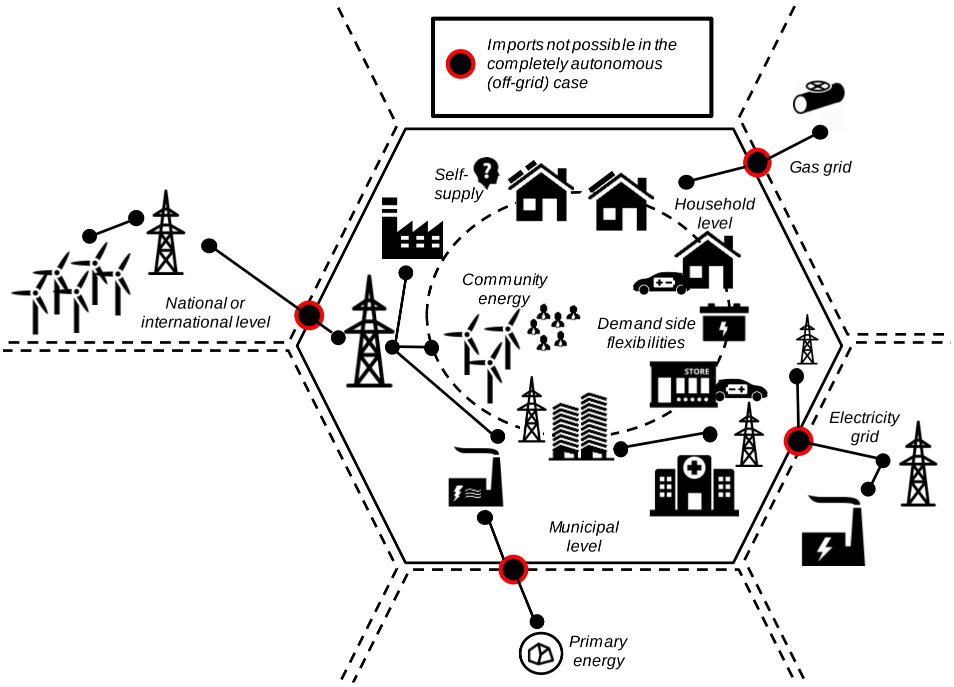

Figure 1: Schematic representation of a decentralised energy system (Weinand et al. 2020b). In contrast to the completely energy autonomous case (off-grid), imports from the national level are permitted in the case of balanced energy autonomy.

Whereas these autonomous energy systems exist in developing countries mainly due to cost considerations, there are also efforts by municipalities and regions to become energy autonomous in industrialized countries with complete electrification like Germany (Weinand et al. 2020b). This is due to the energy transition and the related environmental awareness (Engelken et al. 2016) as well as the desire of citizens to play an active role in energy supply and to be less dependent on central markets and structures (Boon and Dieperink 2014). The majority of municipalities with energy autonomy aspirations in Germany strive for balanced energy autonomy and the focus is usually on electrical energy (Engelken et al. 2016). An analysis of the German energy project "100%-Renewable-Energy-Communities", in which the participating municipalities strive for energy autonomy, confirms these findings of Engelken et al. (2016). According to Figure 2, the number of municipalities in this project has increased exponentially since 1995. In 2016, the 1,300 municipalities corresponded to 12% of all municipalities in Germany and account for 15% of the population (Weinand et al. 2019e).

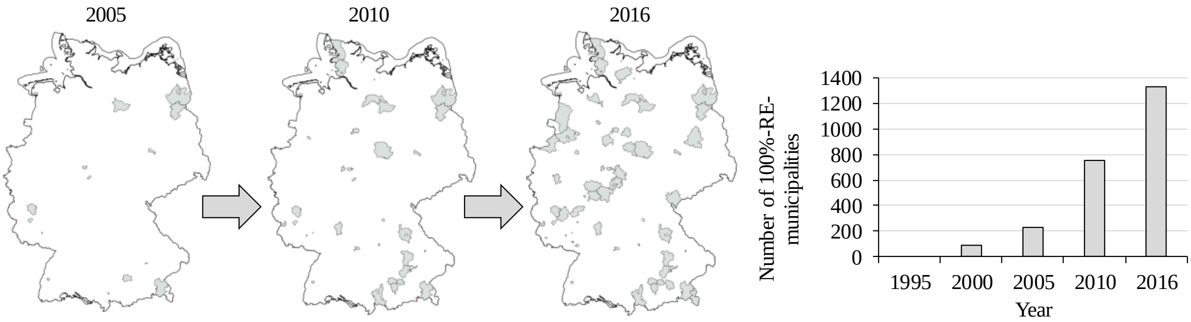

Figure 2: Development of the number of 100%-Renewable-Energy-Communities in Germany since 1995. The grey areas in the maps show the municipalities.

Thus, as described above, a large number of German municipalities are striving for an autonomous energy system. Municipalities that become balanced energy autonomous would utilize the electricity network structure more than traditional consumers. Due to the volatile generation characteristics of renewable energy plants (such as wind and solar), large parts of the electricity generated would have to be fed into the national grid. On the one hand, the municipalities would benefit from the grid feed-in of surplus electricity. On the other hand, the municipalities would make a much lower contribution to the costs of this infrastructure, currently charged per unit of electricity used, due to lower export amounts (McKenna 2018). As a result, economic inefficiencies compared to the established system of centralised generation, transmission and distribution could emerge (Jägemann et al. 2013). Furthermore, the large expansion of renewable energies in the municipalities could make the expansion of the German electricity grid structures even more essential, as it would require the physical integration of the large amount of volatile renewable electricity (i.e. for power transports, Schaber et al. 2012). Alternatively, a nationally or even internationally coordinated expansion of renewable energies could limit the expansion of the electricity grid and the associated costs to a necessary extent. Based on these considerations, the question arises whether the development towards balanced autonomous municipalities will continue at all. Otherwise, a change in political framework conditions (e.g. adjusted subsidy mechanisms / distribution of network fees) could bring this development to a halt.

3. Literature review on municipal energy autonomy[1]

In the context of the decentralised expansion of renewable energies, the number of scientific publications on the topic of municipal energy system analysis is also increasing. The share of these municipal energy system analyses in all publications on energy system analyses has increased from 8% to 20% between 1990 and 2019. Similarly, the share of articles on energy autonomy (cf. dark curve in Figure 3) in publications on municipal energy system analyses (cf. bright curve in Figure 3) has increased from 0% to 15% between 1990 and 2019. Thereby the number of publications has increased exponentially in recent years (cf. Figure 3). Municipal energy system analyses in general and with a focus on energy autonomy are therefore becoming increasingly relevant, as well as the implementation of projects (see municipal energy autonomy projects in section 2). Therefore, this section is intended to provide an overview of the studies on municipal energy autonomy and to highlight research gaps which are addressed by the present thesis. Thereby, this section serves to show the novelty of this thesis as a whole. Further information can be found in the literature reviews of the individual articles (Weinand et al. 2019a; 2019b; 2019c; 2019d; 2019e; 2020a; 2020b).

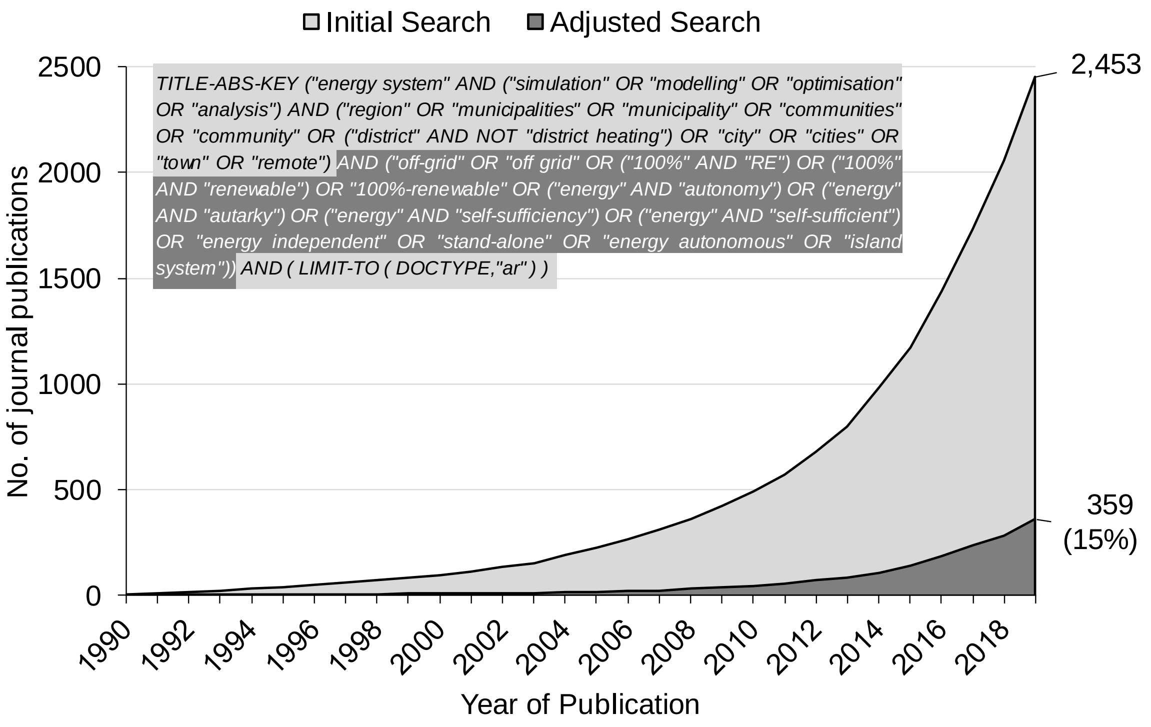

Figure 3: Development of the number of journal publications for two search queries in Scopus (Weinand et al. 2020b). The bright curve contains the publications on energy system analyses at the local level. For the dark curve, the search query has been adjusted so that the studies also deal with autonomous energy systems. The search in Scopus was performed on November 20, 2019.

This literature review is largely based on the review study Weinand et al. (2020b). However, not all 123 discussed articles can be addressed at this point. Therefore, the most relevant results of the review study

[1] This literature review is largely based on the review study Weinand et al. (2020b).

as well as selected articles (cf. Table 1) are shown in this section. Peter (2013), Scheffer (2008) and Woyke and Forero (2014), which are not English language journal articles, have been added because they deal with energy autonomy in German municipalities and are therefore particularly interesting for this thesis. The criteria in Table 1 will be explained column by column in the following paragraphs.

The methods for investigating municipal energy autonomy range from simple energy balancing calculations (e.g. Chmiel and Bhattacharyya (2015) or Jenssen et al. (2014)) to linear optimisation (e.g. the present thesis, Alhamwi et al. (2019) or Šare et al. (2015)), multi-objective optimisation (e.g. Sameti and Haghighat (2018)) or multi-criteria decision analysis (MCDA, e.g. McKenna et al. (2018)). As is generally the case for energy system analyses, a compromise between scope and level of detail is necessary in order to be able to perform the optimisations at all or at least within a reasonable time. For example, Schmidt et al. (2012) and Sameti and Haghighat (2018), which both apply complex methods, use only two or eighteen hourly time slices for their calculations to obtain results for an entire year. Schmidt et al. (2012) compare energy autonomy with conventional energy supply in Sauwald, a rural region with 21,000 inhabitants in Austria. In order to include land use competition in energy system optimisation, this study combines the energy system model BeWhere with the land use optimisation model PASMA. In Sameti and Haghighat (2018), a net-zero energy district is investigated in three scenarios with grid connection and one as a stand-alone variant without grid connection. The district is examined with a bottom-up method, i.e. individual buildings and streets of the district are part of the analysis.

In most studies, only scheduling of the energy system technologies is considered. In such cases, long-term energy system planning is not really beneficial, since no investment decisions can be made. Instead, studies with investment decisions should always have a long-term planning horizon in order to consider possible future investments. These investments may be influenced by price developments or existing technologies such as already installed photovoltaic modules which have to be decommissioned in the future. Municipal energy autonomy studies that model these long-term investment decisions are the present thesis and McKenna et al. (2018). The study of McKenna et al. (2018) includes a participatory approach to developing feasible energy concepts for small municipalities. Thereby, for determining the optimal energy system in the case study municipality of Ebhausen, a linear optimisation is combined with a MCDA.

Furthermore, grid infrastructures are only marginally considered in municipal energy system analyses or local energy autonomy studies. In the FlexiGIS model in Alhamwi et al. (2019), OpenStreetMap is used to obtain data on lines and substations of the distribution network in order to determine the optimal placement of a battery storage in an urban area. Unfortunately, power grid data is not yet completely included in OpenStreetMap and therefore this method is only usable for very few case studies. In McKenna et al. (2018) the grid infrastructures are at least indirectly considered through network flows between various districts of a municipality. In Sameti and Haghighat (2018), designing of district heating networks in a city district is included. An approach for the design of district heating networks was also developed in the present thesis (cf. section 4.2). It differs from the bottom-up approach of Sameti and Haghighat (2018) by designing the district heating network for an entire municipality (top-down) and at the same time optimising the location of the district heating plant. Furthermore, this approach is automatically transferable and applicable for each (German) municipality. The reason for the consideration of district heating in this thesis is shown in the next paragraph. However, as an emerging technology, district heating is also the most emerging technology in terms of research on energy system planning at the municipal level (Weinand 2020).

In order to cover the demand of a municipality without imports, either storage systems to flexibly use the fluctuating renewable energies, or base-load capable technologies are needed. Many studies come to the conclusion that energy autonomy is associated with very high costs. For example in Scheffer (2008), high investments are necessary for balanced energy autonomy in a rural model region with 10,000 inhabitants. Storable biomass is highlighted as the most important energy source for achieving autonomy. However, the agricultural land is not sufficient for an additional use of biomass as transport fuel. Jenssen et al. (2014) also come to this latter conclusion in their case study of an "average" German municipality. In addition, they show, that complete energy autonomy is technically achievable through the "Bioenergy Village" approach, albeit at high cost. Peter (2013) demonstrates that fluctuating renewable energies (PV, wind and solar thermal energy) could cover the electricity demand of an "example village" with 3,850 inhabitants but with tremendous storage costs. The author therefore concludes that base-load-capable technologies such as biomass, hydropower or deep geothermal energy should be included in energy system planning of autonomous municipalities. According to Schmidt et al. (2012), energy autonomy implies a decline in local production of food and feed as well as high costs for consumers. 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, is assessed in Woyke & Forero (2014). Due to grid restrictions, complete energy autonomy is not feasible with the current energy system in Pellworm. Furthermore, the case study in Alhamwi et al. (2019) on Oldenburg, a German city with 165,000 inhabitants, shows that complete energy autonomy in a city of this size is technically and economically not practicable. These examples have led to the consideration of further technologies in this thesis, which could possibly lead to the technical feasibility and cost reduction of autonomous municipal energy systems. In this context, deep geothermal energy was identified as a potentially advantageous technology, as it is base load capable and has a high and widespread potential in Germany (Eyerer et al. 2020). In order to utilise the geothermal heat not only for electricity generation but also as a heating technology, an approach for the design of district heating networks in municipalities had to be developed in this thesis, as already indicated above.

More and more studies emphasize the importance of planning the siting of renewable energy plants together with the expansion of the transmission network (e.g. Neumann and Brown (2019)). For this purpose, future scenarios are often designed on the development of the share of renewable energies in different regions. However, the simultaneous impact of potential completely energy autonomous municipalities on transmission grid planning has not yet been addressed. In general, studies on municipal energy autonomy have not yet examined any influences on the surrounding (national) energy system. The present thesis provides a starting point for this, by determining the technical feasibility and economic expenditures for complete energy autonomy in all 11,131 German municipalities (cf. section 5.5). As discussed in the outlook in section 7, (extreme) scenarios for future energy system analyses or transmission grid planning at the national level with many energy autonomous municipalities can be derived from this.

In addition to the above-mentioned novel methods and applications, such as the additional consideration of heat grid infrastructure and alternative technologies, this thesis presents a novel and transferable methodology to investigate a large number of municipalities with practical computational expenses (cf. section 4). This is a major improvement to the literature on decentralized energy autonomous energy systems, in which only individual energy systems have been investigated as case studies so far (Weinand et al. 2020b).

Table 1: Overview of the most relevant studies for this thesis from Weinand et al. (2020b) (B = energy balancing, LP = linear programming, MILP = mixed-integer linear programming, MCDA = multi-criteria decision analysis, MH = metaheuristics, MO = multi-objective, S = scheduling, I = investment planning, EN = electricity network, HN = heat / gas network, F = fluctuating, BLC = base load capable)

Study	***Method***	***Planning type***	***Transition pathway***	***Network infra-structures***	***Techno-logies***	***System impacts***	***Transfer-ability***
Alhamwi et al. (2019)	LP	S, I	overnight	EN	F, BLC	✕	(✓)
Azaza and Wallin (2017)	MO, MH	S, I	overnight	✕	F, BLC	✕	✕
Bonati et al. (2019)	MILP	S	overnight	✕	F, BLC	✕	✕
Chmiel and Bhattacharyya (2015)	B	S	overnight	✕	F, BLC	✕	✕
Dorotić et al. (2019)	MILP	S	long-term	✕	F	✕	✕
Drysdale et al. (2019)	MILP	S	long-term	✕	F, BLC	✕	✕
Jenssen et al. (2014)	B	-	overnight	✕	BLC	✕	✕
Kötter et al. (2016)	MILP	S, I	overnight	✕	F, BLC	✕	✕
Krajačić et al. (2009)	B	-	long-term	✕	F	✕	✕
McKenna et al. (2018)	MILP & MCDA	S, I	long-term	(EN), (HN)	F, BLC	✕	✓
Oldenbroek et al. (2017)	B	-	overnight	✕	F	✕	✕
Østergaard and Lund (2011)	MILP	S	overnight	✕	F, BLC	✕	✕
Peter (2013)	B	-	overnight	✕	F	✕	✕
Peura et al. (2018)	B	-	overnight	✕	F, BLC	✕	✕
Sameti and Haghighat (2018)	MO, MILP	S, I	overnight	HN	F, BLC	✕	✕
Šare et al. (2015)	MILP	S	overnight	✕	F	✕	✕
Scheffer (2008)	B	-	overnight	✕	F, BLC	✕	✕
Schmidt et al. (2012)	MILP	S, I	overnight	✕	F, BLC	✕	✕
Woyke and Forero (2014)	B	-	overnight	✕	F, BLC	✕	✕
This thesis	**MILP**	**S, I**	**long-term**	**(EN), HN**	**F, BLC**	**(✓)**	**✓**

4. Methodology

The frame of the thesis is the comprehensive literature review study Weinand et al. (2020b), which was already presented in part in section 3 and also includes large parts of the critical appraisal in section 6. The other six studies (Weinand et al. 2019a; 2019b; 2019c; 2019d; 2019e; 2020a) comprise the methodology of the present thesis, which can be divided into three parts (cf. Figure 4) and is explained in the following subsections. First of all, in order to investigate a large number of energy systems, a typology of these energy systems was needed. For this purpose, a municipality typology of the 11,131 German municipalities was developed to show the general suitability of municipalities for decentralised energy systems (cf. section 4.1). Subsequently, selected energy systems that represent this typology had to be optimised. Therefore, novel approaches were developed for estimating the potential and costs for deep geothermal plants and district heating networks (cf. section 4.2) as well as for implementing these technologies in a holistic optimisation model of a municipal energy system. The energy system optimisations as well as the necessary extensions of the optimisation model are explained in section 4.3. In the third step, the results of the optimisations were transferred to all German municipalities (cf. section 4.3.2). This overall approach (cf. Figure 4) is generally transferable to other case studies, in this thesis it is applied to energy system analyses of completely autonomous municipalities. The novelties of the individual articles and the methods developed in connection therewith are summarised in Table 2.

4.1. Municipality typology

A central challenge in energy modelling is to make compromises between model resolution, scope and computational feasibility. As already described in sections 1 and 3, the potential for energy autonomy should be determined in all German municipalities in this thesis. A detailed examination of all 11,131 German municipalities is not feasible in a reasonable amount of time. Weinand et al. (2019a) make a significant contribution to complexity reduction by clustering all 11,131 German municipalities using 34 pre-identified socio-energetic indicators. These indicators are mainly based on open data relating to the consumption sectors of Private Households and Transport, as well as indicators relating to the potentials for renewable energies. The method involves two main steps, namely a factor analysis and a cluster analysis. For the former, different methods are compared with each other, and the most effective methods for allocating the indicators to factors are chosen. Selected cluster validation methods are then used to determine an appropriate number of clusters to which the 11,131 municipalities are distributed.

The study not only applies cluster analysis to all 11,131 German municipalities for the first time, but also uses novel indicators to classify the municipalities. Therefore, many of the indicators, such as hydrothermal potential at 5000 m depth or wind energy potential, were determined at the municipal level. The potentials of renewable energies were assigned to the individual municipalities using the *Geographical Information System* (GIS) *QGIS*. Since this and the allocation of census data to the municipalities involved a great effort, the whole data set was published open access in Weinand et al. (2019b).

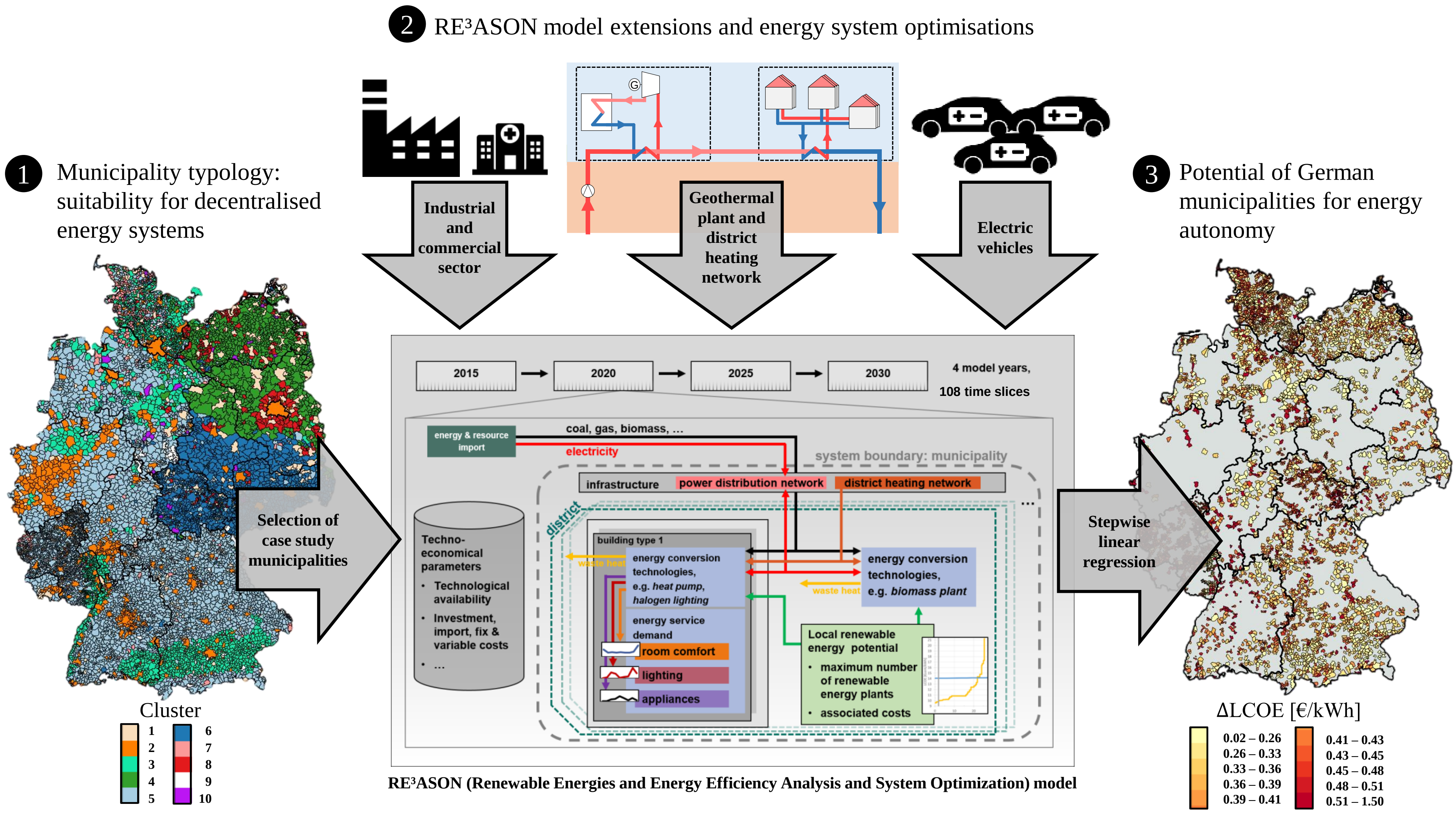

Figure 4: Overview of the novel methodological approach of this thesis, divided into three parts. Parts of the figure are from Weinand et al (2019a) and Weinand et al (2019e).

Table 2: Overview of the main novelties of each study of the present thesis.

Study	*Main novelties*	
	Methodological	*Application-related*
Weinand et al. (2019a)	1) Determination of wind potential and deep geothermal energy potential at the municipal level	1) Classification of all 11,131 German municipalities 2) Clustering with socio-energetic indicators
Weinand et al. (2019b)		1) Open access publication of the calculated and consolidated data from Weinand et al. (2019a), Mainzer et al. (2014) and McKenna et al. (2014)
Weinand et al. (2019c)	1) Combination of a survey on biogas plants excess heat fraction with a heuristic to connect heat sources (biogas plants) with heat sinks (settlements) 2) Determination of the heat demand of all 38,414 settlements in Germany 3) Heuristic to design up to 1.5 million district heating pipelines simultaneously	1) Case study in Germany to determine the potential of utilising excess heat of the 10,446 biogas plants in residential buildings 2) Determining contribution of biogas excess heat to energy autonomy in the 11,131 German municipalities
Weinand et al. (2019d)	1) Simultaneous optimisation of district heating network and location of district heating plant in municipalities 2) Combinatorial optimisation problem based on the theory of minimum spanning trees with several adjustments 3) Three-stage heuristic to make the problem feasible for large municipalities 4) Heuristic automatically applicable to arbitrary municipalities	1) District heating network based on deep geothermal energy 2) Application of the problem to several German municipalities
Weinand et al. (2019e)	1) Method to assess the hydrothermal potential in every German municipality 2) Generic approach for modelling deep geothermal plants 3) Integration of the geothermal plant model and the district heating design from Weinand et al. (2019d) in a holistic energy system optimisation model in order to simultaneously optimise heat and electricity generation	1) Application of the energy system model to several German municipalities 2) Determination of costs for achieving complete energy autonomy in the residential sector
Weinand et al. (2020a)	1) Modelling approach to consider the demand of commercial, industrial and personal transport sector in arbitrary municipalities 2) Combination of energy system optimisations and regression analyses to transfer results to other municipalities	1) Determination of the technical feasibility and economic expenditure for complete energy autonomy in all 11,131 German municipalities
Weinand et al. (2020b)		1) Comprehensive overview and quantitative analysis of applied methods in studies on decentralised energy autonomy 2) Compilation of costs for decentralised energy autonomy

4.2. Modelling of geothermal plants and district heating networks

Section 3 already demonstrated that many case studies on municipalities show a limited base load potential (e.g. land-use restrictions for biomass), which could lead to high costs for energy autonomy. Additional base load capable technologies like deep geothermal plants could therefore be an option to reduce these costs. Therefore, a novel generic optimisation model of a geothermal plant (cf. Figure 5) is developed in Weinand et al. (2019e), which for the first time simultaneously optimises the electricity (P_{el}) and heat ($\dot{Q}_{th}$) side of the the plant (cf. Eqs. 1-2).

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

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

with

$\dot{V}_B$	–	volumetric flow rate of the geothermal water
ρ_w	–	density of the geothermal water
$c_{p,w}$	–	heat capacity of the geothermal water
$T_{PW}(t)$	–	temperature of the geothermal water before utilisation in the electricity plant in time slice t
$T_{ORC,out}(t)$	–	temperature of the geothermal water after utilisation in the electricity plant in time slice t
$T_{DHP,return}(t)$	–	temperature of the geothermal water after utilisation in the heating network in time slice t
η_{el}	–	efficiency of the electricity generation
η_{th}	–	efficiency of the heat utilisation

The optimisation variables are shown in bold, the others are parameters. Variable drilling depths and thus geothermal water temperatures represent some of the novel modelling approaches. As input for the optimisation, a linear regression estimates the achievable geothermal water 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.

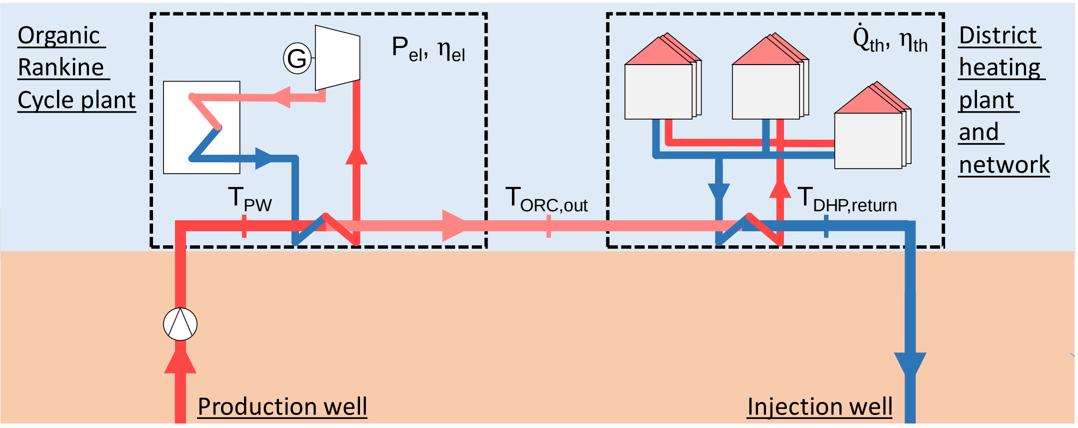

Figure 5: Schematic illustration of the geothermal plant considered in this study. The heat flow in the condenser of the Organic Rankine Cycle process could be water or air. Adapted figure from Weinand et al. (2019e).

Besides the Organic Rankine Cycle plant for electricity generation, district heating networks are necessary to utilise the heat from the deep geothermal plant within buildings. In addition, as already mentioned in section 3, district heating is one of the key research subjects in the field of municipal energy system planning. Therefore, approaches for district heating network modelling in municipalities were developed.

In a first study on district heating, the technical potential for utilising excess heat from biogas plants is analysed (Weinand et al. 2019c), in order to supply local settlements through district heating. Based on a survey of around 600 German biogas plant operators, the fractions of excess heat from the cogeneration unit in these plants have been analysed. The analysis was carried out for the surveyed population as well as scaled up to the whole German biogas plant stock. A heuristic was developed to connect biogas plants (heat sources) with local settlements (sinks) in order to determine a least-cost district heating supply for residential buildings. A heuristic is necessary since more complex methods like linear optimisations are hardly applicable for these problem sizes. In total, 10,446 biogas plants and 38,414 settlements were included and up to 1.5 million district heating pipelines could be designed simultaneously in the analysis for Germany. Thereby two criteria were employed, namely the CO_2 abatement costs and the payback period, which represent the macro- and microeconomic perspectives respectively. By taking these criteria into account and balancing heat supply and demand, the heuristic can cover different district heating network configurations (cf. Figure 6).

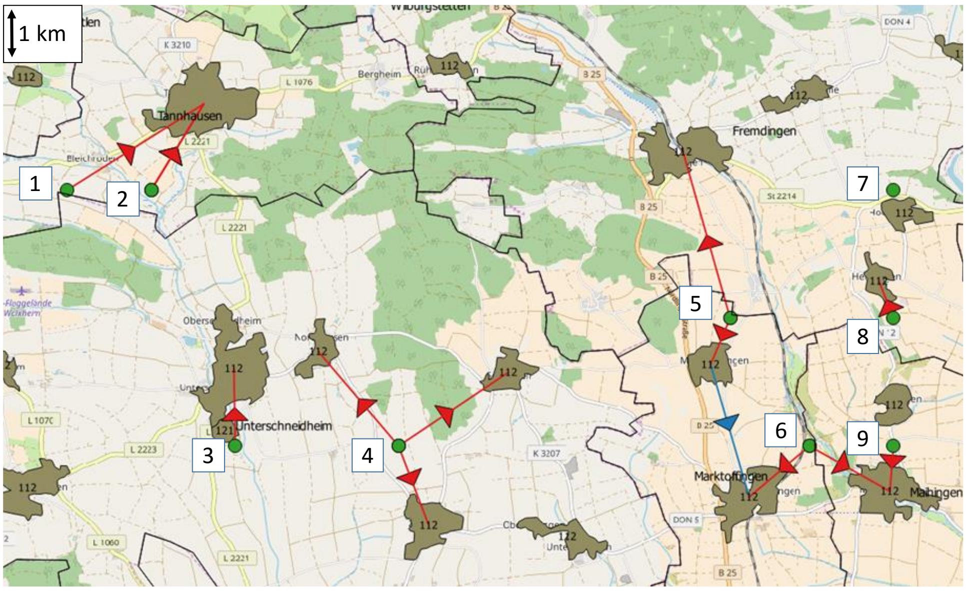

Figure 6: Exemplary illustration of district heating networks for the use of excess heat from biogas plants (green circles) in several municipalities in Baden-Württemberg (Weinand et al. 2019c). The red district heating pipelines lead from a biogas plant to a settlement area (brown shapes) and the blue ones lead from one settlement area to another. The black lines represent municipal borders[2].

[2] The background map is from OpenStreetMap Contributors (https://www.openstreetmap.org/).

Either settlements are supplied with heat by one biogas plant (biogas plants 3, 5, 8 in Figure 6) or several biogas plants (1, 2, 5, 6 and 9), or one biogas plant provides heat to several settlements (4, 5, 6), or the biogas plant does not supply heat to any settlement (7). This approach allows to determine the possible contribution of excess heat from biogas plants to the energy autonomy of German municipalities.

The algorithm from Weinand et al. (2019c) can only be used for existing district heating plants. However, for the use in a municipal energy system analysis, in which the location of a potential district heating plant has yet to be determined, the algorithm needs to be extended. This and further extensions of the algorithm are the subjects of Weinand et al. (2019d). Against the background of a trend towards decentralised and community-owned energy systems, the study developed a method to set up a minimum-cost geothermal-based municipal district heating system. To this end, two approaches based on combinatorial optimisation were presented, in order to support local planners in the design of geothermal district heating systems. The first approach involved a combinatorial optimisation of the district heating network layout, including geothermal plant location and network topology, which is only applicable to municipalities with less than eight discrete settlement areas due to its computational complexity. The second approach is a three-stage heuristic, which serves the same purpose but can be applied to a much larger number of municipalities with many more settlement areas. One of the innovations of the developed optimisation model and the three-stage heuristic compared to previous work is the fact that not only the district heating network but also the location of the district heating plant, is optimised. Thereby, the optimal location is selected from a discrete number of possible locations in the municipality (cf. Figure 7). Furthermore, the nodes / settlements to be connected are not fixed in advance and do not have to be supplied completely with heat.

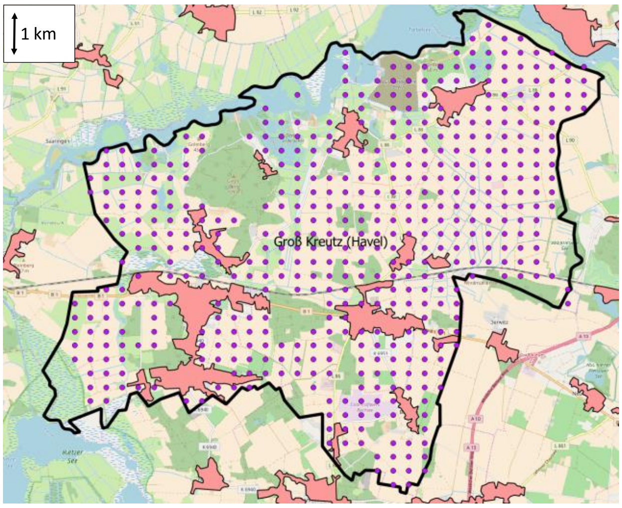

Figure 7: Possible locations (purple circles) for building the geothermal / district heating plant in the municipality Groß Kreutz (Weinand et al. 2019d). The pink areas are the settlements of the municipality. Inadmissible locations in forests, settlements and water areas are automatically excluded by the algorithm[2].

This approach for modelling deep geothermal plants and district heating networks presented in Weinand et al. (2019d) and Weinand et al. (2019e) can be applied to every municipality in Germany and the methodology could be extended to an arbitrary country with equivalent data. The 38 other European countries are particularly suitable for this extension due to the availability of *Corine Land Cover* data which is used to represent the settlement areas. Finally, the geothermal plant model as well as the district heating heuristic are implemented in a holistic energy system optimisation model (RE³ASON, cf. section 4.3.1)

4.3. Energy system optimisations

For the determination of the optimal municipal energy system designs in this doctoral thesis, the *Renewable Energies and Energy Efficiency Analysis and System OptimisatioN* (RE³ASON, Mainzer (2019)) model was used and further extended (cf. section 4.3.1). Since this model is applied in Weinand et al. (2019e) and Weinand et al. (2020a), section 4.3.1 first describes it alongside the extensions developed in this thesis. Subsequently, the method for transferring the model results to all German municipalities is explained in section 4.3.2.

4.3.1. Extension of energy system optimisation model RE³ASON

An overview of the two parts "input data determination" and "energy system optimisation" of the RE³ASON model are shown in Figure 8. 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 this high transferability, the model is applied in the present doctoral thesis, as many municipalities in different locations are investigated. RE³ASON further provides a deterministic model of optimal investment and dispatch for new energy conversion technologies at the municipality 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 are 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. A 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 this thesis, 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). The model can be used to minimise total discounted system costs, CO_2 emissions or energy imports of the municipal energy system. The RE³ASON model is only employed for minimising the total discounted system costs in this thesis, since complete renewable energy autonomy as a prerequisite simultaneously leads to a minimisation of the other two target criteria.

The RE³ASON model uses the macroeconomic perspective of central planners who develop concepts for the design of energy systems in municipalities. It takes into account all decision-relevant expenditures within the energy system, regardless of which actor is responsible for these expenditures. For example, the optimal investments of private households in new heating systems are determined from a system perspective without considering the economic viability of these investments from the perspective of the individual household. Within this macroeconomic perspective, taxes, subsidies and levies are considered as a redistribution of costs and are therefore not considered in the cost calculation. This means, for example, that the Renewable Energy Sources Act levy is not included in the electricity price for consumers, but at the same time the owners of renewable energy plants do not receive any feed-in remuneration for electricity generation. The reason for this approach is that the legislative situation, which showed frequent changes in the past, cannot be assumed to be constant over the comparatively long-term time horizon of the model. Furthermore, this allows a neutral comparison between individual technologies and measures. Regarding the prices of the energy sources, the model only takes into account the costs of procurement and distribution as well as grid fees (Mainzer 2019). Taxes and levies, which in 2019 accounted for about 52% of the household electricity price as well as about 26% of the natural gas price (Bundesnetzagentur 2019d), are also regarded as redistribution of costs and are therefore not considered in the economic evaluation (Mainzer 2019). For further information about the model including the calculation of renewable energy potentials and the mathematical model formulation the reader is referred to McKenna et al. (2018) and Mainzer (2019).

The RE³ASON model extensions shown in Figure 8 are explained in the specific studies of this thesis and the previous subsections. The extensions are implemented within the program environment of the existing RE³ASON model and comprise

1) the design of district heating networks (Weinand et al. (2019d), cf. section 4.2),
2) the implementation of potential determination and model equations for deep geothermal energy systems as well as the integration of extreme days (Weinand et al. (2019e), cf. section 4.2),
3) the modelling of the industrial and commercial sectors as well as the integration of electric vehicles (Weinand et al. 2020a, cf. section 4.3.2).

In addition, some yet unpublished extensions have been made:

1) Some errors in the old model version have been fixed (e.g. for PV potential determination).
2) Development of the possibility to determine the input data (e.g. renewable potentials) as well as to optimise the energy system for several municipalities simultaneously.

3) Integration of *Value of Lost Load*:

The *Value of Lost Load* (VoLL) addresses the economic consequences of power blackouts and the monetary evaluation of uninterruptedness of electricity supply. Various factors influence the level of VoLL: in industrial or commercial enterprises, for example, production holdups or restart times have an influence, whilst in the residential sector lost leisure time is a significant issue (Schröder and Kuckshinrichs 2015). Particularly in the case of energy autonomy, when the LCOEs increase sharply, the idea of dispensing with energy demand in order to save costs is imaginable. Therefore, the VoLL was implemented in the RE³ASON optimisation model version from Weinand et al. (2020a). The amount of energy demand that is dispensed with (*Lost of Load* (*LoL*)) in the respective sector *s* is limited by the energy demand *ED* in this sector in each time step *t* (cf. Eq. 3).

$$LoL_{s,t} \leq ED_{s,t} \qquad \forall\, t = 1, \dots, T;\ \forall s = [residential, commercial, industrial] \qquad 3$$

The VoLL are then used to assign costs to the LoL in the objective function. In line with CEPA (2018), the VoLL were set to 12.41 €/kWh for the residential sector, 12.34 €/kWh for the commercial sector and 1.81 €/kWh for the industrial sector.

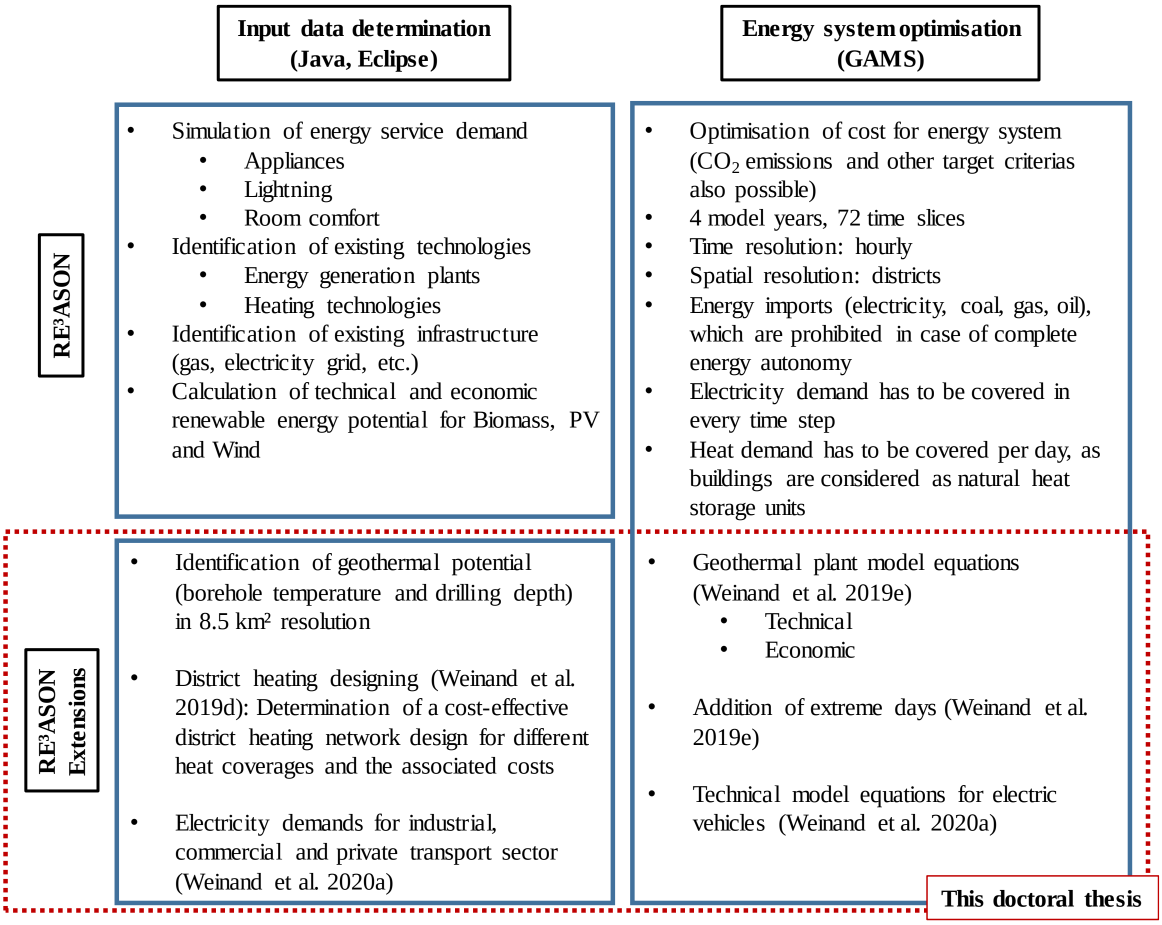

Figure 8: Overview of RE³ASON and the extensions developed in three of the seven studies of this doctoral thesis. Adapted figure from Weinand et al. (2019e).

4.3.2.Transfer of results

In Weinand et al. (2020a), a methodology is developed to determine the feasibility and costs for complete municipal energy autonomy of all consumption sectors. First, methods for estimating the energy demand and potential for renewable energies are proposed. On this basis, municipalities in which complete energy autonomy is not feasible can be excluded. Subsequently, the RE³ASON model is extended to include the industrial, commercial and personal transport sectors. Based on the municipality typology from Weinand et al (2019a), 15 representative municipalities are selected. The RE³ASON model is then applied to determine the cost-minimal energy system for these 15 preselected municipalities as case studies. On the one hand for the reference case without autonomy and on the other hand for the case with complete municipal energy autonomy. In the reference case, the energy system is optimised without restricting imports and exports. Afterwards, the Levelized Cost of Energy (LCOE) are calculated for both cases and all preselected municipalities (cf. Eq. 4, Grosspietsch et al. (2018)). Thereby the conversion factor for electricity into heat is assumed to be the heat pump`s coefficient of performance (3.5) as in Grosspietsch et al. (2018), since the heat load is taken into account for the residential sector.

$$LCOE = \frac{\sum_{y=1}^{Y} \frac{CAPEX_y + OPEX_y}{(1+r)^y}}{\sum_{y=1}^{Y} \frac{E_{m,total,y}}{(1+r)^y}} \qquad 4$$

The LCOEs are calculated depending on the investments (CAPEX), the operational and maintenance costs (OPEX), the total energy demand ($E_{m,total}$) and the year y. The interest rate r is assumed to be 5%.

A regression is used to transfer the results of the 15 case studies to the entire municipality population. The dependent variable is the difference between LCOEs in the autonomous and in the reference case (ΔLCOE). As independent variables the annual demand of each energy consumption sector of the municipalities and the indicators from the cluster analysis in Weinand et al. (2019a) are used. Those independent variables that correlate with other variables are eliminated. Therefore, for all correlations with an absolute value above 0.9 one variable is excluded.

To avoid an overfitting in the regression, a k-fold cross-validation is applied (Zhang and McCalley 2018). Since the sample is small (n = 15), the leave-one-out cross-validation is used, with k = n = 15. 19 different methods are applied, ranging from linear regression models and support vector machines to Gaussian Process Regression models. From these methods, the model that results in the lowest root mean squared error is selected.

5. Results

The subsections 5.1-5.5 summarise the results of the studies which have been conducted to fulfill the objectives of this doctoral thesis (Weinand et al. 2019a; 2019b; 2019c; 2019d; 2019e; 2020a; 2020b). These results were obtained by applying the methods explained in section 4. Since the next section 6 discusses the thesis in its entirety, the individual studies are only briefly critically assessed in sections 5.1-5.5. The validations and plausibility checks of the methods and results, which were performed in detail within the studies, are also only discussed in a few cases in this framework chapter (e.g. section 5.6). Besides the methodological innovations, Table 2 also provides an overview of the novel applications in all studies.

5.1. Municipality typology

The following results are from the studies Weinand et al. (2019a) and Weinand et al. (2019b) and based on the cluster analysis explained in section 4.1. With the help of the cluster validation methods (cf. section 4.1), an appropriate number of ten clusters could be determined, to which the 11,131 German municipalities are distributed (cf. Figure 9). Due to the high number and differentiation of indicators, clusters overlap with each other for different indicators, but the results also show significant differences between the clusters. Table 3 summarises these distinguishing characteristics for all clusters. For example, Cluster 2 contains all major German cities and most of the other cities in Germany and has a low potential for renewable energies. Cluster 9, on the other hand, describes all German municipalities without inhabitants.

Table 3: Summary of the distinguishing characteristics of the ten municipality clusters.

Cluster	***Number of municipalities***	***Characteristics***
1	339	Larger towns with highest share of district heating.
2	727	All major German cities with particularly low potential for renewables.
3	1638	Municipalities with highest hydrothermal potential, high income per household as well as low unemployment rate.
4	839	Municipalities with high hydrothermal potential, building age and unemployment rate.
5	5262	“Average” Cluster containing the majority of municipalities. Municipalities with high number of cars per 1,000 inhabitants and very low share of district heating.
6	1370	Municipalities with high building age and high proportion of people over 65 years of age.
7	460	Municipalities with lowest household density, highest number of cars and motor cycles per 1,000 inhabitants, largest share of detached houses and particularly high potential for renewables.
8	388	Municipalities with low building age, lowest proportion of people over 65 years of age and a high hydrothermal potential.
9	75	Rural municipality-free areas without inhabitants and lowest potential for renewables.
10	33	Smallest cluster containing municipalities with high population growth.

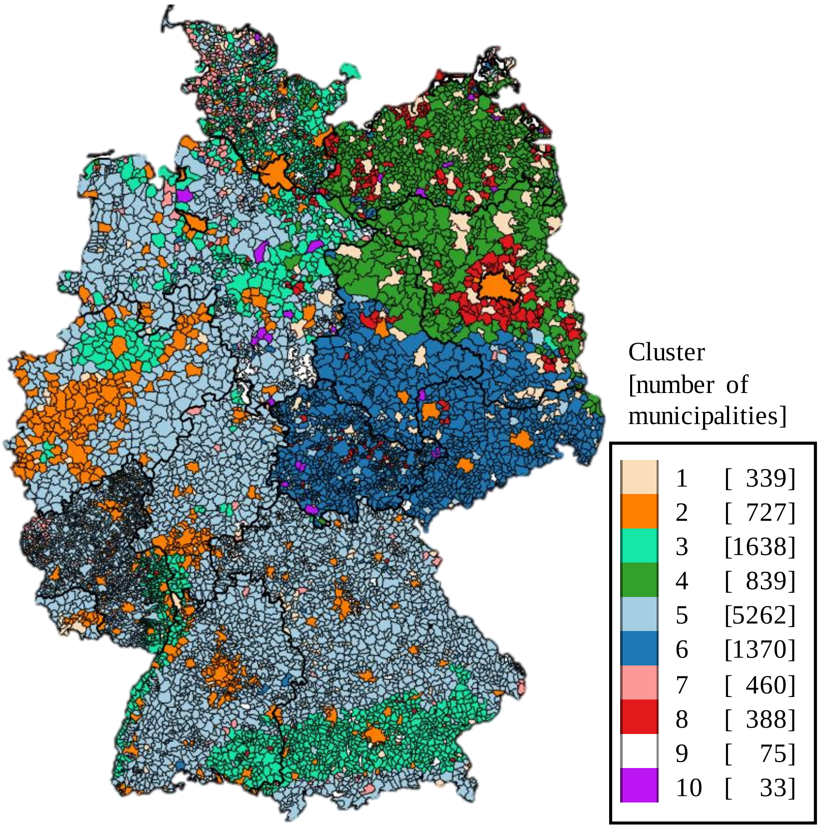

Figure 9: Illustration of all German municipalities with their allocation in the 10 cluster solution (Weinand et al. 2019a). The numbers of municipalities in the clusters are shown in parentheses.

Assigning the municipalities from the three German energy projects “Energy Municipalities”, ”Bioenergy Villages” and “100% Renewable Energy Regions” to the ten clusters shows that in eight of the ten clusters municipalities are aiming for energy autonomy (in varying degrees). As a result, it is not possible to differentiate between the clusters regarding readiness for such energy projects, which is most likely due to the influence of non-technical factors on the emergence of these initiatives. However, the results of the cluster analysis show that some of the municipalities could be technically more suitable for energy autonomy. For example, Clusters 3, 4, 7 and 8 are characterised by a high potential for renewable energies. The results reduce the effort of subsequent studies, as only a few municipalities from the clusters need to be examined regarding their suitability for energy autonomy to be able to make statements for all municipalities of the cluster. Thereby, the results help to identify municipalities in which already successful measures from other municipalities could be applied, and provide a basis for further energy analyses at the national level.

The methodology used in Weinand et al. (2019a) could be improved for more accurate results in future work. On the one hand, further indicators should be considered, including more indicators from the industrial and commercial sectors as well as indicators relating to the local climate. However, this is challenging due to the lack of available data at this spatial resolution. Furthermore, weights for the indicators could be determined with the help of expert interviews. If the indicators are known, which have the most considerable influence on the suitability for energy autonomy, these can be weighted more strongly in the cluster analysis and a new set of clusters generated based on these weights.

The collection and preparation of the data in Weinand et al. (2019a) involved a great effort. In addition, the field of energy system modelling is a science that is not yet fully transparent, as models and data are often not published in open access (Pfenninger 2017). To help overcome this hurdle, an open access data set including the 34 socio-energetic indicators from Weinand et al. (2019a) for all 11,131 German municipalities is provided alongside the Data Descriptor article Weinand et al. (2019b). Most of these indicators originate from the cluster analysis described above. In addition to census data such as population density, mobility data such as the number of vehicles and data on the potential of renewables such as wind energy are included. The data set can support in answering a wide range of energy-related research challenges. In a recently published handbook of the European Union (Siragusa et al. 2020), for example, the data set is recommended for reviewing local *Sustainable Development Goals*.

5.2. Contribution of excess heat from biogas plants to energy autonomy

This subsection presents the results of Weinand et al. (2019c), which is based on the original methodology for designing many district heating networks simultaneously (cf. section 4.2). Based on the survey with 600 biogas plants, a mean fraction of 40% excess heat was determined for these plants, which is in agreement with other empirical studies. Extrapolating this fraction to the German biogas plant stock leads to technically feasible CO_2 savings of around 2.5 $MtCO_2$/a. This involved the simultaneous design of a total of 10,900 district heating networks. Employing the criteria of CO_2 abatement costs and payback period yields about 2 $MtCO_2$/a below CO_2 abatement costs of 200 €/tCO_2 and 9 years respectively. These relatively high average costs are related to the typically low population density in rural regions where biogas plants are located. The potential CO_2 savings represent about 0.25% of the total German CO_2 emissions in 2016 or around 2.5% of all CO_2 in residential buildings. If a threshold value of 80 €/tCO_2, to reflect the German government's suggested external cost of carbon in 2018, is employed, the carbon reduction potential is about 0.5 $MtCO_2$. Similarly, a threshold for the expected payback period of 5 years, to reflect an investor's point of view yields potential savings of about 0.75 $MtCO_2$. These potentials are concentrated in around 3,500 municipalities, where district heating from biogas plants could reduce CO_2 emissions per capita by an average of around 250 $kgCO_2$/a and cover 12% of the total residential heating demand. In some of these municipalities (cf. Figure 10), large proportions of their heating demand could be economically met (according to the criteria employed here) by this excess heat, hence assisting in the transition to more decentralised autonomous energy systems. On the other hand, if the current price of CO_2 in the EU Emissions Trading System of about 7 €/tCO_2 is taken as a benchmark, the economic fraction of this technical potential saving reduces to 0 tCO_2. Although these results are relatively modest in the overall context of decarbonising the energy system, this study does provide a quantitative basis for decision makers, researchers and energy planners.

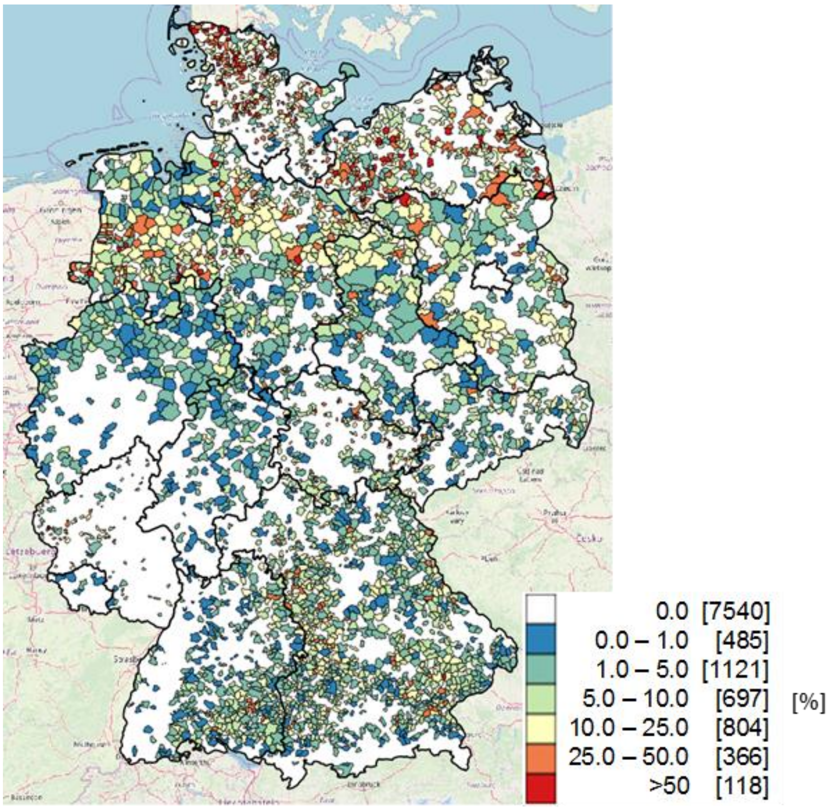

Figure 10: Share of heat demand that can be covered by district heating from biogas in German municipalities (Weinand et al. 2019c). The numbers in brackets represent the number of municipalities to which the shares can be allocated[2].

The developed method was applied to Germany as a case study, but could be equally relevant for other countries with high biogas production. Some of these countries (e.g. Czech Republic) have a significantly more widespread district heating network than Germany. Thus, the use of biogas excess heat could lead to similar or even better results for these countries than in the case study for Germany. Apart from a methodology that can be transferred to any country with similar data availability, the study therefore demonstrates that the use of excess heat in biogas plants can be one contribution towards a global energy system decarbonisation.

The employed methodology, whilst adequate for a national estimation of the technical potential and associated costs, has several uncertainties. Most importantly, the shortest birds-eye route from the biogas plant to the centroid of the settlement is used as the required distance for district heating pipelines. Whilst a good estimate for the order of magnitude, this obviously leads to over- and underestimation of the required district heating pipeline length, and therefore the costs. In addition, the developed heuristic does not (necessarily) determine the optimum allocation of heat sources to heat sinks, and may also therefore overestimate the costs. Finally, the focus on residential buildings and the rough consideration of existing district heating supply (but not infrastructure) add additional uncertainties. All of these aspects remain areas for future work.

5.3. Design of municipal district heating networks

The extension of the previously described district heating algorithm for individual municipalities (cf. section 4.2) was part of Weinand et al. (2019d). A comparison of optimisation and heuristic for designing district heating networks in three exemplary municipalities demonstrates the efficiency of the developed heuristic. For municipalities with three, five and seven settlements respectively, the optimisation takes between 500% and $1x10^7$% more time than the heuristic. The resulting deviations in the calculated total investment for the district heating from the results of the optimisation are in all cases below 5%, and in 80% of cases below 0.3%. The efficiency of the heuristic is also demonstrated by the comparison with the Nearest-Neighbour-Heuristic. The latter is not only less efficient, it substantially overestimates the total costs by up to 80% in all cases with less than 100% heat coverage. In addition, the calculated investments in the investigated municipalities ranged from 500 €/kW to 1,900 €/kW, values which could be validated with investments for existing geothermal district heating networks in Germany.

The developed heuristic consistently yields results within acceptable margins of error of its equivalent combinatorial optimisation problem, is efficient and scales well to other regions or contexts. The methodology would benefit from some further improvements, for example some of the technical aspects such as heat and pressure losses within the district heating network could be modelled more precisely in the heuristic. Furthermore, additional geological and topographical conditions in the municipalities should be taken into account in order to better identify the optimal location of the geothermal plant and the type of network. Additionally, the heuristic should be extended in such a way that the district heating pipelines can also branch off in order to reach several endpoints from one starting point. All of these aspects remain areas for future work. Finally, the results of the heuristic could be compared to the results of the optimisation only for small municipalities (less than 8 settlements). A LP-relaxation of the optimisation problem could help to evaluate the performance of the heuristic also for larger municipalities.

Notwithstanding these shortcomings, the developed method provides a sound basis for decision support for municipal-scale geothermal district heating systems. The heuristic for cost-optimal placement of the geothermal plant (provided as supplementary material of the study) can be extended and should offer useful insights for local planners and authorities when considering the heat source options at their disposal. In addition to supporting the planning of municipal district heating networks, the heuristic can also be used to design district heating networks in holistic energy system optimisations due to the novel possibility of connecting an arbitrary number of buildings to the district heating network.

5.4. Impacts of geothermal plants

In Weinand et al. (2019e), the RE³ASON model was applied for the first time in this thesis to determine the cost-optimal energy system of an autonomous municipality. The focus here is on the residential sector and the industrial, commercial and transport sectors are not considered yet. The main purpose of this study is to assess the influence of deep geothermal energy systems on the technical feasibility and economic expenditures of municipal energy autonomy. The methodology was explained in sections 4.2-4.3.

The specific research questions addressed in Weinand et al. (2019e) are as follows:

- Could the high costs for completely autonomous 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 municipalities from different municipal clusters. Eleven scenarios demonstrated that achieving energy autonomy in the residential sector is (partly) 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.

Weinand et al. (2019e) have developed a generally-applicable method for the optimal setup of a geothermal plant within or near a residential area and considering both heat and electricity generation. Together with the related contribution for optimally locating the geothermal plant within an existing or new district heating network (Weinand et al. 2019d), the consideration of the heat side represents a significant step forward. Compared to previous studies that focussed on a detailed geothermal plant system setup, typically optimised for power generation, Weinand et al. (2019e) adopt a more holistic approach. Weinand et al. (2019e) and Weinand et al. (2019d) together provide a methodological framework for the economically effective and energetically efficient integration of geothermal plants 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. 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 efforts. Therefore the employed method is 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 geothermal plant, 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. Furthermore, the social acceptance of the communities for deep geothermal energy has to be assessed in future studies.

5.5. Complete energy autonomy in German municipalities

The previously described study (Weinand et al. 2019e) focused on complete energy autonomy in the residential sector of a municipality. However, in order to be separated from the German power grid and thus for national transmission grid planning purposes, the entire municipality would have to become energy autonomous, i.e. all consumption sectors have to be included in the energy system analyses. This was achieved in Weinand et al. (2020a), in which RE³ASON is extended to take these additional sectors into account (cf. section 4.3.1) and which uses a methodology for transferring optimisation results to other municipalities (cf. section 4.3.2).

Germany has been selected as case study, where 6,314 (56%) municipalities were identified, in which complete energy autonomy could be technically feasible. Of these municipalities, 15 were used as case studies, which differ greatly in terms of the indicators used in the following regression analysis. The results of the optimisations showed the influence of individual technologies and measures on the LCOE. Thereby, it became apparent that complete energy autonomy is always associated with a high cost increase. Furthermore, the integration of the industrial and commercial sectors can have a reducing effect on the LCOEs, since fixed costs are distributed across a larger amount of energy. In addition, the flexibility through electric vehicles can moderately reduce LCOEs. Using a stepwise linear regression model (mean absolute percentage error = 12.5%), the results of the optimisations could finally be transferred to the 6,314 municipalities. After the correlation analysis and the exclusion of specific indicators (e.g. industrial electricity demand or technical wind energy potential), the technical bioenergy potential P_B, residential electricity demand $ED_{m,r}$, population density PD and technical geothermal potential P_G are selected as features for the regression (cf. Eq. 5). The units are GWh/a for potentials and demands and km^{-2} for population density.

$$\Delta LCOE = 0.5924 - 0.0209 \cdot P_B + ED_{m,r} \cdot (-0.0282 + 0.0003 \cdot PD - 0.0013 \cdot P_G) - 0.0012 \cdot PD - 0.0019 \cdot P_G \quad (5)$$

On average, the additional ΔLCOEs in the autonomous compared to the reference (minimal cost) case, amount to about 0.41 €/kWh. Figure 11 shows the distribution of these additional LCOEs across all German municipalities. When distributing the regression results according to the ten German municipality clusters from Weinand et al. (2019a), the results seem plausible: the highest mean ΔLCOE is reached in cluster 2 (0.578 €/kWh), which mainly contains cities with low renewable energy potential (cf. section 5.1). On the other hand, the lowest mean ΔLCOEs are achieved in clusters 3 (0.350 €/kWh), 4 (0.349 €/kWh) and 8 (0.379 €/kWh), which contain mainly rural municipalities with particularly high potential for renewable energies and especially deep geothermal energy. Apart from energy demand, base load capable bioenergy and deep geothermal energy appear to have the greatest influence on the LCOEs.

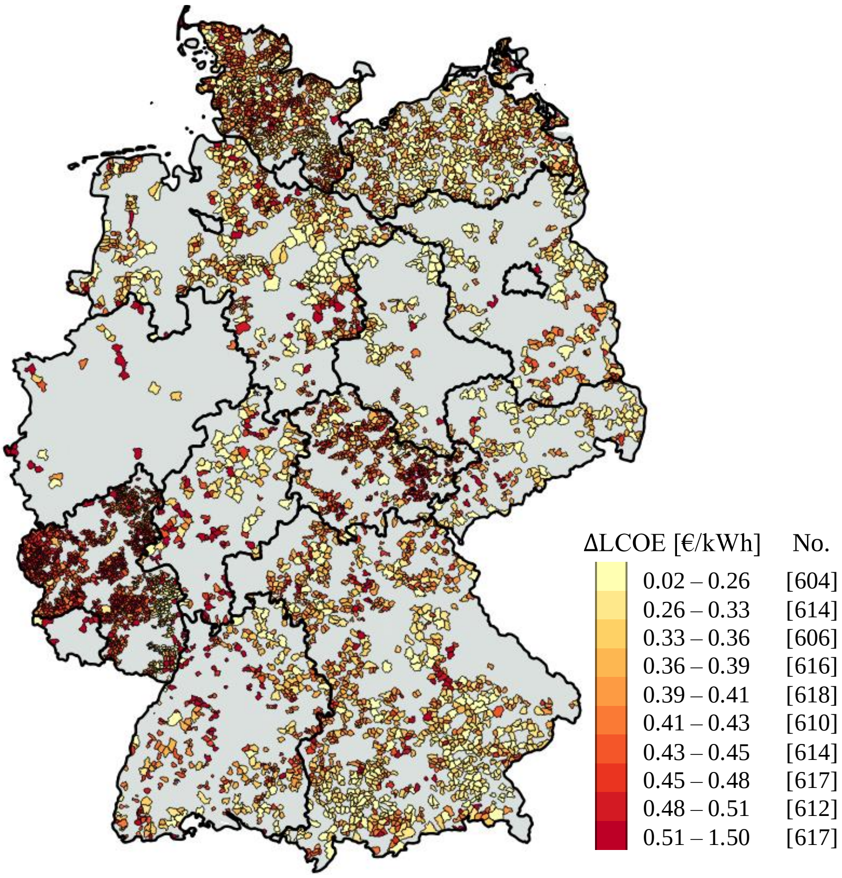

Figure 11: Illustration of 6,314 (56%) German municipalities that can become completely autonomous and the associated ΔLCOE (Weinand et al. 2020a).

As stated above, the ΔLCOE in the 15 case studies result from the comparison of the costs of the autonomous energy systems with an optimised reference system. As the energy systems in reality differ strongly from an optimised system, the real ΔLCOE are probably lower. Assuming that the 15 municipalities in the reference case are not optimised but instead only purchase energy from electricity and gas networks with typical end user prices (Bundesnetzagentur 2019a, 2019b, 2019c) and 2% price increase every 5 years, the ΔLCOE would be reduced by about 0.03 €/kWh on average. This reduction could be even higher as no investments for replacing old energy infrastructures were taken into account in this exemplary calculation. However, in the end, it is obvious that the ΔLCOE in Figure 11 can only serve as a basis for estimating the potential for energy autonomy of individual municipalities in comparison to each other.

Main areas for improving the methodology in Weinand et al. (2020a) include the consideration of grid infrastructures and surplus electricity from neighbouring municipalities, as well as more detailed modelling of industrial demand. The method of calculating and comparing the costs of energy autonomy should be improved to express these costs per municipal end user. In future studies in which the national energy system or transmission grid expansion is planned, the results of this paper can be used as a possible scenario (cf. outlook in section 7).

Section 4.3.1 showed that the RE³ASON optimisation model from Weinand et al. (2020a) was also extended by VoLL to give an example of the possible impacts of load shedding on the energy system and the associated costs. The modified optimisation model was applied to the municipality Prinzenmoor, which was already used in Weinand et al. (2020a) for the detailed sensitivity analyses. As a result, on four extreme days with low wind and solar irradiation, the entire load of industrial and commercial sectors is dropped (a total of 16.9 MWh, which corresponds to 0.5% of the total annual electricity consumption). On the remaining 361 days per year no use is made of the LoL. This changes the energy system compared to the case without LoL: the main energy source changes from deep geothermal energy to wind energy. The total discounted system costs decrease by 54% from 27.7 M€ (or 0.52 €/kWh) to 12.8 M€ (or 0.28 €/kWh) with LoL.

In this case, the LoL has a large impact and could strongly favour the potential or implementation of energy autonomy. However, Prinzenmoor is a very small municipality. Therefore, the influence of LoL should be also investigated in further municipalities in future research. In addition, the modelling of the LoL should be further improved by including maximum energy amounts and maximum length of time intervals for LoL. Furthermore, average nationwide VoLL values should be critically evaluated, as the VoLL could vary greatly depending on the type of household or industrial company.

5.6. Plausibility check of results

During the research on energy autonomy, a comprehensive knowledge on this subject was gained. Thus, a study (Weinand et al. 2020b) has been conducted within this thesis, which reveals research gaps and suggestions for improvement for future studies on municipal energy autonomy. Thereby, the status quo (cf. section 3) and future modelling needs (cf. section 6) for research on decentralised autonomous energy systems is shown. A total of 359 studies were roughly investigated, of which a subset of 123 in detail. The studies were assessed with respect to the characteristics of their methodology and applications, in order to derive common trends and insights.

Some aspects of Weinand et al. (2020b) are presented in the literature review section 3, the discussion in section 6 and the outlook in section 7. However, a compilation of LCOEs, from Weinand et al. (2020b) is discussed in the following since it can be used to check the plausibility of the results of this thesis. Figure 12 shows the LCOEs for 84 articles on decentralised energy autonomy. The studies Weinand et al. (2019e) and Weinand et al. (2020a) are marked by red frames. While in this thesis energy systems based on 100% renewable energies have been considered, there are also case studies in the literature on energy autonomy including conventional energy technologies. In addition, a security of supply below 100% was considered in several studies. This is equivalent to the *Lost of Load* from section 5.5.

The LCOEs for autonomous energy systems in the 84 case studies amount to 0.42 $/kWh on average. However, in some studies the resulting costs should be questioned, as they deviate strongly from the average. With 0.39 $/kWh in Weinand et al. (2019e) and an average of 0.68 $/kWh in the 15 investigated municipalities of Weinand et al. (2020a), the LCOEs calculated in this thesis are close to the average value in the literature (0.42 $/kWh). The results from Weinand et al (2020a) are probably above the average, as the 0.68 $/kWh is the average for 15 optimised municipalities, which were chosen to represent the whole population of 6,314 municipalities. In the other articles, the case studies may have been selected based on their suitability for energy autonomy. Thus the results of this thesis are plausible. If the *Lost of Load* is considered as in section 5.5, the LCOEs (0.28 €/kWh) of an energy autonomous German municipality might even be below the average household electricity price of 0.32 €/kWh (June 2019). However, the calculations with RE³ASON are carried out from a macroeconomic perspective and therefore (in contrast to the household electricity price) no taxes or levies are taken into account.

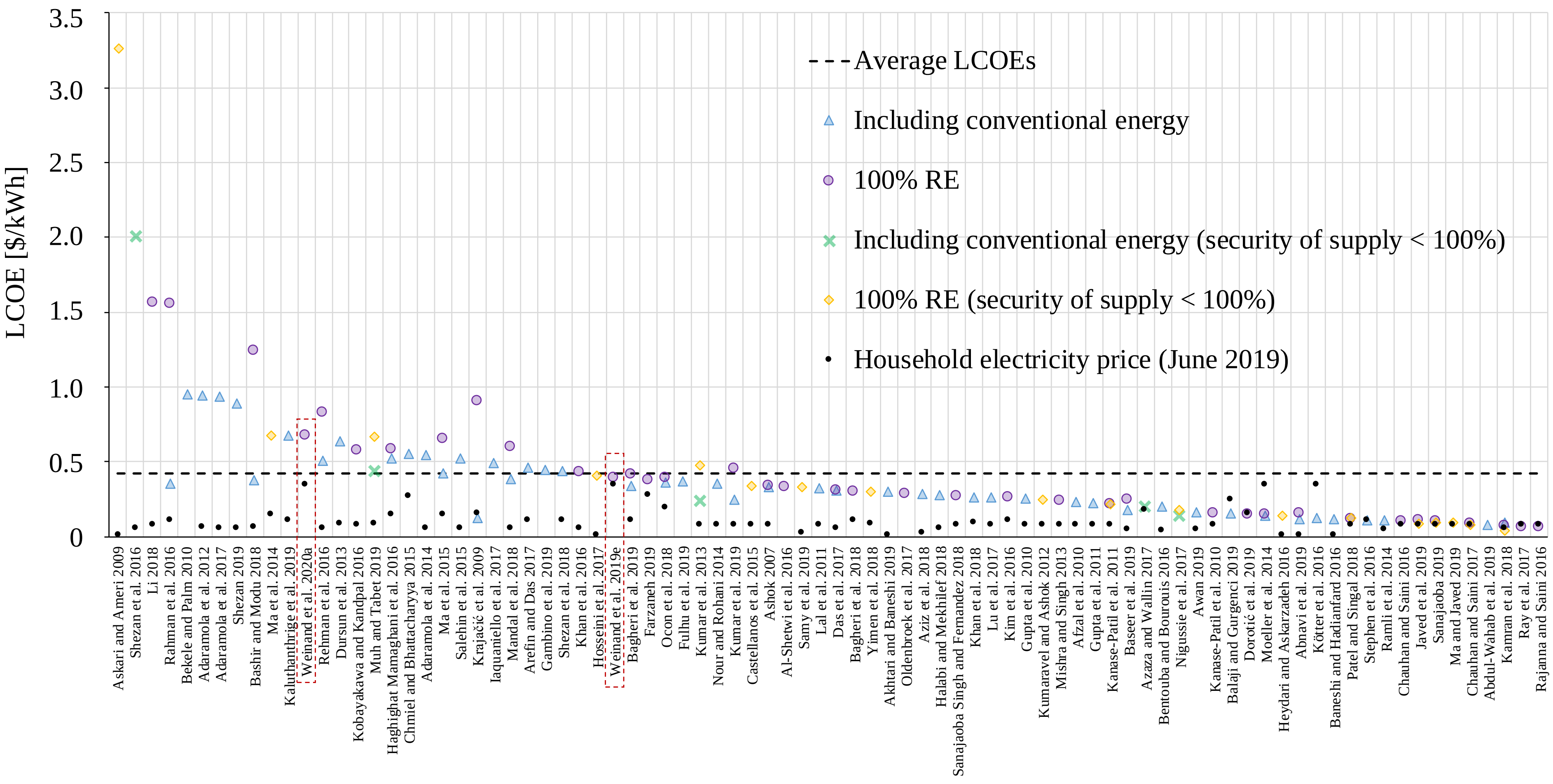

Figure 12: LCOEs of case studies with energy autonomous municipalities in the literature. The studies are sorted by mean LCOEs, from high to low. The LCOEs were adjusted according to inflation until 2019 and converted into $/kWh using the average exchange rates in the year of the respective publication. The household electricity price (black dots) in the different countries is shown for comparison. The black dotted line shows the average value (0.41 $/kWh). The similar figure from Weinand et al. (2020b) is adjusted for this thesis.

6. Critical appraisal

The limitations of the individual studies and methods have already been shown in the subsections of section 5. Therefore, general issues that apply to the entire thesis are discussed in the following.

First, the time resolution of the studies in this thesis is hourly. In non-autonomous energy systems, incorrect dimensioning can be compensated by imports. Thus, the LCOEs of the energy system would change only slightly in case of minor design errors. However, if a completely autonomous energy system is incorrectly designed, a breakdown of the energy supply would result. Therefore, future studies should investigate the influence of a higher time resolution on autonomous energy system planning. In this thesis, an attempt was made to achieve the robustness of the energy system by including extreme days.

Due to the increase of the complexity of the optimisation problem with higher temporal resolution, especially for long-term planning processes, examining a higher resolution is hardly practicable. In these cases, detailed analyses and/or information reduction techniques to generate time typologies and synthetic time slices should be applied. There is an established stream of research focussing on the most suitable/required time resolution for specific research questions, for energy systems with significant renewable generation fractions (e.g. Kotzur et al. (2018) or Nahmmacher et al. (2016)). Studies addressing municipal energy autonomy could also benefit from exploring such approaches. Otherwise there is the above-mentioned risk that systems are incorrectly dimensioned.

Furthermore, the present thesis provides useful information for the economic assessment of the technical potential of energy autonomy. However, there is also a lack of attention paid to non-economic and non-technical criteria in this thesis as well as other studies on energy autonomy. Indeed, economic criteria are arguably the most important, but although they are necessary, they are not sufficient. In Weinand et al. (2020a) it has become apparent that in an industrialised country like Germany there is currently (i.e. with current electricity prices, technology costs and energy-political framework conditions) no economic potential for complete energy autonomy compared to the case with grid connection. Therefore, in future analyses of energy autonomy more criteria than costs need to be considered. There are other important reasons for municipalities to become energy autonomous besides costs, such as increased environmental awareness (cf. section 2).

In addition, this thesis makes use of linear programming from a central planner perspective. It is common practice to leave stakeholder roles outside the scope of energy system analyses and to calculate optimal autonomy transition pathways with a centralized planning approach under the selected objective of technical feasibility and economic viability. However, local energy systems are complex socio-technical systems consisting of different decision-making entities and technological artefacts governed by energy policy in a multi-level institutional space (Koirala et al. 2016). Social relationships among the stakeholders represent a major driver or barrier (Rae and Bradley 2012). In this context, adoption behaviour approaches are useful to understand the types of barriers that exist for new technologies, and what kind of policies are important to increase diffusion. As a consequence, realising the potential of municipal energy autonomy is not simply a question of technical realities but also a question of individual behaviour and group dynamics. Relevant local stakeholders such as households or communities, energy producers, energy suppliers, service providers, as well as local policy-makers are inter-dependent in the realization of their goals. Future system models need to include the heterogeneous roles different stakeholders play in an existing local environment and the resulting impact their decision making might have. One possible solution could be the extension of techno-economic modelling approaches with the help of socio-economic modelling approaches as agent-based models (Rai and Robinson 2015) or system dynamics models (Selvakkumaran and Ahlgren 2018). The integration of social factors such as the acceptance of deep geothermal plants or wind power plants (cf. for example Tröndle et al. (2019)) could reduce the potential for municipal energy autonomy determined in this thesis.

Neglecting taxes and levies ensured that technologies and measures could be assessed and compared neutrally in this thesis (cf. section 4.3.1). However, it is very challenging in reality to implement the optimal energy systems determined from the macroeconomic perspective of a central planner. For households, for example, the cost-optimal energy system determined from a macroeconomic perspective could be very different from the cost-optimal energy system from a microeconomic perspective, taking into account taxes and levies. Future studies should therefore examine the impact of taking into account taxes and levies on the economic viability of energy autonomy in more detail.

Many different spatial scales (e.g. number of households) have been considered in this thesis, but the optimal spatial size of an energy autonomous region has not yet been identified. This is strongly linked to the question of the optimal degree of centralisation (McKenna 2018). Furthermore, in the present thesis the energy systems of individual municipalities were separately investigated. As demonstrated in Weinand et al. (2020a), however, in the case of complete energy autonomy large energy surpluses can result. The use of these surpluses in neighbouring municipalities could significantly reduce the costs for municipal energy autonomy.

Concerning demand and consumption sectors there is also some potential for improvement. The industry sector as well as the private transportation sector are implemented in a simplified approach in Weinand et al. (2020a). For the former, transferable methods to determine the energy demand and load profile of industries in arbitrary regions could facilitate its implementation. For the latter, a particularly interesting approach would be to optimise the number and use of electric (or fuel cell) vehicles. In general, however, all sectors should be taken into account as in Weinand et al. (2020a), especially when estimating the impact of energy autonomous regions on the surrounding energy system.

Furthermore, validation is challenging in the context of municipal energy autonomy. Often detailed data on the existing energy system is lacking and validation for some hypothetical future scenario is obviously not meaningful. Model design and data assumptions of studies used to gain insights to form the decision making should be transparent and accessible. This not only allows independent review of various stakeholders but also the complete reproducibility of the results (Pfenninger et al. 2014). Hence studies on municipal energy autonomy could increase efforts to publicly release data as in Weinand et al. (2019b) and system models as well as assumptions and results interpretation, in order that diverse affected stakeholders are able to participate in the decision-making process (Pfenninger et al. 2014; DeCarolis et al. 2017).

In addition, the focus on the LCOEs as a benchmark for highly-renewable energy systems in this thesis could provide potentially misleading results. Whilst the LCOE is a good first indicator of the generation costs and allows comparisons across technology, it is noted for neglecting the additional costs of integrating non-dispatchable renewable technologies into the energy system. Three additional cost components should be considered, if the system LCOEs of renewable energy technologies are to be considered (Hirth et al. 2015; Ueckerdt et al. 2013):

- **Profiling costs**, related to the requirement for the dispatchable generation technologies to meet the residual load;
- **Balancing costs**, related to the deviation between forecast and actual non-dispatchable renewable generation; and
- **Grid costs**, related to additional grid reinforcement and extension (at all voltage levels) required to connect renewable generators to the network.

Attempts have been made to consider these cost components in the context of large-scale (e.g. national) energy system analyses (e.g. Brown et al. 2018; Chaudry et al. 2014; Nolden et al. 2013). However, at the regional and municipal scale, they are typically not included. For example, the analyses in the present thesis also did not take network capacities into account. As an improvement, an approach would be conceivable in which the grid is upgraded if a high proportion of renewable energies is installed (as in Morvaj et al. (2017)).

7. Conclusions and outlook

Attention on decentralised autonomous energy systems has increased exponentially in the past three decades, as demonstrated by the absolute number of municipal projects as well as the share of publications in the corpus of scientific literature. This is due to the energy transition and the related environmental awareness as well as the desire of citizens to play an active role in energy supply and to be less dependent on central markets and structures. However, local decision-makers often lack the necessary expertise and therefore need decision support in energy system planning. Thus, this thesis follows the objective to develop novel methods for the technical, economic and environmental assessment of a large number of completely energy autonomous municipalities and their impacts on the overall energy system. Completely energy autonomous municipalities are disconnected from the gas and electricity grid and supply themselves with energy from renewable energy plants owned and operated by the municipality.

In order to meet the objective, several novel methods of energy system analysis were developed in this thesis as part of seven original research articles. Germany is used as a case study, but the general approach, methods and results are transferable to other contexts. In order to be able to analyse a large number of municipalities (> 1,000), an approach had to be developed that allows to analyse a multitude of energy systems with practicable computational expenses. Therefore, a typology of the energy systems to be investigated was needed. Subsequently, selected energy systems that represent this typology had to be optimised from a techno-economic perspective. In the final step, the results of the optimisations had then to be transferred to all energy systems.

First of all, the 11,131 German municipalities were clustered with regard to their suitability for decentralised energy systems. For this purpose, social indicators such as population density or number of vehicles and technical factors such as generation potential of different renewable energies were employed. Furthermore, since previous studies on municipal energy autonomy with renewable energies often resulted in high total costs due to limited base load potentials and therefore high storage costs, other technologies were sought that could reduce these costs. Deep geothermal energy was identified as a renewable technology that is capable of providing base load and has a high potential in Germany. This technology was implemented in an already existing holistic municipal energy system optimisation model (RE³ASON). This optimisation model is particularly suitable for the investigation of many different municipalities due to the use of public data and the associated applicability to arbitrary municipalities. In order to be able to use the heat in addition to the power generation of the deep geothermal plants, a transferable combinatorial optimisation approach for district heating network design in municipalities was developed in two studies and also integrated into RE³ASON. In a further study, the technical feasibility and economic expenditure of energy autonomy could finally be determined in all 11,131 German municipalities by combining the extended energy system optimisation model with a stepwise linear regression. In a concluding review study, the experience gained over several years on the topic of energy autonomy was used to present suggestions for further improvement of future energy system modelling of decentralised autonomy.

For the case study Germany, ten municipality clusters could be identified, which differ considerably in terms of their characteristics. For example, one municipality cluster includes all major German cities with low renewable energy potentials, while other clusters include more rural municipalities with high renewable energy potentials. During the subsequent energy system optimisations, the results showed that in the case of complete energy autonomy, deep geothermal plants in combination with district heating networks are in fact usually installed. The total costs for municipal energy systems until 2030 could be reduced by up to 50% by using deep geothermal energy and district heating. This underlines the assumption from the literature review that base load technologies are advantageous in energy autonomous systems due to the associated reduced storage costs. However, it is important to mention that deep geothermal energy and district heating networks have not been installed in any reference scenario of municipal energy systems with grid connection. On average, the energy system costs until 2030 in German municipalities increase by about 0.41 €/kWh in the energy autonomous case compared to the optimised reference case. While a technical potential to achieve energy autonomy is present in 56% of the municipalities, there is therefore no economic benefit of complete energy autonomy in an industrialised country like Germany compared to the optimised reference municipal energy system with grid connection. However, this latter statement only applies to an isolated consideration of the municipal system and requires further investigation in the case of an integrated consideration in a national energy system analysis.

The novel methodological approach of this thesis enabled to obtain optimisation results for a high number of energy systems (6,314 municipalities) with practicable computational expenses. In addition to the original data and planning tools published alongside the articles, the findings of this thesis can help to support local decision makers in determining cost-effective municipal energy systems. Thereby, the insights on the impact of different technologies and geographical conditions in municipalities can benefit not only for the planning of complete energy autonomy but also for energy system analysis in general. Furthermore, the results can be utilised for energy system planning at the national level, such as the design of transmission grids. For this purpose, scenarios could be designed in which municipalities with the greatest techno-economic potential for decentralised energy systems become energy autonomous. For example, the assumption could be made that all municipalities with ΔLCOE less than the mean value (0.41 €/kWh) will become autonomous. Then the demand and feed-in from these municipalities could be excluded from the analyses. Furthermore, simultaneous optimisation of transmission grid expansion and selection of autonomous municipalities could be performed to determine the optimal future national energy system.

The original approaches developed in this thesis have been validated and, if this was not possible, at least checked for plausibility. The transferability of the methods for different applications has also been demonstrated in the various studies of this thesis. For example, the algorithm for designing district heating networks has been extended in a further ongoing study for connecting wind turbines to electricity substations (McKenna et al. 2020).

However, in order to increase the realizability of the case study results identified in this thesis, some methodological extensions are necessary. For example, future research should focus on other perspectives than that of a central planner and other target criteria than costs should be included. In addition, complete autonomous energy systems in particular must be robustly designed, for example by further analysing the Value of Lost Load and whether a security of supply below 100% is acceptable for energy consumers. Furthermore, the temporal resolution should be higher than the usually used hourly resolution. Finally, methodologies should be developed which can involve local stakeholders in the modelling process and thus consider their preferences relating to their future energy system which is also related to the acceptance of technologies like wind power or deep geothermal plants.

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Part B: Articles

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Review

Reviewing energy system modelling of decentralized energy autonomy

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A B S T R A C T

Research attention on decentralized autonomous energy systems has increased exponentially in the past three decades, as demonstrated by the absolute number of publications and the share of these studies in the corpus of energy system modelling literature. This paper shows the status quo and future modelling needs for research on local autonomous energy systems. A total of 359 studies are investigated, of which a subset of 123 in detail. The studies are assessed with respect to the characteristics of their methodology and applications, in order to derive common trends and insights. Most case studies apply to middle-income countries and only focus on the supply of electricity in the residential sector. Furthermore, many of the studies are comparable regarding objectives and applied methods. Local energy autonomy is associated with high costs, leading to levelized costs of electricity of 0.41 $/kWh on average. By analysing the studies, many improvements for future studies could be identified: the studies lack an analysis of the impact of autonomous energy systems on surrounding energy systems. In addition, the robust design of autonomous energy systems requires higher time resolutions and extreme conditions. Future research should also develop methodologies to consider local stakeholders and their preferences for energy systems.

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Abbreviations

ABS	Abstract
ar	Article
BBO	Biogeography Based Optimization
CHP	Combined heat and power
Doctype	Type of document, e.g. article or review
EA	Energy autonomy
ES	Energy system
EV	Electric vehicle
HIC	High income county
KEY	Keyword
LCOE	Levelized cost of electricity
LEA	Local energy autonomy
LIC	Low income country
LMIC	Lower middle income country
LPSP	Loss of load probability
MCDA	Multi-criteria-decision analysis
PV	Photovoltaics
RE	Renewable energy
UMIC	Upper middle income country

1. Introduction

Between 1993 and 2017, the percentage of the worldwide population with access to electricity increased from 77% to around 89% [1]. Since 2012, more than 100 million people per year have gained access to electricity. However, it is estimated that even in 2030 about 670 million people will still have no access to electricity [2]. Most people without access live in rural areas (84%) and in sub-Saharan Africa or developing Asia (95%) [3]. Negative examples include the developing countries of Burundi, Chad and Malawi, where less than 15% of the population have access to electricity [1]. Many of the newly electrified regions in developing countries apply off-grid solutions with diesel engines due to long distances to the national grid. Such completely energy autonomous systems are able to meet the energy demands of an entire community without energy imports [4].

Whereas these completely autonomous (i. e. off-grid) energy systems (ESs) exist in developing countries mainly due to cost considerations, there are also efforts by municipalities and regions to become energy autonomous in industrialized countries with complete electrification (i.e. grid-connected). This is due to the energy transition and the related environmental awareness [5] as well as the desire of citizens to play an active role in energy supply and to be less dependent on central markets and structures (e. g. Refs. [6,7]). The majority of municipalities with energy autonomy (EA) aspirations strive for balanced EA and the focus is usually on electrical energy [5]. In this context, ESs achieve balanced EA if they are energy neutral, i.e. the annual locally provided energy exceeds the annual demand [4]. In contrast to a completely energy autonomous solution, imports and exports are possible.

Local energy autonomy (LEA) can take different forms and degrees (Fig. 1). In particular, autonomous ESs need to exhibit the basic criteria as defined by Rae and Braedly [4]. First, the local system is able to generate at least as much energy to meet the demands. Second, the local system allows energy shifting possibilities for times in which there is a temporal mismatch between demand and supply (i.e. through storage or in the case of balanced autonomy through energy infrastructure). Third, the system is capable of operating independently on a *stand-alone* or *off-grid* basis. Thereby, local autonomy efforts are related to active participation of the community or rather the system components are owned by the community members. In general, autonomy efforts are directly related to the notion of *self-governance* and *community ownership* [4]. In this study, EA is defined the same way: it focusses on plants inside the municipality which tend to be operated by the local community, and may also include conventional technologies. However, due to the dependency on fuel transport and the high costs of diesel-based ESs, a supply consisting at least in part of renewable energies (REs) could be worthwhile in these cases. Fig. 1 shows a schematic representation of decentralized (autonomous) energy systems.

As the above examples demonstrate, balanced or completely autonomous ESs are related to different objectives and have different effects on the local setting but possibly also on the overarching system. Due to the increasing relevance of LEA (c.f. section 3), there is a need to elaborate and define transition process aspects

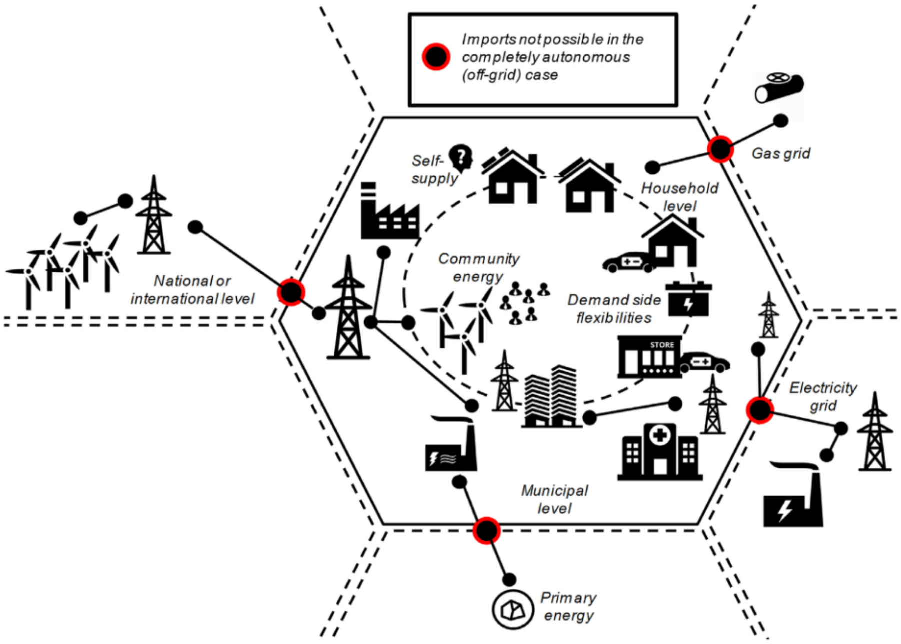

Fig. 1. Schematic representation of a decentralized energy system. Not all technologies found in the reviewed studies are shown. In this review only studies on the municipal level and regional level are included, i.e. no studies on the household or national level. In contrast to the completely energy autonomous case (off-grid), imports from the national level are permitted in the case of balanced energy autonomy.

and successful transition pathways. Therefore, the aim of this study is to review the literature on LEA, i.e. in villages, districts, municipalities and regions, in order to identify the current state of the art and gaps or starting points for future studies. This spatial resolution is chosen since similar conditions apply, for example from a technical point of view (decentralized energy technologies) but also from a social point of view, such as the number and type of stakeholders. Studies on individual buildings and larger regions such as entire nations are therefore excluded. In contrast to the multitude of existing reviews, this paper for the first time shows a comprehensive overview and quantitative analysis of applied methods in EA case studies at the local level (cf. section 2).

This paper is structured as follows: section 2 gives an overview of already published literature reviews about ES analyses with a focus on decentralized EA. Subsequently, section 3 presents the methodology for the literature search. Section 4 then presents and discusses the most important findings from the analysis of the literature, before the studies are critically assessed in section 5. A summary and conclusions are given in section 6.

2. Existing literature reviews

Some review papers have already examined studies on local ES planning for larger (e.g. urban areas) [8,9] and smaller regions (e.g. municipalities/communities) [4,10–16]. In some cases, the focus is on some form of EA [4,10,15,16], or this topic is at least briefly discussed [11,14]. A few other review papers [17–20] discuss EA, but do not focus on the local level as defined in section 1.

Even though there are some undeniable differences regarding the motives of LEA efforts in developed and developing countries, due to the growing utilization of decentralized RE generators LEA projects also represent a business opportunity in industrialized countries according to the review of Engelken et al. [21]. Despite all of the criticism voiced by Heard et al. [19], the feasibility and viability of such local RE systems have been demonstrated in various studies as shown in the reviews of Brown et al. [17] and Hansen et al. [18].

In this context, a strategy to achieve this feasibility requires the discussion of crucial factors regarding EA. Kaundinya et al. [16] present both general success and failure stories of corresponding autonomy projects. According to the authors, a generalized approach to assess the suitability of off-grid and grid-connected systems, based on techno-economic-financial-environmental feasibility does not find adequate coverage in the literature yet. Issues and trends shaping local ESs are conceptually summarized by Keirstead et al. [8] and Koirala et al. [11]. Concerning this matter, local ESs fit very well into the neo-liberal ideas of self-reliance and independence [11]. A shift towards local autonomous systems, however, is not only associated with a host of social, financial and environmental benefits. Key challenges are the degree and scale of EA, the matching of demand with supply, the importance of socio-economic and political factors and the structural requirements in remote communities [11].

These results go in line with the findings of the review of Rae and Bradley [4]. While taking into account the different drivers of balanced or completely autonomous energy projects, the review investigates environmental, political, economic, technical and social concerns. Even though generation and utilization of RE is

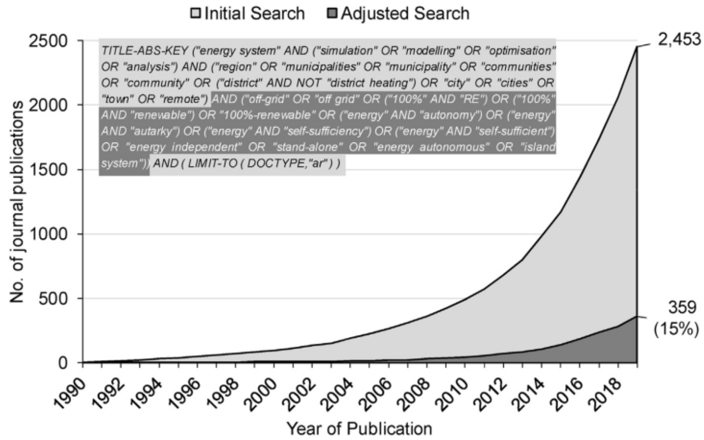

Fig. 2. Development of the number of journal publications for two search queries in Scopus. The bright curve contains the publications on energy system analyses at the local level. For the dark curve, the search query has been adjusted so that the studies also deal with autonomous energy systems. The last search in Scopus was performed on November 20, 2019.

primarily a technical challenge, social and political aspects are the most important factors in its implementation in the community. The conceptual framework of EA by Müller et al. [15] shares a similar focus: the involvement and motivation of administrations and community stakeholders are decisive for the successful transition towards LEA.

Additionally, ensuring stable supply and reliability against all plausible outcomes in RE availability might raise cost and complexity of the systems due to the impacts of worst-case conditions [19]. Distributed energy generation as with local autonomous projects encompasses a wide variety of technologies which tend to be highly sensitive to the deployment context [14]. Thus, it is important to consider the necessary spatial and temporal boundaries of the region or community.

Some of the mentioned aspects have also been posed in terms of future modelling needs. Trans-disciplinary and multi-dimensional features of low-carbon community model approaches are outlined by Nakata et al. [20]: models should consider e.g. the utilization of waste for energy, the inclusion of various sectors, and approaches related to energy-for-development issues in rural areas of developing countries. Dependent on the objectives and constraints, Gamarra and Guerrero [10] point out innovative planning guidelines by reviewing optimization techniques applied to microgrid planning. While the microgrid siting problem of autonomous systems requires robust methodologies, the operation of the autonomous system is only possible with reliable energy management systems. Thereby, stochastic optimization could be one solution for a more realistic estimate [16]. Besides, Scheller and Bruckner [12] present requirements for ES modelling at the municipal level and discuss existing optimization models concerning their fundamental approaches. They provide future modelling needs for successful ES analyses which are also linked with the mentioned challenges of autonomy projects.

In contrast to many other literature reviews, the present paper presents a comprehensive overview and quantitative analysis of applied methods in case studies on energy autonomous systems at the local level. Of the reviews discussed in this section, only [4,10,11,14–16] focus on EA at the local level. Of these six papers, only Kaundinya et al. [16] and Gamarra and Guerrero [10] concentrate on methodological aspects. However, the studies differ from the present review by concentrating on the comparison of grid-connected and off-grid ESs [16] or only on microgrid studies [10]. Furthermore, the studies are from 2009 [16] and 2015 [10], respectively, and since then, the published articles on LEA have more than doubled (cf. section 3). Apart from the general topic, this review also covers new aspects such as a compilation of costs for local energy autonomous systems (cf. section 4.7).

3. Review methodology

The literature on local ES analysis has increased exponentially from 1990 until 2019 (cf. Fig. 2), along with the LEA efforts described in section 1. Scopus[1] was used for the primary literature search, since it covers a wider range of journals [22] as well as more recent sources [23] than other databases like *Web of Science*. The *Initial search* query in Table 1 results in a total of 2,453 studies (cf. Fig. 2). The search query contains the methodology (e. g. ES analysis or simulation), the spatial resolution (e. g. municipality or region) and the restriction that it is a peer-reviewed article. 359 (15%) of the 2,453 studies on local ES analyses deal with autonomous ESs and have also exponentially increased in recent years (*Adjusted search* in Table 1 and Fig. 2).

The increasing importance of the topics could be only related to the generally exponentially increasing number of publications. However, the share of local ES analyses in the field of ES analysis (*Energy system analysis search* in Table 1) has increased from 8% (1990) to 20% (2019) and that of local energy autonomous systems from 0% to 3%.

The 359 studies about LEA were examined for suitability for this review. 236 studies were excluded for the reasons outlined in Table 2. For 122, most of them were excluded because of an unsuitable spatial resolution (e.g. ES analysis of a single building). A total of 123 studies remained ([24–146]), which were mainly published in the journals Energy and Renewable Energy (cf. Table 3). In addition, Table 4 shows the ten most globally cited

[1] https://www.scopus.com/search/form.uri?display=basic.

Table 1
Different search queries for the literature search in Scopus. The abbreviation "TITLE-ABS-KEY" is used to search for the terms in the title, abstract and keywords of the article. Included are original research articles (cf. "(DOCTYPE, "ar")" in the search query), which were published between 1990 and 2019.

Search name	Search query	Number of studies
Initial search	TITLE-ABS-KEY ("energy system" AND ("simulation" OR "modelling" OR "optimization" OR "analysis") AND ("region" OR "municipalities" OR "municipality" OR "communities" OR "community" OR ("district" AND NOT "district heating") OR "city" OR "cities" OR "town" OR "remote")) AND (LIMIT-TO (DOCTYPE,"ar"))	2,453
Adjusted search	TITLE-ABS-KEY ("energy system" AND ("simulation" OR "modelling" OR "optimization" OR "analysis") AND ("region" OR "municipalities" OR "municipality" OR "communities" OR "community" OR ("district" AND NOT "district heating") OR "city" OR "cities" OR "town" OR "remote") AND ("off-grid" OR "off grid" OR ("100%" AND "RE") OR ("100%" AND "renewable") OR "100%-renewable" OR ("energy" AND "autonomy") OR ("energy" AND "autarky") OR ("energy" AND "self-sufficiency") OR ("energy" AND "self-sufficient") OR "energy independent" OR "stand-alone" OR "energy autonomous" OR "island system")) AND (LIMIT-TO (DOCTYPE,"ar"))	359
"Energy system analysis" search	TITLE-ABS-KEY("energy system" AND ("simulation" OR "modelling" OR "optimization" OR "analysis")) AND (LIMIT-TO(DOCTYPE,"ar"))	12,368

Table 2
Studies that resulted from the adjusted search in Scopus (**cf.** Table 1) and are not considered in this literature review for the reasons given in the table.

Exclusion criterion	Number of studies	References
The study does not consider energy autonomy as defined in section 1 (i. e. at least balanced autonomy has to be analysed)	30	[147–176]
Autonomy is considered in a different context than energy	2	[177,178]
Autonomy is only mentioned as a future target in the paper	3	[179–181]
The spatial resolution of the study does not match our definition of local energy systems (cf. section 1)	**122**	
• Single consumer/households/building	41	[182–222]
• Single commercial application	**57**	
o Agricultural well	2	[223,224]
o Desalination unit	7	[225–231]
o Cellular base station/telecommunication unit	11	[232–242]
o Hospital/healthcare facility	5	[243–247]
o Hotel	5	[248–252]
o Library	1	[253]
o Wireless sensor nodes	1	[254]
o Machinery laboratory	1	[255]
	6	[256–261]
o Voter registration centre	1	[262]
o Desert safari camp	1	[263]
o Touristic facility	1	[264]
o Charging station	1	[265]
o Mining site	3	[266–268]
o Factory/enterprise	3	[269–271]
o Refinery	1	[272]
o Road lighting system	1	[273]
o University facility/school	4	[274–277]
o Clean water and toilet system	1	[278]
o Wastewater treatment plant	1	[279]
• Large regions	3	[280–282]
• One or several countries	21	[283–303]
Analysis of a single energy plant/technology	35	[304–338]
Aerospace applications	2	[339,340]
Climate analyses	4	[341–344]
Study focusses on control strategies of an energy system	13	[345–357]
Study introduces a new model without autonomy case study	3	[358–360]
Study develops load profiles for off-grid areas	2	[361,362]
Study focusses on qualitative analysis	15	[363–377]
Analysis of a given 100% renewable system	2	[378,379]
Text language: Korean	2	[380,381]
Publication not found	1	[382]

Table 3
Distribution of the studies among the journals in which they were published. Only those journals are shown which have published five or more studies.

Journal	Number of studies	Share in 123 studies [%]
Energy	16	13
Renewable Energy	14	12
Energy Conversion and Management	9	7
International Journal of Renewable Energy Research	9	7
Applied Energy	7	6
Energies	7	6
Journal of Cleaner Production	6	5
Solar Energy	5	4

Table 4
Most relevant articles on local energy autonomy, based on global citations (January 15, 2020).

Article	Title	Journal	Global citations
Ashok 2007 [33]	Optimized model for community-based hybrid energy system.	Renewable Energy	295
Ma et al. 2014 [134]	A feasibility study of a stand-alone hybrid solar-wind-battery system for a remote island.	Applied Energy	257
Kanase-Patil et al. 2010 [72]	Integrated renewable energy systems for off grid rural electrification of remote area.	Renewable Energy	187
Østergaard and Lund 2011 [100]	A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating.	Applied Energy	180
Ma et al. 2014 [85]	Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong.	Renewable Energy	158
Maleki and Askarzadeh 2014 [88]	Optimal sizing of a PV/wind/diesel system with battery storage for electrification to an off-grid remote region: A case study of Rafsanjan, Iran.	Sustainable Energy Technologies and Assessments	102
Haghighat Mamaghani et al. 2016 [60]	Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia.	Renewable Energy	95
Gupta et al. 2010 [58]	Steady-state modelling of hybrid energy system for off grid electrification of cluster of villages.	Renewable Energy	92
Rohani and Nour 2014 [111]	Techno-economical analysis of stand-alone hybrid renewable power system for Ras Musherib in United Arab Emirates.	Energy	89
Askarzadeh and dos Santos Coelho 2015 [36]	A novel framework for optimization of a grid independent hybrid renewable energy system: A case study of Iran.	Solar Energy	85

Table 5
Overview of the general methodologies applied in the studies.

General methods	Study	Number of studies
Artificial bee swarm optimization	[89,90]	2
Biography based optimization algorithm	[133]	1
Chaotic search	[128,129]	2
Cukoo search	[115]	1
Discrete harmony search	[47,88,128]	3
Electricity System Cascading Analysis	[64]	1
Energy balancing calculation	[70,99,104,122]	4
Firefly algorithm	[114]	1
Flower Pollination algorithm	[113]	1
Fuzzy analytic hierarchy process	[98]	1
Genetic algorithm	[69,106]	2
Grey relation analysis	[98]	1
Life cycle cost analysis	[87]	1
Multi-objective particle swarm optimization	[37,125,126]	3
Multi-objective crow search algorithm	[68]	1
Multi-objective optimization	[112]	1
Non-dominated sorting genetic algorithm-II	[125,126]	2
Optimization	[30,34,49,54,56,58,59,63,72,74,78,92,98,109,117,124,146]	16
Multi-criteria-decision analysis (MCDA)	[80,92]	2
Particle swarm optimization	[36,61,101]	3
Simulated annealing	[128]	1
Simulation	[24]– [29] [31] [33,] [35,38] [43] [45,46,48,50] [53] [55,57,60,62,65] [67,71,75]– [77] [79] [86,91,93]– [97] [100,102,103,105,107,108,110,111,116,118] [121] [123,127,130] [132] [134] [145]	69

articles on LEA.

4. Results of the literature review

This section presents and discusses the main findings of the analysis of the 123 studies. First, section 4.1 explains the methods and models used in the studies. Subsequently, section 4.2 shows the system boundaries of the case studies. The type and feasibility of EA under consideration is presented in section 4.3. In the following section 4.4, the temporal resolution is discussed. Section 4.5 then indicates the included technologies before section 4.6 examines the consideration of grid infrastructures. Finally, section 4.7 compares and discusses the costs for LEA resulting in the studies.

The supplementary Microsoft Excel file in the online appendix contains all the information discussed in this article. Not all aspects could be identified in all studies. In some of these cases, the information in the Excel file are given in parentheses, which indicates assumptions based on detailed analysis of the study. If, in the following sections, the shares in the number of studies do not add up to 123 or the percentages do not add up to 100%, this is due to the fact that not all information could be retrieved from every study.

Table 6
Models used in the analysed literature.

Model	Study	Number of studies
HOMER or HOMER Pro	[24,25,26,27,28,29,32,35,38,39,41,42,43,45,46,48,50,53,55,57,60,62,65,66,71,75,76,77,80,81,82,83,86,91,93,95,96,97,105,107,108,110,111,118,119,120,121,127,131,132,134,135,136,137,138,139,140,141,142,144,145]	61
EnergyPLAN	[44,51,52,100,116,123,130]	7
RE^3ASON	[92,124]	2
BeWhere/Phasma	[117]	1
FINE/TSAM	[146]	1
FlexiGIS	[30]	1
H_2RES	[79]	1
IREOM	[73]	1
ISLA	[98]	1
LINGO v.10	[72]	1
OSeMOSYS	[56]	1
$P^2IONEER$	[78]	1
RegFin	[104]	1

4.1. Methodologies and models

The methods employed in the reviewed literature (cf. Table 5) range from simple energy balancing calculations (e. g. Refs. [70,99,104]) to simulations (e. g. Refs. [79,94,102]), meta-heuristics (e. g. genetic algorithm [69], discrete harmony search [88], artificial bee swarm optimization [89,90] or flower pollination algorithm [113]), mixed-integer linear optimizations (e. g. Ref. [30]) and multi-objective optimizations (e. g. Ref. [112]).

When investigating the methods, it is striking that in most cases only simplified calculations are carried out. For example, the number and size of plants is usually predefined and not optimized. Simulations are frequently used (56%, cf. Table 5) and often referred to as optimization. The best examples are the simulation softwares HOMER and EnergyPLAN, which are used in 61 (50%) and 7 (6%) studies respectively (cf. Table 6). Apart from HOMER and EnergyPLAN, other models appear only once or twice or are not specified in the studies (cf. Table 6).

Although most HOMER studies call it optimization, in its core HOMER is a simulation model [383]. The simulation is used to balance energy generation and consumption and calculate the costs. Thousands of scenarios with different parameters can be simulated in a sensitivity analysis. Subsequently, in the so-called optimization, the best solution is selected from among all scenarios depending on the selected criterion (e.g. minimization of costs or fuel usage) [383]. This explorative approach to identifying a pareto front does not necessarily yield the optimal solution. The vast majority of the studies reviewed here in which HOMER is used have a similar structure: first, the economic parameters, the load profile as well as the renewable potentials and the ES under consideration are described for a particular application. The best ES is then usually selected on the basis of costs (97% of cases). These studies therefore typically focus on case studies rather than methodological innovations. The aim of these studies is usually to reduce the diesel consumption of a remote off-grid area. In three studies, newly developed methods were compared with the HOMER model. The results showed that a Biogeography Based Optimization (BBO) algorithm [133], a Genetic Algorithm [69] or the so-called LINGO model [72] perform better than the HOMER model in terms of computing time and minimization of costs. The BBO algorithm, for example, found a better solution than HOMER and reduced the computing time from 15 h to 0.7 h [133].

Despite the weaknesses that HOMER shows in determining an optimal ES, the advantages of the tool should also be appreciated. It is an open access tool that can be used by everyone and does not require a lot of computing power. Therefore, the model is particularly useful for studies on remote areas in countries with low or middle income (75% of the HOMER studies reviewed here) according to the country classification of the World Bank [384] (cf. Table 8).

In contrast to the HOMER model, the EnergyPLAN model was only used for case studies in countries with middle (China [130]) or high (Italy [44], Croatia [51,116], Denmark [52,100], Ireland [123]) income. However, this model is also classified "as a simulation tool rather than an optimization tool" [385] and only includes a dispatch optimization. This means that the user has to specify the technologies and thus has to have a comprehensive understanding of ES analysis (as in HOMER). A step in the right direction was the introduction of HOMER Pro, which is intended to simplify the use of the HOMER software for inexperienced users [386].

Beyond these two models, there are more and more model approaches that generate inputs for optimization models on the basis of publicly available data such as OpenStreetMap.[2] Examples in the reviewed literature are the FlexiGIS model [30] and the RE^3ASON model [92,124]. At least for FlexiGIS an open-source publication in GitHub is planned, according to the authors [30]. These models would enable inexperienced users in the field of ES analysis to determine the energy potentials of a region and optimize the ES. Neither potentials nor technologies and plant sizes would have to be determined before application of the models.

4.1.1. Perspective

In most ES analyses, a *central planner* was used as the perspective. Only in Ramchandran et al. [107], the perspective of a Renewable Energy Service Company was taken instead. On the one hand, these central planner approaches show the macroeconomic optimum. On the other hand, however, these approaches often fall short of realisation: it could be difficult to convince individual homeowners to install the technologies in their homes that are optimal from a macroeconomic but not a business point of view. Therefore, studies of possible incentive systems that could encourage homeowners to implement the macroeconomic EA plan are required. First conclusions could be drawn by comparing the optimal ES at building level from the perspective of the building owner on the one hand and from the macroeconomic perspective on the other.

Promising approaches include for example the combination of optimization approaches with *multi-criteria-decision analysis* (MCDA), as in Refs. [80,92]. These types of analyses do not yet include the perspective of every inhabitant, but at least the perspective of their most important representatives. This could help to strengthen the feasibility of an EA plan.

[2] https://www.openstreetmap.org/.

Table 7
Applied target criteria besides cost in the studies with MCDA or multi-objective optimizations.

Criterion	Study	Number of studies
CO_2 emissions	[70,80,92,98,112]	5
Land use	[54,70,80,83]	4
Security of supply	[37,68,83,98]	4
Forecast accuracy	[125,126]	2
Renewable share in energy supply	[37,83]	2
Social acceptance	[80,98]	2
Community net imports	[92]	1
Creation of jobs	[80]	1
Ease of installation and operation	[98]	1
Flexibility of the system for future expansion	[98]	1
Gross domestic production	[104]	1
Health issues	[80]	1
Human development index	[80]	1
Noise	[80]	1
Risk of flash floods	[80]	1
Technical efficiency	[80]	1
Technical reliability	[80]	1
Technical lifespan	[80]	1
Technical scalability	[80]	1
Technical maturity	[80]	1
Universal education and gender equality	[80]	1
Water consumption	[54]	1
Water quality	[80]	1

Table 8
Classification of the countries according to The World Bank [384], in which the case studies are conducted in the reviewed literature as well as the share in the total of 123 publications. This country classification is based on the gross national income per capita [384].

Income group [384]	Gross national income per capita [384] [$]	Countries and studies	Share [%]
Low income	[0; 1,025)	Ethiopia [66,96], Rwanda [144], Tanzania [140], Yemen [31]	4
Lower middle income	[1,025; 3,995]	Bangladesh [50,91,136], Cameroon [95,127], Egypt [113], Ghana [26,28], India [29,33,45–47,58,59,72,73,77,81,87,93,101,106,107,109,114,115,131,133], Indonesia [32,120], Nigeria [27,137,139], Pakistan [71,75,110], Philippines [98], Timor-Leste [56]	33
Upper middle income	(3,995; 12,375]	Algeria [43,135], Brazil [118], China [69,80,82–84,130], Colombia [60], Cuba [132], Iran [25,34–36,41,61,63,65,68,88–90,125,126,128,129,141], Iraq [138], Malaysia [62,64,119,121], Maldives [55], Mexico [54], Turkey [53]	30
High income	(12,375; inf)	Australia [40,57], Austria [117], Canada [38,39,105,122,145], Croatia [51,79,116], Denmark [52,100], Finland [104], Germany [30,70,78,92,94,124,146], Greece [102,103], Hong Kong [85,86,134], Ireland [123], Italy [44], Japan [143], Korea [76], Oman [24], Saudi Arabia [42,108,142], Scotland [48], Sweden [37], Switzerland [112], United Arab Emirates [97,111], USA (Alaska) [49]	33

4.1.2. *Target criterion*

The adopted perspective is closely linked to a further shortcoming of many of the studies examined: the choice of the target criterion. In 103 (84%) of the studies only costs were minimized. As already shown in section 1, however, costs are not the only reason for EA projects. In a few studies, a different target criterion than costs is applied, but these analyses do not represent an improvement since also only one criterion is considered: technical feasibility [85,116], annual efficiency [102,103] or coal consumption [130]. However, beside the above-mentioned MCDA approaches, other multi-objective approaches represent improvements. In addition to costs, the criteria in Table 7 are also taken into account in the reviewed studies. Possible weightings for the criteria could either be determined on site before the case studies, or taken from surveys such as in Ref. [5].

4.2. *System boundaries*

This section first presents the spatial resolution and location of the case studies in the reviewed literature (cf. section 4.2.1). Section 4.2.2 then shows that the focus is primarily on the demand product electricity. Finally, the demand sectors considered in the studies are highlighted (cf. section 4.2.3).

4.2.1. *Spatial resolution and location*

Table 8 classifies the case studies of the reviewed papers according to the income classification of *The World Bank* [384]. Most of the studies were conducted in the *lower middle income country* (LMIC) India (21), *upper middle income countries* (UMIC) Iran (17) and China (6) as well as the *high income country* (HIC) Germany (7). Whilst the case studies in India and Iran focused mainly on the ESs of remote areas without grid connection, in Germany a complete electrification already exists. The case studies on complete autonomous ESs in HICs are therefore more about isolating communities from the transmission grid. These studies are linked to the question whether the ES transformation should be achieved through decentralized or centralised expansion of RE sources. In Ref. [387], for example, the decentralized expansion is evaluated as more cost-effective for the German case due to higher required transmission grid expansion costs in the centralised case. The possible impacts of autonomous communities on the surrounding ES (cf. section 4.3) therefore plays a very important role especially in the HIC studies.

Whilst the *low income countries* (LIC), the LMIC and the UMIC mainly consider remote rural areas as case studies with 100%, 92% and 74% of the studies, respectively, these remote areas account for only 23% of the studies on HIC. Instead, studies on HIC also often investigate EA for islands (23%), cities (20%), regions (17%) and municipalities (14%). This is also reflected by the number of residents examined in the case studies: in the studies on LIC, LMIC and

UMIC case studies with a maximum of 4,750 inhabitants are analysed; in the HIC studies, case studies with up to 640,000 inhabitants are investigated. The exact area or city names of the case studies as well as the number of households and inhabitants examined can be found in the supplementary Excel file.

In this context, it is noticeable that the complexity of the applied methodology adapts to the size of the considered region. This means, the smaller a region is chosen, the more details can be included in the analysis. For example, in Waenn et al. [123] the operation of the ES with 640,000 inhabitants is determined with the help of a less complex simulation (EnergyPLAN). The largest case study in which an ES is designed with the help of an optimization is in Schmidt et al. [117]: a large region with 21,000 inhabitants. However, in Schmidt et al. only two time slices are considered during the optimization (cf. section 4.4.2) to reduce the model complexity.

In [60,76,104,106,111,124,144] different spatial scales were compared as case studies, i.e. the number of households or inhabitants was varied. However, these studies do not yet provide indications about the optimal size of energy autonomous ESs.

4.2.2. Demand

In all the studies reviewed, the electricity demand of the ES is included. Heating or cooling demand, on the other hand, is only considered in 30 (24%) or 13 (11%) of the studies, respectively. As already indicated in section 1 for EA projects, this also demonstrates the focus on electricity in the literature. In most cases, the demand is based on time series that have been determined or collected beforehand. However, there are also examples of EA case studies such as Refs. [30,92,124], in which the demand and load profiles are determined automatically on the basis of publicly available data. The electricity and heat generation technologies used in the studies are presented in section 4.5.

In addition to electricity and heat, other demand products such as food are also indirectly taken into account, for example through land-use competition as in Schmidt et al. [117]. However, only direct demand products are discussed in the present literature review. This includes the demand for water considered in ten studies. In Refs. [28,46,47,63,93] this is considered by the electricity demand of a water pump, e. g. for an agricultural well. In Refs. [67,74,79,89] the ES contains a desalination unit for water distillation. In Fuentes-Cortés et al. [54] the *water-energy nexus* is considered in the analysis, which means that water demand in the energy supply is taken into account. In this case the water demand includes fresh water for households, water used for regulating the temperature of the thermal demand as well as water needed as by-product in the combined heat-and-power (CHP) units. Water consumption is included in Ref. [54] alongside costs and land use in the multi-objective function of the optimization model. Therefore [54], in particular shows a suitable way to consider water demand in future studies about autonomy. The studies [47,54,74,79] are the only examples which consider all three types of demand (electricity, heat and water).

4.2.3. Consumption sectors

Among the consumption sectors, mainly the residential sector is considered (102 studies; 83%), followed by the commercial sector (55; 45%), industrial sector (23; 19%) and transportation sector (11; 9%). The ES is usually designed for all considered sectors. By contrast, in Bagheri et al. [38] the residential, commercial and industrial sectors are examined in separate analyses. Thereby, the ES for the industrial sector shows the lowest *levelized cost of electricity* (LCOE) in the autonomous case with 100% RE. Whilst the commercial sector with schools and hospitals also is important in studies about remote areas, larger industries and the transport sector are considered almost exclusively in case studies for municipalities, cities, islands or larger regions. In Refs. [72,73], industries are also considered in remote villages. However, they are referred to as *rural industries*, which probably corresponds more to the commercial sector of HICs in terms of demand structure. An interesting point is that in the cases where heat and industry were regarded, only a balanced autonomy is part of the analysis. This is probably due to the fact that, for example, high-temperature heat in industry can only be generated with specific RE plants and, in the completely autonomous case, would be associated with excessively high costs.

For residential, commercial and industrial sectors, the demand is usually known in advance in the studies. However, for the consideration of the transport sector several different approaches are applied. In Refs. [70,100,104,123] a fixed fuel demand for traditional vehicles is covered. In Refs. [51,52,116], electric vehicles (EVs) are considered within the EnergyPLAN model. In Dorotić et al. [51] all vehicles and ferries on the island of Korčula in Croatia are replaced by electrically powered alternatives. The EVs not only serve as batteries, but can also be used for vehicle-to-grid, i.e. feeding electricity from the EV battery into the grid. Šare et al. [116] analyse three scenarios for the municipality Dubrovnik in Croatia with different EV penetrations in 2020, 2030 and 2050. Krajačić et al. [79] and Oldenbroek et al. [99], on the other hand, included fuel cell vehicles in their ES analyses. In some scenarios in Ref. [79] the transport load is covered 100% by renewable hydrogen. None of the studies optimizes the number of electric or fuel cell vehicles.

4.3. Feasibility and type of autonomy

In the reviewed literature, studies on completely autonomous ESs predominate with 110 (89%), whereas balanced LEA is only considered in 14 (11%) studies. The only study that analyses both cases seems to be Sameti and Haghighat [112], in which a net-zero energy district is investigated in three scenarios with grid connection and one as a stand-alone variant without grid connection.

Generally EA is feasible in the case studies. The only exception is the study by Alhamwi et al. [30] who do not obtain a feasible solution in their ES model and come to the conclusion that an off-grid city (165,000 inhabitants) is economically and technically not practicable. However, there are also other examples which do not come to a favourable result for LEA. Krajačić et al. [79] find that the cost of electricity for a *100% renewable island* is up to 15 times higher than the current (2009) electricity price. Furthermore, in Oldenbroek et al. [99] a 100% renewable supply can only be achieved if 20% of the vehicle fleet are fuel cell vehicles. Also Šare et al. [116] come to the conclusion that large storage capacities are necessary for a 100% renewable supply. Jenssen et al. [70] show that the available biomass potentials of a model municipality are sufficient for 100% power and heat supply, but not to replace transport fuel. All these examples have in common that they examine bigger regions, cities and islands as case studies in high-income countries in Europe.

In the studies on completely autonomous ESs, uncertainties due to disconnection from the grid infrastructures should play a very important role, since a non-optimal design of the ES cannot be compensated by imports. Therefore it is even more important to design these ESs robustly. There are several appropriate approaches in the studies. For example, in 39 (32%) studies a possible security of supply below 100% is implemented as a *loss of power supply probability* (LPSP). In most cases ([34–36,45,47,58,59,63,65,69,71–73,81,82,84,85,89–91,95–97,101,109,113,114,127,129]), the LPSP is modelled as a fixed value or results from other fixed values. Other studies ([37,61,68,83,98,106,115]) in which the LPSP is associated with weightings or penalty costs and thus integrated into the objective function of an optimization represent an improvement. In Hakimi et al. [61] different penalty costs were assumed for the residential, commercial and industrial sector. In future studies, the so-called *value of loss load* could be a suitable estimation of penalty costs. In Shivakumar et al. [388], for example, the value of loss load was calculated for households in all European Union member states. This data set with penalty costs based on the same methodology could make results of studies more comparable. As expected, the LPSP are rarely considered in HICs, as the inhabitants are accustomed to high security of supply. Four case studies in Canada [145], Sweden [37] and Hong Kong [85,134] are the only examples. However, for autonomous systems these LPSP become more relevant.

Further studies try to robustly design off-grid ESs by taking extreme conditions into account. In Petrakopoulou et al. [102,103], the plants of the ES are over-dimensioned and complementary technologies are used. In addition, the optimization model in Weinand et al. [124] considers extreme days on which demand is particularly high and no wind or solar radiation is present.

4.4. Time structure and pathway

In this section the time horizon (section 4.4.1), the chosen temporal resolution (section 4.4.2) and the pathway for the ES transition (section 4.4.3) are demonstrated.

4.4.1. Time horizon

The time horizon in the case studies is usually chosen between 15 and 25 years, which represents an appropriate choice for estimating total discounted system costs or LCOEs for an ES. However, there are also variations upwards and downwards: Adamarola et el [28]. and Drysdale et al. [52] even consider 35 and 45 years respectively. Jenssen et al. [70], Moeller et al. [94], Oldenbrock et al. [99], Østergaard and Lund [100] as well as Šare et al. [116] consider one year whereas Kandil et al. [74] use only a time horizon of 24 h. For the latter study, a time horizon of 24 h could be too short, even though only the operating costs of an autonomous ES are determined. At least an extreme day should have been considered for this analysis.

4.4.2. Time resolution

The time resolution of models is of particular importance in studies on EA. This is especially true for completely autonomous ESs (cf. section 4.3). Non-optimal design of balanced energy autonomous systems could be compensated by imports from surrounding energy infrastructures. This does not apply for complete autonomy. Therefore, a particularly critical assessment is made when off-grid ESs are designed on the basis of an annual energy balance, as it seems in Stephen et al. [122]. Stephen et al. [122] investigate the residential and commercial energy supply for an off-grid Canadian aboriginal community. There are also other examples with a very rough time resolution, but these studies only consider balanced autonomy: Jenssen et al. [70] and Peura et al. [104] also conduct an annual balancing of energy (i.e. one time step) whereas the optimization model of Schmidt et al. [117] is based on two seasons (winter/summer) per year (i.e. two time steps).

In almost all studies (91, 74%) the time resolution is set to hours. There is only one study with a higher time resolution, namely Kötter et al. [78] with 15-min time steps. Kötter et al. investigate the balanced EA of a region consisting of 17 sub-regions in Germany. However, it is not clear how many of the 15-min time steps are used in the analysis. The robustness of results on completely autonomous ESs based on models with hourly resolution must at least be questioned. In these cases it is even more important to consider the methods explained in the previous section, such as LPSP or extreme conditions. In addition, ESs based on base-load capable technologies such as biomass can be considered more robust than those based only on volatile energy such as wind or photovoltaics (PV) (more on this in section 4.5). Usually all hours of a year are considered in the investigations with hourly resolution (59 of 91, 65%).

Overall it seems, however, that the number of time steps decreases with the complexity of a model, presumably in order to avoid computing time problems: the RE^{3}ASON model based on public data uses only 288 [92] or 432 [124] time slices and the multi-objective optimizations of Fuentes-Cortés and Ponce-Ortega [54] or Yazdanpanah Jahromi et al. [125] use only 96 and 744 time slices respectively. Another example is the optimization with *multi-tier targets* (e. g. scenarios with different demands) according to the *World Bank Global Tracking Framework* by Fuso Nerini et al. [56], which comprises only 18 time steps per year. This is a general problem of ES analyses. However, as mentioned above, the number of time steps is more crucial in ES analyses including complete EA.

4.4.3. Pathway

EA projects are always associated with the objective that the ES will become energy autonomous in the medium to long-term future. This means that there will be a *transition* over several years. However, in almost all reviewed studies (115, 94%), *overnight* is chosen as the pathway, i.e. the new ES replaces the old one immediateley and not during several years. This would correspond to an inaccurate calculation of total discounted system costs or LCOEs, as demands and costs may change during the considered time horizon. Only in Dorotić et al. [51], Drysdale et al. [52], Fuso Nerini et al. [56], Krajačić et al. [79], McKenna et al. [92] and Weinand et al. [124] was the pathway modelled as a transition. Dorotić et al. [51] seem to simulate at least every second year in EnergyPLAN from 2011 to 2030. The CO_2 emissions of the system are decreasing and the REs share is increasing until they reach their minimum (0% CO_2 emissions) or maximum (100% RE share) values in 2030. Drysdale et al. [52] also use the EnergyPLAN model. However, they seem to simulate only two years, 2016 and 2050. Fuso Nerini et al. [56] apply the system optimization model *OSeMOSYS* for a case study village in Timor Leste. The authors seem to optimize every year from 2010 until 2030. However, as mentioned above, for each year only 18 time steps are considered (six per day and three seasons per year), i.e. 360 time steps in total. Thereby the demand changes during the time horizon. For example, it is assumed, that the households reach the *target tier* in 2025. The target tier would be one of five tiers: for example the households would get access to general lighting, air circulation and television in *tier-2* or small appliances in *tier-3*. In the H_2RES model in Krajačić et al. [79] every fifth year from 2005 until 2015 is simulated. The same applies to the RE^{3}ASON model in McKenna et al. [92] and Weinand et al. [124] (time horizon from 2015 until 2030). In the two latter studies, however, the method is a mixed-integer linear optimization: all four years are optimized simultaneously, i.e. it is decided when which plant or measure will be installed. By considering the existing infrastructure (e.g. already installed PV modules), as in the RE^{3}ASON model, models are enabled to consider a transition pathway.

4.5. Technologies

As already discussed in section 4.1, many case studies on energy autonomous remote rural areas deal with the reduction of diesel and the increase of REs in the system. As shown in Table 9, diesel, therefore, is the most frequently considered in the studies after PV, wind and stationary batteries. A total of 73 studies (59%) consider

Table 9
Classification of the technologies included in the reviewed literature as well as the frequency of their consideration.

Category	Technology	No. of studies
Renewable electricity generation technologies	PV	117 (95%)
	Wind (onshore)	85 (69%)
	Biomass CHP	39 (32%)
	Hydropower plant	21 (17%)
	Concentrated solar power	3 (2%)
	Deep geothermal plant	2 (2%)
Heating/cooling technologies	District heating/cooling	10 (8%)
	Heat pump	7 (8%)
	Solar thermal collector	6 (5%)
	Electric heater	6 (5%)
Storage technologies	Stationary battery	93 (76%)
	Hydrogen with fuel cell	18 (11%)
	Thermal	8 (7%)
	Pumped-hydro	4 (3%)
	Power-to-Gas (methanisation)	2 (2%)
Transport technologies	Electric vehicle (modelled with battery)	3 (2%)
	Fuel cell vehicle	3 (2%)
Conventional generation technologies	Diesel generator	63 (51%)
	Gas fired CHP	6 (5%)
	Gas turbine plant	6 (5%)

conventional generation technologies such as diesel generators and gas fired CHP/turbine plants in their ES analyses.

When classifying biomass CHP, hydropower plants, deep geothermal plants as well as conventional generation technologies as baseload-capable, 26 studies (21%) remain, in which only volatile generation technologies are considered. In 16 of these 26 studies, no long-term storage options such as hydrogen storage, pumped-hydro-storage or power-to-gas are considered. In such cases, it is essential to take account of uncertainties. In ten of the 16 studies [34–36,65,69,84,90,114,115,134], these uncertainties are at least addressed via LPSP and in another study [102] by including extreme conditions. Even more than in other studies, the results of the completely autonomous ESs in Al-Shetwi et al. [31], Khan et al. [75], Kim et al. [76] and Mas'ud [137] must therefore be questioned, in which only volatile energy technologies and no uncertainties are considered.

The fact that so few studies examine heating or cooling technologies (cf. Table 9) is related to the focus on electricity in the studies (cf. section 4.2.2). In addition, technologies that do not belong to the standard technologies such as PV or wind are primarily investigated in case studies in HIC in Europe. For example, the technologies deep geothermal energy, power-to-gas or district heating are analysed primarily in Germany (deep geothermal energy: [124]; power-to-gas: [78,94]; district heating: [70,124]) or Denmark (deep geothermal energy (only heat): [100]; district heating: [52,100]), while unconventional vehicles such as EVs [51,52,116] or fuel cell vehicles [79,99,141] are examined primarily in case studies in Croatia. This suggests that the studies on remote rural areas are primarily concerned with the electrification of the area and not with the choice of optimal energy technologies. On the other hand, technologies such as deep geothermal energy (despite high potential in e.g. India or Sub-Saharan Africa [389]) are not relevant for these rather small regions (see section 4.2.1) due to high fixed costs [124].

In summary, the studies on LEA investigate a wide range of technologies. However, for a robust design of an energy autonomous system based on REs, the combination of fluctuating and non-fluctuating generation technologies as well as different storage technologies could be advantageous. Some of these technologies that could be beneficial in a completely autonomous case, such as seasonal heat storage, have not yet been analysed. In general, the more diverse the technologies under consideration, the more economically or environmentally sustainable the ES could be designed. On the other hand, the complexity and computing time of ES models increases with the number of technologies. In any case, work still needs to be done in which a very broad range of technologies is considered and the optimum technologies for EA are identified. Based on the results of the reviewed studies, no definite trend towards the most economic technologies for achieving EA can yet be identified (cf. section 4.7).

4.6. Grid infrastructures

Grid infrastructures are rarely modelled in the studies. Heating grids are implemented only in Refs. [92,112,124], the electricity grid only in Refs. [30,92,94,124]. In Refs. [26,77] at least the costs for setting up the distribution network are taken into account. It is interesting to note that all four case studies that consider the electricity grid are located in Germany. In Refs. [92,124] the electricity and heating network is only represented in a simplified way by energy flows between districts. However, Weinand et al. [124] also contains a transferable approach for designing district heating networks in arbitrary municipalities. District heating systems are also designed in Sameti and Haghighat [112]. While in Ref. [124] the district heating network is modelled top-down for entire municipalities, Ref. [112] is better suited as a bottom-up application for districts for which exact building locations and energy demands are known. Therefore, depending on the application, the two studies offer possible approaches for future analyses.

In Moeller et al. [94], the capacities and connections of the electric transmission network between German regions are modelled. The analysis also examines whether the transmission capacities are sufficient, depending on the share of REs. In the FlexiGIS model in Alhamwi et al. [30], OpenStreetMap is used to obtain data on lines and substations of the distribution network in order to determine the optimal placement of a battery storage in an urban area. Unfortunately, power grid data is not yet completely included in OpenStreetMap and therefore this method is not useable for every case study.

Electricity grids are only considered in a simplified way in the papers. A promising approach for future studies could be the one of Morvaj et al. [156], in which the distribution network is modelled according to a linearized AC power flow approach. Of interest is the implementation of a binary modelling variable, which determines

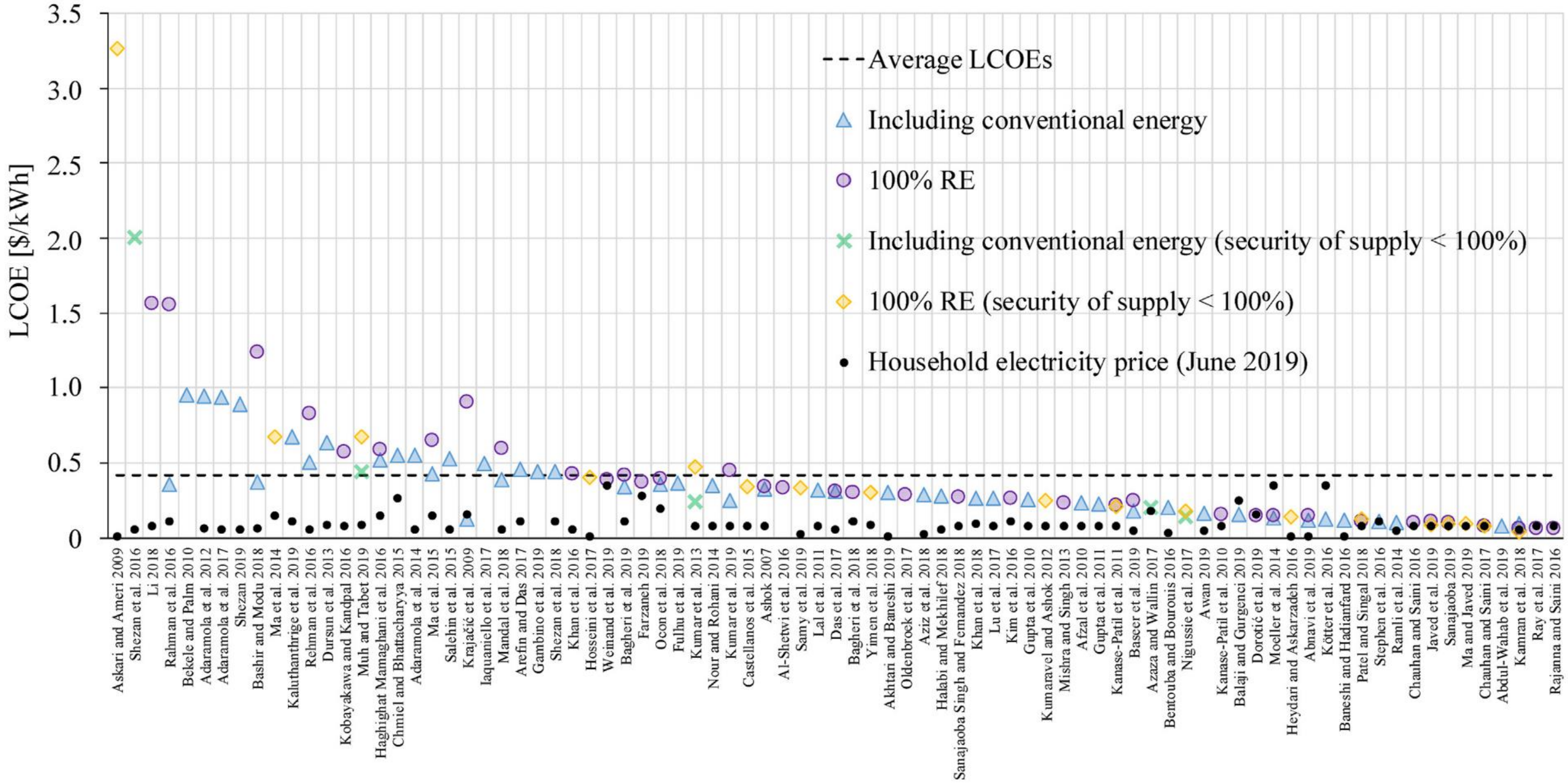

Fig. 3. LCOEs of the energy autonomous case studies in the literature. The studies are sorted by mean LCOEs, from high to low. The LCOEs were adjusted according to inflation until 2019 [391] and converted into $/kWh using the average exchange rates [392-394] in the year of the respective publication. The household electricity price (black dots) in the different countries is shown for comparison [395]. The black dotted line shows the average value (0.41 $/kWh).

Table 10
Mean levelized cost of electricity in the 83 studies depending on the characteristics of the energy systems. The LCOEs were adjusted according to inflation until 2019 [391] and converted into $/kWh using the average exchange rates [392-394] in the year of the respective publication.

Characteristics of energy system	Number of studies	Mean LCOE [$/kWh]	Highest outlier [$/kWh] and respective study	Mean LCOE without highest outlier [$/kWh]
All energy systems	83	0.41	3.27 (Askari and Ameri [34])	0.38
Including conventional energy	48	0.37	0.95 (Bekele and Palm [66])	0.36
Including conventional energy (security of supply < 100%)	5	0.61	2.01 (Shezan et al. [121])	0.26
100% RE	37	0.41	1.57 (Li [82])	0.38
100% RE (security of supply < 100%)	18	0.43	3.27 (Askari and Ameri [34])	0.27

whether the distribution grid needs to be upgraded, depending on the amount and type of REs added to the ES. In the case of an upgrade, the expansion of REs would involve additional costs. However, the study uses available grid data of the *IEEE European Low Voltage Test Feeder case* [390]. Since this grid data is not available for arbitrary case studies, the grid capacities would have to be estimated.

4.7. Costs

Section 4.1 has already shown that the ESs in the literature were mostly designed on the basis of cost minimization. Therefore, a comparison of these costs is reasonable. In 83 (68%) of the 123 studies, the LCOEs for autonomous ESs were stated (cf. Fig. 3). For Fig. 3, the LCOEs from the studies were adjusted according to inflation until 2019 [391] and converted into $/kWh using the average exchange rates [392–394] in the year of the respective publication. As all but one of the 83 studies consider the residential sector, the household electricity price (import from grid) in the different countries is shown for comparison [395]. For eight countries (e.g. Ethiopia [66] or Yemen [31]), the household electricity price could not be found.

The mean LCOEs amount to 0.41 $/kWh (black dotted line in Fig. 3 and Table 10). Consequently, the costs in the studies of Khan et al. [75] and Hosseini et al. [65] are nearly average. The LCOEs in an ES with 100% RE (case studies with 100% RE as well as with 100% RE and a security of supply < 100% in Fig. 3 and Table 10) are on average 0.42 $/kWh (0.37 $/kWh without the outlier in Askari and Ameri [34]) whereas in an ES with conventional energy 0.39 $/kWh (0.36 $/kWh without the outlier in Shezan et al. [121]) is achieved. As expected, in studies considering both cases, the LCOEs of 100% RE systems are higher than of conventional ESs. Likewise, the LCOEs decrease if cases with security of supply below 100% are considered. Furthermore, the household electricity prices are lower than the LCOEs for the autonomous system for almost every study. The only exceptions include case studies in countries with above-average electricity prices (Australia [40], Croatia [51] and Germany [78,94]), or the two studies with the lowest LCOEs [106,109] in Fig. 3.

18 out of the first 20 upward outliers in Fig. 3 apply the HOMER model (for the other two, the applied model cannot be found in the article), i.e. a non-optimal design of the ES could be responsible for the high LCOEs (cf. section 3.1). In the following, the three studies from Fig. 3 with the highest upward outliers in the LCOEs are discussed (up to the study Li [82] with 1.57 $/kWh on average). The highest LCOEs in the study by Askari and Ameri in 2009 [34] are caused by the high inflation in Iran between 2009 and 2019 (+364%). As a result, the costs are adjusted from originally 0.75 $/kWh to 3.27 $/kWh. The study by Shezan et al. [121] with the high LCOEs of 2.01 $/kWh needs further investigation, especially since an unmet load of 0.01% is considered here, which should reduce the LCOEs. Unfortunately, by analysing the study it is not really possible to determine how the HOMER model achieves the high LCOEs for the most economic ES with PV, wind, diesel generator and stationary battery. However, surprisingly, a figure in the study shows more realistic HOMER results with LCOEs of 0.62 $/kWh, but these LCOEs are not discussed further in the text. In Li [82] the predefined design of the ES seems to lead to the high LCOEs of 1.54 $/kWh. In fact, an ES with 500 kW of PV and 9.1 MWh of stationary batteries is assumed for 100 households in China. This ES appears to be oversized, which again demonstrates the need for a good understanding of the ES when designing ESs with HOMER (cf. section 4.1). In addition, the PV-battery system is compared with a PV-battery-fuel cell system, but the capacities of PV and battery are not changed. Thus, it is obvious that the PV-battery system leads to lower costs.

The reason for the low LCOEs for energy autonomous systems of the downward outliers is more difficult to determine and would require an in-depth analysis in a separate study. In the case study in Rajanna and Saini [106], for example, there is great potential for baseload hydropower and bioenergy, which could be related to the low LCOEs of 0.07 $/kWh. Examining further studies for reasons related to LCOE would be beyond the scope of this literature review. However, the detailed table in the supplementary Excel file could be used in further studies to investigate the dependencies of the LCOEs on the characteristics of the studies, e.g. through cluster or regression analyses. The supplementary Excel File and Fig. 3 are useful as a basis for evaluating future studies about LEA. If, for example, the LCOEs deviate as much from the average of 0.41 $/kWh in future studies as in Li [82], the applied methods and results have to be further investigated.

Since most of the studies calculate LCOEs, these figures are very suitable for comparing the results of LEA studies. However, another cost parameter that is particularly relevant for the inhabitants who have to pay for the costs of the autonomous ES is rarely shown in the studies: total costs per inhabitant. These are only shown in Jenssen et al. [70] (1.4–2.3 k$), Schmidt et al. [117] (220 $/a more than in the reference scenario without autonomy) and Weinand et al. [124] (21.0–54.8 k$). However, the cost per inhabitant should be included in all future studies in order to assess the feasibility of the EA project.

In some studies, the costs of the completely autonomous ES are compared with the costs of grid connection [33,87,97,101,111,131]. In all examples, the grid connection scenario turns out to be less economical. This is due to the fact that these studies only consider remote areas that are far away from the nearest grid connection point. The break-even points for the distance from which the network connection would be worthwhile are calculated in Refs. [87,101,111,131]. This is also related to the question of the optimal degree of centralisation as well as the optimal size of energy autonomous municipalities (cf. section 5).

5. Critical appraisal of energy autonomy studies

In this section, some of the key findings of section 4 are subjected to further critical evaluation. Firstly, though it is difficult to generalize across all 123 reviewed studies, some emerging trends may be highlighted:

- Mostly conventional/established technologies are analysed, with less attention paid to emerging but potentially game-changing technologies such as deep geothermal energy and fuel cell vehicles;
- The sectoral focus is on residential, with much less consideration of industrial and transportation sectors;
- Network infrastructure is rarely considered, including electricity, gas and heat/cooling;
- Only a minority of studies account for the existing infrastructure as well as the transition from this state to some improved future state along a pathway;
- Most studies focus on complete EA, with some (12%) dealing with balanced EA.

The time resolution of most studies is hourly, with one study going into more detail at the 15-min level. For long-term planning purposes, the hourly resolution is suitable, but it should also be combined with more detailed analyses and/or information reduction techniques to generate time typologies and synthetic time slices. There is an established stream of research focussing on the most suitable/required time resolution for specific research questions, for ESs with significant renewable generation fractions (e.g. Refs. [396,397]). Studies addressing LEA could also benefit from exploring such approaches. Otherwise there is a danger that systems are incorrectly dimensioned and are inadequate to ensure supply security in times of peak demand, which for autonomous/off-grid systems is potentially critical.

There is also a lack of attention paid to non-economic and non-technical criteria in studies of EA at the local scale. Indeed, economic criteria are arguably the most important, but although they are necessary, they are not sufficient. In section 1, among others, it has already been highlighted that certain areas are very far from the national grid and therefore a stand-alone system is appropriate. In this case, the focus on costs as a target criterion is justified, however, the comparison of complete autonomy with the grid connection case should always be demonstrated. Otherwise, in future analyses of EA more criteria than costs need to be considered. There are other important reasons for municipalities to become energy autonomous besides costs, such as increased environmental awareness (cf. section 1). Furthermore, a comparison with the electricity price in section 4.7 shows that EA usually leads to significantly higher costs, and thus from a cost perspective there is no potential for EA.

In terms of the modelling approaches employed for highly renewable, autonomous ESs there is a clear dominance of linear programming (i.e. optimization) and simulation (i.e. dispatch rules for energy balancing), from a central planner perspective. It is encouraging to find that many researchers are also capturing the non-economic criteria such as health, noise, water and acceptance issues (cf. Table 7). However, these contributions are still in the minority of those reviewed here, and the overwhelming majority do not satisfactorily reflect the true complexity encountered in real-world energy transitions. It is common practice to leave stakeholder roles outside the scope of the studies or models and to calculate optimal autonomy transition pathways with a centralised planning approach under the selected objective of technical feasibility and economic viability. However, local ESs are complex socio-technical systems consisting of different decision-making entities and technological artefacts governed by energy policy in a multi-level institutional space [11]. Social relationships among the stakeholders represent a major driver or barrier as also stated by previous reviews [4]. In this context, adoption behaviour approaches are useful to understand the types of barriers that exist for new technologies, and what kind of policies are important to increase diffusion. As a consequence, realising the potential of LEA is not simply a question of technical realities but also a question of individual behaviour and group dynamics. Relevant local stakeholders as households or communities, energy producers, energy suppliers, service providers, as well as local policy-makers are inter-dependent in the realisation of their goals. Future system models need to include the heterogeneous roles different stakeholders play in an existing local environment and the resulting impact their decision making might have. One possible solution could be the extension of the presented techno-economic modelling approaches with the help of socio-economic modelling approaches as agent-based models [398,399] or system dynamics models [400].

Many different spatial scales (e.g. number of households) have been considered in the case studies (cf. section 4.2.1). Whilst the optimal spatial size of an energy autonomous region has not yet been identified, it is interesting to note that the mean number of households and inhabitants in energy-autonomous regions is 340 and 18,200, respectively (based on the 56 and 49 articles containing this information, respectively). This is strongly linked to the question of the optimal degree of centralisation [401]. Concerning demand and consumption sectors there is also some potential for improvement (cf. section 4.2). The demand product water, for example, which is strongly linked to energy, or the consumption sector industry is only very rarely taken into account. For the latter, transferable methods to determine the energy demand and load profile of industries in arbitrary regions could facilitate its implementation. The transport sector is also almost completely ignored in studies about LEA. A particularly interesting approach would be to optimize the number and use of electric or fuel cell vehicles. In general, however, all sectors should be taken into account, especially when estimating the impact of one or many energy autonomous regions on the surrounding ES.

Validation is challenging in the context of local ESs, which might explain why very few existing studies attempt to do this. Often detailed data on the existing ES is lacking and validation for some hypothetical future scenario is obviously not meaningful. Model design and data assumptions of studies used to gain insights to form the decision making should be transparent and accessible. This not only allows independent review of various stakeholders but also the complete reproducibility of the results [402]. Whilst there is a strong trend towards open-source models and data within the wider ES modelling field [403], of the reviewed models, none appear to be fully open source, with HOMER and EnergyPLAN only being open access. Hence LEA studies could increase efforts to publicly release data and system models as well as assumptions and results interpretation, in order that diverse affected stakeholders are able to participate in the decision-making process [402,404].

In the future, the increasing availability of large(r) amounts of (more) open data should facilitate the implementation of data-driven methodologies. These approaches are already providing helpful insights into different aspects of energy production and demand. For example, machine learning approaches are capable of capturing non-linear and complicated relationships, and could be implemented more often [405]. In future EA case studies, such approaches could be used to detect existing renewable energy plants [406], predict renewable energy generation [407] or predict energy demands [408,409]. Data availability can therefore not only facilitate the validation of results, but also create novel insights through the application of innovative methods. Improved data quality should help to increase the accuracy of energy system models for decentralized energy systems.

In addition, the focus on the LCOEs as a benchmark for highly-RE systems could provide potentially misleading results. Whilst the LCOE is a good first indicator of the generation costs and allows comparisons across technology, it is noted for neglecting the additional costs of integrating non-dispatchable renewable technologies into the ES. Three additional cost components should be considered, if the true *system LCOEs* of RE technologies are to be considered [410,411]:

- **Profiling costs**, related to the requirement for the dispatchable generation technologies to meet the residual load;
- **Balancing costs**, related to the deviation between forecast and actual non-dispatchable renewable generation; and
- **Grid costs**, related to addition grid reinforcement and extension (at all voltage levels) required to connect renewable generators to the network.

Attempts have been made to consider these cost components in the context of large-scale (e.g. national) ES analyses (e.g. Refs. [412–414]). However, at the regional and municipal scale, as demonstrated by this review, they are typically not included. This is despite the fact that, when considering balanced autonomy, these effects on the surrounding ES are of particular importance. Balanced EA and the associated increasing feed-in by renewables could make network expansion even more essential and also make new allocation systems for grid fees necessary [401]. The result could be economic inefficiencies compared to the established system of centralised generation, transmission and distribution [415]. However, possible ES impacts were not considered in any of the 14 studies on balanced autonomy. Hence there is a need for further research to address these and the above mentioned deficits.

6. Summary and conclusions

Research attention on decentralized autonomous energy systems has increased exponentially in the past three decades, as demonstrated by the absolute number of publications and the share of these studies in the corpus of energy system modelling literature. This paper shows the status quo and future modelling needs for research on local autonomous energy systems. A total of 359 studies are roughly investigated, of which a subset of 123 in detail. The studies are assessed with respect to the characteristics of their methodology and applications, in order to derive common trends and insights.

The results show that most case studies were conducted in the middle-income countries India, Iran and China as well as the high-income country Germany. In the middle-income country studies, mostly remote rural areas without an electricity network connection are considered, whereas in high-income countries the case studies are much more diverse and also include cities and islands. In addition, most studies only focus on the residential sector and the supply of electricity. A wide range of technologies has already been covered in the literature, including less common technologies such as power-to-gas and fuel cell vehicles. However, the network infrastructure is rarely considered. The levelized costs of electricity for local autonomous energy systems in 83 case studies amount to 0.41 $/kWh on average. Thereby, studies are identified in which the resulting costs should be questioned, as they deviate strongly from the average.

In terms of the employed methodology, most of the reviewed literature reports an optimization or simulation approach, with a central planner perspective. They typically employ a time resolution of 1 h, but for some studies also increase this to 15-min resolution. Whilst it is commendable that some of the studies also consider non-economic criteria such as social and environmental aspects, neither the system-level impacts nor the diverse stakeholders are included in most works. Furthermore, there is a general lack of transparency across most reviewed literature, meaning that neither open data nor open models are widely applied to local energy systems.

Hence, future research should focus on the following methodological innovations. Other perspectives than that of a central planner and other target criteria than costs should be included. This could contribute to the realizability of the case study results. System impacts of many local autonomous energy systems have not yet been investigated, which could make new distribution systems and grid fees necessary. Complete autonomous energy systems in particular must be robustly designed, for example by analysing the value of lost load and whether a security of supply below 100% is acceptable for consumers of the case study, preferably using penalty costs for unmet load in the target function. In addition, extreme conditions such as extreme days with low solar radiation or wind should be considered and the temporal resolution should be higher than the usually used hourly resolution. Finally, methodologies should be developed which can involve local stakeholders in the modelling process and thus consider their preferences relating to their future energy system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2020.117817.

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Developing a municipality typology for modelling decentralised energy systems

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ABSTRACT

One solution to the large-scale integration of renewable energies could be decentralised autonomous municipal energy systems. Several studies have already analysed the technical and economic implications of the mainly decentralised future energy system, but most are restricted in their insights by limited temporal and spatial resolution. This study employs a cluster analysis to develop a municipality typology in order to analyse the techno-economic suitability of municipalities for autonomous energy systems. A total of 34 socio-technical indicators are employed at the municipal level, with a particular focus on the sectors of Private Households and Transport, and the potentials for decentralised renewable energies. Selected quantitative cluster validation methods are employed alongside qualitative criteria to determine the optimal number of clusters. This results in a total of ten clusters, which show a large variation as well as some overlap with respect to specific indicators. An analysis of the municipalities from three German renewable energy projects "Energy Municipalities", "Bioenergy Villages" and "100% Renewable Energy Regions" shows that in eight of the ten clusters municipalities are aiming for energy autonomy (in varying degrees). It is challenging to differentiate between the clusters regarding readiness for energy autonomy projects, however, especially if the degree of social acceptance and engagement for such projects is to be considered. To answer the more techno-economical part of this question, future work will employ the developed clusters in the context of an energy system optimisation. Insights gained at the municipal level will then be qualitatively transferred to the national context to assess the implications for the whole energy system.

1. Introduction

Ambitious national targets in energy policy are leading to a radical change in the energy industry, which is particularly marked by the expansion of renewable energies. Germany already generated 30% of electricity with renewable energy technologies in 2016 (Statistisches Bundesamt, 2017a), including around 50 GW of wind (on- and off-shore), about 7 GW of bioenergy and 40 GW photovoltaic (PV) plants (BMWi, 2016), of which around 98% are connected to the low voltage distribution networks (Wirth, 2016). Municipalities are often referred to as the driving force behind the energy transition since renewable energies alongside energy efficiency are exploited on a decentralised basis due to their characteristics. Hence the characteristics of the energy system are changing towards a more decentralised structure, which also applies to the owners and operators of energy plants. In Germany, private individuals are increasingly investing in renewable energy systems or forming so-called citizen-energy cooperatives for this purpose. In fact, the majority of renewable plants in Germany are owned and operated by private individuals, farmers and communities (Klaus Novy Institut e.V. & trend:research 2011). This development is based on various socio-economic motives: among other things, citizens have the desire to play an active role in energy supply and to be more independent of central markets and structures (e.g. Boon and Dieperink, 2014; Volz, 2012).

In this context, the concept of municipal energy autonomy (Deutschle et al., 2015; Rae and Bradley, 2012; McKenna et al., 2014b, 2015, 2017b) has become established, which is employed here to also include energy autarky (Müller et al., 2011), self-sufficiency (Deutschle et al., 2015; 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 can be made between complete energy autonomy (i.e. off-grid), net or balanced energy autonomy, whereby local generation equals or exceeds demand on an

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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 overwhelming number of municipalities with energy autonomy aspirations strive for the state of balanced energy autonomy and that the focus is usually on electrical energy.

The feasibility of municipal energy autonomy has been investigated in several case studies. In Scheffer (2008), a rural model region with 10,000 inhabitants and agriculture as well as trade and commerce, but without large-scale industry, is considered. The suitability of a rural settlement structure for energy autonomy is also investigated in Peter (2013), who shows that renewable energies could cover the electricity requirements of the "example village" with 3850 inhabitants, but with immense storage costs. Jenssen et al. (2014) conclude that complete energy autonomy in an "average" German municipality is technically attainable through the "bioenergy village" approach, albeit at high costs. Schmidt et al. (2012) examine the advantages and disadvantages of energy autonomy compared to conventional energy supply in Sauwald, Austria. Woyke and Forero (2014) evaluate complete energy autonomy in Pellworm, a municipality with 1100 inhabitants, which has already been a model location for the construction of renewable energies. Although the supply of energy exceeds the demand, complete energy autonomy is not possible with the current energy system in Pellworm due to grid constraints. Finally, the study by Burgess et al. (2012) examines the Marston Vale region in the UK, which would have to import heat energy and fuel in particular, while a large proportion of the demand for electricity could be met by energy supplied by the region itself.

Despite some general conclusions from these studies, such as a tendency to focus on balanced energy autonomy and electricity in more rural municipalities, there is until now no general framework within which to assess the feasibility of energy autonomy for a specific municipality. In addition, the high spatial and temporal resolutions required to satisfactorily model decentralised energy systems with large fractions of renewable energies make approaches to information reduction indispensable. This paper goes some way towards filling these gaps by developing a typology of Germany's 11,131 municipalities to support the selection of municipalities for future decentralised energy autonomy projects. With the help of a cluster analysis, these municipalities are divided into homogeneous clusters according to socio-energetic indicators. The objective is to identify municipalities where energy autonomy aspirations could make technical and economic sense, and thereby to support the transferal of successful projects to other municipalities within the same cluster. In addition, a foundation for energy system models is developed which enables large-scale modelling of decentralised energy systems without the requirement for high spatial resolutions, which is often a central limitation in such models at the national scale and above (Keles et al., 2017). Finally, representatives of municipalities can be encouraged to initiate energy autonomy projects themselves if they have already been successfully implemented in a similar municipality.

The paper is structured as follows. Section 2 presents a literature review and more clearly locates this paper in context. Section 3 then presents the methodology, before section 4 presents and section 5 discusses the results. The paper closes with a summary and conclusions in section 6.

2. Literature review

Several areas of energy research are relevant to this contribution, including those relating to the analysis of decentralised and centralised energy systems, the field of urban morphology, and the application of cluster analysis to energy systems in order to reduce information quantity whilst retaining quality.

Characterising and contrasting centralised and decentralised energy systems is a relevant area of research for this paper because it strongly relates to the suitability of decentralised energy systems to become energy autonomous. Examples of contributions in this area include Funcke and Bauknecht (2016), who develop typologies for both of these types of energy infrastructure, by focussing on infrastructure location and operation. Further, Schmid et al. (2016) analyse the actor types, motives and conceivable roles within today's centralised and tomorrow's decentralised energy systems from the perspectives of technology, actors and institutions. Others raise the question of the optimal "degree of centralisation" (Zentralisierungsgrad), first coined by Jensch (1989), i. e. the level at which decentralised energy systems should be aggregated and balanced (Bauknecht et al., 2015). Currently, most energy autonomous regions rely on the overarching centralised energy system for their flexibility and controllability (Funcke and Bauknecht, 2016). For example, Wimmer et al. (2014) compare centralised with decentralised wind expansion scenarios, concluding that the overall flexibility requirements are similar in both cases. Reiner Lemoine Institut (2013) finds that a decentralised renewables expansion would be economically favourable, largely due to higher required network expansion costs in the centralised case. Others reach the opposite conclusion, however, that centralised and hybrid energy systems are more economically efficient than purely decentralised ones (acatech, 2016). Although it is clear that a completely renewable energy supply based on decentralised, autonomous regions does not seem economical due to very large storage requirements (Peter, 2013), there is no clear consensus about the optimal degree of centralisation. Especially the related question of the technical feasibility of decentralised energy autonomy is addressed in this paper whilst the micro- and macroeconomic assessment is left to future work.

Urban morphology is the second relevant research area. It focusses on the form of the urban environment, including building types, ages and forms, and (amongst other things) its implications for the energy system. The field is well established, as demonstrated by the earlier contribution of Steemers (2003), who analysed the relationship between urban morphology and energy use in buildings and transport, the two main sectors (other than industry) that are relevant for urban planning. Also Ratti et al. (2005) explored the effects of urban textures on building energy consumption with digital elevation models, with case studies in three European cities. Similar methods were also more recently employed in the LSECities project (Rode et al., 2014a, 2014b), which analysed the effects of different types of urban forms on heat energy demand and derived generalised insights into these relationships in larger European cities. In the context of her PhD thesis, Miller (2013) approaches the connection between urban form and building energy use with a multi-scale approach and using the Metro Vancouver region in Canada as an example. All of these studies demonstrate the diversity amongst the urban building stock, leading to a substantial variation in heat demand. Others within this field have examined the relationship between solar energy potential and urban morphology in London, concluding that by optimising combinations of eight variables of urban form the solar irradiation of roofs and facades could be increased by around 9% and 45% (Sarralde et al., 2015). More recently, Urquizo et al. (2017) explored different urban morphology metrics and their impact on energy consumption in four districts of Newcastle, UK. In a more detailed analysis, Hargreaves et al. (2017) investigate the most cost-effective decarbonisation options for regions with different urban forms in a UK context, showing for example how low-density urban areas are more suited to exploit ground-source heat pumps. Summarising, then, the field of urban morphology offers insights into the connection between energy demand and urban structures, but does not provide a transferable typology for the whole decentralised energy system.

The third and most relevant research field for this paper is that of cluster analysis. Despite being a common method in energy studies more widely, it has not often been employed in the analysis of decentralised energy systems. One example is Chévez et al. (2017), who examine the single region "Great La Plata" in Argentina at the administrative level. The region is clustered into eight census area types with a k-means cluster analysis according to the consumption of electrical energy and other socioeconomic variables. The most important result is that electricity consumption increases strongly with the household sizes, which could, for example, support the construction of distribution networks. In addition, Unternährer et al. (2017) cluster 6224 buildings not yet connected to the local heating network at the administrative level. Depending on indicators such as the demand for space heating and domestic hot water, as well as georeferenced drilling costs for deep geothermal energy, the cluster analysis results in 16 clusters. Clusters and typologies have often been applied at the district scale, in identifying the most cost-effective low carbon energy solution for different types of districts (Hargreaves et al., 2017; McKenna et al., 2016, 2017a; Su et al., 2017), as well as at the building scale, for example in the context of residential heat demand studies (McKenna et al., 2016, 2017a). In addition, Marquant et al. (2017) present a holistic approach for the optimisation of multi-scale distributed energy systems, by employing clusters of similar buildings at the district level.

There are some examples of applications of cluster analysis at higher levels of spatial aggregation. For example, Kaundinya et al. (2013) employ a k-medoid clustering method to divide a region in India into clusters of villages for supply with decentralised biomass power plants, and the value of k is chosen to minimise the total system costs. For Austria, Bramreiter et al. (2016) divide all of the 82 Austrian “Climate and Energy Model Regions (CEMs)”, which aim for energy autonomy, into three clusters by ten indicators (e. g. population density, employment figures, energy consumption). In a subsequent step, all other Austrian municipalities are examined by cluster analysis, with the aim of identifying municipalities with characteristics similar to those of the CEMs. It is shown that large parts of Austria could also become CEMs and thus have the potential to become energy self-sufficient, at least on an annual basis. In the study of Requia et al. (2017), all 5570 municipalities in Brazil are divided into five clusters. However, the analysis does not focus on socio-energetic indicators, but on six types of pollutant emissions in the Transport sector such as CO_2 and NO_X. To transfer the results to energy systems of municipalities, indicators for the other consumption sectors Private Households, Industry and Commercial would have to be included in the cluster analysis. The investigations are not always limited to one country. For example, Noiva et al. (2016) investigate 142 cities, spread across all continents. Indicators for the analysis of the cities divided into six clusters are the parameters of supply and demand for water.

Another relevant example in the present case is the PhD dissertation of Wall (2016), who conducted a cluster analysis with the German district-free cities ("kreisfreie Städte") as objects and based on 41 socio-energetic indicators. The cluster analysis in Wall (2016) differs from this study not only in the choice of indicators but also in the choice of the research objects. The survey objects are not the municipalities, but only the 107 district-free cities in Germany. Other studies have employed cluster analysis to German regions, but most of these neither have a high spatial resolution nor focus on energy aspects. For example, in Kronthaler (2003) Germany was divided into 97 regions, which were then assigned to ten clusters in a cluster analysis. The study looked at 13 socioeconomic indicators, including employment figures and investment in industry. The research showed that the economic power of the regions in eastern Germany is still significantly lower than that of the western German regions. Heinritz (2000) also came to a similar conclusion, by evaluating the economic strength of the 441 districts in Germany, and dividing the districts into five clusters by socio-economic indicators such as gross domestic product per inhabitant. In three other studies, German municipalities are investigated, but none of the studies considers all 11,131 municipalities. Geyler et al. (2008) only analyse 240 municipalities in the core region of Central Germany. The delimitation into six clusters is based on local development trends. These include 16 indicators such as the development of the settlement and traffic area or business tax revenue per inhabitant. In Schultz and Brandt (2016) 2916 of the 11,131 German municipalities are divided into nine clusters by demographic indicators (among other things, the “share of single-person households” or “share of under-18s”). Finally, the 1102 municipalities in the federal state of Baden-Württemberg are investigated in Statistisches Landesamt Baden-Württemberg (2009). The goal was not to place the municipalities in clusters but to identify the two municipalities that are closest to each other. Indicators such as population density or cars per 1000 inhabitants were used. Hence, although several German regions have been analysed with cluster analysis, a classification with energy indicators has not yet been made at the municipal level. This is the research gap addressed in this paper, as outlined in the following section.

3. Methodology

This section describes the data collection and standardisation (cf. section 3.1) as well as the execution of the factor analysis (cf. section 3.2) and cluster analysis (cf. section 3.3). The vast majority of cluster analyses evaluated in section 2 perform a hierarchically agglomerative cluster analysis with the Ward algorithm. 17 of the 23 analyses evaluated in Wall (2016) also apply hierarchically agglomerative cluster analysis. Hierarchical cluster analysis generates high-quality clusters and is, therefore, also used in this paper. To support the traceability of the cluster analysis, the most important information according to Bacher et al. (2010) is listed in Table 1.

3.1. Data collection and standardisation

Many of the indicators used in the studies mentioned in section 2 are also used in the cluster analysis presented in this paper, as well as newly selected indicators. This study uses the indicators in a comprehensive analysis and for the first time clusters all 11,131 municipalities in Germany. The 59 indicators used in the cluster analysis include data on the energy consumption sectors Private Households, Transport, Industry and Commercial as well as data to estimate the potential for renewable energies (see Table 2). The indicators whose data is only available at the district level are shown in italics in Table 2. In the following, the “X” values in brackets are used as abbreviations for the indicators. For the last three groups of indicators in the Private Household sector, the specific allocations of the “X” values will be described later in the text. Only the indicators used in the final analysis are assigned to “X” values. The question of why not all indicators are used is answered in section 3.1.5. A complete list of all indicators and their references is given in Table 8 in the Appendix.

27 of the 59 indicators were also used by Wall (2016) in his analysis of district-free cities. In the following, the reasons for selecting the additional indicators are explained.

3.1.1. Indicators of the consumption sector private households

Private households account for 26% of Germany's final energy consumption and should not be neglected in the energetic classification of municipalities. The majority of the final energy (69%) is used in households for space heating (Umweltbundesamt & BMWi, 2017).

3.1.1.1. Share of heating types. For the shares of heating types, the available data have been grouped into three groups:

Table 1
Overview of the most important aspects of traceability of a cluster analysis.

Objects	11,131 German municipalities
Variables/Indicators	59 Indicators (see section 3.1)
Algorithm	Ward
Cluster analysis method	Hierarchical-agglomerative
Criteria used to determine the number of clusters	26 different methods and elbow criteria (see section 3.3.2)
Software used	R

Table 2
Overview of the indicators used in the cluster analysis. Italics means that the data of the indicators were only available at the district level.

Consumption sector Private Households (29)	Consumption sector Transport (11)	Consumption sector Industry and Commercial (12)	Potential for renewable energies (7)
Population development between 2010 and 2015 (X1) [%]	Number of motor vehicles per 1000 inhabitants (X27)	*Share of employment in the industrial sector* [%]	Achievable hydrothermal temperature (X32) [°C]
Living space per person (X2) [m^2]	Number of cars per 1000 inhabitants (X28)	*Share of employment in the commercial sector* [%]	Necessary hydrothermal drilling depth (X33) [m]
Share of single-person households (X3) [%]	*Share of diesel vehicles* [%]	*Energy productivity of manufacturing industry* [€/GJ]	Technical PV potential per inhabitant (X34) [kWh/y]
Average household size (X4) [Persons]	*Share of petrol vehicles* [%]	*Energy intensity of manufacturing industry* [MJ/€]	Technical PV potential per km^2 (X35) [MWh/y]
Household density (X5) [Housholds per km^2]	*Share of gas vehicles* [%]	*Productivity level of manufacturing industry* [€/GJ]	Technical wind potential per inhabitant (X36) [MWh/y]
Share of owner-occupied apartments (X6) [%]	*Share of hybrid vehicles* [%]	*Specific energy consumption of manufacturing industry* [MJ/€]	Technical wind potential per km^2 (X37) [MWh/y]
Income per household (X7) [k€]	*Share of electric vehicles* [%]	*Share of industrial sales tax* [%]	Share of forest and agricultural land (X38) [%]
Share of over 65-year-olds (X8) [%]	*Share of other vehicle types* [%]	*Share of commercial sales tax* [%]	
Unemployment rate (X9) [%]	Population density (X29) [Inhabitants per km^2]	*Development of employment share in the industrial sector* [%]	
Share of settlement and traffic area (X10) [%]	Share of 18-64-year-olds (X30) [%]	*Development of employment share in the commercial sector* [%]	
Heating days	Share of commuters in the workforce [%]	*Development of energy intensity in the manufacturing sector* [%]	
Heating degree days		Number of manufacturing enterprises per 1000 households (X31)	
Degree day number			
Share of heating types (3 indicators) (X11-X13) [%]			
Share of building age class (9 indicators) (X14-X22) [%]			
Share of building type (4 indicators) (X23-X26) [%]			

1) Share of buildings with heating systems based on district heating (X11)
2) Share of buildings with heating systems not based on district heating (X12)
3) Share of buildings without heating system (X13)

This segmentation allows conclusions to be drawn as to whether and to what extent there is a district heating network, a gas network or both in the municipalities. The existing infrastructures influence the selection decision of technologies which are suitable in the municipalities. As an example, power-to-heat plants and power-to-gas plants offer great opportunities for future flexibility in power generation. However, to store the energy from these plants, various networks are required, such as a district heating network for power-to-heat plants or a gas network for power-to-gas plants (Böttger et al., 2014). Furthermore, district heating systems are suitable for the integration of heat from renewable energies such as geothermal plants (Durst, 2015).

3.1.1.2. Shares of building age classes. The insulation condition of the building envelope has a significant influence on the space heating requirement in buildings (Braun, 2010). The building age class influences the insulation condition of the building envelope and is, therefore, an essential indicator for estimating the heat demand (Schuler et al., 2000). In the cluster analysis applied here, the building ages were divided into nine groups (see Table 8 in the Appendix).

3.1.1.3. Shares of building types. The type of building also has a significant influence on the demand for space heating in private households (Wei et al., 2014). Shipworth et al. (2010), for example, showed that the operating hours of the heating system in English homes are statistically dependent on the type of building. The biggest difference was found between detached houses, in which the heating is on for much longer, and terraced houses. This study distinguishes between detached houses (X23), semi-detached houses (X24), terraced houses (X25) and "other types of buildings" (X26).

3.1.2. Indicators of the consumption sector transport

For the indicators representing the Transport sector, the shares of hybrid, gas and other vehicles in the vehicle stock have been added (compared to Wall, 2016). Hybrid vehicles also include an internal combustion engine in addition to the electric motor. The combustion engine can compensate for the disadvantage of the limited range of electric vehicles (Høyer, 2008). The number of gas vehicles in Germany is around 100,000, and they can contribute to a significant reduction in pollutants and, in some cases, CO_2 emissions. If biomethane or synthetic methane is added to the fuel, gas vehicles can be as climate-friendly as electric vehicles (BMWi, 2016).

3.1.3. Indicators of the consumption sector Industry and Commercial

The Industry consumption sector accounts for almost 50% of the electricity supplied in Germany (Javied et al., 2016). Most of the data from the Industry consumption sector are only available for the manufacturing sector. These data are suitable for estimating the energy consumption of industry, as manufacturing accounts for the largest share of energy consumption (27.4% of Germany's total primary energy demand) (Umweltbundesamt, 2016).

3.1.3.1. Number of manufacturing enterprises per 1000 households. The number of manufacturing enterprises is the only indicator of this sector provided at the municipal level. The indicator is based on 1000 households to compare the values for the different municipalities.

3.1.4. Indicators of the potential for renewable energies

In most practical examples of municipal energy autonomy, renewable energies are used to establish a sustainable energy system (Schmidt et al., 2012). Therefore, the potentials of renewable energies in a region are important indicators. The potentials of renewable energies applied in the cluster analysis are explained below.

3.1.4.1. Achievable hydrothermal temperature. In Germany, an increase in deep geothermal power stations is expected by 2030 (installed capacity in 2030: 850 MW_{el}) (Hechler and Bredel-Schürmann, 2011). From 2003 to 2017, the annual supply of thermal energy by deep geothermal energy plants has increased from 60 GWh_{th} to 1.3 TWh_{th}, the supply of electrical energy has increased from 0 GWh_{el} to 155 GWh_{el} (Agemar et al., 2014, 2018 Umweltbundesamt, 2018). In this study, the focus is on hydrothermal systems, because petrothermal systems are not yet used in Germany (Hechler and Bredel-Schürmann, 2011). Electricity from geothermal energy currently receives a subsidy of 25.2 €-cents/kWh (Deutscher Bundestag, 2017).

Hydrothermal power plants have two main advantages: on the one hand, unlike many other renewable energy plants, they are capable of providing energy as base load. On the other hand, they show the lowest emissions of pollutants after hydroelectric power plants during the life cycle of the plant (Purkus and Barth, 2011). At the municipal level, several geothermal power plants are already being used to supply local and district heating (Hechler and Bredel-Schürmann, 2011). Therefore, the use of this technology should also be considered in future energy autonomy efforts.

An important indicator for estimating the economic potential of a geothermal plant is the achievable hydrothermal temperature. Hydrothermal temperatures above 110 °C are required for the economical operation of a geothermal plant to generate electricity (Agemar et al., 2014). Fig. 1 shows that the achievable hydrothermal temperatures strongly depend on the region. This means that municipalities have different hydrothermal potentials. Therefore, the indicators for

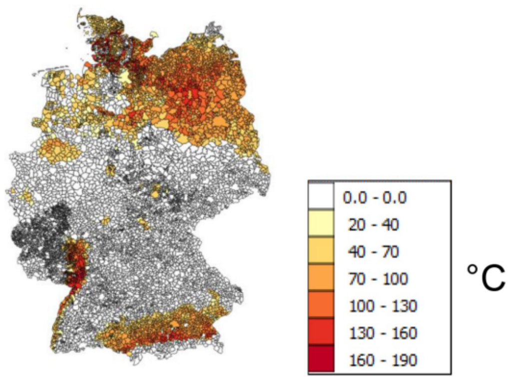


Fig. 1. Achievable average hydrothermal temperature (°C) at a depth of up to 5000 m in German municipalities according to Agemar (2017).

hydrothermal energy are included in the cluster analysis.

3.1.4.2. Necessary hydrothermal drilling depth. The depth of drilling to the water reservoirs mainly determines the amount of investment for a geothermal plant. The depth of the well depends on the local temperature gradient. In Germany, the average temperature gradient is 32 K/km, in some regions (Upper Rhine valley) up to 100 K/km are reached (Agemar et al., 2014).

3.1.4.3. Technical photovoltaic (PV) potential per inhabitant/per km^2. The data from Mainzer et al. (2014) were used to estimate the PV potential in municipalities. However, this data must be made comparable for the cluster analysis. The indicator is therefore determined by dividing the PV potential in kWh by the number of inhabitants. This means that the technical PV potential per inhabitant can now be used for each municipality. However, this does not yet complete the estimation of the PV potential, as this indicator does not allow a statement to be made about the potential of the PV systems in the relation to the area. For this purpose, the energy density of the PV systems is determined by dividing the PV potential in MWh by the area in km^2.

3.1.4.4. Technical wind potential per inhabitant/per km^2. The indicators for the technical wind potential in MWh were determined in analogy to the technical PV potential per inhabitant and per km^2. The data from McKenna et al. (2014a) was used for this. This data is available at postcode level and could be assigned to the municipalities using the geoinformation system QGIS.

3.1.4.5. Share of forest and agricultural land in total area. Land areas are required for the construction and operation of many technologies based on renewable energies such as wind power plants, ground-mounted photovoltaics and biogas plants (Marx Gómez et al., 2014). While wind power plants may only be built in certain areas such as forests or agricultural land, biogas plants require entire areas for the cultivation of energy crops (mainly maize) (Lüker-Jans et al., 2017; McKenna et al., 2014a). The proportion of woodland and agricultural land in the total area of the municipalities can, therefore, be used as an indicator to estimate the potential for these renewable energies.

3.1.5. Data in the investigation

In the final study, only 38 of the 59 indicators were used. The indicators used are marked in Table 2 with a compounded X-value. The first cluster analysis with all indicators showed that there was too much dependence on the indicators based on district data for them to accurately represent values for municipalities. For this reason, the indicators shown in italics in Table 2 were excluded from further analysis. In addition, the indicator “Share of commuters in employment” could not be included in the study, as the data only exist for 2014 and are incomplete.

Furthermore, one indicator for each of the proportions of heating types, building age classes and building types were eliminated for a reason described below. Many calculation steps of a factor and cluster analysis require a positive semi-definite data matrix (Lorenzo-Seva and Ferrando, 2006). A symmetrical matrix is positive semi-definite if all eigenvalues are nonnegative (Zhang, 2011). In this study, the matrices were not positive semi-definite. This problem was solved by eliminating linearly-dependent variables. Since the proportions of the indicator groups heating types, building age classes and building types can be added up to 100% in each case, an indicator value can always be calculated with the other indicator values. Therefore, X13, X22 and X26 are deleted from the dataset. More information about positive semi-definite matrices can be found in Zhang (2011).

3.1.6. Standardisation

Once the data is complete, it must be standardised for factor analysis. Standardisation serves to make the indicators comparable in their range of values (Milligan and Cooper, 1988). This prevents indicators with larger values from being weighted more strongly. Many studies use the Z-transformation to standardise the data. The standardised values Z are calculated using the original indicator value X, the arithmetic mean $\bar{X}$ and the standard deviation s (Heyde, 1990):

$$Z = \frac{X - \bar{X}}{s} \quad (1)$$

However, Milligan & Cooper (1988) showed that this traditional Z-value method leads to poorer results in cluster analyses than other standardisation methods. In most cases, the Z-value method works well only with normally distributed data (Office for National Statistics, 2015). The following calculation has proved to be the best method, which is also used in the present study (Milligan and Cooper, 1988):

$$Z = \frac{X - \min(X)}{\max(X) - \min(X)} \quad (2)$$

3.2. Exploratory factor analysis

An exploratory factor analysis serves to examine the data and reduce the number of (required) indicators. The j-th factor F_j can be determined using the k indicators $X_1, X_2, \ldots, X_k$ and the weights or factor loadings W_{ji}:

$$F_j = W_{j1}X_1 + W_{j2}X_2 + \ldots + W_{jk}X_k \quad (3)$$

The larger the factor load W_{ji}, the stronger the value of the factor F_j is determined by the indicator X_i (Aljandali, 2017). The R-function "fa" from the package "psych" is used here for factor analysis (Revelle, 2017). Factor analysis was conducted following the steps proposed in Osborne (2014), which are explained below.

3.2.1. Selection of the extraction method

An extraction method is used to investigate the correlation between all indicators with the aim of extracting the latent variables. A latent variable, here a factor, is a variable that cannot be measured directly but is the basis of the observed variables. If the data is predominantly normally distributed, then the maximum likelihood method is best suited as an extraction method, if it is not normally distributed, the principal axis factor method should be used (Osborne, 2014). Fig. 7 in the Appendix shows the distributions of the standardised indicators. The data were checked for normal distribution with the Kolmogorov-Smirnov test since the Shapiro-Wilk test is only suitable for data records with up to 5000 datasets (Shapiro and Wilk, 1965; Lopes, 2011). The p-values were smaller than $2.2 * 10^{-16}$, so all data series are not normally distributed. Therefore, the principal axis factor method seems to be suitable as an extraction method.

However, in the factor analysis using the principal axis factor method, so-called Heywood cases occurred. A Heywood case occurs when variances are negative, or correlations (in this case some factor loadings) are greater than one. Due to the Heywood cases, the solution of the factor analysis is inadmissible. In addition, the causes of Heywood cases are difficult to distinguish (Dillon et al., 1987). With the recommended extraction method in Revelle (2017), the "minimum residual" method, almost the same result was obtained as with the principal axis factor method, since only one indicator was assigned to a different factor. However, Heywood cases also occurred when using this extraction method. The Heywood cases were not discussed in Osborne (2014), so no other method was recommended for this case. Revelle (2017) states that in contrast to other methods, the "Minimum Rank Factor Analysis" (MRFA) does not include Heywood cases. Therefore, the MRFA method is selected below as the extraction method. The MRFA method is described in Lorenzo-Seva and Ferrando (2006) as the only method that calculates the part of the variance explained by each factor. This is also the only difference between this extraction method and the "minimum residual" method (Shapiro and Berge, 2002).

3.2.2. Selection of the number of factors

In his study, Osborne (2014) indicates that no criterion for selecting the number of factors is better than another, the suitability of the criteria varies depending on the case. Therefore, several methods should be used. In this paper, the Kaiser criterion from Kaiser (1960) combined with a "Scree-Plot" and the "Parallel Analysis" from Horn (1965) are applied. Ten factors are recommended with the Kaiser method, and nine with the Parallel Analysis (cf. Fig. 8 in the Appendix). In the following, ten factors are assumed according to the Kaiser criterion (cf. curve "Eigenvalues > 0" in Fig. 8 in the Appendix).

3.2.3. Selection of the rotation method

The rotation was invented shortly after the factor analysis to facilitate the interpretation of the results of the factor analysis (Osborne, 2014). The goal is a simple structure in which each indicator describes as few factors as possible (or "loads onto them"). In addition, rotation creates groups of factors containing related indicators (Yong and Pearce, 2013). This analysis uses the "Varimax" method, which is widely used in practice, to maximise the variance of factor loadings and minimise the number of factors (Eckstein, 2016).

3.2.4. Results of the factor analysis

Table 3 shows the allocation of the indicators to the factors resulting from the factor analysis with the extraction method MRFA. The indicator X31 is the only one of the indicators not described by the factors, as its factor loading is very low for each factor. This means that X31 is no longer included in the further analysis. Fig. 9 in the Appendix shows the size of the factor loadings of all remaining indicators for each factor. The results can be assessed as plausible since each factor describes a specific issue (see column "Factor name" in Table 3). Fig. 10 in the Appendix also shows a correlation diagram of the indicator values. As an example, a high correlation between X29, X5 and X10 is shown there. These indicators are therefore all assigned to Factor 1 (see Table 3).

3.3. Cluster analysis

As already described above, high quality clusters are generated with hierarchical agglomerative cluster analysis. However, this method requires high computing times (Bouguettaya et al., 2015). In the cluster analysis implemented here, the high computing times were mainly due to the complex determination of the number of clusters. Similar to Wall (2016), the results of the factor analysis were used as input for the cluster analysis.

3.3.1. Ward algorithm

The clusters can be classified using distance metrics. To determine the distance matrix, the distance or similarity between all objects is determined (Johnson, 1967). The Ward algorithm is the only method among the agglomerative cluster methods that is based on the classical sum of squares and determines groups, minimising dispersion within the groups at each step. The sum of the squares is determined with the help of the distance matrix (Murtagh and Legendre, 2014). In this study, the distance matrix is calculated using the Euclidean distance, since it should be the basis for the Ward method (Miyamoto et al., 2015).

To use the Ward algorithm, the R function "hclust" has been executed (Müllner, 2016). Within this function, two different algorithms Ward1 or Ward2 can be selected. Murtagh and Legendre (2014) showed that only the algorithm Ward2 minimises the Ward criterion and should, therefore, be used. For more information about the mathematical differences of Ward1 and Ward2, the authors refer to Murtagh and Legendre (2014). The difference d^2 of two clusters R and Q is calculated with the help of the cluster foci $\bar{x}$ using the following equation (Gentle et al., 1991):

Table 3
Assignment of the indicators with their factor loadings to the ten factors and naming of the factors.

Factor	Indicators	Abbre-vations	Factor loading	Factor name
1	1) Household density	X5	0.917	Area factor (all indicators refer to the area of the municipality)
	2) Share of settlement and transport area	X10	0.918	
	3) Population density	X29	0.934	
	4) Technical PV potential per km^2	X35	0.921	
	5) Share of forest and agricultural area	X38	−0.768	
2	1) Income per household	X7	0.464	East/West Factor (this factor reflects the inequalities between West and East Germany)
	2) Unemployment rate	X9	−0.503	
	3) Share of buildings built before 1919	X14	−0.629	
	4) Share of buildings built between 1919 and 1949	X15	−0.791	
	5) Share of buildings built between 1960 and 1969	X17	0.587	
	6) Share of buildings built between 1970 and 1979	X18	0.791	
	7) Share of buildings built between 1980 and 1989	X19	0.560	
3	1) Achievable hydrothermal temperature	X32	0.949	Hydrothermal factor
	2) Necessary hydrothermal drilling depth	X33	0.937	
4	1) Number of motor vehicles per 1000 inhabitants	X27	0.857	Traffic factor
	2) Number of cars per 1000 inhabitants	X28	0.882	
5	1) Share of over 65-year-olds	X8	−0.726	Age factor
	2) Share of buildings built between 1990 and 1999	X20	0.737	
	3) Share of buildings built between 2000 and 2005	X21	0.529	
	4) Share of 18-64-year-olds	X30	0.626	
6	1) Share of buildings with heating systems based on district heating	X11	−0.939	Heating system factor
	2) Share of buildings with heating systems not based on district heating	X12	0.934	
7	1) Population development between 2010 and 2015	X1	0.459	Population Factor (all indicators depend on population size)
	2) Living space per person	X2	−0.660	
	3) Average household size	X4	0.811	
	4) Technical PV potential per person	X34	−0.555	
8	1) Share of buildings built between 1950 and 1959	X16	0.891	–
9	1) Share of single-person households	X3	0.436	Building factor
	2) Share of owner-occupied apartments	X6	−0.550	
	3) Share of detached houses	X23	−0.863	
	4) Share of semi-detached houses	X24	0.663	
	5) Share of terraced houses	X25	0.719	
10	1) Technical wind potential per inhabitant	X36	0.823	Wind factor
	2) Technical wind potential per km^2	X37	0.754	

$$d^2(R,\,Q) = \frac{2|R|\,|Q|}{|R|+|Q|}\bar{x}(R) - \bar{x}(Q)^2. \quad (4)$$

3.3.2. *Determining the number of clusters*

In hierarchical agglomerative cluster analysis, the number of clusters is not known in advance but must be determined using suitable methods (Salvador and Chan, 2004). The more clusters selected, the more similar the objects within the clusters are. At the same time, the clusters are more difficult to distinguish between each other as the number of clusters increases.

In some studies such as Wall (2016) or Yang et al. (2017), the number of clusters is estimated using the common but often inaccurate "elbow" method. Alternatively, the R-function "NbClust" from Charrad et al. (2014) offers 30 methods for determining the optimal number of clusters. None of the criteria studied so far can predict the optimal number of clusters in any case (Albatineh and Niewiadomska-Bugaj, 2011). Therefore, all 30 methods were implemented. More information about the mathematical description of the methods can be found in Charrad et al. (2014). The results of the procedures in the context of this study are shown in Table 9 in the Appendix. Only 26 of the 30 methods are listed in the table since the computationally intensive methods such as "gamma" had to be aborted after almost two months of computing time. As can be seen in Table 9 in the Appendix, the 26 methods yielded quite different values for the number of clusters. It is therefore necessary to examine more closely whether the methods should be used at all in this particular case. 22 of the 30 procedures are already explained and evaluated in Milligan and Cooper (1985). For Example, the "ch" procedure of Calinski and Harabasz (1974) was rated as the best procedure. However, Islam et al. (2016), showed that "ch" is poor with a high number of clusters and usually prefers - as in this study - a 2 cluster solution. Almost all 26 methods have poor functionality with a high number of clusters (cf. Table 9 in the Appendix). The only algorithm for which a good functionality with high cluster numbers could be found in the relevant literature is "duda", which suggests ten clusters in this study. However, it should be further examined whether the ten clusters represent the optimal number of clusters in this study.

Therefore, several cluster solutions with different numbers of clusters are compared to determine an appropriate number of clusters. Table 4 shows how the structure of the clusters changes from five clusters up to 15. For example, Cluster 1 from the 5 cluster solution divides into two further clusters at 14 cluster solution.

Fig. 2 shows the course of the within-cluster sum of squares as a function of the number of clusters. The within-cluster sum of squares describes the squared distance of an object to the cluster centre, i. e. how similar the object is to the other objects of the group (Anderson, 2001). The smaller the within-cluster sum of squares is, the more similar the objects in the clusters are.

The aforementioned elbow method is based on the within-cluster sum of the squares, as shown in Fig. 2, where the elbow represents the point of decreasing marginal returns. This means that right behind the elbow, with an increase in the number of clusters, the increase in information is very small. However, the region of the elbow is often not as clearly visible, as in Fig. 2 (Kodinariya and Makwana, 2013), so this method alone could not be used. The elbow method is after all only a heuristic one (Tibshirani et al., 2001). The elbow could be between 5 and 20 clusters in the area delimited by black dotted lines. The 10 cluster solution proposed by the "duda" method (see Table 9 in the Appendix), is also in this area (red dotted lines).

Therefore, the clusters need to be analysed further. It emerged that the new clusters formed in the 11 cluster solution differed significantly less from each other than the clusters formed in the previous steps. The

Table 4
Development of cluster composition for solutions with 5–15 clusters.

Number	Cluster														
5	339		727		2898				5722					1445	
6														1370	75
7					1671		1227								
8									5262				460		
9					1638	33									
10							839	388							
11									3927		1335				
12									1899	2028					
13			181	546											
14	11	328													
15											726	609			

upper diagram of Fig. 3 illustrates the deviation in the mean values of all indicators for the two new clusters in the 11 cluster solution. The values have been scaled to values between 0 and 1 to improve the comparability. The two new clusters are clusters 5 with 3927 municipalities and 8 with 1335 municipalities, as the cluster numbers change in each step (cf. Table 4). The diagram shows that the mean values for each indicator are approximately the same.

This means that a further separation of the clusters from ten clusters onwards creates only a low added value. As a comparison, the curves of the mean values of the two newly created clusters in the 10 cluster solution are shown in the bottom diagram of Fig. 3. In this case, the mean values vary significantly, so the number of clusters should be increased from nine to ten. In the following, ten clusters will be selected as the appropriate number of clusters, since this number can be justified by the "duda" method, the elbow method and further analysis.

4. Results of the cluster analysis

Fig. 4 shows all German municipalities with a colour assignment to the clusters of the 10 cluster solution. The broader outlines separate the 16 federal states in Germany. Especially in Rhineland-Palatinate and Schleswig-Holstein, some municipalities seem to be dark to black. This is due to the small size of the municipalities; in Rhineland-Palatinate, the municipalities have by far the smallest size. Due to the poor visibility of these municipalities, the map is magnified in Figs. 11–13 in the Appendix.

The mean values of all 34 indicators were determined for all clusters and every single cluster (see Table 5). The different colours are chosen to distinguish between the sectors Private Households (blue/red) and Transport (yellow) as well as potential for renewable energies (green).

The following description of the clusters is based on the mean values in Table 5. To help classify the clusters, the proportions of municipalities per cluster are assigned to the seven municipality types of the BBSR typology in Fig. 5 (BBSR, 2015). The criteria for classifying the municipalities are the population and the central function of the municipality. The evaluation of the central function is based on the central place theory of Christaller (1980). A municipality is defined as a rural municipality if either the population is less than 5000 inhabitants or if the municipality has no basic central function. The cities in the BBSR typology are classified according to population size with the lower limits of 5,000, 10,000, 20,000, 50,000, 100,000 and 500,000 inhabitants.

Cluster 1 contains an above-average number of larger towns (see Fig. 5). This cluster is characterised by the highest share of district heating systems by far. This is obvious since district heating networks are particularly suitable in towns and conurbations with high heat demand densities (Connolly et al., 2014). The high proportion of over 65-year-olds is also typical of German cities (Lauf et al., 2016). The population density is above average, while vehicles per 1000 inhabitants are the second lowest. The potential for renewable energies is below average except for the mediocre wind power potential.

The largest share of cities is in **Cluster 2** (see. Fig. 5). In this cluster, the rural municipalities account for the smallest share compared to the other clusters, and the cities from the larger small town to the larger cities take the highest share. Fig. 4 shows that the largest cities in Germany, such as Berlin, Hamburg, Munich and Cologne, are all part of this cluster. For this reason, the indicators household density, population density as well as the shares of terraced houses and semi-detached houses are particularly high in this cluster, and the share of detached houses is particularly low. Furthermore, buildings built between 1950 and 1979 dominate the municipalities in this cluster. This is due to the destruction of many cities during the Second World War. In the city of Dresden, for example, large areas of prefabricated concrete slab buildings were created in the 1970s due to a shortage of housing (Wurm et al., 2009). The number of vehicles per 1000 inhabitants is the lowest, as there are more transport alternatives in cities and the average

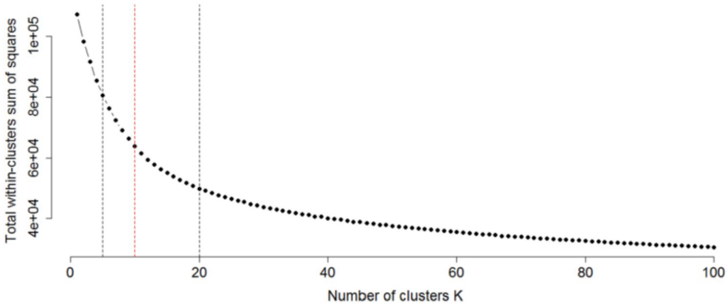
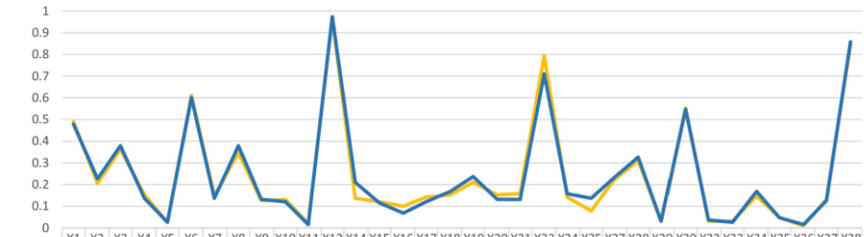
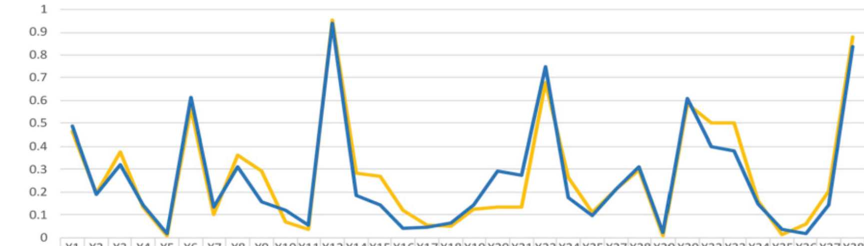


Fig. 2. Sum of squares within clusters as a function of the number of clusters.



	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X14	X15	X16	X17	X18	X19	X20	X21	X23	X24	X25	X27	X28	X29	X30	X32	X33	X34	X35	X36	X37	X38
Cluster 5	0.5	0.2	0.4	0.1	0	0.6	0.1	0.3	0.1	0.1	0	1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.2	0.8	0.1	0.1	0.2	0.3	0	0.6	0	0	0.1	0	0	0.1	0.8
Cluster 8	0.5	0.2	0.4	0.1	0	0.6	0.1	0.4	0.1	0.1	0	1	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.7	0.2	0.1	0.2	0.3	0	0.5	0	0	0.2	0	0	0.1	0.9

Cluster 5 Cluster 8



	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X14	X15	X16	X17	X18	X19	X20	X21	X23	X24	X25	X27	X28	X29	X30	X32	X33	X34	X35	X36	X37	X38
Cluster 4	0.5	0.2	0.4	0.1	0	0.6	0.1	0.4	0.3	0.1	0	1	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.7	0.3	0.1	0.2	0.3	0	0.6	0.5	0.5	0.2	0	0.1	0.2	0.9
Cluster 8	0.5	0.2	0.3	0.1	0	0.6	0.1	0.3	0.2	0.1	0.1	0.9	0.2	0.1	0	0	0.1	0.1	0.3	0.3	0.7	0.2	0.1	0.2	0.3	0	0.6	0.4	0.4	0.1	0	0	0.1	0.8

Cluster 4 Cluster 8

Fig. 3. The mean values of the two newly formed clusters in the 11 cluster solution (upper figure) and the 10 cluster solution (bottom figure) over the 34 indicators.

distances travelled are shorter because of the high population density (Woldeamanuel et al., 2009). Due to the high building density, the technical PV potential per km^2 is the highest here. On the other hand, the technical PV potential per inhabitant is the lowest after Cluster 10 due to the high population density. As expected, the proportion of forest and agricultural land in this cluster is the smallest, so that the technical wind power potential is also very low. The geothermal potential is below average.

In **Cluster 3**, the hydrothermal potential is very high; an average hydrothermal temperature of 90 °C at a depth of 2400 m can be used in the municipalities. Fig. 4 also shows that the municipalities of this cluster are predominantly located in the three large German hydrothermal regions "North German Basin", "Upper Rhine Graben" and "South German Molasse Basin" (Agemar et al., 2014). The potentials for the other renewable energies are average. Furthermore, there are more modern detached houses in the municipalities of the cluster, the income per household is high, and the unemployment rate is particularly low. From this cluster onwards, the share of rural municipalities in each cluster is more than 45%, and larger cities from the small midtown onwards are only represented to a small extent (see. Fig. 5).

In Fig. 4, **Cluster 4** is represented by dark green coloured municipalities and occupies a large, almost continuous area. A closer look reveals that the western border of the area corresponds to the border of the former German Democratic Republic (GDR). The municipalities from Cluster 6 and 8 are also predominantly located in the territory of the former GDR. Cluster 4 is characterised by a high proportion of old houses, and the proportion of buildings built between 1919 and 1949 reaches its maximum here. Buildings built between 1970 and 1989 are very scarce in these municipalities. Also, the unemployment rate is particularly high. In line with this, the population in these municipalities has been declining the most in recent years, and income per household is the lowest. The sharp decline in the population is due to the growing childlessness in eastern Germany since German reunification (Bernardi and Keim, 2017). At the same time, population density and average household size are the lowest in this cluster. These two latter indicators also determine the high value of photovoltaic potential per inhabitant. On the other hand, the photovoltaic potential per km^2 in this cluster is the second lowest after cluster 9, due to the small share of settlement areas in the total area. In contrast to this, the wind power potential in this cluster is the second highest. In addition, the municipalities of the cluster could exploit the second highest hydrothermal potential in Germany, but this would require drilling 300 m deeper on average than in Cluster 3.

With 47% of all German municipalities, **Cluster 5** contains the largest number of municipalities. In contrast to Cluster 1, district heating systems are the least widespread in this case, whereas the proportion of heating types that are not based on district heating is the highest. The number of cars and motor vehicles per 1000 inhabitants is also very high. The cluster has the second lowest hydrothermal potential. In addition, the potential for photovoltaics in this cluster is only mediocre, and the potential for wind power is low. Based on the indicators selected in this study, Cluster 5 represents the "average" municipalities in Germany.

Like Cluster 4, **Cluster 6** is also characterised by a high building age because of its location in eastern Germany. Due to the increasing childlessness, the population is declining and the proportion of people over 65 years of age is steadily increasing. The values of the indicators representing the transport sector are rather average. In contrast to the low to average wind power and photovoltaic potential, the hydrothermal potential in this cluster is particularly low.

Cluster 7 contains almost exclusively rural municipalities and small towns (see Fig. 5). The proportion of apartments occupied by the owner and the living space per person are at their maximum, while at the same time the household density is minimal. Due to the low density of households and population, the number of cars and motor vehicles per 1000 inhabitants reaches its maximum here. In addition, the detached

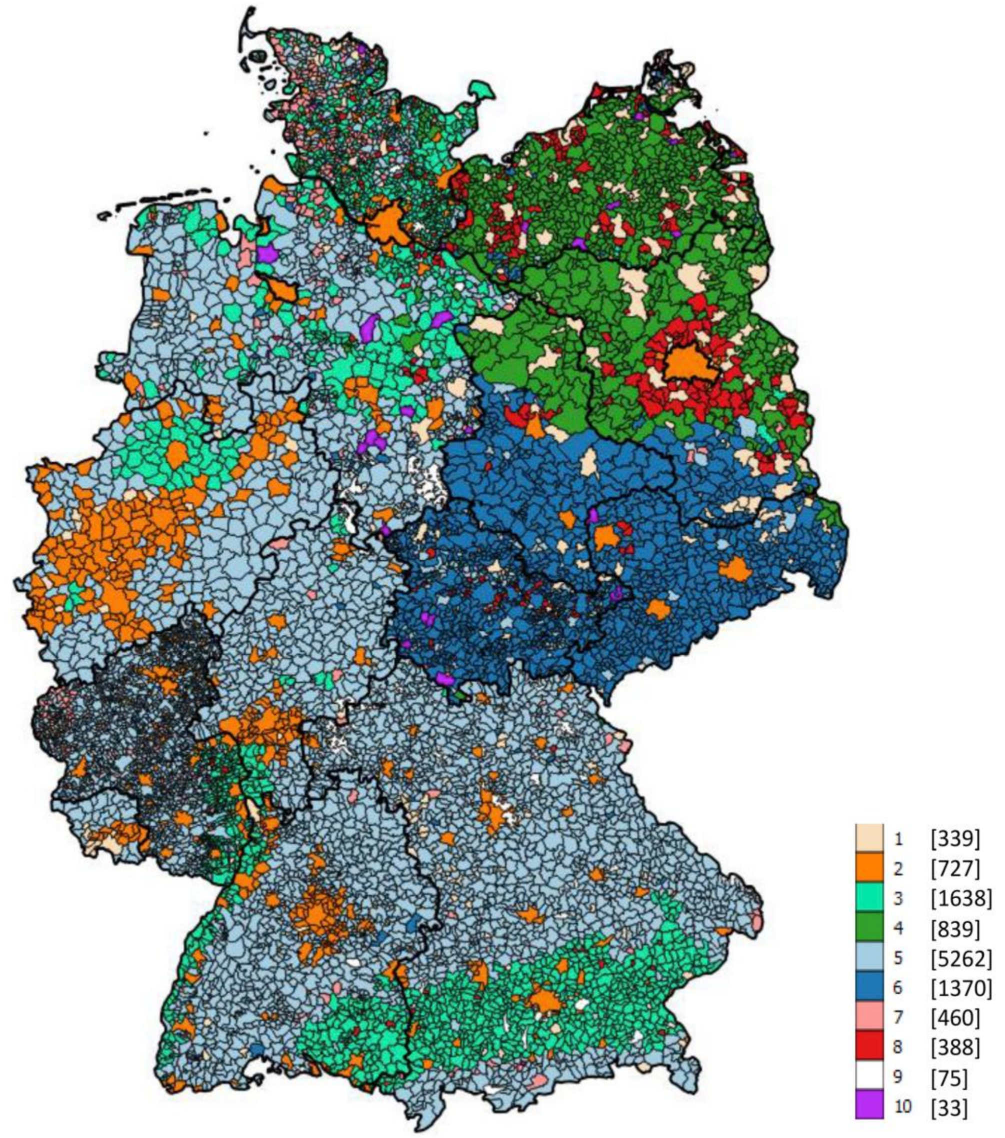


Fig. 4. Illustration of all German municipalities with their allocation in the 10 cluster solution. The numbers of municipalities in the clusters are in parentheses.

houses reach the largest share in this cluster. Furthermore, this cluster has the highest potential for renewable energies, despite its very low geothermal potential. The high living space per person and the low density of households mean that the highest photovoltaic and wind power potentials per person are achieved. Also, the wind power potential per km^2 is at its maximum, as most of the municipalities in the cluster are located in Northern Germany and thus in areas with high wind speeds and have a high proportion of forest and agricultural land.

The building age in **Cluster 8** is unusually low, although these municipalities are mainly located in Eastern Germany. This can be explained by an example: in the description of Clusters 4 and 6, the decline in population in eastern Germany has already been discussed. Although this development applies to all the new federal states, the decline in Brandenburg between 1990 and 2008 was significantly lower. This was mainly due to new settlements in the surrounding area of Berlin, the so-called "commuter belt" (Jesse et al., 2014). Municipalities from Cluster 8 almost exclusively form this commuter belt (cf. Fig. 4). Due to the rising rent in Berlin, more and more young families

Table 5
Mean values of the indicators X1-X38 for the ten Clusters and all Clusters.

Indicator	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12
Mean value	-1.0	51.2	27.1	2.4	81.1	63.0	34.2	20.1	3.7	13.0	2.7	96.3
Cluster 1	-1.3	47.6	31.2	2.3	118.9	51.4	30.3	21.4	5.6	16.6	20.0	78.9
Cluster 2	1.1	46.7	34.1	2.3	417.5	49.9	37.8	21.1	4.4	34.9	3.8	95.8
Cluster 3	1.1	50.5	25.8	2.5	71.3	63.3	41.3	18.8	2.9	12.7	2.1	97.2
Cluster 4	-4.3	49.5	27.4	2.2	23.5	61.7	24.9	20.2	6.9	6.7	3.3	95.9
Cluster 5	-0.8	53.3	26.7	2.4	59.9	65.2	35.7	19.7	3.0	12.3	1.5	97.4
Cluster 6	-3.7	47.2	27.2	2.3	54.6	62.4	26.2	22.5	4.7	10.1	2.5	96.5
Cluster 7	-2.1	58.0	24.3	2.4	21.4	69.7	32.8	20.2	3.3	7.7	1.9	96.9
Cluster 8	-0.9	48.6	23.4	2.4	40.7	65.9	33.9	17.3	3.7	11.4	4.9	94.6
Cluster 9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	2.0	90.7
Cluster 10	33.5	21.3	28.3	6.2	37.7	62.5	57.6	20.9	4.6	9.5	2.9	96.5

Indicator	X14	X15	X16	X17	X18	X19	X20	X21	X23	X24	X25
Mean value	18.9	11.4	8.5	11.3	13.4	11.1	14.6	7.5	77.2	10.2	7.8
Cluster 1	17.5	14.0	9.0	10.9	12.3	10.0	14.6	8.1	68.0	12.3	15.1
Cluster 2	10.0	10.9	12.1	16.4	16.3	11.8	12.0	6.8	58.3	17.5	20.8
Cluster 3	14.3	7.6	7.6	12.4	16.8	12.6	15.9	8.6	76.7	11.5	6.2
Cluster 4	28.1	20.5	11.8	5.4	5.1	7.0	13.4	6.6	72.6	15.7	7.6
Cluster 5	15.2	8.9	9.0	13.5	15.7	12.4	14.4	7.5	80.9	8.5	6.2
Cluster 6	35.2	19.9	5.4	4.7	6.5	8.5	12.6	5.0	75.8	9.1	9.7
Cluster 7	28.5	9.4	6.4	11.4	12.8	8.8	12.2	7.6	85.2	4.7	2.9
Cluster 8	18.6	10.9	4.0	4.3	6.4	8.2	29.2	13.6	78.6	10.5	6.7
Cluster 9	15.4	8.3	8.5	13.2	14.8	11.0	12.8	6.5	74.0	9.4	6.0
Cluster 10	26.0	16.6	8.2	10.4	10.3	8.8	12.0	5.4	79.5	11.4	5.1

Indicator	X27	X28	X29	X30	X32	X33	X34	X35	X36	X37	X38
Mean value	832.7	634.5	183.3	62.8	29.6	842.8	2482.7	398.4	41.4	2000.9	83.6
Cluster 1	785.7	598.5	273.0	62.4	44.5	1342.1	2173.0	501.4	44.9	2062.8	77.2
Cluster 2	697.2	588.3	928.8	62.0	21.6	552.4	1987.0	1703.7	1.1	605.7	60.9
Cluster 3	855.0	649.7	171.0	62.4	90.8	2438.4	2390.4	389.8	33.0	2327.2	83.7
Cluster 4	819.9	618.2	33.5	65.2	88.1	2740.0	2755.9	88.0	120.4	2759.8	88.2
Cluster 5	860.6	652.5	141.4	62.5	5.6	156.9	2570.9	342.4	24.0	1737.4	84.8
Cluster 6	800.5	615.0	114.7	63.6	3.4	106.9	2477.5	260.0	34.1	1704.4	86.7
Cluster 7	957.1	661.5	41.7	61.3	25.3	789.4	2818.0	113.7	222.6	5863.6	89.9
Cluster 8	819.9	645.4	104.5	66.7	69.8	2086.4	2486.1	247.2	32.0	1897.8	83.8
Cluster 9	0.0	0.0	0.0	0.0	19.4	592.5	0.0	7.0	0.0	320.1	90.0
Cluster 10	711.9	560.1	86.3	63.4	41.5	1297.3	1285.5	211.1	46.8	2123.2	84.1

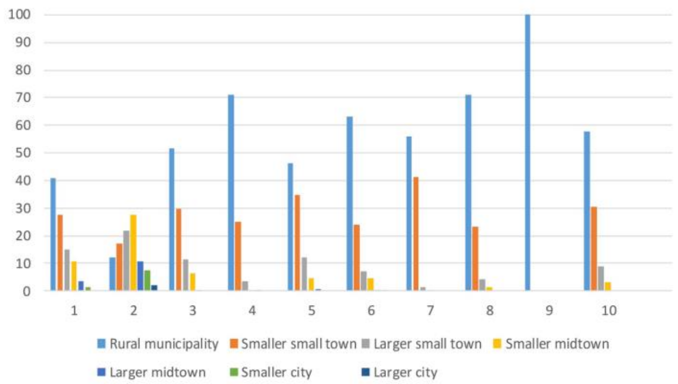


Fig. 5. Classification of municipalities according to the BBSR municipality typology.

are moving into the commuter belt. This also explains the maximum proportion of 18-64-year-olds and the minimum proportion of 65 year-olds in this cluster (Bünger, 2017). The proportion of cars per 1000 inhabitants is also above average here, presumably because most people have to drive to work in the city. A closer examination of the red municipalities shown in Fig. 4 reveals that most of the municipalities are located in the surrounding area of major cities in clusters 1 and 2. Thus, the conclusions mentioned above on the Berlin "commuter belt" can also be transferred to the other municipalities in Cluster 8. Also, this cluster has the third highest geothermal potential, while the potential of the other renewable energies is below average.

Cluster 9 contains all areas in which there are no inhabitants. Therefore, all indicators that depend on the population have a value of zero. These areas are municipality-free (in German: "gemeindefrei"), and therefore 100% of them are rural municipalities (see Fig. 5). Settlement and traffic area is present in these municipalities, because of roads leading through these areas. However, this indicator has the smallest value here. At the same time, the proportion of forest and agricultural land reaches its highest level. It is interesting to note that the technical wind power potential per km^2 is nevertheless at its minimum in this cluster. The reason for this could be, among other things, nature reserves in which no wind turbines may be installed. The technical photovoltaic potential in this cluster also approaches zero since only a few buildings are located here. Despite the buildings, no residents are assigned to these areas, as the buildings in the municipal areas belong to military training areas or similar (Goderbauer, 2016). This cluster has the lowest potential for renewable energies, as the geothermal potential is also below average.

With only 33 municipalities, **Cluster 10** represents the smallest cluster in this study. This cluster is characterised by the highest population growth between 2010 and 2015. Due to the largest average household size by far, the income per household is also reaching its maximum value and the technical PV potential per inhabitant its minimum value. In addition, the number of vehicles per 1000 inhabitants in this cluster is below average. The cluster must be evaluated as an outlier since many of the characteristics of this cluster are due to the high population growth. The population figures from 2015 have been used in the calculation of many indicators to establish a uniform reference. However, the most recent household data are available for 2014 and have only been roughly updated since the last survey in 2011. As a result, the high population growth leads to, among other things, high values for the average household size, as the number of households is no longer up to date. This cluster, therefore, includes outliers. Nevertheless, the heterogeneity and independence of the cluster can be justified by the significantly higher population growth as in the other clusters. The distinguishing characteristics of the ten clusters are summarised in Table 6.

The data and results of the cluster analysis can be made available upon request.

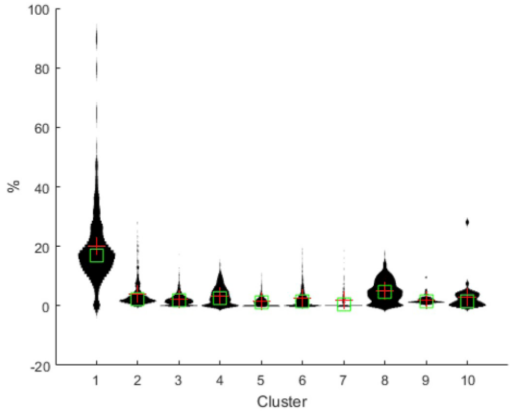


Fig. 6. Violin Plot of indicator X11 in % for the ten clusters.

5. Discussion

5.1. Critical appraisal of the methodology

Wall (2016) shows that factor analysis is an important step ahead of cluster analysis. However, most studies describe cluster analyses without prior factor analysis. For this reason, the cluster analysis was repeated again without the factor analysis. The results were worse than those of the cluster analysis with the values from the factor analysis. For example, with the factor values, the 75 municipality-free areas without population (Cluster 9) were already divided into a cluster in the 6 cluster solution (cf. Table 4). In the analysis with the raw data, these municipalities were not separated, at least up to the 20 cluster solution.

Whilst cluster analysis provides a good basis for transferring the results of energy autonomy studies to other municipalities, results cannot always be completely transferred and an examination of the individual case will be necessary. This is illustrated by the following example: Fig. 6 shows the violin plot of the indicator "Share of buildings with heating systems based on district heating (X11)" for all clusters. In a violin plot, the density trace and the box plot are combined into one diagram (for more information see: Hintze and Nelson, 1998). The red plus signs indicate the position of the mean value and the green boxes indicate the position of the median.

Cluster 1 is characterised by a high average share of district heating. However, Fig. 6 shows that this cluster also contains a few municipalities with very low shares of district heating. These municipalities are then more similar to the cluster focus in the other indicators.

Table 6
Summary of the distinguishing characteristics of the ten clusters.

Cluster	Number of municipalities	Characteristics
1	339	Larger towns with highest share of district heating.
2	727	All major German cities with particularly low potential for renewables.
3	1638	Municipalities with highest hydrothermal potential, high income per household as well as low unemployment rate.
4	839	Municipalities with high hydrothermal potential, building age and unemployment rate.
5	5262	"Average" Cluster containing the majority of municipalities. Municipalities with high number of cars per 1000 inhabitants and very low share of district heating.
6	1370	Municipalities with high building age and high proportion of people over 65 years of age.
7	460	Municipalities with lowest household density, highest number of cars and motor cycles per 1000 inhabitants, largest share of detached houses and particularly high potential for renewables.
8	388	Municipalities with low building age, lowest proportion of people over 65 years of age and a high hydrothermal potential.
9	75	Rural municipality-free areas with no inhabitants and lowest potential for renewables.
10	33	Smallest cluster containing municipalities with high population growth.

Table 7
Comparison of the model, example and average municipalities/regions from relevant literature with the average municipality from this study. The cells containing "n/a" show indicators that were not specified in the sources.

Municipality from	Number of inhabitants	Number of buildings	Average household size [people]	Share of settlements and traffic areas [%]	Population density [Inhabitants/km²]	Number of vehicles per 1000 inhabitants
Jenssen et al. (2014)	3000	800	2.2	n/a	n/a	n/a
Scheffer (2008)	10,000	n/a	n/a	n/a	n/a	630
Peter (2013)	3850	1224	3.1	8	106	n/a
Burgess et al. (2012)	25,550	n/a	2.4	8	310	n/a
Schmidt et al. (2012)	20,619	n/a	n/a	< 11	68	n/a
Woyke and Forero (2014)	1100	n/a	n/a	n/a	n/a	n/a
Average munici-pality (cf. Table 5)	7380	1670	2.4	13	183	830

The following explains in more detail why it is necessary to carry out a cluster analysis to appropriately transfer the results of energy system analyses in municipalities by comparing the model or average municipalities from the studies described in Section 1 with the mean values of all municipalities in this study (cf. Table 7).

Table 7 shows that the average municipality differs from the municipalities/regions of the studies of Jenssen et al. (2014), Scheffer (2008) and Peter (2013). A comparison of the values reveals that none of the surveyed municipalities represents an average municipality in Germany. Even though it was not the intention to select an average municipality in Germany in some of the studies, the results are difficult to transfer to other municipalities or regions. Rather, the choice of municipalities and data appears to be influenced by many other than technical factors in some cases. For example, Scheffer (2008) tried to use the indicator values to describe a rural municipality. In the classification of German municipalities in BBSR (2015), the municipality would be placed in the category "Smaller Small Town". In addition, only a few data on the municipalities are described in the studies. This could give the impression that the results from Jenssen et al. (2014), for example, can be transferred to municipalities with 3000 inhabitants, 800 buildings and a household size of 2.2 persons. Instead, a transferability depends on how precisely the municipality is represented, i.e. how many indicators are used to describe the municipality. Since the cluster analysis conducted in our study uses considerably more indicators to describe the municipalities, the result can be used as a basis for transferring appropriate energy systems to other municipalities.

5.2. *Suitability of municipalities for energy autonomy*

To investigate the suitability of individual municipalities and clusters for energy autonomy, precise calculations must be performed. Nevertheless, in this section an attempt is made to determine an initial assessment of this suitability by analysing the clusters in which municipalities are already aiming for energy autonomy. For this, 165 municipalities from the energy projects "Energy Municipalities", "Bioenergy Villages" and "100% Renewable Energy Regions" are assigned to the ten clusters. These projects aim to achieve the goal of an autonomous energy supply in the municipalities. However, the municipalities have defined different objectives in the projects about autonomous supply, including "100% heat", "100% electricity" or "100% renewable energies" (McKenna et al., 2014b). Some of the municipalities take part in several of the projects mentioned above. Districts involved in the projects were not included in the analysis. The result of the assignment is shown in Table 8.

First of all, it is noticeable that no municipalities from Clusters 9 and 10 participate in the energy projects. This fact is quickly explained since there is no population in Cluster 9 and Cluster 10 is very small and is also more of an outlier cluster. The first two clusters, on the other hand, have the largest proportion of municipalities that are members of the energy projects. As shown above, these clusters contain most of the cities (see Fig. 5). One reason for the high proportions in these clusters could be the existence of a critical mass of innovators (cf. Deutschle et al., 2015), but such aspects could not be included in this analysis. On the other hand, however, achieving the goal of energy autonomy is all the more difficult, the more inhabitants a municipality has. While in rural municipalities the focus is often on the expansion of renewable energies, development in large cities depends to a large extent on development outside the city borders. Discussions in major cities are mainly focused on increasing energy efficiency, creating smart grids and providing storage capacity. For example, the City of Munich aims to halve per capita emissions by 2030 (Gailing et al., 2013). In the other clusters, the municipalities' participation in energy projects is not so pronounced. However, in each of the clusters 3 to 8, at least two municipalities are involved in energy projects. This is likely to be due to the non-technical reasons mentioned above rather than a suitability of the municipalities per se. If the potential for renewable energies is used as a basis for the assessment, the municipalities from Cluster 3 and Cluster 7 could be particularly suitable for energy autonomy: Cluster 3, among other things, due to its high hydrothermal potential and the associated potential base-load energy supply; Cluster 7 because of the highest potential for renewable energies.

6. Summary and conclusion

In the context of the trend towards decentralised energy systems, both high temporal and spatial resolutions are required in order to adequately consider their interactions with the centralised system. This is a central challenge in energy modelling, as compromises must inevitably be made between model resolution, scope and computational feasibility. This paper makes a significant contribution to complexity reduction in this area by clustering the 11,131 German municipalities using 34 pre-identified socio-energetic indicators, mainly based on freely available data relating to the consumption sectors of Private Households and Transport, as well as indicators relating to the

Table 8
Assignment of the municipalities from the energy projects "Energy Municipalities", "Bioenergy Villages" and "100% Renewable Energy Regions" to the ten clusters.

Cluster	1	2	3	4	5	6	7	8	9	10
Number	25	21	20	6	76	12	2	3	0	0
Fraction in the cluster	7.4%	2.9%	1.2%	0.7%	1.4%	0.9%	0.4%	0.8%	0%	0%
Example	Jühnde	Munich	Furth	Barth	Brilon	Jena	Hürup	Pleß	–	–

potentials for renewable energies. The method involves two main steps, namely a factor analysis and a cluster analysis. For the former, different methods are weighed against each other, and the most effective methods for allocating the indicators to factors are chosen. Selected cluster validation methods are then used to determine an appropriate number of 10 clusters to which the 11,131 municipalities are distributed. Due to the high number and differentiation of indicators, clusters overlap with each other for different indicators, but the results also show significant differences between the clusters. For example, Cluster 2 contains all major German cities and most of the other cities in Germany and has a low potential for renewable energies. Cluster 9, on the other hand, describes all German municipalities in which there are no inhabitants.

The methodology used in this study could be improved for more accurate results in future work. On the one hand, other indicators should be included in the study, including, if possible, indicators from the Industry and Commercial sector as well as indicators relating to the local climate. However, this is challenging due to the lack of available data at this spatial resolution. If available, data should also refer to the same year, as some of the results might be distorted because of different reference years, as shown by the average household size in cluster 10. Furthermore, weights for the indicators should be determined with the help of expert interviews. If it is known which indicators have the most considerable influence on the suitability for energy autonomy, these can be weighted more strongly in the cluster analysis and a new set of clusters generated based on these weights. In addition, the employed cluster methodology should be scrutinised more closely. Although the selection methods can be adequately justified in this study, others (e.g. Chicco, 2012) have shown that the Ward algorithm is not always the best choice for cluster analysis. Further work is also required to analyse the economic effects of municipal energy autonomy on the overarching energy system (for a discussion see Jägemann et al., 2013, McKenna, 2018).

A comparison of the average municipality from the dataset used here with the average municipalities from other energy autonomy studies is difficult due to a lack of data at the level of detail employed here. Based on the available data in these studies, a comparison shows few similarities, which means the results of the studies relating to their transferability to other municipalities should be questioned. Assigning the municipalities from the three German energy projects “Energy Municipalities”, “Bioenergy Villages” and “100% Renewable Energy Regions” to the 10 clusters further shows that in eight of the ten clusters municipalities are aiming for energy autonomy (in varying degrees). As a result, it is not possible to differentiate between the clusters regarding readiness for such energy projects, which is most likely due to the influence of non-technical factors on the emergence of these initiatives. However, the results of the cluster analysis show that some of the municipalities could be technically more suitable for energy autonomy, for example Cluster 7 is characterised by a high potential for renewable energies. A comparison of the ten clusters with the average municipality from the data set also demonstrates their benefit, with a large variation across clusters in terms of energy demand structure, renewables potentials and overall size. The results therefore reduce the effort of subsequent studies, as only a few municipalities from the clusters need to be examined regarding their suitability for energy autonomy to be able to make statements for all municipalities of the cluster. However, this study also makes it clear that not every result can be transferred to all the other municipalities within a cluster, instead an individual examination is required for each municipality. Nevertheless, the results help to identify municipalities in which already successful measures from other municipalities could be applied, and provide a basis for further energy analyses at the national level.

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A. Appendix

Table 8
Indicators for cluster analysis and the associated units and references.

Indicator	References
Indicators of the Consumption Sector Private Households	
Population development between 2010 and 2015 [%]	(Statistisches Bundesamt, 2011a; 2017b) and own calculation
Living space per person [m^2]	(Statistisches Bundesamt, 2017b; 2014d) and own calculation
Share of single-person households in total number of households [%]	(Statistisches Bundesamt, 2014e) and own calculation
Average household size [Number of persons]	(Statistisches Bundesamt, 2014e; 2017b) and own calculation
Household density [Households per km^2]	(Statistisches Bundesamt, 2017b; 2014e) and own calculation
Share of owner-occupied apartments in total number of apartments [%]	(Statistisches Bundesamt, 2014d) and own calculation
Income per household [k€]	(Statistisches Bundesamt, 2014e; 2011b) and own calculation
Share of over 65-year-olds in total population [%]	(Statistisches Bundesamt, 2014a) and own calculation
Unemployment rate [%]	(Statistisches Bundesamt, 2017b; 2014a, 2016a) and own calculation
Share of settlement and traffic area in total area [%]	(Statistisches Bundesamt, 2016b) and own calculation
Heating days (long-term average)	Institut für Wohnen und Umwelt (2017)
Heating degree days (long-term average)	Institut für Wohnen und Umwelt (2017)
Degree day number (long-term average)	Institut für Wohnen und Umwelt (2017)
Share of buildings with heating systems based on district heating [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings with heating systems not based on district heating [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings without heating system [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings built before 1919 in total building stock (X14) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings built between 1919 and 1949 in total building stock (X15) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings built between 1950 and 1959 in total building stock (X16) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings built between 1960 and 1969 in total building stock (X17) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings built between 1970 and 1979 in total building stock (X18) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings built between 1980 and 1989 in total building stock (X19) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings built between 1990 and 1999 in total housing stock (X20) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings built between 2000 and 2005 in total building stock (X21) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of buildings built from 2006 onward in total building stock (X22) [%]	(Statistisches Bundesamt, 2014d) and own calculation

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Table 8 (*continued*)

Indicator	References
Share of detached houses in total building stock (X23) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of semi-detached houses in total building stock (X24) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of terraced houses in total building stock (X25) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Share of "other building types" in total building stock (X26) [%]	(Statistisches Bundesamt, 2014d) and own calculation
Indicators of the Transport consumption sector	
Number of motor vehicles per 1000 inhabitants	(Statistisches Bundesamt, 2017b; Kraftfahrt-Bundesamt, 2017a) and own calculation
Number of cars per 1000 inhabitants	(Statistisches Bundesamt, 2017b; Kraftfahrt-Bundesamt, 2017a) and own calculation
Share of diesel vehicles in vehicle fleet [%]	(Kraftfahrt-Bundesamt, 2017b) and own calculation
Share of petrol vehicles in vehicle fleet [%]	(Kraftfahrt-Bundesamt, 2017b) and own calculation
Share of gas vehicles in vehicle fleet [%]	(Kraftfahrt-Bundesamt, 2017b) and own calculation
Share of hybrid vehicles in vehicle fleet [%]	(Kraftfahrt-Bundesamt, 2017b) and own calculation
Share of electric vehicles in vehicle fleet [%]	(Kraftfahrt-Bundesamt, 2017b) and own calculation
Share of "other vehicle type" in vehicle fleet [%]	(Kraftfahrt-Bundesamt, 2017b) and own calculation
Population density [Inhabitants per km^2]	(Statistisches Bundesamt, 2017b) and own calculation
Share of 18-64-year-olds in the total population [%]	(Statistisches Bundesamt, 2014a) and own calculation
Share of commuters in total workforce [%]	(Statistisches Bundesamt, 2014f) and own calculation
Indicators of the Consumption Sector Industry and Commercial	
Share of employment in the industrial sector [%]	(Statistisches Bundesamt, 2015a) and own calculation
Share of employment in the commercial sector [%]	(Statistisches Bundesamt, 2015a) and own calculation
Energy productivity of manufacturing industry [€/GJ]	(Statistisches Bundesamt, 2014b; 2014c) and own calculation
Energy intensity of manufacturing industry [MJ/€]	(Statistisches Bundesamt, 2014b; 2014c) and own calculation
Productivity level of manufacturing industry [€/GJ]	(Statistisches Bundesamt, 2014b; 2014c) and own calculation
Specific energy consumption of manufacturing industry [MJ/€]	(Statistisches Bundesamt, 2014b; 2014c) and own calculation
Share of industrial sales tax in total sales tax [%]	(Statistisches Bundesamt, 2014g) and own calculation
Share of commercial sales tax in total sales tax [%]	(Statistisches Bundesamt, 2014g) and own calculation
Development of employment share in the industrial sector [%]	(Statistisches Bundesamt, 2015a, 2000) and own calculation
Development of employment share in the commercial sector [%]	(Statistisches Bundesamt, 2015a, 2000) and own calculation
Development of energy intensity in manufacturing industry from 2003 to 2014 [%]	(Statistisches Bundesamt, 2014b; 2014c, 2003a; 2003b) and own calculation
Number of manufacturing enterprises per 1000 households	(Statistisches Bundesamt, 2015b) and own calculation
Indicators of the potential for renewable energies	
Achievable hydrothermal temperature [°C]	(Agemar 2017) and own calculation
Necessary hydrothermal drilling depth [m]	Own calculation
Technical PV potential per inhabitant [kWh/y]	(Mainzer et al., 2014; Statistisches Bundesamt, 2017b)
Technical PV potential per km^2 [MWh/y]	(Mainzer et al., 2014; Statistisches Bundesamt, 2017b)
Technical wind potential per inhabitant [MWh/y]	(McKenna et al., 2014a; Statistisches Bundesamt, 2017b) and own calculation
Technical wind potential per km^2 [MWh/y]	(McKenna et al., 2014a; Statistisches Bundesamt, 2017b) and own calculation
Share of forest and agricultural land in total area [%]	(Statistisches Bundesamt, 2016b) and own calculation

Table 9
Number of clusters resulting from 26 different procedures and evaluation of the procedures. A high number of clusters in the "evaluation of the procedure" column means a number of more than 4 clusters.

Index	Nu-mber	Evaluation of the procedure
"ch" (Calinski and Harabasz, 1974)	2	Poor with a high number of clusters. Often prefers 2 cluster solutions (Islam et al., 2016; Arbelaitz et al., 2013; Vendramin et al., 2010).
"duda" (Duda and Hart, 1973)	10	Good with a high number of clusters (Milligan and Cooper, 1985; Islam et al., 2016). Second best procedure in (Milligan and Cooper, 1985).
"pseudot2" (Duda and Hart, 1973)	10	–
"cindex" (Hubert and Levin, 1976)	6	Determines the optimum number of clusters ± 1 with a probability of only 50% (Islam et al., 2016). Poor with a high number of clusters (Arbelaitz et al., 2013).
"beale" (Beale, 1969)	2	Poor with a high number of clusters (Arbelaitz et al., 2013).
"ptbiserial" (Milligan, 1980, 1981)	10	A high number of clusters is often underestimated (Milligan and Cooper, 1985).
"db" (Davies and Bouldin, 1979)	10	In (Arbelaitz et al., 2013) the third-best index with a high number of clusters, but low success rate with a high number of clusters (Milligan and Cooper, 1985; Arbelaitz et al., 2013).
"frey" (Frey and van Groenewoud, 1972)	1	Result contradicts the cluster idea because of the number of clusters < 2. The Number of clusters is rather underestimated with a high number of clusters (Milligan and Cooper, 1985).
"hartigan" (Hartigan, 1975)	5	Works well with a small number of indicators (Tibshirani et al., 2001; Albatineh and Niewiadomska-Bugaj, 2011). Poor with a high number of clusters (Milligan and Cooper, 1985).
"ratkowsky" (Ratkowsky and Lance, 1978)	8	Poor with a high number of clusters (Milligan and Cooper, 1985).
"scott" (Scott and Symons, 1971)	3	Poor with a high number of clusters (Milligan and Cooper, 1985).
"marriot" (Marriott, 1971)	7	Poor with a high number of clusters (Milligan and Cooper, 1985).
"ball" (Ball and Hall, 1965)	3	Poor with a high number of clusters (Milligan and Cooper, 1985).
"trcovw" (Milligan and Cooper, 1985)	3	Poor with a high number of clusters (Milligan and Cooper, 1985).
"tracew" (Milligan and Cooper, 1985)	5	Poor with a high number of clusters (Milligan and Cooper, 1985).
"friedman" (Friedman and Rubin, 1967)	3	Poor with a high number of clusters (Milligan and Cooper, 1985).
"mcclain" (McClain and Rao, 1975)	2	Poor with a high number of clusters (Milligan and Cooper, 1985).
"rubin" (Friedman and Rubin, 1967)	8	Poor with a high number of clusters (Milligan and Cooper, 1985).
"kl" (Krzanowski and Lai, 1988)	3	Identifies only 40–50% of the clusters (Albatineh and Niewiadomska-Bugaj, 2011; Islam et al., 2016).
"silhouette" (Rousseeuw, 1987)	3	Poor with a high number of clusters (Islam et al., 2016; Arbelaitz et al., 2013).
"gap" (Tibshirani et al., 2001)	2	Poor with a high number of clusters (Islam et al., 2016).
"dindex" (Lebart et al., 2002)	5	–

(*continued on next page*)

Table 9 (*continued*)

Index	Nu-mber	Evaluation of the procedure
"dunn" (Dunn, 1974)	9	Poor with a high number of clusters (Arbelaitz et al., 2013).
"hubert" (Hubert and Arabie, 1985)	4	–
"sdindex" (Halkidi et al., 2000)	2	–
"sdbw" (Halkidi and Vazirgiannis, 2001)	7	Poor with a high number of clusters (Arbelaitz et al., 2013).

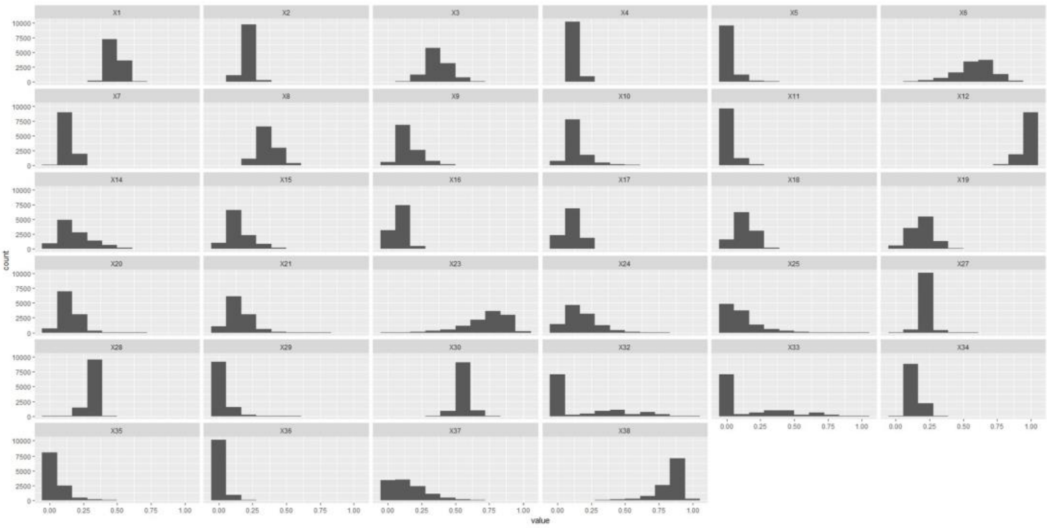

Fig. 7. Distributions of indicator values.

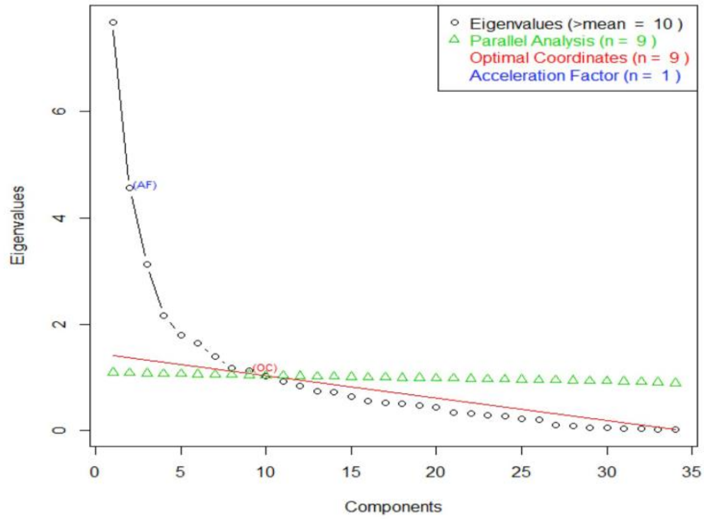

Fig. 8. Results in determining the number of factors.

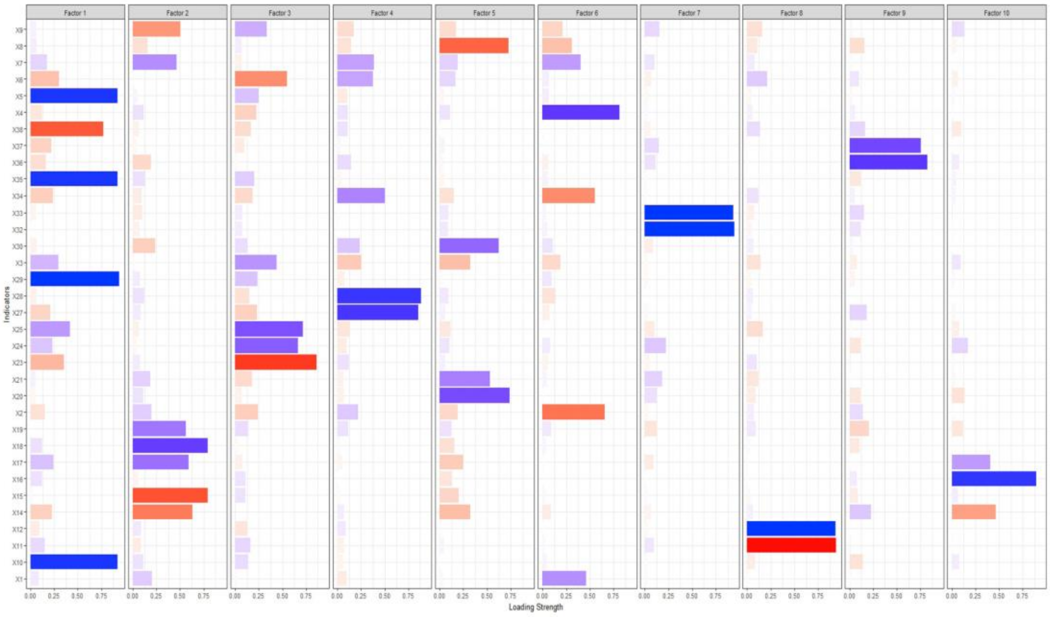

Fig. 9. Factor loadings in each of the ten factors.

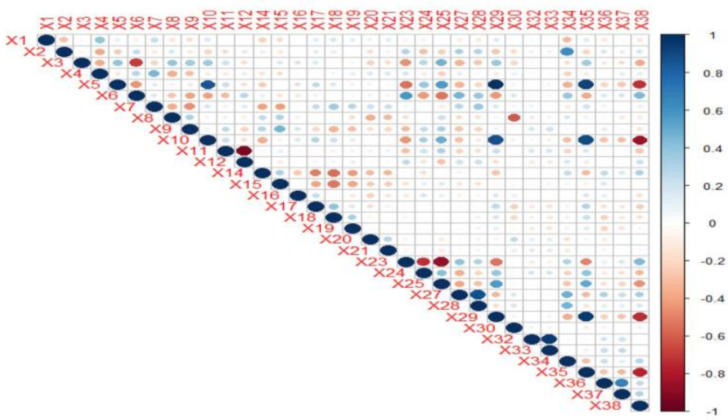

Fig. 10. Correlation matrix of the indicator values.

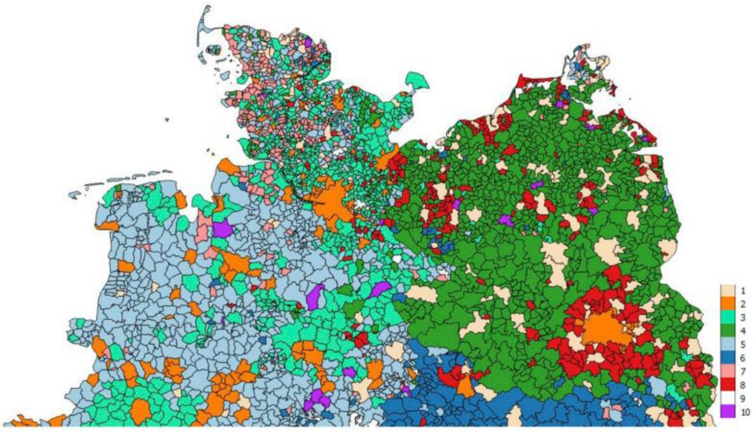

Fig. 11. Illustration of the northern German municipalities with their allocation in the 10 cluster solution.

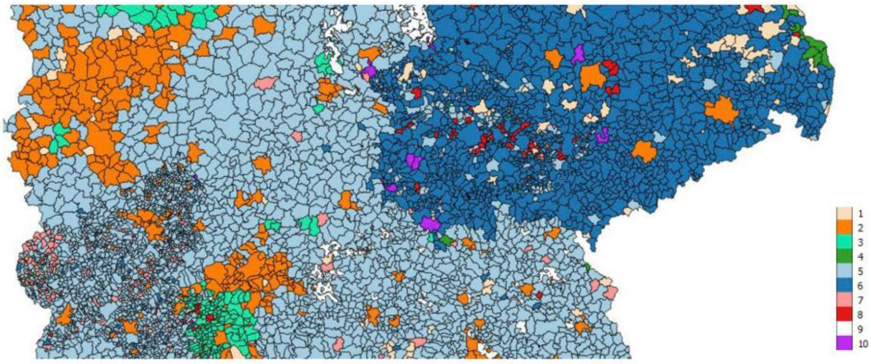

Fig. 12. Illustration of the central German municipalities with their allocation in the 10 cluster solution.

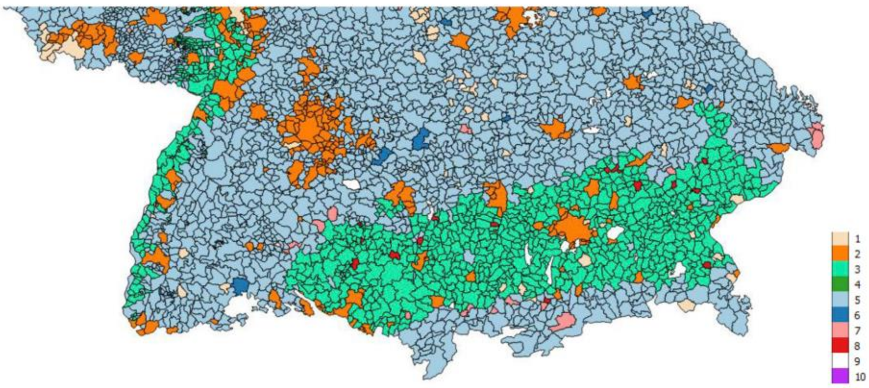

Fig. 13. Illustration of the southern German municipalities with their allocation in the ten cluster solution

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DATA DESCRIPTOR

Spatial high-resolution socio-energetic data for municipal energy system analyses

Jann M. Weinand[1]*, Russell McKenna[2] & Kai Mainzer[1]

In the context of the energy transition, municipalities are increasingly attempting to exploit renewable energies. Socio-energetic data are required as input for municipal energy system analyses. This Data Descriptor provides a compilation of 40 indicators for all 11,131 German municipalities. In addition to census data such as population density, mobility data such as the number of vehicles and data on the potential of renewables such as wind energy are included. Most of the data set also contains public data, the allocation of which to municipalities was an extensive task. The data set can support in addressing a wide range of energy-related research challenges. A municipality typology has already been developed with the data, and the resulting municipality grouping is also included in the data set.

Background & Summary

National targets in energy policy are leading to a radical change in the energy sector. The associated expansion of renewable energies is mainly decentralised, which 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[1]. More and more municipalities are striving to exploit renewable decentralised energy generation. Thereby they participate in municipal projects like "Bioenergy villages" and "100%-Renewable-Energy-Communities"[2].

In the course of the growing interest in renewable energy systems, an increasing number of energy system analyses for the development of climate protection plans are conducted at the municipal level. However, many municipalities lack both the financial resources and the expertise to determine the potential for renewables or develop effective climate protection plans[3]. These municipalities would benefit from studies on their suitability for decentralised energy systems.

In addition, a growing number of energy system models are used whose input values are based on public data[4,5]. The availability of data can therefore also support the development of energy system models.

We recently grouped the 11,131 German municipalities with regard to their suitability for decentralised energy[6]. The cluster analysis included 38 socio-energetic indicators which comprised data on the energy consumption sectors "Private Households" and "Transport" as well as data to estimate the potential for renewable energies. Among the data on renewable energies are spatial high-resolution photovoltaic[7], wind[8] and hydrothermal[6] potentials. The hereby-published dataset contains all indicators and the resulting cluster composition for all German municipalities.

The dataset[9] enables energy researchers to conduct studies at municipal and national levels without having to obtain and synthesize a large amount of data. For example, the cluster composition can help to transfer results from energy system analyses of individual municipalities to other, similar municipalities.

Methods

In the following, the various methods for determining and allocating the data to the municipalities are described. A distinction is made between data on census, mobility and renewable energies as well as cluster data (cf. Online-only Table 1).

Census data. Despite the fact that the census data are public, consolidating the data is an extensive task[6]. This is related on the one hand to different identifiers for the municipalities in the various census data tables. On the other hand, the number of municipalities in Germany is constantly reducing as several municipalities are merged into one. In addition, the data tables are rarely complete and data are missing for individual municipalities.

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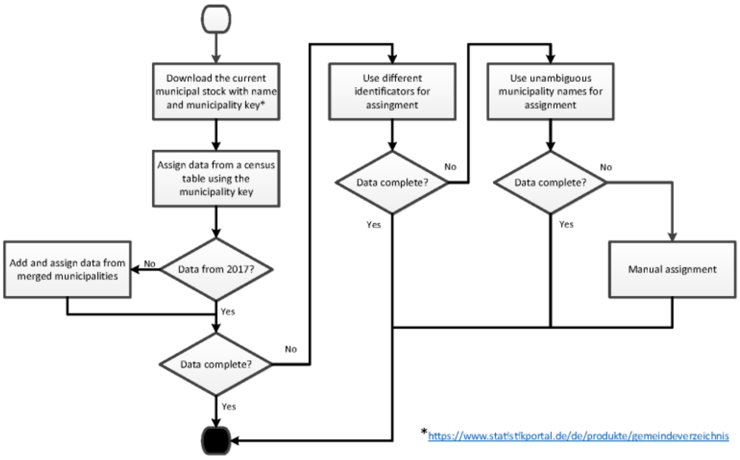

Fig. 1 Procedure for consolidating the census data.

Figure 1 shows the procedure for consolidating the data for one census table. The data were assigned to the municipalities from the municipal register of 2017 (https://www.statistikportal.de/de/produkte/gemeindeverzeichnis). Some census data tables, however, do not exist for 2017. Apart from the table from 2011, which was needed for the population development, the oldest table used is from 2014. In these cases, municipalities are indicated which no longer existed in 2017 as they were merged into one municipality. Then the values in the older tables were combined and assigned to the newly established municipality. If not all municipalities could be assigned a value after these steps, other identification numbers than the municipality key were applied. In case this was not sufficient, the names of the municipalities were used to assign the data. However, there are many municipalities with the same name in Germany. Therefore, attention was paid to the unambiguity of the names, e.g. by combining them with numbers from the municipality key. In a few cases, data could still not be assigned after these steps (for less than 2% of municipalities). Then the data was manually collected, e.g. via web searches.

The population density in the data set is related to the municipal area. Population density in relation to settlement areas would be an even more relevant indicator for energy system analyses as this data could be used to estimate costs for district heating networks. This more accurate data is published in a parallel study[10].

Mobility data. The mobility data in the municipalities in Germany are published in PDF format[11]. The delivery of the data in a processable format such as csv is subject to a fee. Therefore, the data was transferred from the PDF to a csv chart. Subsequently, the data could be allocated according to the same procedure as for the census data (cf. Fig. 1).

Renewable energy data. In earlier studies, potentials for electricity generation from photovoltaics, wind and geothermal energy were determined. The methods are explained in more detail below.

Technical photovoltaic potential. A high-resolution determination of the technical potential of residential roof-mounted photovoltaic systems for each municipality in Germany was presented by Mainzer *et al.*[7]. The method for calculating these potentials consists of two stages (see Fig. 2): first, the usable roof area in each municipality is calculated using statistical data such as the number and type of residential buildings as well as statistical data on roof geometries and the usable share of the roofs for photovoltaic systems. Next, the calculated roof area together with assumptions on the distribution of inclination and azimuth angles is combined with each municipalities' solar radiation data as well as the relative irradiation for specific inclination and azimuth angles to calculate the geographical potential. Combined with the technical PV plant efficiency, the technical potential for each municipality can then be inferred. Since the calculation method is described in detail in Mainzer *et al.*[7], all assumptions can easily be adjusted to the readers own preferences.

Non-residential buildings could be considered with our newer, more detailed methods[12], which, however, could not yet be applied to the whole of Germany due to the higher resource demand (calculation time and storage capacity) of these methods.

Technical wind potential. In another study, the potentials for onshore wind in Germany were calculated[8]. The applied method employs multiple data sources for land use categories, annual average wind speeds and techno-economic wind turbine data for several hundred plants as shown in Fig. 3. By excluding unsuitable areas, such as areas with a gradient above 20°, urban areas and natural parks, and inserting a buffer area around these as well as residential, commercial and industrial areas, the technically feasible area for onshore wind energy was determined. These remaining areas are associated with suitability factors based on empirical values and annual

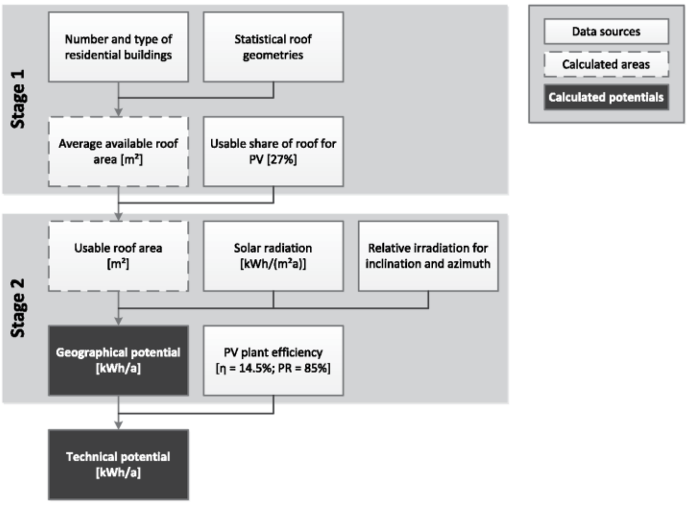

Fig. 2 Methodology for the assessment of technical PV potentials. References are used for the number and type of residential buildings[20], the statistical roof geometries[21], the solar radiation[22] and the relative irradiation for inclination and azimuth[23].

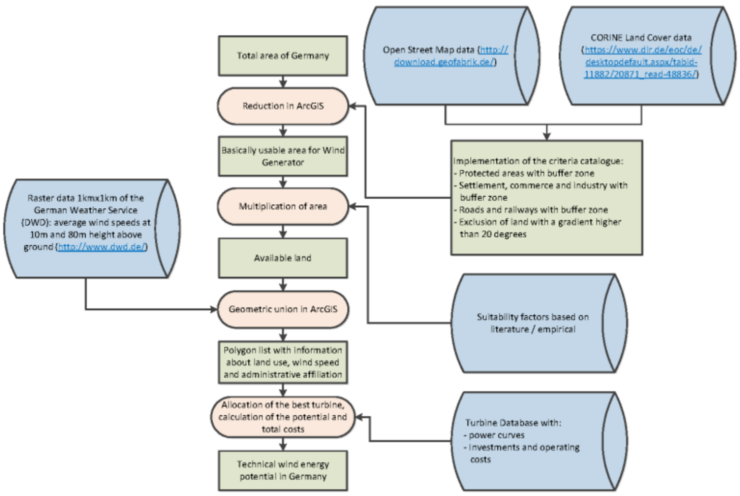

Fig. 3 Methodology for the assessment of technical wind energy potentials.

average wind speed data at 1 km² resolution. The final step, and one key innovation of the study, involved matching a wind turbine to the polygon types (combination of wind speed and land use category) based on the lowest levelized costs of electricity (LCOE). The results represent the lowest cost realization of the technical potential for onshore wind in Germany, based on the then (2013) state of the art in turbine technology.

The technical onshore wind potential data was aggregated to postcode level in McKenna *et al.*[8]. With the help of the geo-information system QGIS, the postcode areas were intersected with the administrative municipal areas from 2017. In this way, the wind potentials could be divided among German municipalities.

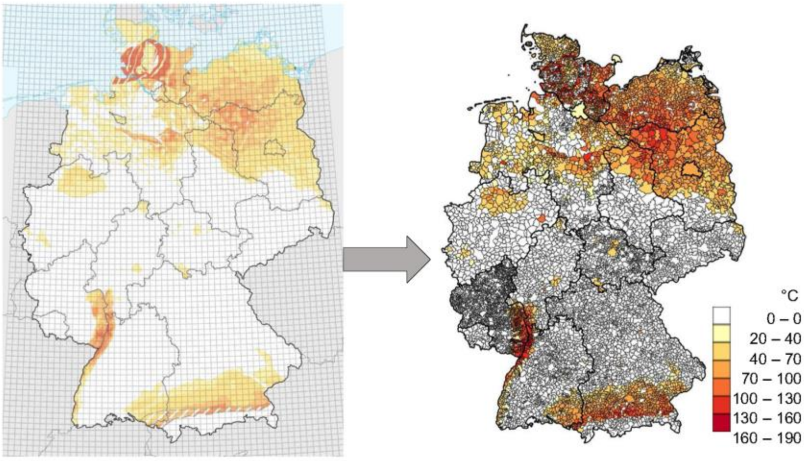

Fig. 4 Achievable hydrothermal temperatures (°C) in Germany at depths of up to 5000 meters. Data from the GeotIS project was transferred and assigned to the German municipalities.

Achievable hydrothermal temperature. Figure 4 shows that the achievable hydrothermal temperatures in Germany strongly depend on the region. This means that municipalities have different hydrothermal potentials. In the GeotIS project, the hydrothermal temperatures in Germany were determined (cf. left part of Fig. 4)[13]. With the help of a raster contained in the GeotIS tool, the temperatures could be transferred manually to a spatial resolution of 8.5 km². Subsequently, achievable hydrothermal temperatures could be assigned to the municipalities. Thereby, the temperature in a municipality and closest to the centre of the municipality was assigned to the municipality. Since on the one hand the transfer of 57,535 data points from the GeotIS map was very time-consuming and on the other hand different assignment methods to the municipalities could be chosen, a data table for the hydrothermal temperatures depending on the precise coordinates is also provided[9]. These coordinates represent the intersections of the grid shown in the left part of Fig. 4.

Cluster data. In Weinand *et al.*[6], indicators from Online-only Table 1 were first standardised to values between zero and one to ensure that all indicators have the same weight in the cluster analysis. Subsequently, a factor analysis was used to filter out the indicators that were not relevant for the further steps. Then the municipalities were grouped using a hierarchical cluster analysis. Thereby, 26 cluster validation criteria were applied to determine an appropriate number of clusters. The ten resulting clusters can also be found in the provided data set. Among these clusters are municipality groups with a high potential for renewable energies (Cluster 3, 4, 7 and 8), with a high proportion of district heating (Cluster 1) or cities with a high population density (Cluster 2).

Data Records

The municipality data summarised in Online-only Table 1 are available as an xls file in an online repository[9]. More than 400,000 data entries can be clearly assigned and identified on the basis of the column headings. The data for the hydrothermal temperatures are available as point coordinates in 8.5 km² resolution in a csv file[9]. The first column contains the latitudes, the first row the longitudes. The hydrothermal temperature is in the cell where latitudes and longitudes intersect. The entries are numbers from 0 to 5, where 0 means that there is no hydrothermal potential. For 1 the temperature is between 40 °C and 60 °C, for 2 between 60 °C and 100 °C, for 3 between 100 °C and 130 °C, for 4 between 130 °C and 160 °C and for 5 between 160 °C and 190 °C.

Technical Validation

When validating the data, the heterogeneity of the "concept of municipality" as used by the different federal states becomes apparent. For example, Baden-Wuerttemberg, which accounts for about 13% of the population, has only 75 municipalities with less than 1000 inhabitants. The neighbouring Rhineland Palatinate, which accounts for 5% of the population, yet counts 1624 municipalities with less than 1000 inhabitants (https://www.statistikportal.de/de/produkte/gemeindeverzeichnis). In an international context, the "concept of municipality" is even more heterogeneous. The data set thus provides high-resolution data, but the system boundary of a municipality is not necessarily the most suitable one for energy system analyses.

Census and mobility data. The census and mobility data are official data from German authorities and are therefore assumed to be accurate. Nevertheless, we have checked these data for anomalous values. For example, in 75 municipalities the population is zero. These municipalities are "municipality-free areas", i.e. municipalities without inhabitants. These are usually municipalities with nature reserves or military stations (for more details please refer to Weinand *et al.*[6]).

Technical photovoltaic potential. A validation of the technical PV potential has been performed for two intermediate results, using cadastral data from the federal state of Baden-Württemberg, which comprises about 10% of the area and 13% of the residential buildings in Germany. The validation shows that the number of residential buildings from the Baden-Württemberg cadastral building data differs by just 1.65% from the publicly available statistical data. It also shows that the assumed residential building sizes as well as the total ground floor area for Baden-Württemberg agree with the building sizes extracted from the cadastral data. It can thus be assumed that the employed assumptions as well as the statistical data used represent the German building stock adequately (see Mainzer *et al.*[7] for more details).

Technical wind potential. The onshore wind cost-potentials were validated with other studies in the literature. With central key assumptions of this method adjusted to reflect those in BWE[14], the results in both cases are very similar. Our study estimates a total potential area of about 41,000 km^2 compared to the BWE's 46,000 km^2. In terms of the available area for wind energy in Germany, the present work with 41,613 km^2 also agrees well with the UBA[15] study, which determined 49,000 km^2. The reason for the lower results in our case lies in the more conservative assumed suitability factors and offset distances from obstacles.

The discrepancy is significantly larger in relation to the installable power and generated energy, however: UBA conclude that about 1,190 GW could be installed to generate about 2,900 TWh/a (i.e. average full load hours of about 2400), compared to 367 GW and 855 TWh/a (full load hours of 2329)[8]. Whilst some of the discrepancy can be explained by the difference in the determined areas, the majority is probably due to the significantly higher turbine densities employed by UBA. The high overall turbine density is achieved through an aggregation procedure that clusters nearby polygons together (similarly to Fueyo *et al.*[16,17]). For Baden-Württemberg, McKenna *et al.*[18] found a technical potential of 29 to 41 GW at costs between 6 and 21 €ct/kWh. This compares well to the technical potential calculated in our study of 34 GW at average costs of 9.5 €ct/kWh. Similarly, McKenna *et al.*[19] found a potential and land area for Germany of 707 TWh and 35,700 km^2 respectively in a similar study at the European level. The only other recent study that considered the whole of Germany was EEA (www.eea.europa.eu/), which did not differentiate between different land use categories. This explains the very high total technical potential of 4000 TWh/a identified in Germany. The calculated fraction of this potential, which by 2020 should be competitive, was found to be 258 TWh/a, which corresponds to generation costs of about 7 ct/kWh in McKenna *et al.*[8]. A direct comparison of the generation costs with EEA is not possible, however, as they were not divulged for individual countries or states.

Achievable hydrothermal temperature. As already described above, the data for the achievable hydrothermal temperature were transferred based on the GeotIS project results[13]. On the one hand, visual inspection of the maps in Fig. 4 shows that the data was transferred correctly. On the other hand, this has also been confirmed by a sampling check.

Cluster data. In the cluster analysis, 26 cluster validation criteria were applied to determine the number of clusters[6]. Further validation methods came to the same results as the 26 cluster criteria.

Code availability

Microsoft Excel version 2010 and ArcGIS version 10.1 were used to determine the technical PV and wind potentials. QGIS version 2.14.10 was used for the transfer of wind and hydrothermal potential to the municipality level. MATLAB version 2017b and Microsoft Excel version 2016 were used to compile the census and mobility data. Microsoft Excel or another program for processing CSV or XLS files is required to process the data set provided with this data descriptor. The codes for generating the data can be made available on request.

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Author contributions

J.M.W. collected and synthesized the data, wrote the majority of the manuscript and created/modified the figures. R.M. and K.M. determined the original data on wind and photovoltaic potential, wrote parts of the manuscript and supervised the ENRES project.

Competing interests

The authors declare no competing interests.

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Assessing the potential contribution of excess heat from biogas plants towards decarbonising residential heating

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ABSTRACT

This paper analyses the technical potential for utilising excess heat from biogas plants, in order to supply local settlements through district heating. Based on a survey of around 600 biogas plant operators, the fractions of excess heat from the cogeneration units in these plants are analysed. A heuristic is developed to match biogas plants (heat sources) with local settlements (heat sinks) in order to determine a least-cost district heating supply for residential buildings. Two criteria are employed, namely the CO_2 abatement costs and the payback period, which represent the macro- and microeconomic perspectives respectively. Based on the survey, the mean fraction of excess heat is 40%, which is in agreement with other empirical studies. Extrapolating this fraction to the German biogas plant stock, which is selected as a case study, leads to technically feasible CO_2 savings of around 2.5 $MtCO_2$/a. Employing the criteria of CO_2 abatement costs and payback period yields about 2 $MtCO_2$/a below CO_2 abatement costs of 200 €/tCO_2 and below a payback period of 9 years. This represents about 0.25% of the total German CO_2 emissions in 2016 or around 2.5% of all CO_2 in residential buildings. Alternative threshold values of 80 €/tCO_2 and 5 years payback period reduce the carbon reduction potential to about 0.5 $MtCO_2$ and 0.75 $MtCO_2$ respectively. These relatively high average costs are related to the typically low population density in rural regions where biogas plants are located. These potentials are concentrated in around 3,500 of 11,400 municipalities, where district heating from biogas plants could reduce CO_2 emissions per capita by an average of 250 $kgCO_2$ /a and cover 12% of the total heating demand. Apart from a methodology that can be transferred to any country with comparable data availability, the present study demonstrates that the use of excess heat in biogas plants can contribute to global decarbonisation.

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1. Introduction

The expansion of renewable energy technologies (RETs) is largely being driven by private individuals, farmers and energy cooperatives in the context of *community energy* (Klaus Novy Institut e.V. & trend:research 2011; trend:research 2017). This trend involves these actors investing in and/or operating RETs, including wind, solar and bioenergy plants, in some cases also buying the local energy infrastructure (gas, electricity, heating networks) back from the local utility. They are mainly motivated by a desire to 'take control' of their local energy supply (system) and thus become more independent from centralised markets and energy suppliers (for reviews, cf. Müller et al., 2011; Rae and Bradley, 2012). Many community energy projects declare an objective of energy autonomy, with some examples in Germany including the 100% Renewable Energy Regions and the Bioenergy Villages. Despite possibly having potentially negative system wide impacts (McKenna, 2018), municipalities typically define autonomy on an annual basis and for electricity alone.[1] The costs of these RETs were

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[1] At the time of writing only one German municipality is known to the authors that is aiming to be completely energy autonomous, namely Bordelum, cf. http://www.sonnenseite.com/de/energie/norddeutsche-gemeinde-stellt-komplett-auf-erneuerbare-energien-um.html.

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Nomenclature

af	Annuity factor (−)
a_{111}	Area size of a settlement area with continuous urban fabric (m^2)
a_{112}	Area size of a settlement area with discontinuous urban fabric (m^2)
A_{BC}	Share of brown coal in heat supply for settlement area (%)
A_{EL}	Share of electricity in heat supply for settlement area (%)
A_{Gas}	Share of gas in heat supply for settlement area (%)
A_{HC}	Share of hard coal in heat supply for settlement area (%)
A_{Oil}	Share of heating oil in heat supply for settlement area (%)
BSA_{SA}	Total building space of a settlement area (m^2)
$CO2_{costs}$	CO_2 abatement costs (€ /tCO_2)
$CO2_{saved,SA}$	Saved CO_2 emissions in a settlement area (tCO_2)
$C1$	Construction cost parameter per length unit for district heating network (€/m)
$C2$	Construction cost parameter per area unit for district heating network (€/m^2)
CR	Coverage ratio of the heat supply (%)
df	Discount factor (%)
d_{SA}	Average diameter of the district heating pipelines (m)
DIS_{SA}	Distance between a biogas plant and a settlement area (m)
e	Plot ratio, used to categorize typical city districts (−)
EF_{BC}	CO_2 emission factor of brown coal (kgCO_2 /kWh)
EF_{EL}	CO_2 emission factor of electricity (kgCO_2 /kWh)
EF_{Gas}	CO_2 emission factor of gas (kgCO_2 /kWh)
EF_{HC}	CO_2 emission factor of hard coal (kgCO_2 /kWh)
EF_{Oil}	CO_2 emission factor of oil (kgCO_2 /kWh)
EH_{BGP}	Share of available excess heat in a biogas plant (%)
EH_{used}	Share of already used excess heat in a biogas plant (%)
EXP_{SA}	Sum of expenses for the supply of a settlement with district heating (€)
F_1	Number of residential buildings in a federal state/ municipality with one apartment (−)
F_2	Number of residential buildings in a federal state/ municipality with two apartments (−)
F_3	Number of residential buildings in a federal state/ municipality with three or more apartments (−)
F_{mean}	Mean living space per apartment in a federal state (m^2)
$F_{mean,m}$	Mean living space per apartment in a municipality (m^2)
F_{total}	Total living space in a federal state (m^2)
hd_{mean}	Mean specific heat demand in a settlement area (kWh /m^2)
HD_{SA}	Total heat demand in a settlement area, reduced by the share of heat generation technologies that should not be replaced by the excess heat (kWh)
$HD_{SAtotal}$	Total heat demand in a settlement area (kWh)
HDC_{SA}	Specific heat distribution costs of the excess heat (€ /GJ)
$I_{con,SA}$	Investment in the pipeline for connecting the biogas plant and the settlement area (€)
$I_{DHG,SA}$	Investment for the building or the densification of the district heating grid in the settlement area (€)
I_{SA}	Total investment to use the excess heat from the biogas plant to supply the settlement area (€)
IR	Investment rate for the district heating pipeline (€ /m)
LHD_{SA}	Linear heat density in a settlement area (GJ /m)
LP_{BGP}	Excess heat profile of a biogas plant (−)
LP_{SA}	Heat demand load profile of a settlement area (−)
LS_1	Living space in a settlement area (m^2)
LS_2	Adjusted living space in a settlement area, if LS_{total1} is not equal to LS_{total2} (m^2)
LS_{total1}	Calculated sum of the living space over all settlements in a municipality (m^2)
LS_{total2}	Measured total living space in a municipality (m^2)
n_a	Number of apartments in a settlement area (−)
n_b	Total number of buildings in a square kilometre of the census data grid (−)
n_{b111}	Number of buildings in a settlement area with continuous urban fabric (−)
n_{b112}	Number of buildings in a settlement area with discontinuous urban fabric (−)
NPV_{SA}	Net present value for the supply of a settlement with district heating (€)
P	Total population of a settlement area (Inhabitants)
PD_{SA}	Population density of a settlement area (Inhabitants /km^2)
PP	Payback period (a)
P_{th}	Thermal power of a biogas plant (kW)
Q_{sell}	Amount of excess heat that is supplied by the biogas plant to the settlement area (kWh)
REV_{SA}	Sum of revenues for the supply of a settlement with district heating (€)
S_{Bio}	Proportion of heat supplied by biomass (%)
S_{DH}	Proportion of heat supplied by district heating (%)
S_{GT}	Proportion of heat supplied by geothermal and other environmental heat (%)
S_{SE}	Proportion of heat supplied by solar energy (%)
S_{WP}	Proportion of heat supplied by wood pellets (%)
SLP_{BGP}	Standardised excess heat profile of a biogas plant (−)
SLP_{HD}	Standardised heat load profile of a settlement area (−)
SR	Supply ratio of the heat supply (%)
w	Effective width, relationship between an area and the length of contained district heating pipelines (m)
x	Average number of apartments in a residential building with more than two apartments (−)

historically higher than those of conventional technologies, meaning they relied on subsidies to be economic. However, recent rapid reductions in costs for photovoltaics and batteries have provided a renewed incentive for attempts to become energy autonomous at a local scale (Nykvist and Nilsson, 2015).

Many studies have techno-economically analysed the scope to achieve a local energy supply from renewable sources (e.g. Jenssen et al., 2014; Schmidt et al., 2012 and Burgess et al., 2012). Most conclude that a completely autonomous energy supply is only feasible in rural municipalities with large bioenergy resources, and even then, large storage capacities are required which lead to high costs. In the context of decentralised energy supply, a related stream of research is concerned with (industrial) excess heat and the possibilities of utilising this as an energy input, e.g. for space heating. Several studies in this area have analysed the technical and/or economic potential of excess heat from industry, often based on emissions data from individual industrial plants. Noteworthy are the studies McKenna and Norman (2010), Fang et al. (2013, 2015), Brueckner et al. (2014), Miró et al. (2015, 2016), Bühler et al. (2017), and the ongoing Heat Roadmap Europe project (Persson et al., 2014).

One additional source of excess heat potential are biogas plants, which valorise organic matter into biogas through fermentation (cf. section A.1 in the appendix). This biogas is typically combusted in a cogeneration unit, whereby the electricity is generally fed into the grid. Within Europe, Germany accounts for around 50% (329 PJ in 2015) of the total biogas production (Scarlat et al., 2018). A legal requirement was introduced in Germany with the Renewable Energy Sources Act (EEG) 2012, that new biogas plants must utilise at least 25% of their excess heat in the first year of operation and 60% thereafter (Mergner et al., 2013). Despite this, there are many operating plants, some of which were commissioned before this time, with much lower levels of heat utilisation. Section A.1 in the appendix gives an overview of the current status of the German biogas industry.

Against this background of decentralised energy systems, aspirations for local energy autonomy and excess heat potentials, this study analyses the technical and economic potential for recovering excess heat from biogas plants in Germany to supply local buildings with low-carbon space heating. Germany is selected as the case study due to the high biogas production mentioned above. The objective is to determine the amount of heat that could technically be recovered as well as its associated costs, in order to give indications of promising locations. The paper addresses the following research questions:

- How does the excess heat from biogas plants match the existing heat sinks?
- What contribution can the use of biogas excess heat make to the energy autonomy of municipalities?
- In which locations is the utilisation of biogas excess heat economically interesting for investors?

The employed methodology involves input from a survey of around 600 biogas plant operators for a GIS-based analysis of heat sources and sinks. Thereby, a developed heuristic matches and connects the heat sources and sinks with district heating pipelines based upon a least-cost approach. The results are therefore of relevance to local decision makers, biogas plant operators and researchers in the field of energy system analysis. In particular the quantitative results offer an indication of the costs and related CO_2 saving potentials on a local level, in order to underpin local decision-making.

The remainder of the paper is structured as follows. The following section 2 gives an overview of relevant literature on the subject of designing district heating networks (DHNs). The subsequent section 3 outlines the employed methodology, including the plant operator survey, the approach to spatially locating the analysed plants, the determination of the residential building heat demand at a local level and the heuristic to match heat sources and sinks. Then section 4 presents and discusses the results, first for the survey sample and then for a tentative scale-up for the whole of Germany. The paper closes in section 5 with conclusions and an outlook.

2. Literature review

In the following literature review, Table 1 provides a summary of the methodology and problem sizes used in the evaluated studies. The distinction between bottom-up and top-down studies is made in such a way that bottom-up studies, for example, are based on individual buildings and roads, while the top-down approach uses heat and population densities to calculate potentials. District heating (DH) pipelines with length-dependent costs are required to utilise the excess heat of biogas plants in residential settlements. In section 2.1, studies on small-scale DHNs will be discussed before section 2.2 focuses on large-scale DHNs.

2.1. Small-scale district heating networks

Approaches for the design and dimensioning of small-scale DHNs have already been presented and discussed in numerous studies. In Chinese (2008), DH and cooling systems are designed using a mixed integer optimisation model. Central and decentralised heat production are combined while taking network costs into account. A mixed integer linear program was developed by Casisi et al. (2009) to determine the optimal layout of a DH system and the optimal operating strategy for a distributed cogeneration system while minimising the total cost of ownership and operation. Dobersek and Goricanec (2009) identify the optimal tree branch path of a DHN in an urban area, under consideration of construction costs, pump and electricity costs. The optimal network for a complete supply of all consumers is determined, whereby the locations of the heat source and consumers are defined in advance. Some specific nodes that do not represent consumers are used for branches of district heating pipelines (DHPs). Delangle et al. (2017) investigate the extension of existing DHNs. Besides DH, gas boilers, biomass boilers, heat pumps and heat storages are included in a mixed integer linear optimization. The model can determine the optimal investment plan for a DHN extension and can be applied to other case studies. In the latter case, the existing DHN and the buildings to be connected must be known. Karschin and Geldermann (2015) present an optimisation model which determines the location and capacity of a bioenergy plant and the associated DHN. Possible locations are defined beforehand as the locations of the plant. The study serves to support bioenergy villages in planning their energy systems. The fuzzy optimisation model in Balaman and Selim 2016 designs biomass based renewable energy supply chains and DH systems with heat storages in specific regions. Another study on small scale DHNs is that of Coss et al. (2018). In their article, a multiobjective optimisation model is presented, which determines the energy supply of a biomass plant for DH purposes. However, the model does not optimise the design but only the operation mode of the DHN. Marty et al. (2018) highlight the relevance of a simultaneous optimisation of a DHN and an organic rankine cycle as parts of a geothermal plant. The location of the DH plant is specified in advance for the optimisation model, and one consumer is already connected to the DHN. In the case of the utilisation of excess heat from biogas as in our study, the connection of a customer in advance is not meaningful, since the use of excess heat is not always worthwhile. Karner et al. (2018) investigate heat flexibilities in cities through excess heat from industry. One of the presented options is the use of the heat in DHNs. Nielsen (2014) develops an algorithm for the economic evaluation of possible network expansions based on existing DHNs. Geographical data are used for cost calculations for heat generation, distribution and transmission. In order to reduce model complexity, Fazlollahi et al. (2014) design the DHN on the basis of cluster analyses. The clustering of urban areas is intended to reduce the model complexity of a subsequent optimisation model by aggregating the energy demand and DH distribution costs in the resulting urban districts. In the investigated city there are already 13 clusters needed to adequately represent the demand and costs.

In many cases, the studies do not address the applicability of the

Table 1
Studies about designing and dimensioning DHNs (R = residential sector, C = commercial sector, I = industrial sector).

Study	Methodology	Bottom-up or top-down methodology	Network building or expansion	Sector	Region	Number of customers/ nodes/sinks	Number of suppliers/sources
Chinese (2008)	Optimisation model	Bottom-up	Building	R, C, I	Urban area (Italy)	11	1
Casisi et al. (2009)	Optimisation model	Bottom-up	Building	C	Urban area (Italy)	6	9
Dobersek and Goricanec (2009)	Optimisation model	Bottom-up	Building	n.a.	Urban area	23	1
Fazlollahi et al. (2014)	Cluster analysis and optimisation model	Top-down	Building	n.a.	Urban area	13	n.a.
Nielsen (2014)	Heuristic	Bottom-up	Expansion	n.a.	Arbitrary Danish municipality	n.a.	n.a.
Karschin and Geldermann (2015)	Optimisation model	Bottom-up	Building	R	Rural area	71	1
Bordin et al. (2016)	Optimisation model	Bottom-up	Expansion	R, C	Urban area	1,000	1
Balaman and Selim (2016)	Optimisation model	Bottom-up	n.a.	R	Urban area (Turkey)	10	1
Delangle et al. 2017	Optimisation model	Bottom-up	Expansion	n.a.	Urban area	31	1
Unternährer et al. (2017)	Cluster analysis and heuristic	Top-down	Building	n.a.	Urban area (Switzerland)	410	n.a.
Coss et al. (2018)	Optimisation model	Top-down	Just operation of the DHN	R, C	n.a.	n.a.	n.a.
Guelpa et al. (2018)	Optimisation model	Bottom-up	Expansion	R, C, I	Urban area (Italy)	182	5
Karner et al. (2018)	Heuristic	Bottom-up	Expansion	R, C, I	Urban area (Austria)	n.a.	n.a.
Marquant et al. (2018)	Cluster analysis and optimisation model	Bottom-up	Building	R, C	Urban area (Switzerland)	32	n.a.
Marty et al. (2018)	Optimisation model	Bottom-up	Building	n.a.	n.a.	9	1
Soltero et al. (2018)	Heuristic	Top-down	Just cost calculation	R	Rural areas	499	n.a.
This Study	**Heuristic**	**Top-down**	**Building**	**R**	**Whole Germany**	**38,414**	**10,446**

methods to large-scale problems with many heat suppliers and it can be assumed that the models are not suitable for this purpose (Casisi et al., 2009; Dobersek and Goricanec, 2009; Karschin and Geldermann, 2015; Marty et al., 2018). In addition, the studies show that the investigation of small-scale problems with the applied methods already leads to computational and time restrictions and is therefore not suitable for large-scale applications (Chinese, 2008; Fazlollahi et al., 2014; Balaman and Selim 2016). Chinese (2008) recommends the use of heuristics instead of optimisation to solve larger problems in a reasonable time. Other studies require extensive data for the application of the models, which are not available for large-scale problems and/or for application in Germany (Nielsen, 2014; Karner et al., 2018).

2.2. Large scale district heating networks

In the literature are only a few studies which design DHNs for large regions. Soltero et al. (2018) follow a similar approach to our study. The authors develop a methodology to design biomass DH systems in rural areas and examine 499 municipalities in Spain that are not connected to the gas network. In the region under consideration, DH from biomass can save 5.4 Mt_{CO2} per year. The study shows several differences to our paper. Firstly, the heuristic estimates the length of the DHN instead of determining the length by geographical methods. Furthermore, no existing plants are considered, but the potentials of new plants are estimated. In addition, the approach is only applicable to rural areas and the investment decision is made for entire municipalities, while in our analysis it is possible to connect parts of municipalities, i.e. settlements, to the DHN. Marquant et al. (2018) develop a combined clustering schema to overcome time-constraints while estimating the potential for DHNs. In this study, however, only 32 buildings are examined in a case study. These buildings are divided into four clusters to reduce the variables for the subsequent DH optimisation model. However, the calculation for the whole model takes even in this case more than 250 h. Unternährer et al. (2017) also use a clustering approach before determining the optimum design of a geothermal DHN for the resulting clusters. The cluster analysis is performed using an optimisation model. On the computer used in the study with 8 cores and 32 GB RAM, the model could not be executed from a cluster number of 420 clusters or larger due to memory restrictions. The extension of existing DHNs is subject in the study of Bordin et al. (2016). The network can be expanded by potential pipelines and customers in an optimisation model to maximise the net profit. The tree configuration of the network is optimised with one heat supply plant as starting point. However, the model is not suitable for the purposes of our study, as only one network with one heat generation plant can be considered and existing networks are extended. The same applies to the study by Guelpa et al. (2018), in which large DHNs are also expanded with the help of optimisation.

The evaluation of the literature on the design of DHNs shows that a large problem size of the kind described in our article has not yet been investigated in any study. In some methods, even smaller DHNs encounter temporal or computing problems (Unternährer et al., 2017; Marquant et al., 2018). In addition, the methods developed so far are not applicable to the case presented in this paper (Soltero et al., 2018), for example due to the need for extensive building data (Guelpa et al., 2018). Furthermore, no procedure has yet been developed to design many DHNs at the same time. The methodology developed in our study is therefore not only applied to the novel case of utilising excess heat from all German biogas plants, but also represents a further development with regard to dealing with large problems in DH design. Due to the evaluated literature and the time and calculation restrictions mentioned therein, the method developed in our study is not an optimisation but a heuristic. The developed heuristic differs in the following points from the problem formulations in the above mentioned studies:

- It is evaluated whether a connection of a settlement is worthwhile and "to which percentage" a settlement should be

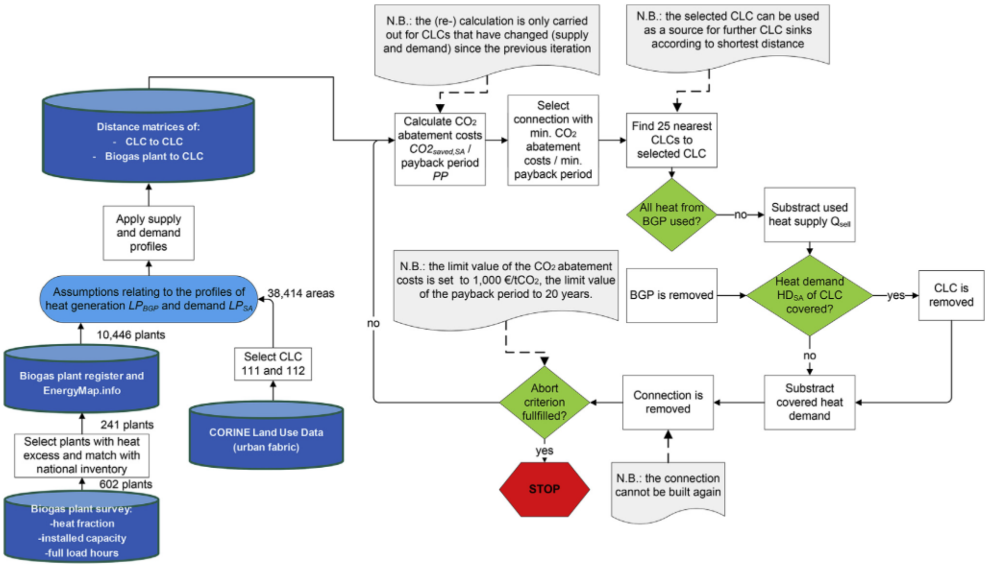

Fig. 1. Overview of the algorithm developed and used in this study to select biogas plants (BGP) and settlement areas for DH supply.

connected. This can result in a biogas plant not being connected to heat consumers, which means that the excess heat remains unused.

- A very large problem has to be solved (with about 50,000 biogas plants/settlements).
- Subtrees/independent DHNs are allowed (up to 10,000, as there are as many sources/biogas plants).
- Possible pipelines go from any biogas plant/settlement to any other nearby settlement.

Besides Germany, the data used to represent settlement areas are available for 38 other European countries (EEA, 2018). The heuristic could be extended to any country with similar available data. As demonstrated in Scarlat et al. (2018), there is also a lot of biogas production in other countries than Germany.

3. Method and approach

This study uses different methods in a multi-stage approach. The summarizing representation in Fig. 1 is intended to provide a better understanding of the algorithm explained in this section. Firstly, the results of an extensive survey of biogas plant operators in Germany are taken into account with regard to their heat utilisation rates (cf. section 3.1, Herbes and Halbherr, 2017). Secondly, 10,446 biogas plants as well as the 38,414 CORINE Land Cover (CLC) settlement areas in Germany are examined with regard to their technical and geographical characteristics (cf. section 3.2). Subsequently, the local demand for heat in buildings in all German settlement areas and the excess heat availability of biogas plants are calculated (cf. section 3.3). In order to provide a least cost solution, options to integrate the excess heat from the biogas plants into DHNs are explored. In this context, in particular the distances between the biogas plants and the settlement areas are determined. Based on published methods for DH systems assessment and dimensioning, the possible CO_2 savings and associated costs as well as the payback periods are determined for combinations of biogas plants and their nearest residential areas. By focussing on the connections with the lowest CO_2-abatement costs/payback period, the most environmentally and economically attractive locations for a district heating network development are identified (cf. section 3.4).

3.1. Biogas plant survey

In the summer of 2016, an online survey of those members of the German Biogas Association that run a biogas plant was conducted, resulting in a gross sample of 2,724 operators[2] (Herbes et al., 2018a). After the development of the questionnaire, which was a joint undertaking of Nuertingen-Geislingen University and the German Biogas Association (GBA), extensive cognitive pretesting with external biogas experts, GBA staff and plant operators was carried out before fielding the survey. To decrease nonresponse bias after the first phase, a telephone campaign in those federal states that were underrepresented in the answers was conducted. These efforts resulted in a final data set of n = 602 plant operators, which is equivalent to a response rate of 22% (according to response rate 2 (RR 2), cf. AAPOR (2015)). Regarding the distribution of federal states, the sample shows a small overrepresentation of Bavaria and Baden-Wuerttemberg (cf. Fig. 5). Regarding size and commissioning year, the sample is statistically representative of the entire German biogas plant stock. Amongst other things, the data set includes location, plant size, percentage of the already used heat, utilisation paths and various data on prices and price models, which are not relevant for the present study (cf. Section A.2 in the appendix and Herbes and Halbherr, 2017 for more information).

[2] For an overview of the historical development and current status of the German biogas sector, the interested reader is referred to Appendix A.1.

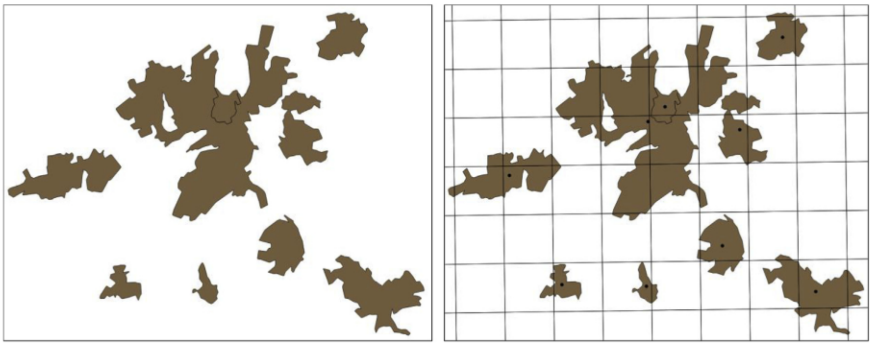

Fig. 2. Exemplary section of the "111" and "112" CORINE areas (left part) and the intersection with the ETRS89-LAEA grid (right part).

3.2. Biogas plant register and CORINE land use data

The plants from the survey can be identified and mapped in the Energymap plant register (Engel, 2015) on the basis of their year of commissioning, postcode and nominal power. Further and more detailed information could then be taken from the plant register, such as the full load hours in recent years. The full load hours in this study represent the total operating hours recalculated to full load hour equivalents. The data from the survey were used for heat utilisation (cf. section 4.2).

The Energymap plant register contains the coordinates of the biogas plants with a maximum error of 3 km. Therefore, the locations of the 10,446 plants in Germany could be mapped with the help of the geoinformation system QGIS. The plants from the survey are a subset of these 10,446 plants. CLC data from the European Environment Association (EEA, 2016) were used as a source for the settlement areas. The shapefiles of these areas for Germany are provided by the Federal Office of Cartography and Geodesy (Lenk et al., 2017a). Urban areas are distinguished according to the density of the urban fabric, into "continuous urban fabric" (denoted with the number "111") and "discontinuous urban fabric" areas (denoted with the number "112"). The boundary between the 111 and 112 areas is mainly determined by the presence and quantity of vegetation (EEA, 1995). Overall, the German settlement areas are divided into 38,414 of these areas. The left part of Fig. 2 shows an exemplary section of these areas.

3.3. Heat demand and generation

The method for determining the heat demand of the settlement areas and the excess heat availability of the biogas plants is explained in sections 3.3.1, 3.3.2 and 3.3.3.

3.3.1. Heat demand

Data on the building stock in Germany were taken from the census of the Federal Statistical Office to determine the heat demand in the settlement areas. For more information on determining the census data, see Statistisches Bundesamt (2015b). The census data include data on building age, building type and share of DH, and are assigned with the help of the Lambert-Azimuthal-Equal Area Projection (ETRS89-LAEA) into INSPIRE-compliant 1-km^2 grid cells (Statistisches Bundesamt, 2016b). Therefore, the CLC settlement areas must also be assigned to this grid. For this purpose, the CLC settlement areas were intersected with the ETRS89-LAEA grid. The result can be seen on the right part of Fig. 2. The black dots in the CLC areas represent the area centroids. Industrial and commercial areas are excluded from this analysis due to the lack of data for industrial heat demand.

After the allocation of the CLC sub-areas to the square kilometres, the census data were assigned to the CLC areas. The data per square kilometre must be distributed to all CLC sub-areas in the grid. In addition to taking into account the area share, a distinction is also made between 111 and 112 areas (cf. section 3.2). The 111 areas represent settlement areas of which on average 90% are covered with buildings. For the 112 areas, the proportion of building area is on average 65% (EEA, 1995). These values are used as building densities. Since the census data is related to buildings, this information can be used to divide the census data into areas. Section A.3 of the appendix shows the calculation of the heat demand $HD_{SAtotal}$ in the individual settlements using these census data in detail. In many settlement areas there are buildings whose heat demand is covered by DH systems. For these settlements, the heat demand HD_{SA} is deducted from the total heat demand $HD_{SA_{total}}$. Since it is not known which building types have DH systems, the share of DH systems S_{DH} in the settlement is deducted from the total heat demand. In addition, the heat demand is reduced by the share of technologies that should not be replaced by DH with biogas excess heat, such as renewables (cf. Eq. (1)).

$$HD_{SA} = HD_{SAtotal} \cdot (1 - S_{DH} - S_{WP} - S_{Bio} - S_{SE} - S_{GT}) \quad (1)$$

S_{WP} stands for the proportion of heat supplied by wood pellets, S_{Bio} for biomass, S_{SE} for solar energy and S_{GT} for geothermal and other environmental heat. These shares are not to be replaced because the emission factors are lower or not significantly higher than those for DH from biogas plants (LfU, 2016). Apart from the share of DH (municipality level), all shares are based on figures at federal state level (Statistisches Bundesamt, 2016a). Eq. (1) is based on the assumption that the heat demand of buildings which already have a building connection for DH is completely covered by the existing DH. With the census of 2011 as a basis, the share of DH in settlement areas in Germany ranges from 0 to 95% (mean value is 2.65%[3]).

In the next step, a heat load profile LP_{SA} is assigned to each settlement area (cf. Eq. (2)). For this purpose, a standardised profile of a DHN SLP_{HD} with an hourly resolution is used, which is adapted

[3] In the calculation of this value, all municipalities are equally weighted. Therefore it must not be confused with the proportion of district heating in the residential heat supply in Germany of 13.8% (Euroheat and Power 2017).

according to the previously determined heat demand HD_{SA} (for the standardised profile, see Karner et al. (2016)).

$$LP_{SA} = HD_{SA} \cdot SLP_{HD} \tag{2}$$

3.3.2. Heat generation

For each biogas plant, the thermal capacity, the full load hours and the share of already used excess heat EH_{used} are known, as explained above. If the thermal power P_{th} is not given, it is determined with the help of the electrical power and a heat-to-power coefficient of 1 (Klein et al., 2014). In case no full load hours are known, these are determined on the basis of the electrical power and the amount of energy generated per year. On the basis of this data, an hourly load profile SLP_{BGP} can now be assigned to each biogas plant. Biogas plants are typically operated as baseload, but recent changes to the energy-political framework (cf. section A.1 in the appendix) have led to more flexible operation. Since the maximum thermal power requirement is in winter, it is assumed that the biogas plant will be primarily operated during these months. On the basis of the full-load hours, the time window of operation during the winter is extended in both directions until the full load hours are reached (cf. Fig. 12). Since excess heat is only generated during operation, the period of electricity production also corresponds to the period during which excess heat is generated. The excess heat profile LP_{BGP} is determined according to Eq. (3).

$$LP_{BGP} = SLP_{BGP} \cdot P_{th} \cdot (1 - EH_{used}) \tag{3}$$

3.3.3. Coverage and supply ratio

Having assigned load profiles to both the biogas plants and the settlement areas, the coverage ratio CR and the supply ratio SR can be determined. The supply ratio is based on the total amount of available excess heat EH_{BGP} and puts the available excess heat in proportion to the heat demand HD_{SA} of the settlement areas (cf. Eq. (4)).

$$SR = \frac{EH_{BGP}}{HD_{SA}} \tag{4}$$

By contrast, the coverage ratio is based on an hourly coverage and thus takes into account the time characteristics of supply and demand. As a result, the coverage ratio cannot be greater than the supply ratio. The coverage ratio CR is calculated in Eq. (5) for every hour. If the heat demand HD_{SA} is greater than the excess heat EH_{BGP} in an hour t, the share that can be covered by the excess heat is calculated in Eq. (6). If the share of excess heat is greater, the heat demand can be fully covered (cf. Eq. (7)). The hourly coverage ratios are then integrated in order to obtain the overall coverage ratio. The calculation of this indicator allows a statement about the autonomy of the settlement area.

$$CR = \frac{100}{8760} \cdot \int_{t=0}^{8760} CR_t \cdot dt \tag{5}$$

$$HD_{SA,t} \geq EH_{BGP,t} \Rightarrow CR_t = \frac{EH_{BGP,t}}{HD_{SA,t}} \tag{6}$$

$$HD_{SA,t} < EH_{BGP,t} \Rightarrow CR_t = 1 \tag{7}$$

3.4. Allocation of the biogas plants to CLC areas

As described in section 3.2, the shape files of the CLC settlement areas and the coordinates of the biogas plants were used in the geoinformation system QGIS. After the calculation of the centroids of the CLC areas, QGIS was used to calculate the distance matrices for the distances between biogas plants and CLC areas as well as for the distances between the CLC centroids. In the first case, the closest 50 CLC areas and their distances to each biogas plant were determined. In the latter case, due to computational restrictions, only the closest 25 CLC areas were determined for each of the 38,414 CLC areas. Our results indicate that the limitation to the next 25 or 50 areas is sufficient. The distances are needed to calculate the costs of the DHPs, as will be explained in the following sections.

Now the loop shown in the algorithm in Fig. 1 after determining the distance matrices is explained. In the first step, CO_2 abatement costs/payback periods are calculated for each of the 10,446 biogas plants, which would result from the supply of DH. This is done for every biogas plant for all 50 of the closest CLC areas. In the next step, the connection is selected from the resulting 10,446 × 50 connections, which results in the lowest CO_2 abatement costs/payback period. Then the 25 closest CLC areas to the selected CLC area are added to the selected biogas plant because this CLC area can now be considered as a new starting point for the heat supply. The amount of heat provided to the settlement is deducted in the next steps from the heat supply of the biogas plant and from the heat demand of the settlement. The maximum possible amount of heat is provided in each step. If there is no heat supply left after this step, the biogas plant will be removed from consideration, otherwise the CLC area. The abort criterion is then checked, and if the last CO_2 abatement costs/payback period are above a predefined limit value, the loop is aborted. The limit values are described in more detail in section 4. Otherwise the loop is carried out again, but the recalculation is carried out only for the biogas plants and CLC areas where the heat supply or heat demand has changed since the last iteration, in order to reduce simulation time. In addition, all variables that change are recalculated, such as CR and SR from section 3.3.3. All biogas plants that have the selected CLC area among the nearest 50 areas will therefore be included in the new calculation. In each step, for economic reasons it is ensured that the total length of the DHP does not exceed 50 km (Arbeitsgemeinschaft QM Fernwärme, 2017).

The following sections explain the determination of the CO_2 emissions saved (section 3.4.1), the costs for the DHN and the CO_2 abatement costs (section 3.4.2) as well as the payback period (section 3.4.3).

3.4.1. Calculation of the saved CO_2 emissions

The calculation of the saved CO_2 emissions is based on the allocation of used energy to provide heat to the settlement areas. The emission factors (EF) of the energy sources and their average allocation in Germany are shown in Table 2. The allocation of the energy for the determination in the settlement areas is based on the average values in the respective federal state (Statistisches

Table 2
The emission factors EF of the heating energy sources and their average allocation in Germany (LfU, 2016; Statistisches Bundesamt, 2016a).

Energy carrier	Allocation A [%]	Emission factor EF [kgCO_2/kWh]
Gas	62.50	0.252
Heating oil	31.84	0.315
Electricity (EL)	4.90	0.646
Brown coal (BC)	0.54	0.429
Hard coal (HC)	0.22	0.428

Bundesamt, 2016a). Since the shares of DH, wood pellets, biomass, solar energy and geothermal and other environmental heat in the total heat demand are deducted from the total heat demand (cf. section 3.3.1), these types of energy are not listed in Table 2.

The calculation of the saved CO_2 emissions $CO2_{saved,SA}$ in Eq. (8) is based on the calculated coverage ratios per settlement area CR_{SA}. Excess heat replaces part of the fossil energy used to supply the settlement areas. It is assumed that excess heat replaces the existing energy carriers proportionally. The usage of excess heat has an emission factor of 0 kg/kWh (Theissing, 2012).

$$CO2_{saved,SA} = \frac{HD_{SA}\cdot CR_{SA}\cdot\left(A_{Gas}\cdot EF_{Gas} + A_{Oil}\cdot EF_{Oil} + A_{EL}\cdot EF_{EL} + A_{BC}\cdot EF_{BC} + A_{HC}\cdot EF_{HC}\right)}{1000} \quad (8)$$

3.4.2. Determination of the CO_2 abatement costs

The investment for the DH grid construction, or densification in case a DHN already exists, are mainly based on the length of the grid. The grid length cannot be determined without a detailed on-site investigation or analysis of the heat demand density/distribution using a geographic information system. Persson and Werner (2011) developed a method to determine the investment for DH grids without the mentioned procedures. In this way, the investment can be estimated based on publicly available data such as population density, specific building space, specific heat demands and some cost parameters.

First, the fraction of the excess heat that is supplied by the biogas plant to the settlement area Q_{sell} is determined using Eq. (9).

$$Q_{sell} = HD_{SA}\cdot CR \quad (9)$$

The investment $I_{DHG,SA}$ for the construction or the densification of the district heating grid (DHG) in a settlement is determined by the specific heat distribution costs HDC_{SA} and the excess supplied heat Q_{sell}. In Section A.4 of the appendix, a detailed description of determining the specific heat distribution costs HDC_{SA} in the settlements is given. Additionally, the investment in the pipeline for connecting the biogas plant and the settlement area $I_{con,SA}$ has to be calculated. There an investment rate IR of 200 €/m for the pipe is multiplied by the distance DIS_{SA} between biogas plant and settlement area (Fraunhofer UMSICHT, 1998; C.A.R.M.E.N. e.V, 2012; Pfnür et al., 2016). The relatively low value of 200 €/m is supposed to reflect the fact that biogas plant operators receive a subsidy in the context of the Combined Heat and Power Act (KWKG) amounting to 100 €/m of DHN built (BMJV, 2018). Finally, the investment can be summed up in Eq. (10) and results in the necessary investment I_{SA} to use the excess heat from the biogas plant to supply the settlement area with heat.

$$I_{SA} = I_{DHG,SA} + I_{con,SA} = HDC_{SA}\cdot Q_{sell}\cdot 0.0036 + IR\cdot DIS_{SA} \quad (10)$$

The multiplication by 0.0036 is performed to convert Q_{sell} to GJ. In the section 3.4.1, the saved CO_2 emissions were determined. These are now taken into account to calculate the specific CO_2 abatement costs $CO2_{costs}$ (cf. Eq. (11)).

$$CO2_{costs} = \frac{I_{SA}}{CO2_{saved,SA}} \quad (11)$$

3.4.3. Determination of the net present value and payback period

The net present value (NPV) is used as a further economic criterion and is calculated in Eq. (12) using the sum of the discounted revenues REV_{SA} less expenses EXP_{SA}. Discounting over a certain period is taken into account by the discounting factor df of 0.05 (5%), which is intended to represent a compromise between social and commercial discount rates. Finally, the investment I_{SA} is deducted to calculate the NPV_{SA}. Annual costs are caused by maintaining the DHG and driving the DH pumps. As operating power of the pumps, a factor P_p of 10 kWh_{el} /MWh_{th} is used (Good, 2004). This means that 10 kWh_{el} is required for each MWh_{th} of DH transported to drive the pump. Revenue is generated by selling heat to the customers. The used input data is shown in Table 3, which gives the mean heat prices from a random sample of ten district heat providers in Germany.

$$NPV_{SA} = \sum \frac{REV_{SA} - EXP_{SA}}{(1+df)^t} - I_{SA} \quad (12)$$

The NPV is not a key result for this analysis, but is used to determine the payback period PP of the excess heat utilisation. In the algorithm, a loop is used to identify the time t at which the NPV becomes positive.

4. Results and discussion

In this section, the algorithm is validated before the results are discussed in more detail (cf. section 4.1). Initially, the calculations are only carried out with 241 biogas plants included in the survey. Section 4.2 demonstrates how these 241 plants were selected. Thereafter, it will be shown in section 4.3 how the results change when all 10,446 biogas plants in Germany are included in the analysis. In order to provide the algorithm with appropriate abort criteria, the limit value of the CO_2 abatement costs is set in all calculations to 1,000 €/tCO_2, the limit value of the payback period to 20 years. The reason for these high values is that we wish to economically assess the technical potential, rather than to directly determine an economic potential based on some predefined criteria. Finally, the procedure is critically appraised in section 4.4. The algorithm was implemented in MATLAB and solved using a standard desktop PC (2x Intel Xeon 5430 Processor and 24 GB RAM). The solution time for the 241 plants is around 10 min and that for the whole German biogas plant stock about two days. The code can be made available by the authors upon request.

4.1. Validation of the algorithm

Fig. 3 gives an overview of the possible types of DH connections

Table 3
Input data for economic evaluation, (Statista, 2018a; BDEW, 2018; SWB, 2014).

Asset	Costs	Units
Maintenance cost rate of the DHG	0.5	% of investment
Electricity purchase price EP	0.2324	€/kWh
Thermal connection power Pa	5	kW
Heat selling prices HS:		
Energy price	0.0664	€/kWh
Demand charge	30.99	€/kW
Base price	10.81	€/month

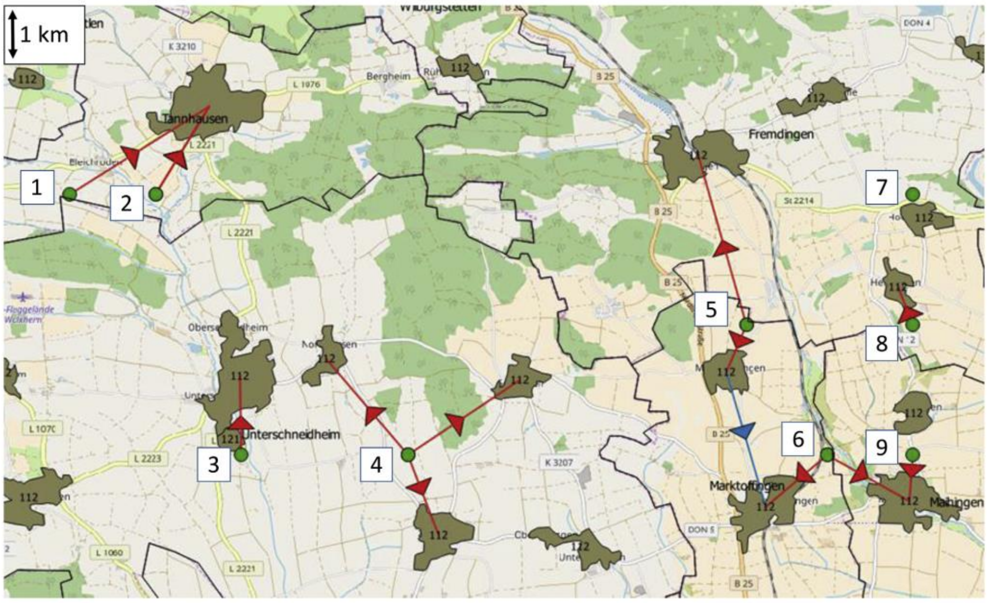

Fig. 3. Exemplary illustration of resulting DHPs for the use of excess heat from biogas plants in several municipalities in Baden-Württemberg. The background map is from OpenStreetMap contributors (2018).

that can be created by the algorithm in Fig. 1. The red DHPs lead from a biogas plant to a settlement area and the blue ones lead from one settlement area to another. The black lines represent municipal borders. The results shown in this figure were derived from the calculation with all biogas plants in Germany and the CO_2 abatement costs as a selection criterion (cf. scenario A.1 in section 4.3). The first case shows biogas plant 7 (number in box), which has no connection to a settlement area. This can have several reasons. On the one hand, 100% of the excess heat from the biogas plant could already be used. In this case, this biogas plant would be one of the 241 plants from the survey, since only in these plants over 60% heat is used (cf. section 4.3). On the other hand, the settlement area in the vicinity could have no heat demand, e.g. because all buildings are already supplied with heat from alternative technologies. In addition, a DH supply might not be worthwhile in this case, since the limit values of the target criteria are exceeded in the algorithm. The second case is the one in which a settlement area is supplied with DH by only one biogas plant, and these biogas plants also supply only one settlement area (biogas plants 3 and 8). If a settlement area is supplied by several biogas plants, this is the third case (biogas plants 1, 2, 5, 6 and 9). The fourth case is the supply of several settlement areas by a biogas plant, as in the case of the biogas plants 4, 5 and 6. Finally, the connections of biogas plant 5 show that the DHP can also lead from one settlement area to the next, as shown by the blue-coloured DHP.

The heat demand of the settlement areas from section 3.3.1 can also be validated. The sum for all settlement areas $HD_{SA_{total}}$ results in a heat demand of 576 TWh (cf. Eq. (18) in the appendix). The heat demand for space heating and hot water in private households (mainly gas demand, cf. DIW Berlin and EEFA, 2017) is subject to large annual fluctuations (Umweltbundesamt, 2017a) and ranged from 544 to 578 TWh between 2010 and 2015 (Statista, 2018b). In 2010, from when the census data, heat consumption data and renovation data originate, the heat requirement was 578 TWh (Deviation: 0.35%). Thus, the procedure presented in section 3.3.1 can be deemed to be very accurate.

4.2. Results from the survey

In the survey, respondents provided information on the percentage share of heat utilisation for different categories such as in schools, hospitals and fish farming. In 262 of the 602 plants, the total shares were above 100% (cf. Fig. 4). The plants with a heat utilisation of more than 100% are excluded from the analysis in this study, as it seems the survey participants misunderstood the questions and/or made mistakes in stipulating these shares. In total, this results in an average heat utilisation of 60% and an unused heat fraction of 40%.

Of the 602 biogas plants from the survey, 241 plants (40%) could be identified and mapped in the Energymap plant register (cf. section 3.2). 111 of the 241 plants, however, are among the 262 plants in which a heat utilisation value of above 100% was reported. As the left part of Fig. 5 shows, the majority of the 241 biogas plants (green circles) identified are located in the federal state of Bavaria (143 plants ≙ 59%). This also corresponds to the distribution of the responses from the survey (cf. section 3.1).

The heat map on the left side of Fig. 5 shows the population density. White areas mark settlements with a low population density and the population density then rises to dark red. The heat map shows that the calculation with only 241 plants does not take into account the settlements with the highest population densities. A comparison of the 241 plants with all plants in Germany (cf. right part of Fig. 5) shows that the latter are clearly more evenly distributed across Germany. Of the 241 biogas plants allocated, only

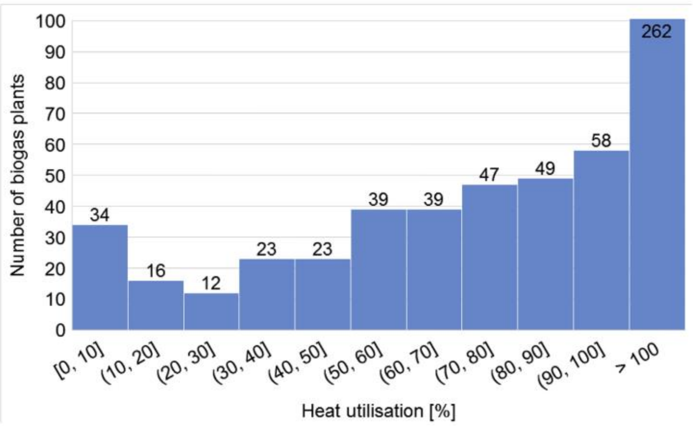

Fig. 4. Number of biogas plants surveyed as a function of the specified share of heat that is already being used.

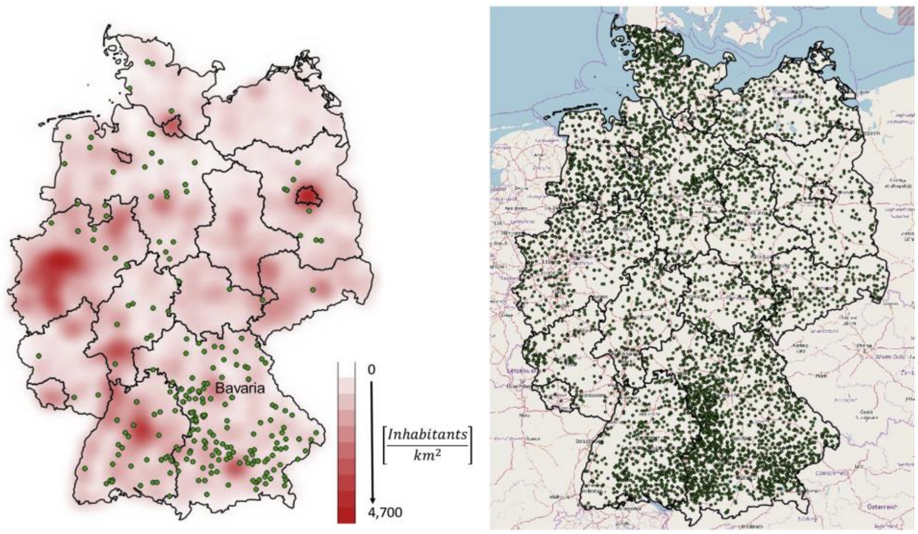

Fig. 5. Location of the 241 biogas plants identified among the plants surveyed in Germany and a heat map showing the population density in the settlements (left part). Location of all biogas plants in Germany (right part) (Engel, 2015; Statistisches Bundesamt, 2017c).

121 plants still have unused heat. The remaining 120 plants already use 100% of their excess heat.

First of all, the results of the calculations with CO_2 abatement costs as a decision criterion are presented in section 4.2.1, followed by the results of the calculations with payback period as a decision criterion in section 4.2.2. A sensitivity analysis is performed for both cases to show how some key parameters affect the results. The values of the parameters were changed in 10% steps from −50% to +50%. The only exception is the distance of the biogas plant from a specified location. As described in section 3.2, the location of the biogas plant can have a maximum uncertainty of 3 km. The smallest distance between a biogas plant and the centroid of a settlement area is 10 m, which lies far below this maximum uncertainty. However, it can also be a so-called satellite CHP unit located within the settlement area (Rutz and Güntert, 2012). After all, 17% of the biogas plant operators in Germany have a satellite CHP unit (Liebetrau et al., 2017). To cover this uncertainty, the distance of the plants to the settlement areas was varied between −3 km and +3 km. Since this parameter is shown together with the other parameters in Fig. 6 below, - 3 km corresponds to −50% and +3 km to +50% and the change of 10% corresponds to 600 m steps. A further examination of over 700 plants in the most recent EEG biogas plant register from Bundesnetzagentur (2018) enabled them to be matched to their records in Energymap (Engel, 2015). The

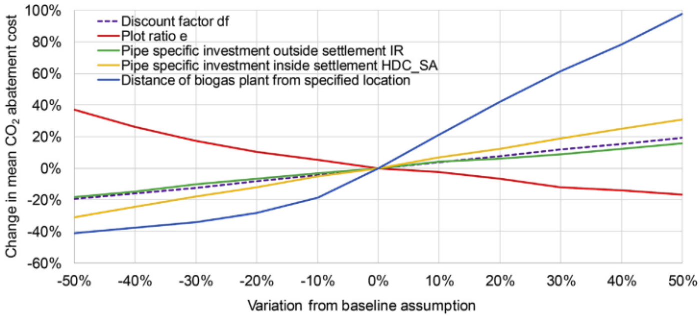

Fig. 6. Change in the mean CO_2 abatement costs of the reference scenario when changing specific parameters.

average distance between the matched plants was 1.5 km, which corresponds to a range in Fig. 6 of ± 25%, but it is unclear which of these two sources is more accurate.

4.2.1. CO_2 abatement costs as decision criterion

In the reference scenario, defined by the parameter values from section 3, the CO_2 abatement costs range from 55 €/tCO_2 to 987 €/tCO_2 (mean: 120 €/tCO_2) and 41,500 tCO_2 /a is saved. 129 DHPs are built in this case.

Fig. 6 shows the mean CO_2 abatement costs resulting from the sensitivity analyses. The strongest deviation occurs when the coordinates of the biogas plants are changed (distance of biogas plant from specified location). The mean CO_2 abatement costs change by −41% if the biogas plants are 3 km closer to the settlement areas and by +97% if the biogas plants are 3 km further away from the settlement areas. The deviation for the 3 km closer plants is smaller, since some plants are already less than 3 km away from the settlement areas. The gradient of the curve becomes more constant the less the distance is reduced. Nevertheless, the curves do not have constant gradients. This is related to the abort criteria, as a result of which more and more connections between plants and settlements are excluded from the analysis or included in the analysis when parameters are changed. This will be further explained in section 4.2.2. If the biogas plants deviate 1.5 km from their location as described above, the costs could change between −31% and +52%.

The pipe specific investment outside a settlement *IR* and the discount factor *df* have approximately the same effect on the mean CO_2 abatement costs and reduce them by a maximum of 19% at −50% and increase them by a maximum of 19% at +50%. It is interesting to note that the pipe specific investment inside a settlement HDC_{SA} has a stronger effect on costs than *IR*. This means that the DHPs within a settlement have a greater influence on costs than the DHPs leading to the settlement, i.e. the population density of a settlement is of crucial importance. The same conclusion can be drawn when looking at the curve of the plot ratio *e*. This is the only parameter that leads to a reduction of the average cost when it is increased. An increase of *e* is equivalent to an increase of the building density in the settlements. In this case, more heat can be delivered per settlement area that would otherwise remain unused.

As illustrated in Fig. 7, the variation of the parameters does not have a large influence on the total CO_2 abatement. The change in total CO_2 abatement of the reference scenario (41,483 tCO_2 /a) varies only between −1.5% and +0.5%. The greatest influence has once again the variable “distance of biogas plant from specified location”.

Some of the curves in Fig. 7 are not linear, which would not be directly suspected. For example, it has been concluded that an increase of the plot ratio *e* continuously reduces the CO_2 abatement costs. It is also likely that an increase of *e* would increase the total CO_2 abatement. However, the curve in Fig. 7 shows that, for example, with an increase of *e* from +40% to +50%, the total CO_2 abatement decreases again (by 28 tCO_2 /a). This example is now explained on behalf of the other non-linearities in Fig. 7. In the case of +40%, a biogas plant in a municipality in Bavaria will initially supply the CORINE area 8940 with 485 tCO_2 /a for 108 € /tCO_2 and later on a connection to the CORINE area 8876 will be installed with 65 tCO_2 /a for 345 €/tCO_2 (cf. left part of Fig. 8). In the case of +50%,

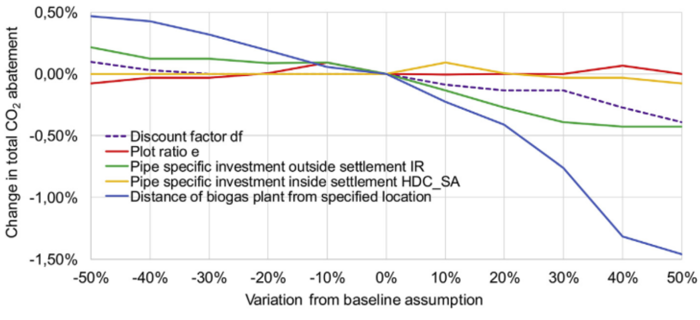

Fig. 7. Change in the total CO_2 abatement of the reference scenario when changing specific parameters.

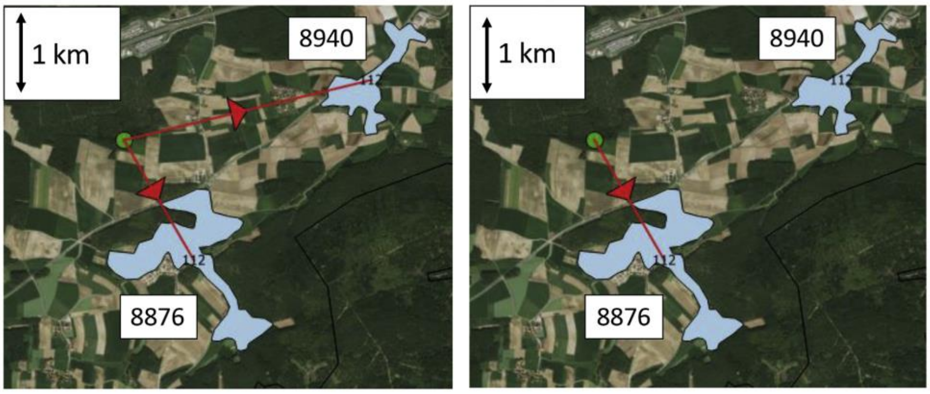

Fig. 8. DHN for the utilisation of the excess heat from a biogas plant in a municipality in Bavaria. The left part of the figure shows the connections that result in the case where plot ratio e is increased by 40%, in the right part e is increased by 50%. The background map is from Microsoft (2018).

the CORINE area 8876 will be selected directly with 522 tCO_2 /a for 105 €/tCO_2 (cf. right part of Fig. 8).

In the first case, CORINE area 8876 is also supplied, since approx. 14% of the excess heat in the biogas plant remains after supplying CORINE area 8940. In the second case, however, only 7.4% excess heat is left after supplying CORINE area 8876, so that the supply of area 8940 is no longer worthwhile (CO_2 abatement costs of 1,180 €/tCO_2 ≥ 1,000 €/tCO_2). The reason for the fact that settlement area 8940 is supplied before area 8876 (up to case +50%), although in settlement area 8876 there is more heat demand, is, among other things, the almost twice as high population density in settlement area 8940 (3,400 persons per km^2 compared to 1900 persons per km^2). In order to avoid fluctuations in the curves of the total CO_2 abatement costs in Fig. 7, the total CO_2 abatement costs would have to be used as a decision criterion in the algorithm. In this case, however, the CO_2 abatement costs involved could be excessively high in some cases.

4.2.2. Payback period as decision criterion

If the payback period is selected as the decision criterion, the reference scenario results in a mean payback period of 7.2 years (payback periods of between 2.5 and 20 years). In this case, 122 DHPs are built and 40,600 tCO_2 /a is saved.

The mean payback period increases the most when HS decreases (+69%) and is the lowest when the distance of biogas plant from specified location decreases (−44%, cf. Fig. 9). If HS decreases, only a lower profit can be achieved by selling the heat. Since the variation of DH pump power P_p has exactly the same effect on the payback period, only the electricity price EP is shown in the figure. If EP increases, the costs for driving the DH pumps and thus the payback period increase. P_a has an opposite effect on the payback costs, since the rate at which the heat is delivered, and hence the amount of heat sold, depends strongly on this parameter. The distance, e, *df*, HDC_{SA} and *IR* have almost the same effect on the mean payback period as on the mean CO_2 abatement costs (cf. section 4.2.1).

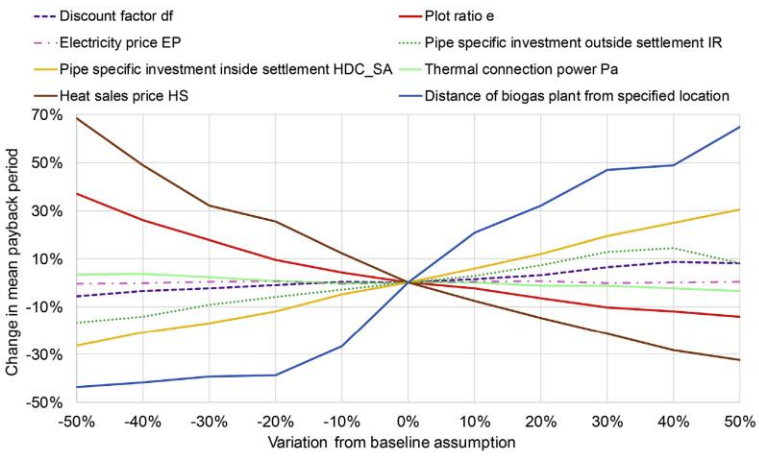

Fig. 9. Change in the mean payback period of the reference scenario when changing specific parameters.

However, the declining mean payback period with a change of *IR* from +40% (8.3 years) to +50% (7.8 years) is remarkable. The other non-linearities in the curves in Fig. 9 can also be explained using the following example: Fig. 10 shows the change in the number of DHPs when increasing *IR* from −50% to +50%. The number of connections is reduced from 132 at −50% to 107 at +50%. In each step, the changes are within a range of one to three no longer existing connections. However, in the last step from +40% (115 connections) to +50% (107 connections), eight connections no longer exist due to a payback period of more than 20 years. As a result, many of the connections with a long payback period will be eliminated in this step. Therefore, the mean payback period decreases in this case. This can be proven by repeating the calculation in the case of +50%, and this time not using the payback period as a criterion for aborting the algorithm, but by aborting at a number of 115 DHPs as in case +40%. This would result in a mean payback period of 8.8 years, which is higher than in the case of +40%.

4.3. Results for all German biogas plants

The analysis with all 10,446 biogas plants assumes an average value of 40% unused heat in the biogas plants that were not part of the survey. Whilst there will obviously be deviations in individual cases, the assumption of 40% excess heat seems reasonable and is verified by other studies (e.g. DBFZ, 2015). Table 4 shows the various scenarios developed with all biogas plants.

When using the CO_2 abatement costs as a decision criterion in scenario **A.1**, the excess heat from 9,790 different biogas plants is used. A total of 10,989 DHPs are built in this case and 2.55 $MtCO_2$ /a can be saved (cf. yellow line Fig. 11). This corresponds to 0.3% of the amount of CO_2 emitted in Germany in 2015, equivalent to 792 $MtCO_2$ /a (Umweltbundesamt, 2017c). 85% of the 2.55 $MtCO_2$ /a can be saved with CO_2 abatement costs below 200 €/tCO_2. The first 78 tCO_2 are saved at a minimum cost of 13.5 €/tCO_2, which is 41.5 €/tCO_2 less than the best connection in the case of the 241 plants. The reason for this is that this biogas plant is located only 70 m from the settlement area centroid. In total, around 8 TWh of heat demand in German households are covered by the biogas plants.

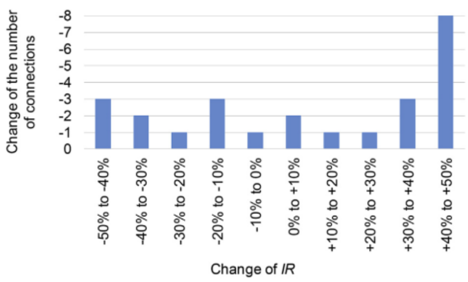

Fig. 10. Change in the number of DHPs when changing *IR*.

Scenario **A.2** assumes that the biogas plant can replace all forms of existing heat supply (i.e. neglecting Eq. (1), so $HD_{SA} = HD_{SA\,total}$). In this case, the CO_2 abatement is only 5 $ktCO_2$ /a higher at almost the same cost. This can be explained as follows. At the beginning of the calculation with all plants, approx. 10 TWh of excess heat are available from all biogas plants. In the end of calculation A.1 above, only 0.22 TWh (2%) remain at the end. This shows that there is scarcely any potential for an increase and that there is a bottleneck on the supply side of the biogas plants, rather than on the demand side in the existing heat supply systems. For the second scenario (without Eq. (1)) only 0.03 TWh more heat is used, due to the small amount of non-fossil-fuel-based existing heating that is replaced in this case. Since the CO_2 abatement cost curve does not change significantly, the curve for A.2 is not shown in Fig. 11. The bottleneck on the supply side of the biogas plants explains the lower CO_2 abatement here than in Soltero et al. (2018) (cf. section 2.2). In their study, 5.4 $MtCO_2$ were avoided, however, the entire heat of biomass plants was used instead of unused excess heat as in our study.

As explained in section 3.3.2, a constant load profile for the excess heat from the biogas plants was assumed. However, this profile could look different in reality, since the digester or residential buildings that are already supplied with heat require more heat in the colder months (Rutz et al., 2015). Based on the values from Rutz et al. (2015), the load profile of a biogas plant that supplies residential buildings and the digester with excess heat is changed in scenario **A.3** according to Fig. 12. The short period in summer, in which the load is 0 kW, is due to the fact that the biogas plant shown as an example has full load hours of less than 8760.

Actually, curve A.3 would be expected to differ significantly from curve A.1, as more heat is now available in summer, i.e. at a time when less heat is required. However, this is not the case due to the bottleneck in the heat supply of the biogas plants already mentioned in the description of scenario A.2. This means that in most cases, however, the settlement areas require more heat in summer than the biogas plants can provide. In total, 5 $ktCO_2$ /a or 0.2% less is saved than in scenario A.1, with slightly higher mean CO_2 costs.

Compared to scenario A.1 with CO_2 abatement costs as a decision criterion, if the payback period is used as a decision criterion in **B.1**, the number of biogas plants whose heat is used decreases by 835 to 8,955 plants and 344 DHPs fewer are built (10,645 pipelines). Overall, 0.08 $MtCO_2$ /a less than in scenario A.1 is saved (2.47 $MtCO_2$ /a). The first 85% CO_2 can be saved with a payback period of fewer than 10 years (cf. Fig. 11). Only 0.53 TWh (5%) of excess heat remains unused in this calculation.

The scenarios discussed above do not include the cogeneration bonus from the Renewable Energy Sources Act 2009, so that **B.2** is carried out with the cogeneration bonus in order to estimate its effect on the result. It is assumed that the cogeneration bonus for the heat supply of residential buildings in the amount of 3 ct/kWh (Clearingstelle EEG, 2009) will be paid to all plant operators whose plants were commissioned before 31.12.2011 (Clearingstelle EEG, 2012) and have a nominal power of less than 5 MW (Clearingstelle EEG, 2009).

Table 4
Overview of the scenarios carried out with all biogas plants.

Number	Decision criterion	Adjustment
A.1	CO_2 abatement costs <1,000 €/tCO_2	-
A.2	CO_2 abatement costs <1,000 €/tCO_2	Not considering Eq. 1
A.3	CO_2 abatement costs <1,000 €/tCO_2	New excess heat profile, cf. Fig. 12
B.1	Payback period <20 years	-
B.2	Payback period <20 years	Considering the cogeneration bonus of 3 ct/kWh for district heat from biogas plants

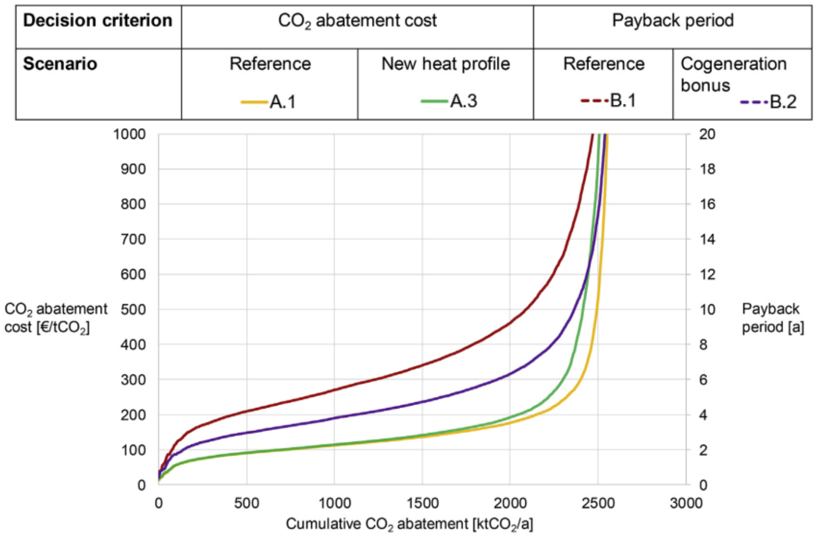

Fig. 11. Cumulative CO_2 abatement in the scenarios with CO_2 abatement costs or payback period as the decision criterion. The curves refer to the y-axes with the corresponding decision criterion of the scenario.

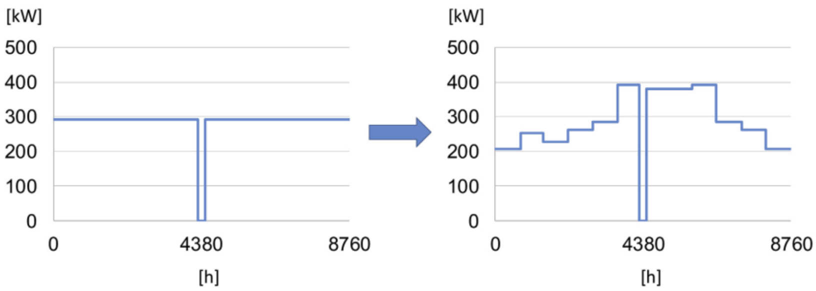

Fig. 12. Change in excess heat load profile, without (left) and taking into account monthly differences in heat utilisation (right).

Taking into account the cogeneration bonus, the amount of CO_2 saved increases by 70 ktCO_2 /a (3%). This means that the amount cannot be significantly increased due to the above mentioned heat supply bottleneck. However, the mean payback period is considerably shorter than for calculation B.1. Thus, 2 MtCO_2/a are already saved within a payback period of 6 years (instead of 9 years in B.1). This has to be considered as an upper limit, however, as it is not certain whether all biogas plants will receive the cogeneration bonus to the extent assumed here. This is especially the case for plants with a nominal power of more than 500 kW, as they only receive the cogeneration bonus of 3 ct/kWh for 500 kW (Clearingstelle EEG, 2009). However, the plants commissioned between 2004 and 2008 receive a cogeneration bonus of 2 ct/kWh regardless of their nominal power (Clearingstelle EEG, 2006).

Using the criteria of CO_2 abatement costs and payback period, a yield of 2 MtCO_2/a is achieved for values below 200 €/tCO_2 (A.1) and 9 years (B.1). This corresponds to around 0.25% of the total German CO_2 emissions in 2015 (Umweltbundesamt, 2017c) or around 2.5% of all CO_2 in residential buildings (Umweltbundesamt, 2017b). The CO_2 reduction potential is approximately 0.5 MtCO_2 and 0.75 MtCO_2, if thresholds of 80 €/tCO_2 and 5 years are set to reflect the proposed external cost of carbon and an expected payback period from an investor's point of view respectively (Schwermer, 2012). However, if the current price of CO_2 in the EU Emissions Trading System of about 7 €/tCO_2 is taken as a benchmark, the economic fraction of this technical potential saving diminishes to 0 tCO_2.

Fig. 13 shows the share of residential heat demand in German municipalities that can be covered by the excess heat from biogas plants with the help of DH. The calculation A.1 serves as a basis for the figure, and DH connections where the payback period is longer than 20 years were not taken into account. The figure shows that especially in the southern (Baden-Wuerttemberg and Bavaria) and northern federal states (Schleswig-Holstein, Mecklenburg-Western Pomerania, Lower Saxony, Saxony-Anhalt and Brandenburg), the most heat demand per municipality can be covered. In total, there is a potential in 3,591 (32%) of the 11,400 German municipalities, in the other municipalities the value is 0%. The mean value in the

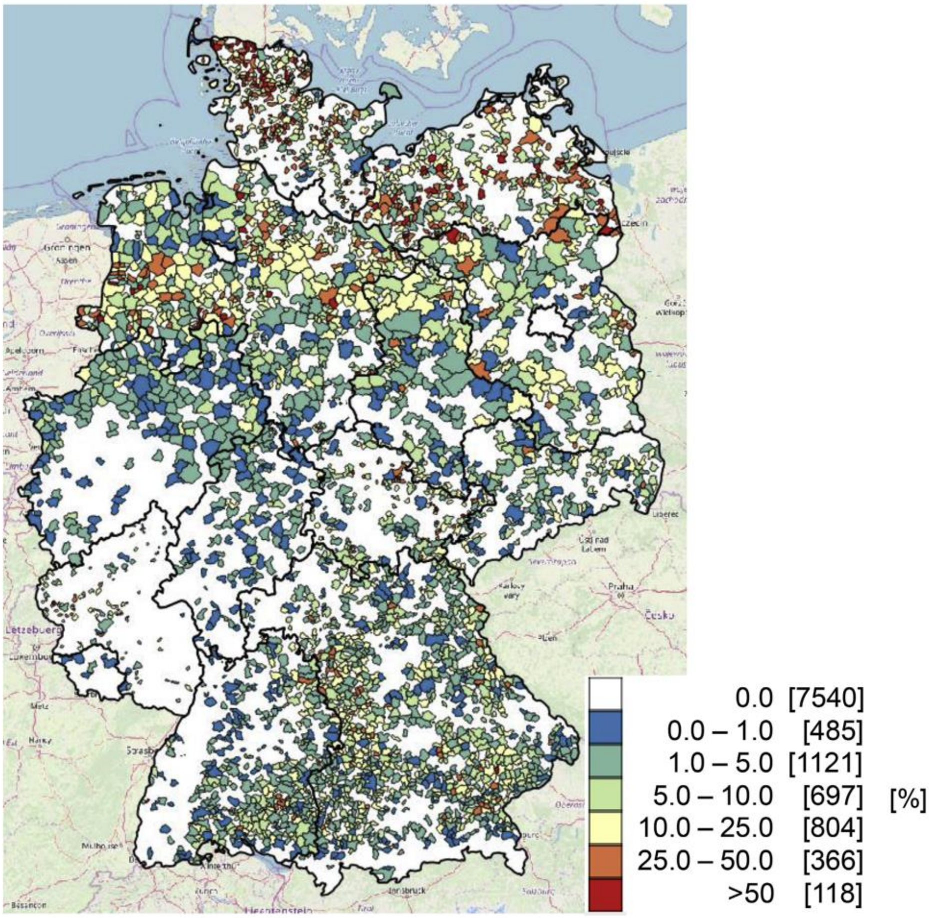

Fig. 13. Share of heat demand that can be covered by DH from biogas in German municipalities. The numbers in brackets represent the number of municipalities to which the shares can be allocated. The background map is from OpenStreetMap contributors (2018).

3,591 municipalities is 12% and the CO_2 emissions per capita are reduced by an average of 250 $kgCO_2$ /a. Some of the municipalities can cover almost all of their heat demand with DH from the biogas plant(s). More than 85% of the heat demand is met in 21 municipalities, while a maximum value of 98% is reached in the municipality of "Bresegard bei Eldena" (200 inhabitants) in Mecklenburg-Western Pomerania. In some municipalities, excess heat from biogas plants can therefore contribute to achieving energy autonomy. These results at the municipal level can be found in the online supplementary material.

4.4. Critical appraisal of the methodology

The sensitivity analysis considered the uncertainties in the parameters used, such as costs. However, the algorithm applied here also has some weaknesses that would not occur in the detailed planning of each individual biogas plant. This section first explains the weaknesses, which may lead to overestimating the calculated technical potential of DH by excess heat from biogas plants. Subsequently, the weaknesses that reduce the real technical potential are identified. Finally, the uncertainties relating to the method are discussed.

First of all, some assumptions are made in the algorithm used here, which can lead to a moderate to severe underestimation of the costs. For example, the shortest route from the biogas plant to the settlements is always used for the DHPs. Here, however, the topology and other obstacles should be considered as in Nielsen (2014). Whilst data on surface topology is available in the form of Digital Elevation Models, it was not possible in this study to consider other obstacles. Given the objective of the study, to determine the overall technical potential for excess heat utilisation, this would also have been beyond the scope. In practice, however, a detailed DHN planning process would have to be carried out for individual municipalities.

In addition, the profiles for heat supply and demand were assumed. On the one hand, it is not certain that the biogas plants

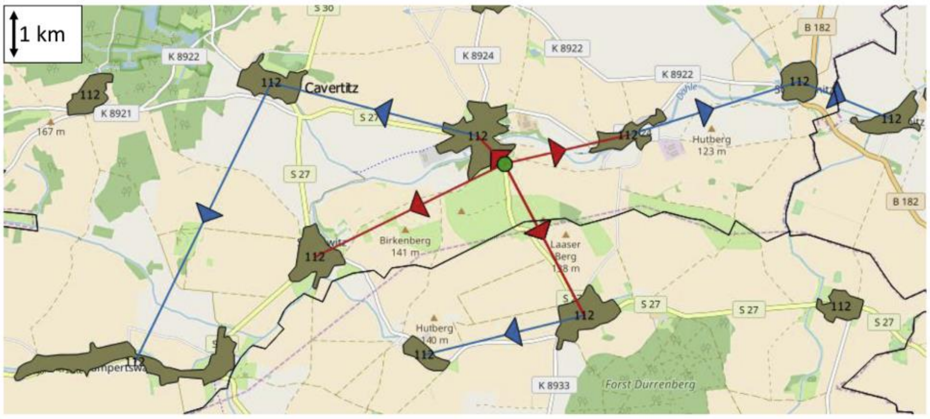

Fig. 14. DHN for the utilisation of the excess heat from a biogas plant in the municipality of Cavertitz in Saxony. The background map is from OpenStreetMap contributors (2018).

will actually be operated in the periods in which the heat demand in the settlements is highest (winter). On the other hand, the standard load profile SLP_{HD} from Eq. (2) can only be accurately be applied in municipalities with several hundred households. In the smallest settlement area, there are only three households with a total of five inhabitants. However, the influence of this uncertainty is low, since in the calculations only 7% of the connected settlement areas have less than 100 households. Furthermore, the standard load profile was assumed to be equal for all settlements in Germany. In reality, differences between settlements from different regions could be found. In general, however, for this study the standard load profile should represent an appropriate estimation of the real load profiles in the settlements.

In some cases the costs are overestimated, however, as the following example illustrates. Fig. 14 shows the DHN for using the excess heat from a biogas plant in the municipality of Cavertitz in Saxony. The problem lies in the fact that the algorithm iteratively selects the optimal connection in each step. The result is that the blue-coloured DHP furthest to the left is selected before the red coloured DHP furthest to the left. If the red DHP had been “built” first, there would have been a shorter distance to the settlement area in the bottom left, which is supplied by the blue DHP. This uncertainty has a low impact on costs, due to the fact that this phenomenon only occurs very rarely. In scenario A.1, for example, only 6% of DH connections start in settlement areas. Of this 6%, only a few connections will show this fault, in Fig. 14 it is only one connection of five.

Fig. 14 also shows that the selection of the area centroid for distance measurement overestimates the length of the DHPs from the biogas plants to the settlement areas in this case. Actually, only the distance to the border of the settlements should be measured here. However, this determination was not possible since the distance calculation is only possible with point coordinates. This could lead to a moderate increase in costs. For example, the settlement area at the bottom left of Fig. 14 has a width of 4.2 km. In extreme cases, the length of the DHPs could therefore be overestimated by around 2 km.

Additionally, an existing DH supply can be deducted from the heating demand of the settlements, but no existing DHG can be taken into account due to a lack of data. If these data were available, the length of the DHPs to be built could be reduced, as they would no longer have to lead to the settlement, but only to the nearest connection point of the existing DHG. The impact on costs is estimated to be negligible, due to the limited number of existing district heating networks in Germany. In other countries, such as Iceland or Denmark, the costs for the use of waste heat from biogas plants could be considerably lower due to the significantly higher DHG share (Euroheat and Power 2016).

A further overestimation of costs results from the fact that only residential areas are considered and not industrial or commercial areas. Some promising progress in this area has been made by the Pan-European Thermal Atlas (PETA) in the context of the Heat Roadmap Europe project.[4] Within the PETA urban areas are considered as “coherent urban areas”, including industry and commercial sector, and existing DHNs are considered on a detailed level. However, at the time of carrying out this study, this data was not publicly available.

Fig. 15 shows the municipality of Leutenbach in Baden-Württemberg. Blue surfaces are used here to represent the CLC areas. Red areas are individual buildings from Geofabrik (2018). The figure shows that the CLC data do not cover all existing settlement areas (cf. red circles in the Fig. 15), as there is a minimum threshold for the size of an urban area to be differentiated in the CLC data (0.05 km^2) and the data are from 2012 (so do not consider newer buildings). In the example shown in Fig. 15, the excluded settlement areas are relatively small, so the implications for the results are likely to be only marginal.

A further uncertainty arises from the age of biogas plants. The age profile of the existing plants means that some of these plants will cease to benefit from the feed-in tariffs (FIT) of the Renewable Energy Sources Act upon which they rely to be economic. After this time, their continued operation is uncertain. The plants should already have broken even after twenty years, as studies have shown payback periods in the region of 7–12 years depending on the substrate and the output (Balussou et al., 2011). Hence the plant may continue to operate, but the negative impact on the economics of losing the FITs could force the operators to seek other business models such as biomethane uprading and feed-in (cf. section A.1 in the appendix). In the absence of new business models, the plants might be forced to close, which would mean the excess heat considered here is no longer available. Instead, this study assumes constant cash flows over the 20 year lifetime of the DH project, which obviously neglects this issue. However, this study aimed to

[4] http://www.heatroadmap.eu/maps.php.

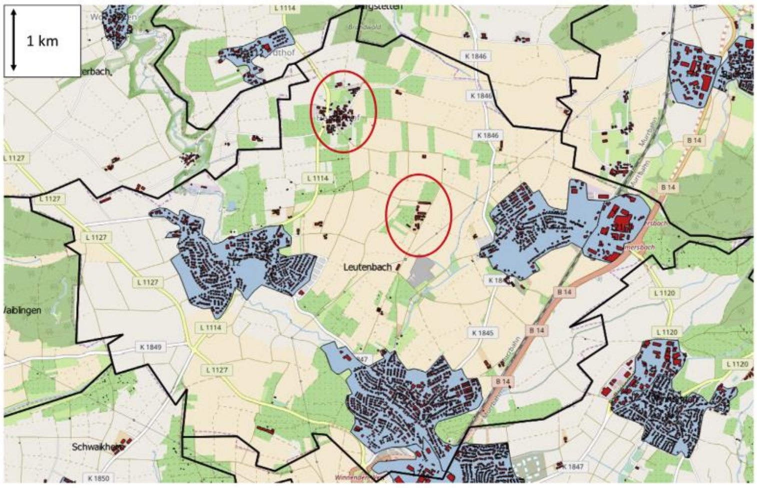

Fig. 15. Settlement areas from the CLC data set and buildings in the municipality of Leutenbach in Baden-Württemberg (Geofabrik, 2018). The background map is from OpenStreetMap contributors (2018).

assess the current technical potential for excess heat use from biogas plants, and there are always future uncertainties associated with such analyses. Potential future business models for biogas plant operators in a post-EEG context could be the subject of a future contribution.

Finally and partly independently of the future development of the biogas sector, the dynamic of the surrounding energy system was not analysed in any detail in this study. In particular, the decarbonisation of the energy system means a shift away from fossil fuels towards renewable heat and electricity supply. The German government has ambitious climate targets in the context of the energy transition, including 50% renewable electricity consumption by 2030 and an 80% reduction in building primary energy demand by 2050. Assuming these targets are met within this timeframe implies a deep insulation of existing buildings as well as shift towards gas-fired cogeneration (in the short term) and heat pumps (in the long term, cf. Merkel et al., 2016). Hence the CO_2 intensity of existing heat supply would significantly reduce and similarly tend to decrease the potential impact of the results for CO_2 abatement through district heating from biogas plants presented in this paper.

5. Summary and conclusions

This paper has analysed the current technical potential for utilising excess heat from biogas plants, in order to supply local settlements through district heating. Due to the high production of biogas, Germany was selected as the case study. Based on a survey of around 600 biogas plant operators, the fractions of excess heat from the cogeneration unit in these plants have been analysed. The analysis was carried out for the surveyed population as well as scaled up to the whole German biogas plant stock. A heuristic was developed to connect biogas plants (heat sources) with local settlements (sinks) in order to determine a least-cost district heating supply for residential buildings. Thereby two criteria were employed, namely the CO_2 abatement costs and the payback period, which represent the macro- and microeconomic perspectives respectively.

Based on the survey, a mean fraction of 40% excess heat was determined, which is in agreement with other empirical studies. Extrapolating this fraction to the German biogas plant stock leads to technically feasible CO_2 savings of around 2.5 $MtCO_2/a$. Employing the criteria of CO_2 abatement costs and payback period yields about 2 $MtCO_2/a$ below CO_2 abatement costs of 200 €/tCO_2 and 9 years respectively. These relatively high average costs are related to the typically low population density in rural regions where biogas plants are located. The potential CO_2 savings represent about 0.25% of the total German CO_2 emissions in 2016 or around 2.5% of all CO_2 in residential buildings. If a threshold value of 80 €/tCO2, to reflect the German government's suggested external cost of carbon, is employed, the carbon reduction potential is about 0.5 $MtCO_2$. Similarly, a threshold for the expected payback period of 5 years, to reflect an investor's point of view yields potential savings of 0.75 $MtCO_2$. These potentials are concentrated in around 3,500 municipalities, where district heating from biogas plants could reduce CO_2 emissions per capita by an average of 250 $kgCO_2$ /a and cover 12% of the total residential heating demand. In some of these municipalities, large proportions of their heating demand could be economically met (according to the criteria employed here) by this excess heat, hence assisting in the transition to more decentralised autonomous energy systems. On the other hand, if the current price of CO_2 in the EU Emissions Trading System of about 7 €/tCO_2 is taken as a benchmark, the economic fraction of this technical potential saving reduces to 0 tCO_2. Although these results are relatively modest in the overall context of decarbonising the energy system, this study does provide a quantitative basis for decision makers, researchers and energy planners. The detailed results provided as supplementary material should offer useful insights for local planners and authorities when considering the sustainable energy options at their disposal.

The developed method was applied to a German case study, but could be equally relevant for other countries with high biogas production. Some of these countries (e.g. Denmark) have a significantly more widespread district heating network than Germany. Thus, the use of biogas excess heat could lead to similar or even better results for these countries than in the case study for Germany. Apart from a methodology that can be transferred to any country with similar data availability, the present study therefore demonstrates that the use of excess heat in biogas plants can be one contribution towards a global energy system decarbonisation.

The employed methodology, whilst adequate for a national estimation of the technical potential and associated costs, has several uncertainties. Most importantly, the shortest birds-eye route from the biogas plant to the centroid of the settlement is used as the required distance for the pipeline. Whilst a good estimate for the order of magnitude, this obviously leads to uncertainties relating to the required district heating pipeline length, and therefore also to the costs. In addition, the developed heuristic does not (necessarily) determine the optimum allocation of heat sources to heat sinks, and may also therefore overestimate the costs. Finally, the focus on residential buildings and the rough consideration of existing district heating supply (but not infrastructure) add additional uncertainties. All of these aspects remain areas for future work.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.117756.

Appendix A.1 Current status of the German biogas industry

At the end of 2017, the number of biogas plants in Germany stood at around 10,500 plants. This makes Germany the country with the largest biogas plant population in Europe by far (European Biogas Association, 2016), clearly over-fulfilling the National Renewable Energy Action Plan (NREAP) targets for 2015 (Pablo-Romero et al., 2017). The 10,500 plants relate to 4.3 GW_{el} and 25.7 TWh_{el} of capacity and generation respectively in 2015 (Engel, 2015).

A period of fast growth between 2009 and 2011 saw the installation of more than 1,300 new plants per year on average. The expansion of the sector subsequently came to a halt in 2012 and the average number of newly built plants dropped to an average of below 150 per year for the period from 2014 to 2016 (German Biogas Association, 2017). The main growth driver until 2012 was the German Renewable Energy Sources Act, which guaranteed generous feed-in-tariffs (FIT) for electricity produced in biogas plants. It especially promoted the use of energy crops, which is why 51% of all material input of German biogas plants consists of energy crops, of which 73% is maize silage (FNR, 2017). But the public as well as the political discourse have turned against the use of energy crops (Herbes et al., 2014). Subsequently, policy makers first introduced a cap on the amount of maize silage that can be used in new plants and finally redesigned the subsidy system in a way that only allows very few new plant projects to be financially viable (Markard et al., 2016; Herbes et al., 2014). Recently, the German government introduced a tender system for electricity from biomass, but the first tender in September 2017 was perceived as unsuccessful, since the bids totalled to only about a third of the tender volume (Bundesnetzagentur, 2017a). While not many new biogas plants are built at the moment, the outlook for the existing sites beyond the end of their 20 year FIT period is unclear, and without a new remuneration period, a large part of the plant population in Germany will be shut down (Lauer and Thrän, 2017).

The majority of German plants use the gas onsite to fuel combined heat and power (CHP) units, thus cogenerating heat and electricity. The electricity is fed into the electricity network to receive a feed-in tariff, and heat is used locally if at all feasible. A further around 200 plants (in 2016, around 9 TWh of gas, cf. dena 2016) upgrade the biogas into biomethane or Bio-SNG (Synthetic Natural Gas) and inject it into the public gas grid (cf. Fig. 16). Particularly where a local heat sink is lacking, despite the overall utilisation efficiency of biogas valorisation. For example, a typical CHP unit can achieve 40% electrical efficiency, reaching an overall efficiency of up to 80% if all the generated heat can be used locally (Pöschl et al., 2010). In the absence of a local heat sink, biogas upgrading and feed-in can result in overall efficiencies of around 75–80%, based on the utilisation of Bio-SNG as a fuel for transport, for heating and/or power generation (Niesner et al., 2013; Köppel et al., 2014).

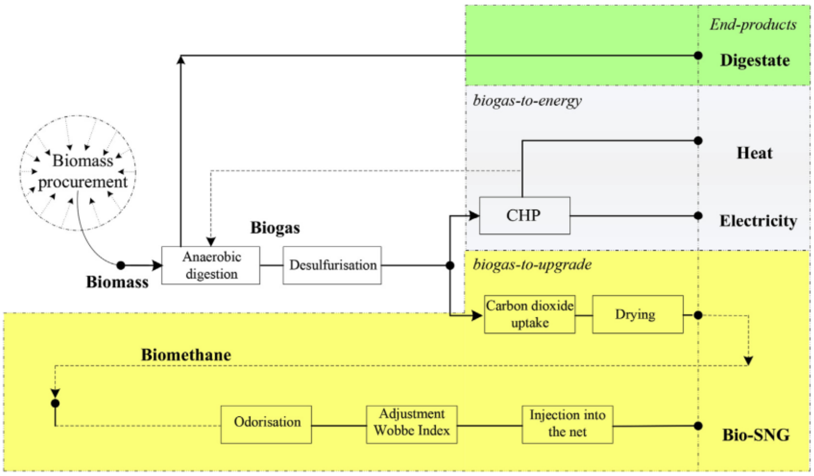

Fig. 16. Schematic of biogas plant, showing key valorisation steps and pathways (Figure from Bidart (2013)).

What are potential future perspectives for biogas in Germany, given the reduced financial support for electricity from biogas and the widespread reservations against biogas from energy crops? In order to compensate the reduced income from FIT or auction prices for electricity from biogas, plant operators need to open up new income streams in the near and middle future. At the moment, three such streams look promising.

The first one is offering system services to network operators, e.g. balancing energy (Bundesnetzagentur, 2017b). In order to supply these services, plant operators have to invest into flexibility, i.e. gas storage and additional CHP units (Hahn et al., 2014; Hochloff and Braun, 2014; Ertem et al., 2016; Lauer et al., 2017). The German Renewable Energy Sources Act incentivizes flexibilization through a premium but the prices for these services have decreased significantly reducing financial attractiveness (Bundesnetzagentur, 2017b; Purkus et al., 2018). Plants with a cumulative installed capacity of 2.8 GWel which equals about 60% of installed electrical capacity of biogas plants overall in Germany are already pursueing this strategy and benefiting from the flexibility premium under the REA (Fraunhofer IEE, 2018).

A second income stream is revenues from selling heat. Many plants have unused heat and/or are selling their heat into applications with a low value added that only pay low prices, such as grain or wood drying (Herbes et al., 2018a). The application that we found most often in the survey dataset was heating of the digester (91% of all plants under review, multiple answers possible), followed by heating of residential buildings (81%), wood drying (47%), heating commercial buildings (45%) and grain drying (37%). Innovative applications like using the heat for pre-treating the input material (e.g. Maroušek et al., 2018) or producing bio coal (e.g. Maroušek, 2014) did not play any role for the biogas plants under review. This is in line with the literature as reviewed in Herbes et al. (2018a).

A third income stream is the upgrading and monetarization of digestates. The majority of digestates today is sold to agricultural businesses in the vicinity of the biogas plant without upgrading. Farmers pay very low prices and in some regions that are rich in nutrients, they even ask fees for taking on digestate. On the other hand, hobby gardeners, landscapers and other potential target groups outside the agricultural sector are looking for organic fertilizers and soil products that do not deplete finite resources e.g. in phosphorous. By upgrading their digestate and turning it into a marketable product, biogas plant operators can increase their value added considerably (Dahlin et al., 2015, 2016, 2017, 2018).

A fourth income stream that would replace rather than supplant income from FIT, is revenues from selling biomethane. In order to realize this stream, biogas plant operators have to invest into biogas upgrading facilities (Herbes, 2015).

Another important issue is which feedstock German biogas plants will use in the future, especially given the widespread resistance against using energy crops. This will influence the long-term future of biogas in Germany. Researchers and practitioners alike are constantly looking into new types of feedstock, such as aquatic macrophytes or algae that do not compete with food production (Ertem et al., 2017; Herbes et al., 2018b). However, when looking at the total technical biomass potential in Germany in 2050, it becomes clear that the vast majority comes from energy crops (41%) that are cultivated on arable land and wood (38%), where the latter is not suitable for biogas plants. Household waste as a non-competing biomass on the other hand is rather negligible with only 7% (FNR, 2017). As of today, two thirds (69%) of the technical potential of residual and waste materials, both from agriculture and from other sectors in Germany, are already used, which leaves an unused technical potential of only 31 Mt of dry matter that is either unused or where the use is unclear. If we look at material that is suitable for biogas plants, the unused potential is even much smaller with around 18 Mt of dry matter and a total energetic value of 213 PJ. 66% of that potential are straw and the rest consists mostly of various types of manure (FNR, 2015). To summarize, if the biogas sector is to grow significantly, there is no way around energy crops. In other words: if biogas will be largely restricted to waste and residues in the future, a growth of this sector is impossible.

A.2. Information about biogas plant survey

Table 5
Locations of biogas plants in the sample

Federal state	Number of biogas plants in the sample (total: 602)
Baden-Wuerttemberg	93
Bavaria	280
Berlin	0
Brandenburg	21
Bremen	0
Hamburg	0
Hesse	19
Mecklenburg-Western Pomerania	1
Lower Saxony	86
North Rhine-Westphalia	30
Rhineland-Palatinate	16
Saarland	1
Saxony	4
Saxony-Anhalt	4
Schleswig-Holstein	21
Thuringia	9
No location available	17

Table 6
Size of biogas plants in the sample

Size	Number of biogas plants in the sample (total: 602)
Below 70 kW_{el}	11
71 to 150 kW_{el}	44
151 to 500 kW_{el}	238
500 to 1,000 kW_{el}	214
Above 1,000 kW_{el}	83
Missing value	12

A.3. Heat demand calculation

The number of buildings in the 111 areas n_{b111} and the number of buildings in the 112 areas n_{b112} is calculated in equation Eqs. (13) and (14) using the total number of buildings in the square kilometre n_b as well as the area sizes of the 111 areas a_{111} and 112 areas a_{112}.

$$n_{b111} = \frac{\sum 0.9 \cdot a_{111}}{\sum 0.9 \cdot a_{111} + \sum 0.65 \cdot a_{112}} \cdot n_b \tag{13}$$

$$n_{b112} = \frac{\sum 0.65 \cdot a_{112}}{\sum 0.9 \cdot a_{111} + \sum 0.65 \cdot a_{112}} \cdot n_b \tag{14}$$

The values 0.9 and 0.65 are the mentioned building densities. With the help of this procedure, the data from the census is assigned to the settlement areas. Furthermore, for comparison with data at the municipal level, it is necessary to assign settlement areas to municipalities. In QGIS, the settlement areas were also intersected with administrative boundaries of the German municipalities from Lenk et al. (2017b) for this purpose.

In Landesamt für Statistik Niedersachsen (2014), the average living space per apartment can be found for all federal states. For federal states, districts and municipalities, Statistisches Bundesamt (2015a) indicates the number of residential buildings with one apartment (F_1), two apartments (F_2) and three or more apartments (F_3). In addition, the total living space is given in m^2 (F_{total}). The mean living space (F_{mean}) could be calculated for each federal state using Eq. (15).

$$F_{mean} = \frac{F_{total}}{F_1 + F_2 \cdot 2 + F_3 \cdot x} \tag{15}$$

Variable x represents the average number of apartments in a residential building with more than two apartments. The variable is adjusted iteratively for each federal state until the mean living space corresponds to the specified value of Landesamt für Statistik Niedersachsen (2014) at the federal state level. Then the value of x was adopted for all municipalities in the state. In this way, the average living space $F_{mean,m}$ was determined for each German municipality m. For 141 of the 38,414 CLC areas, the average living space of the federal state was adopted, since there were no values for the municipalities in the housing data.

In order to calculate the living space LS_1 on CLC settlement area level, the number of apartments n_a in the CLC area is required. The census data contains the categories "number of buildings with living space" with: 1 apartment, 2 apartments, 3–6 apartments, 7–12 apartments and more than 13 apartments. In the last 3 categories, the average value was estimated so that the sum of the living space in the CLC areas is equal to the total living space in residential buildings in Germany (i.e. 3,670,870,000 m^2). For this purpose, an average value of 3–6 apartments was assumed to be 5, for 7–12 apartments 9.5 and for 13 or more apartments 16. The sum of the apartment number (40,411,000) calculated in this way is taken as the number of households in the settlement areas for later calculations. Compared with the actual number of apartments on 31.12.2010 of 40,479,000, the deviation is only −0.15% (Statistisches Bundesamt, 2017a). Then the living space per CLC area LS_1 was calculated using the number of apartments n_a and the mean living space $F_{mean,m}$ in the municipality (cf. Eq. (16)).

$$LS_1 = F_{mean,m} \cdot n_a \tag{16}$$

Now the sum of the CLC's living space LS_{total1} for each municipality is compared with the measured total living space of this municipality LS_{total2} (for which data are available). If the sum of the living space LS_{total1} deviates from the total living space of the municipality LS_{total2}, the new living space of each CLC area LS_2 will be adjusted accordingly to Eq. (17).

$$LS_2 = LS_1 - \left(\frac{LS_1}{LS_{total1}} \cdot (LS_{total1} - LS_{total2}) \right) \tag{17}$$

As described above, percentages for building age are also given in the census. With the help of these parameters and specific heat demand per year, square meter and building type, the total specific heat demand per settlement area can be determined. For this purpose, the consumption values for single-family houses, two-family houses and multi-family houses are taken from Walberg et al. (2011). The calculation of consumption values in Walberg et al. (2011) also takes into account the modernisation rate for each age group. The building age classes from the census and in Walberg et al. (2011) are not completely identical, as Table 7 shows. The data has therefore been assigned in such a way that a minimal error occurs. The assignment was made according to the colours in Table 7.[5]

Table 7
Comparison of the building age classes from Statistisches Bundesamt (2015b) and from Walberg et al. (2011) as well as the allocation of the classes by colour.

Statistisches Bundesamt (2015b)	Walberg et al. (2011)
Before 1919	Before 1918
1919-1948	1918-1948
1949-1978	1949-1957 1958-1968 1969-1978
1979-1986	1979-1987
1987-1990 1991-1995	1988-1993
1996-2000	1994-2001
2001-2004 2005-2008 2009 and later	2002-2008

[5] Please refer to the online version of the article for the colours in this table and all figures.

The census data does not reveal the age profiles of different building types in a settlement. Therefore, a mean heat demand must be calculated for the different building types. The building stock model from McKenna et al. (2013) was used to determine how the single-family houses/two-family houses (SFHs) and multi-family houses (MFHs) are distributed among the building age classes. This was differentiated according to new and old federal states. With the help of the specific heat demand per age group and building type from Walberg et al. (2011), the total heat demand for old and new federal states can be determined for SFHs and MFHs. These total heat demands divided by the number of SFHs/MFHs gives the mean specific heat demand per SFHs or MFHs in a settlement area.

In order to calculate the total heat demand in a settlement area (SA), the share of SFHs or MFHs in the settlement must be known. For this purpose, the mean living space (differentiated by age group, building type and federal state from the building stock model) was multiplied by the number of apartments in SFHs or MFHs in the settlement. In the case of MFHs, the number of apartments x from Eq. (15) was used to determine the number of apartments. The shares of SFHs in the living space were then multiplied by the specific heat demand of the SFHs in the settlement area (MFHs analogously). The two mean specific heat demands are then added together to form the mean specific heat demand hd_{mean} per settlement area. Now the total heat demand per settlement area $HD_{SAtotal}$ can be calculated according to Eq. (18).

$$HD_{SAtotal} = hd_{mean} \cdot LS_2 \tag{18}$$

A.4. Determination of specific heat distribution costs

An important parameter to determine the specific heat distribution cost is the plot ratio e. The plot ratio is a city planning parameter that captures the building density within an area. Plot ratio values are used to categorize typical city districts: (A) inner city areas ($e = 0.5–2.0$), (B) outer city areas ($e = 0.3–0.5$) and (C) sparse areas ($e = 0–0.3$). Those parameter ranges are based on Statens Planverk (1985). The plot ratio is calculated with the population density PD_{SA} and the total building space BSA_{SA} of the settlement area divided by the total population P of the settlement. By dividing the calculated residential area per settlement area by the residential area per person of the municipality from Statistische Ämter des Bundes und der Länder (2011), the number of inhabitants per settlement area can be estimated. All in all, Germany will then have a population of 81.711,000, close to the actual population of 2010 (81.750,000, Statistisches Bundesamt, 2017b). By dividing the number of inhabitants by the settlement area, the population density can be determined and in the following step the plot ratio e (Eq. (19), cf. Persson and Werner, 2011).

$$e = PD_{SA} \cdot BSA_{SA}/P \tag{19}$$

The effective width w is a parameter that describes the relationship between a land area and the length of district heat pipelines within this land area. It can also be seen as a correction factor to avoid the overestimation of distribution costs and is based on the plot ratio e (Persson and Werner, 2011). The effective width is calculated by using Eq. (20).

$$w = 61.8 \cdot e^{-0.15} \tag{20}$$

In order to calculate the investment for heat distribution, the linear heat density LHD_{SA} is necessary. The linear heat density is calculated in Eq. (21) based on the effective width, the plot ratio and the specific heat demand.

$$LHD_{SA} = e \cdot w \cdot \frac{HD_{SA}}{BSA_{SA}} \tag{21}$$

Subsequently the average diameter of the DH grid d_{SA} is calculated as this is one of the major cost influencing factors (cf. Eq. (22)). The determination of the diameter depends on the linear heat density.

$$d_{SA} = 0.0486 \cdot \ln(LHD_{SA}) + 0.007 \tag{22}$$

Finally, the determined values are used to calculate the specific heat distribution costs HDC_{SA} using Eq. (23). These costs represent the investment for distributing 1 GJ of heat inside a settlement area. The construction cost parameters $C1$ and $C2$ vary depending on the plot ratio e. $C1$ is a base cost that solely depends on the length of the heat pipe, whereas $C2$ depends on the pipe diameter d_{SA}. Three district types are considered in this study and for each type there are different cost parameters applied. The higher the plot ratio e, the higher are $C1$ and $C2$. In Table 8 the values for the construction cost parameters $C1$ and $C2$ can be found for the according district plot ratio and the district type. Furthermore, an annuity factor af of 0.08 is integrated in the calculation.

$$HDC_{SA} = \frac{af \cdot (C1 + C2 \cdot d_{SA})}{LHD_{SA}} \tag{23}$$

Table 8
Cost parameter values and district type according to plot ratio range (Persson and Werner, 2011)

Plot ratio (e)	C1 [€/m]	C2 [€/m²]	District Type
0.5 < e	286	2022	Inner city area (A)
0.3 < e < 0.5	214	1725	Outer city area (B)
0 < e < 0.3	151	1378	Park area (C)

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Developing a combinatorial optimisation approach to design district heating networks based on deep geothermal energy

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HIGHLIGHTS

- Development of combinatorial optimisation model to design district heating networks.
- Optimisation of the location of the district heating plant in municipalities.
- Deep geothermal energy is used as heat source.
- Heuristic has high accuracy and is significantly faster than the optimisation.
- Applicable for any German municipality and extendable to other locations.

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ABSTRACT

Plants increasingly exploit high geothermal energy potentials in German district heating networks. Municipal planners need instruments to design the district heating network for geothermal heat. This paper presents a combinatorial mixed-integer linear optimisation model and a three-stage heuristic to determine the minimum-cost district heating systems in municipalities. The central innovations are the ability to optimise both the structure of the heating network and the location of the heating plant, the consideration of partial heat supply from district heating and the scalability to larger municipalities. A comparison of optimisation and heuristic for three exemplary municipalities demonstrates the efficiency of the latter: the optimisation takes between 500% and 1×10^7% more time than the heuristic. The deviations of the heuristic's calculated total investments for the district heating system compared to the optimisation are in all cases below 5%, and in 80% of cases below 0.3%. The efficiency of the heuristic is further demonstrated by comparison with the Nearest-Neighbour-Heuristic, which is less efficient and substantially overestimates the total costs by up to 80%. The heuristic can also be used to design district heating networks in holistic energy system optimisations due to the novel possibility of connecting an arbitrary number of buildings to the network. Future work should focus on a more precise consideration of heat losses, as well as taking additional geological and topographical conditions into account.

1. Introduction

The German energy sector is currently undergoing radical structural change due to ambitious national climate targets and supportive energy policy. This change is dominated by the expansion of renewable energy generation technologies, which are mainly decentrally exploited due to their characteristics [1]. This development has led to the generation of 33% of the electricity in Germany by renewable energies in 2017 [2]. In contrast, the proportion of renewable heat supply is around 13% [3]. The installed capacity of renewable energies includes around 55 GW of wind energy (on- and offshore), 42 GW photovoltaic systems, about 7 GW of bioenergy [4] and 39 MW of geothermal energy [3]. In comparison to the other renewable energies, relatively little electricity is generated by geothermal plants (GTPs, for abbrevations see Table 1) in Germany. Despite the potential of GTPs to make a major contribution to reducing greenhouse gas emissions, the installed capacity in Germany is still very low compared to the available resources [5].

The currently (2017) installed 30 GTPs in Germany generate about 155 GWh of electricity [3] and 1.3 TWh of heat [5] annually, which is generally used for district heating (DH) applications [6]. However, the German district heating networks (DHNs) are currently mainly supplied with heat by conventional gas and coal-fired plants [7]. Most of the

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Table 1
Abbreviations used in the present study and their meaning.

Abbreviation	Full description
CLC	CORINE Land Cover
DCMST	Degree-constrained minimum spanning tree
DH	District heating
DHN	District heating network
GTP	Geothermal plant
MST	Minimum spanning tree
NGB	North German Basin
ORC	Organic Rankine cycle
URG	Upper Rhine Graben

heat is consumed in the residential sector [7], in which the market share of DH is 13.8% [8]. Between 2000 and 2017, DHNs were constantly expanded [9] and the consumption of DH in the residential sector increased by about 40% [7].

The low emission of pollutants during the operation of GTPs means that they could provide low-carbon heat for future DH systems. They could thereby contribute to higher levels of renewable heat supply, as already achieved in some DHNs based on GTPs at the municipal level [10]. As the literature review in Section 2 shows, transferable planning instruments are needed to support decision-making in the dimensioning of DHNs. The focus of this study is on the development of a novel method for designing a DH system based on geothermal heat in an arbitrary municipality. In comparison to existing work, this paper presents a generic approach for the simultaneous optimisation of DHN and DH plant locations under local geographic conditions. The novel possibility of connecting an arbitrary number of buildings to the DHN is thereby also given. Due to the high complexity of this combinatorial optimisation problem, an optimisation is not possible for a municipality with a large number of settlements. Therefore, a heuristic is developed for the planning of the DHNs, whose efficiency is evaluated with the aid of the optimisation model. The location of the GTP, as well as the DHN, are specified depending on the location, heat demand and heat density of the individual settlements within a municipality. In the first stage of the three-stage heuristic, the integrated selection of the GTP location and the initial design of the DHN is performed. In the second stage, an algorithm is employed to optimise the design of the DHN. Based on the results, the optimum heat allocation to the settlements connected to the DHN is determined in the third stage.

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 Section 4 presents the results. A sensitivity analysis with subsequent critical discussion follows in Section 5. The paper concludes with a summary and conclusions in Section 6.

2. Literature review

This section highlights the novelty of the methodology developed in this study. In the literature many studies analyse existing DHNs and do not design new networks. For example, based on the results of a demonstration system for decentralized cooling in DHN, a simulation is developed in Udomsri et al. [11] to improve the performance of the existing network. Furthermore, Fang & Lahdelma [12] design a new methodology to minimise production and distribution costs in existing DHNs during simultaneous heat production in multiple heating plants. In Pini Prato et al. [13], an existing DHN is considered as a test case for optimising the matching between the heat generation of a combined heat and power plant and the heat demand of the thermal consumers of the network. The development of biomass-based industrial DHNs in Italy in Chinese & Meneghetti [14] involves the sizing of new DHNs, however, these networks are not designed from a topographical perspective. Finally, the study by Mørck et al. [15] analyses the EU CONCERTO project class 1, in which settlements with low energy buildings were constructed which are supplied with heat by biomass and solar based DHNs.

In fewer studies, which are discussed in the following, the design of new DHNs is optimised. First of all, Section 2.1 shows that previous energy system analyses with geothermal DH systems do not dimension the DHNs. Afterwards, approaches for dimensioning DHNs are analysed and the differences to the developed methods are identified (cf. Section 2.2). Section 2.3 concludes by clarifying the differences between the developed methods and typical combinatorial optimisation problems.

2.1. Energy system analyses with geothermal district heating

A few studies have already investigated energy systems in municipalities in which geothermal DH is used. Østergaard et al. [16] investigate the feasibility of supplying the municipality of Aalborg in Denmark with renewable energy through a combination of low-temperature geothermal heat, wind power plants and biomass. 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 [17] also takes deep geothermal energy into account as a heat generation plant with DHN. It analyses a 100% renewable energy supply for Frederikshavn in Denmark. The simulations demonstrate that the operation of the GTP and the DHN reduces the energy imports of Frederikshavn. In the study of Sveinbjörnsson et al. [18], the municipality of Sønderberg in Denmark is considered, which is aiming for zero net CO_2 emissions by 2029. As in Østergaard & Lund [17], the GTP is combined with an absorption heat pump. The optimisations indicate that by supplementing combustion with modern energy conversion technologies, the climate targets can be achieved in a cost- and energy-efficient manner.

In the studies described above, the DHN already exists and is not further analysed. Besides, the location of the DH plant is not optimised but is specified manually beforehand. Some studies on DH in energy system analyses have been conducted in which the DH is not based on geothermal energy such as Möller & Lund [19]. The authors examine the expansion of DH in a region in Denmark which is currently supplied with natural gas. The energy system of the region, however, is not optimised, but only analysed with the help of various scenarios. One conclusion is to replace natural gas with DH, especially in the vicinity of cities, and to increase the share of DH in the heat supply from 46% to 50–70%. However, this paper indicates that the use of geothermal energy should be included in future analyses when considering DH. According to this literature review, so far, energy system optimisations of entire municipalities in which the DHNs are designed simultaneously with other technologies have not been implemented.

2.2. Algorithms for district heating design

Studies in which the design of DHNs is determined without the involvement of other energy technologies, by contrast, have been conducted with several different approaches. In general, however, these studies are based on a basic methodology, in which different nodes/buildings/settlements are connected by edges/pipelines. This methodology is also the basis of the analysis in the present study. Table 2 summarises important characteristics of the studies discussed in this section. This paper distinguishes between bottom-up methods, in which the calculations are based on data of individual buildings and roads, and top-down approaches, which use e.g. heat densities and population densities.

The majority of studies dealing with the dimensioning and placement of DHNs are limited to DH pipelines within one urban area and do not consider the connection of several urban areas. Casisi et al. [20], for example, determine the optimum layout of a DHN in conjunction with combined heat & power units in the city centre of Pordenone, Italy. The distances between the six considered buildings are specified

Table 2
Overview of relevant studies of algorithms for DH design (R = residential sector, C = commercial sector, I = industrial sector, BU = bottom-up method, TD = top-down method).

Study	Method	Network building or expansion?	Determination of plant location?	Sector	Region	Easily *trans*-ferable?
[21]	Optimisation model (BU)	Building	No	R, C, I	Urban area (Italy)	No
[20]	Optimisation model (BU)	Building	No	C	Urban area (Italy)	No
[23]	Optimisation model (BU)	Building	No	n.a.	Urban area	No
[31]	Cluster analysis and optimisation model (TD)	Building	No	n.a.	Urban area	No
[27]	Heuristic (BU)	Expansion	No	n.a.	Arbitrary Danish municipality	Yes
[29]	Optimisation model (BU)	Expansion	No	R, C	Urban area	No
[25]	Heuristic (BU)	Building	Yes	R	German town	No
[22]	Heuristic (BU)	Building	No	R, C	Urban area	No
[28]	Optimisation model (BU)	Expansion	No	n.a.	Urban area	No
[33]	Optimisation model (BU)	Building	No	R, C	Urban area	No
[32]	Cluster analysis and graph theory (TD)	Building	No	n.a.	Urban areas (Switzerland)	No
[24]	Optimisation model (BU)	Building	No	n.a.	n.a.	No
Present Study	Optimisation model and heuristic (TD)	Building	Yes	R	Arbitrary German municipality	Yes

beforehand. The location of the DH plant is not optimised here, but the authors note that this could lead to cost reductions. Chinese [21] designs two district heating and cooling networks in the municipality of Udine in Italy with the help of an optimisation model. In designing the size and layout of the network, central and distributed generation of heating and cooling are combined and compared in consideration of the network costs. In the simulation model of Bratoev et al. [22], the DHN with connections to the buildings is first generated on the basis of a road network. Afterwards, the location of the DH plant can be selected, which is then connected to the DHN via the shortest distance. The algorithm requires an extensive building database, which must be collected in advance, for example through surveys. Dobersek & Goricanec [23] determine the optimal tree branch path of a DHN in an urban area taking economy and functionality into account. The influence of construction cost, pump and electric energy cost on the type of optimal network is investigated. The locations of heat source and consumers are defined in advance and the optimal network for a complete supply of all consumers has to be determined. The edges are also fixed in advance and cannot lead from each node to any other node. Marty et al. [24] highlight the relevance of a simultaneous optimisation of the DHN and the Organic Rankine Cycle (ORC) as parts of a GTP. Although the algorithm is similar to the methodology of the present study, some differences are apparent. The location of the DH plant is specified in the study and is not optimised. Furthermore, there is always a consumer who is connected, i.e. the construction of the DH plant is not decided but the DHN is built in any case. The heat demand of the consumers has to be completely covered and no statement is made on the transferability of the model. Overall, however, it can be stated that the model in the study cannot be used for the purposes intended by the present study.

Falke et al. [25] is the only other study, compared to the present study, which determines the location of the district heating plant. However, the entire planning of the DHN is based on a heuristic whose performance is not demonstrated in comparison to an optimal solution. First, the heuristic determines a few random DHNs that connect all buildings. The minimum network length is then calculated using the Kruskal [26] algorithm. This algorithm, which is based on the Greedy heuristic, would not be suitable for the problem presented in the present study, since it connects all nodes with each other. In the present study, however, it must be decided simultaneously which nodes should be part of the network at all.

In Nielsen [27], Delangle et al. [28] and Bordin et al. [29], existing DHNs are expanded. Nielsen [27] developed an algorithm to economically evaluate possible network expansions based on existing DHNs. This is done on the basis of cost calculations for heat production, distribution and transmission, based on geographical data. Although the model presented is transferable to Danish regions, its application in German municipalities is hindered by the unavailability of data. To the authors' knowledge, shapefiles with building locations are not available for the whole of Germany. An extension of existing DHNs is also investigated by Delangle et al. [28]. In addition to DH, gas boilers, biomass boilers, heat pumps and heat storages are considered in a mixed-integer linear optimisation. The model can identify the optimal investment schedule for a DHN extension by a couple of buildings. The methodology can be applied to other DHNs, but in this case, the existing DHN and the potential buildings to be connected have to be known. In the optimisation approach of DHNs in Bordin et al. [29] the tree configuration of a network is determined by starting from one heat supply plant. An existing network is assumed, which can be extended by potential pipelines and customers to maximise the net profit. For more complex analyses in future studies, the authors propose the use of heuristics to reduce computing times. Like the studies described above, the model from Bordin et al. [29] is suitable for the individual planning of a DHN, but not as part of a larger energy system optimisation model of a municipality or region. Although there have been some studies on the expansion of existing DHNs, a planning instrument should focus more on the construction of new DHNs, since the share of DH in residential heating systems is less than 5% in over 85% of German municipalities [30].

In Fazlollahi et al. [31], Unternährer et al. [32] and Marquant et al. [33], the DHN is dimensioned based on cluster analyses, in order to reduce the model complexity. The clustering of urban areas in Fazlollahi et al. [31] results in combined urban districts whose energy demand and distribution costs of DH can be aggregated in order to subsequently optimise the DHN design. In Unternährer et al. [32], the optimum design of the DHN is determined for each cluster. As in the present analysis, geothermal energy is used for DH. The authors highlight the economic value of geothermal energy for DH supply. However, memory restrictions occur during this analysis. Since only one settlement and not an entire municipality is analysed, this approach is not suitable to meet the objectives of the present study. Marquant et al. [33] use a density-based cluster analysis to divide large city-scale problems into sub-problems. The subsequent optimisation of the DHNs in the individual clusters requires demand profiles of the individual buildings and is therefore not automatically transferable.

In summary, the studies analysed use optimisation models and heuristics respectively (cf. Table 2). In articles about optimisation models, the choice of heuristics is suggested for more complex studies, but these two approaches are not compared in any of the studies. In addition, none of the studies in which the networks are newly built is suitable for application to entire municipalities, but only for planning DHNs in urban areas. In addition, the novel possibility to connect an arbitrary number of buildings to the DHN is given in this study. This results in various optimal solutions for the connected buildings, depending on the arbitrary specification of heat coverage by the DHN. This also enables the use of discrete DHN solutions in holistic energy system optimisations (cf. Sections 2.1 and 5.4). Furthermore, the methodologies of the studies cannot be applied to arbitrary municipalities in Germany. All of these points are addressed with the approaches in the present article.

2.3. Combinatorial optimisation of networks

Most, if not all of the studies in the previous section use the methodology of combinatorial optimisation. As particularly evident in the studies of Dobersek & Goricanec [23] and Bordin et al. [29], the optimisation of network design in DH systems falls within the scope of minimum spanning tree (MST) problems. Therefore, articles on MST problems are analysed in the following in order to draw conclusions for DHN optimisations.

Smith & Walters [34] describe an evolutionary approach based on genetic algorithms to find the optimal trees in undirected water, gas or material networks. Based on the construction and operating costs, a network tree is identified that is close to the optimum. In order to be able to execute the genetic algorithm, however, starting solutions must first be identified. Blanco et al. [35] extend the MST problem so that the nodes are not points but belong to regions with a certain geometry to reflect the uncertainty of the location of a node. Efficient algorithms and formulations of the problem have been implemented in Blanco et al. [35] to solve the problem in a reasonable time. The methodology with the uncertain locations of the heat consumers could also be relevant for DH designing models (cf. Section 5.4). Fernández et al. [36] focus on multiobjective spanning trees and aggregate the vector of the objective values. Formulations of the problem are developed which reduce the number of decision variables and thus the time needed to solve the problem.

Gao & Jia [37], Salgueiro et al. [38] and Gouveia et al. [39] investigate another form of the MST, the degree-constrained minimum spanning tree (DCMST). The problem formulation of the DCMST contains additional restrictions regarding the degree of the nodes, i.e. how many edges are connected to a node. This restriction is not meaningful for the DHNs considered in the present study, as a large number of pipelines should be allowed to enter and leave the nodes. In addition, there is no need to limit the number of end nodes/leaves as done in Gouveia & Simonetti [40], whereby they develop a competitive model for the max-leaves problem. Cerrone et al. [41] show in their paper that a spanning tree with a minimum number of leaves is better suited to minimising the number of light-splitting devices required in optical networks than two other MST problems. In Marín [42], the MST problem is adjusted to minimise the number of branches, i.e. nodes with a degree greater than two. As in the present study, a multi-stage heuristic is developed for this problem. However, the limitation of the number of branches should not apply to DH systems either.

The approach for DHNs in the present study differs from the MST problems described above in the following points:

- Not every node has to be connected (cf. Eq. (8) in section 3.2).
- Not only the edges but also the nodes have weights (cf. Eq. (3) in section 3.2).
- Edges can connect any node to any other node (cf. Eq. (2) in section 3.2).
- A decision must be made “to which percentage” a node is connected (cf. Eq. (3), (5) and (9) in section 3.2).
- Instead of one starting point/source, there is an arbitrary number of sources, of which one must be selected (cf. section 3.1 and Eq. (6) in section 3.2).

The aim of this paper is not only to provide a unique optimisation problem/heuristic for the planning of DHNs in municipalities but also to solve the problem in a reasonable time. Furthermore, the method presented in the following section is applicable to every municipality in Germany.

3. Methodology

The distance to the heat consumers is crucial for the costs of DHNs. Therefore, an optimisation model, as well as a heuristic, to design DHNs and position the DH plant is developed in this study. The location of the GTP and the connection of the settlements by a DHN are determined for an arbitrary municipality considering the minimisation of the investment for the DHN. Possible locations for the GTP are specified in advance, as the following section 3.1 shows, which also describes the determination of input data and the most important assumptions (see also Table 3). The optimisation model for determining the optimal DH system is presented in section 3.2 and the heuristic in 3.3.

3.1. Input data generation and assumptions

The optimisation model and the heuristic are demonstrated using the German municipality “Groß Kreutz”, which is shown in Fig. 1. The figure illustrates the possible locations for the GTP as purple circles and the pink areas are CORINE Land Cover (CLC) settlement areas from EEA [43]. The number of possible locations of the GTP can be specified manually via the distances between the purple circles. The locations were set so that 35 locations are between the minimum and maximum longitude coordinates and/or latitude coordinates. In Groß Kreutz this results in 497 possible locations i.e. 5 locations per km^2. Section 5.2 shows that this number is sufficient, as a further increase does not significantly affect the results. The shapefiles of these CLC areas are provided by the Federal Office of Cartography and Geodesy [44]. Some of the purple circles are close to the settlement areas since GTPs do not have to keep a minimum distance to settlements as long as measurements are taken to assess vibrations according to DIN 4150-3 [45]. Using OpenStreetMap, inadmissible areas such as settlements, water areas and forests were excluded as locations for the GTP.[1] The settlements marked in pink differ in terms of their heat demand and building density. The most important assumptions include the specific costs c_p for pipelines outside the settlements, which are estimated to be 200 €/m [46,47]. In addition to pipelines, these costs also include network pumps and planning costs [46]. The relatively low value of 200 €/m is supposed to reflect the receipt of a subsidy in the context of the Combined Heat and Power Act (KWKG) amounting to 100 €/m [48]. However, the 200 €/m are above the 160 €/m in the geothermal project Grünwald [49]. The pipeline costs within the settlements, which depend largely on building density, are estimated using the methodology of Persson & Werner [50]. By applying this methodology, exact roads within the settlement do not have to be known in order to estimate the costs. The DH substations are assumed to have a reference size of 250 kW [51,52]. If the heat demand in a settlement exceeds 250 kW, more than one substation has to be built. According to Connolly et al.

[1] The red encirclement at the right of Fig. 1 represents a possible error in the placement of the purple circles. The error occurs due to the fact that OpenStreetMap uses slightly different municipal boundaries, which differ from the municipal boundaries of the shapefiles from the Federal Office of Cartography and Geodesy used here to illustrate the municipality. These possible errors can be neglected as they only occur at the municipal boundaries. Due to the large distance to the settlements, they are rather unlikely to be chosen as the location for the GTP.

Table 3
Data and methods used in the present study.

Description	Value	Unit	Sources of data / method
DH substation size	250	kW	Connolly et al. [51], Le Truong et al. [52]
DH substation cost c_s	21,500	€	Connolly et al. [51], Le Truong et al. [52]
Inadmissible areas	–	–	OpenStreetMap contributors [60]
Pipeline costs within the settlements	–	–	Persson & Werner [50]
Settlement areas (CORINE Land Cover data)	–	–	EEA [43], Lenk et al. [44]
Settlement data (i.e. heat demand)	–	–	Weinand et al. [53]
Specific costs c_p for pipelines outside the settlements	200	€/m	C.A.R.M.E.N. e.V [46], Pfnür et al. [47]

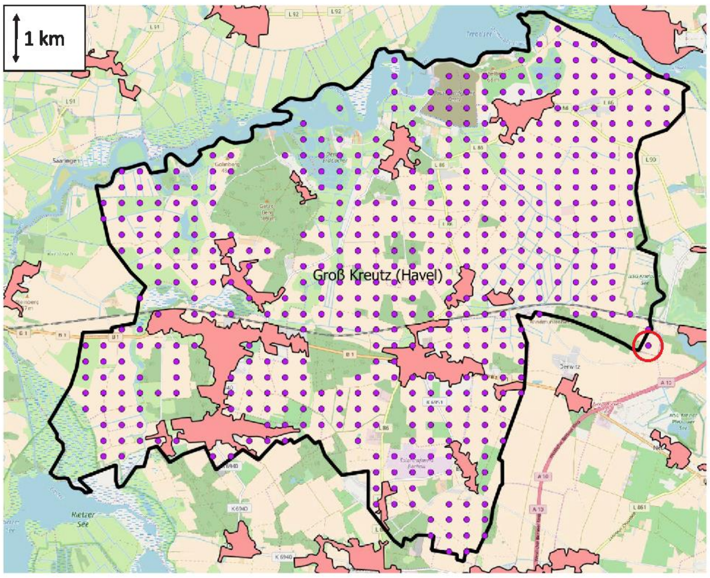


Fig. 1. Possible locations (purple circles) for building the GTP in the municipality Groß Kreutz (Havel). The background maps in this and the following figures are from OpenStreetMap contributors [60].

[51] and Le Truong et al. [52], the costs for one substation c_s are assumed to be 4000 € and 70 €/kW, i.e. 21,500 € for 250 kW.

Parameters for all German settlements required for this study are taken from Weinand et al. [53], including the heat demands, living spaces, population densities and coordinates of the centroids. This also includes the shares of existing DH supplies in the total heat supply, which are subtracted from the heat demand of the settlements in the optimisation as well as in the heuristic. This is intended to prevent DHNs from being built where networks already exist. These data for all German settlements and the heuristic are made available as online supplementary material associated with this article. In addition, the necessary input data for the municipality Groß Kreutz are provided as an example. This input is needed to execute the optimisation, which is explained in the following section.

3.2. District heating system optimisation

In this section, variables are marked in bold letters. A nomenclature of variables and parameters can be found in Table 4.

The combinatorial optimisation model for the cost-optimised placement of the GTP as well as the determination of the optimal DHN minimises the total costs C_{total} (cf. Eqs. (1)–(13)). These costs consist of the costs for the DH pipelines in and outside the settlements, $C_{pipe,in}$ and $C_{pipe,out}$, as well as the DH substations C_{sub} according to Eq. (1).

$$min C_{total} = \boldsymbol{C_{pipe,out}} + \boldsymbol{C_{pipe,in}} + \boldsymbol{C_{sub}} \tag{1}$$

subject to

$$\boldsymbol{C_{pipe,out}} = \left(\sum_{l=1}^{m}\sum_{i=1}^{n} \boldsymbol{x_{G,l,i}}\cdot l_{G,i,l} + \sum_{i=1}^{n}\sum_{j=1}^{n} \boldsymbol{x_{S,i,j}}\cdot l_{S,i,j}\right)\cdot c_p \tag{2}$$

$$\boldsymbol{C_{pipe,in}} = \sum_{i=1}^{n} \left(HDC_i\cdot \sum_{t=1}^{T=8760} \dot{Q}_{i,t}\cdot \boldsymbol{p_i}\right) \tag{3}$$

$$\boldsymbol{C_{sub}} = \sum_{i=1}^{n} (N_{S,i}\cdot \boldsymbol{p_i})\cdot c_s \tag{4}$$

$$\dot{Q}_{G,t} - \sum_{i=1}^{n} \dot{Q}_{i,t}\cdot \boldsymbol{p_i} = 0 \qquad \forall\, t = 1, 2, \cdots, 8760 \tag{5}$$

$$\sum_{l=1}^{m} \boldsymbol{b_{GL,l}} = 1 \tag{6}$$

$$\sum_{i=1}^{n} \boldsymbol{x_{G,l,i}} \leq \boldsymbol{b_{GL,l}}\cdot n \qquad \forall\, l = 1, \cdots, m \tag{7}$$

Table 4
Nomenclature.

Variable / Parameter	Description	Unit
b_{GL}	Binary variable for deciding whether a geothermal plant should be built at a specific location	–
b_{GS}	Binary variable for deciding whether a settlement can be reached by a certain path	–
c_p	Specific costs for pipelines outside the settlements	€/m
$C_{pipe,in}$	Investment for district heating pipelines inside a settlement	€
$C_{pipe,out}$	Investment for district heating pipelines outside a settlement	€
c_s	Investment for one district heating substation	€
C_{sub}	Investment for all district heating substations	€
C_{total}	Investment for the entire district heating network	€
D_{heat}	Heat demand of the municipality	kWh
HDC	Specific heat distribution costs	€/kWh
l_G	Distance between a district heating plant and a settlement	m
l_S	Distance between two settlements	m
M	A big number	–
N_S	Number of district heating substations	–
p	Proportion of the heat demand in a settlement covered by district heating	–
$\dot{Q}$	Heat supply to a settlement	kWh
$\dot{Q}_G$	Heat generation of a geothermal plant	kWh
S_i	Matrix in which every path from every possible source to the sink i is contained	–
x_G	Binary variable for deciding whether a district heating pipeline between a district heating plant and a settlement should be built	–
x_S	Binary variable for deciding whether a district heating pipeline between two settlements should be built	–

$$\begin{pmatrix} b_{GS,i,1} * 1 \\ b_{GS,i,2} * 2 \\ \vdots \\ b_{GS,i,\left(\sum_{a=1}^{n}(n-1)!/(n-a)!\right)-1} \cdot n \\ b_{GS,i,\sum_{a=1}^{n}(n-1)!/(n-a)!} \cdot n \end{pmatrix} \le S_i \qquad \forall\, i = 1,\cdots,n \tag{8}$$

$$p_i \le b_{GS,i,1} + b_{GS,i,2} + \cdots + b_{GS,i,\sum_{a=1}^{n}(n-1)!/(n-a)!} \qquad \forall\, i = 1,\cdots,n \tag{9}$$

$$x_{G,l,i} \in \{0, 1\} \qquad \forall\, l = 1,\cdots,m \qquad \forall\, i = 1,\cdots,n \tag{10}$$

$$x_{S,i,j} \in \{0, 1\} \qquad \forall\, i, j = 1,\cdots,n \tag{11}$$

$$b_{GL,l} \in \{0, 1\} \qquad \forall\, l = 1,\cdots,m \tag{12}$$

$$b_{GS,i,k} \in \{0, 1\} \qquad \forall\, i = 1,\cdots,n \qquad \forall\, k = 1,\cdots,\sum_{a=1}^{n} (n-1)!/(n-a)! \tag{13}$$

The costs for the pipelines outside the settlements $C_{pipe,out}$ are determined using the vectorised geodetic distances $l_{G,i,l}$ between the GTP at location l and a settlement area i as well as the distances $l_{S,i,j}$ between two settlement areas i and j (cf. Eq. (2)). The binary variables x_G and x_S are used to decide which pipelines should be constructed. Thereby m possible locations of the GTP and n different settlements are given. One of the m different geothermal locations has to be selected via the binary variable b_{GL} (cf. Eq. (6)). The variable b_{GL} then also restricts the possible pipelines that can be built using Eq. (7). This ensures that only connections starting from the chosen geothermal location can be selected.

The costs for the DH pipelines inside the settlements $C_{pipe,in}$ are determined with the help of the specific heat distribution costs HDC_i and the heat supply Q per hour t in a settlement i (cf. Eq. (3)). The variable p_i gives an indication of which proportion of the settlement is supplied with heat and therefore takes values between 0 and 1. The heat distribution cost is calculated on the basis of Persson & Werner [50], depending on the population and building density as well as the specific heat demand. The settlements have to consume the entire heat $\dot{Q}_G$ of the GTP (cf. Eq. (5)). This amount of heat should be adjusted in advance according to the specific use case or the geothermal potential available in the municipality. Fig. 2 qualitatively illustrates the influence of p on the proportion of heat demand to be covered in a certain settlement. For example, the whole heat demand is covered, if $p = 1$ is selected. The GTP, if operated during the whole year, would generate surplus energy in summer. Although the use of the surplus energy is not relevant in this study, electricity could be generated in a GTP in this time period.

For each settlement at least one DH substation is required to connect the heating system of the buildings with the DHN. The costs for one substation c_s are multiplied by the number of substations N_S and the proportion of the settlement supplied with heat to determine the costs for DH substations C_{sub} in Eq. (4).

A subtour is the term used when two or more coherent graphs are created as a solution instead of one coherent graph. In order to prevent subtours, it must be ensured that each sink/settlement is connected with the source/GTP via a coherent path. For this purpose, equations are set up for each possible path from the source to the sink (cf. Eq. (8)). S_i represents a matrix in which every path from every possible source to the sink i is contained. The binary variable b_{GS} is used to decide by which path a certain settlement can be reached. This path must begin at the GTP. For a certain settlement, several paths could be selected, but this would lead to higher costs according to Eq. (2). For example, in the first row in Eq. (8) the pipeline would lead directly from the GTP to a settlement ($b_{GS,i,1} = 1$), while in the last row in Eq. (8) the pipeline would lead across all other settlements ($b_{GS,i,\sum_{a=1}^{n}(n-1)!/(n-a)!} = 1$). In the penultimate row of Eq. (8) b_{GS} is also multiplied by n, since the path leads over as many settlements as in the last row, but the order of the settlements on this path is different. The number of restrictions in Eq. (8) depends on the number of settlements and can be calculated via $\sum_{a=1}^{n} n!/(n-a)!$. Therefore, the number of equations increases exponentially with the number of settlement areas in a municipality. Eq. (9) has to be included so that no settlement can be supplied with heat that is not connected to the GTP via DH pipelines. The optimisation problem described above can only be solved for municipalities with less than eight settlements due to calculation time limitations (cf. section 4.1). Even the building of equations is not possible for municipalities with more than ten settlements due to computational constraints (cf. section 4.1). In order to solve the problem for larger municipalities, a heuristic has been developed, which is described in section 3.3.

3.3. Heuristic for designing district heating systems

The heuristic is similar to algorithms for solving the combinatorial optimisation problem of the minimum spanning tree. In contrast to the general minimum spanning tree problem, the nodes to be connected are not previously fixed and the weights of the edges can change in each

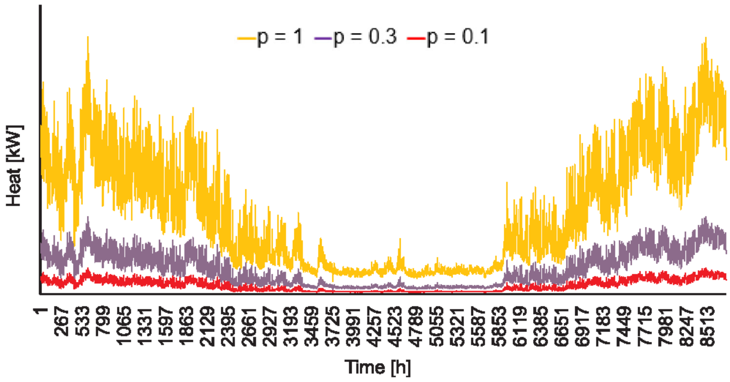


Fig. 2. Influence of the variable p on the heat demand covered by the DH plant in a settlement.

iteration. The heuristic is executed for each possible GTP location, which is determined in advance (cf. Fig. 1). Before starting the heuristic, the percentage of the municipality's heat demand to be covered by the GTP must be specified (cf. Fig. 4). After determining the distance matrices l_S and l_G, a loop is performed for all GTP locations. Due to these iterations the rectangular boxes in Fig. 4 are shown nested. The heuristic then selects a connection from the geothermal system to one of the settlements in the municipality. In the example of the municipality Groß Kreutz, a choice must be made between twelve settlements. The decision is made on the basis of the investment for the DH system C_{total} per supplied amount of heat. If only costs for the pipelines would be considered, the nearest and most densely built-up areas would be selected. This would lead to high costs, as in most cases more settlements would have to be connected with DH pipelines since the first connected settlements might not occur in the optimal solution. Subsequently, the hourly heat demand Q of the settlement is subtracted from the heat supply Q_G of the GTP. The next DH connection is selected if the GTP still has heat available and there is still unmet demand in the settlements. All settlements to which a connection already exists are now included as possible heat sources. This means that in each iteration there is an additional heat source that can be connected to the other settlements.

The first stage of the heuristic is completed as soon as the heat supply of the geothermal plant is exhausted and is a modified form of the algorithm from Weinand et al. [53]. The upper part of Fig. 3 shows the result after the first stage for the case that 100% of the heat demand is covered in Groß Kreutz. The red lines represent the DH pipelines originating from the GTP, the blue ones those originating from a settlement. The GTP is illustrated as a purple circle. The upper part of the figure shows, above all in the part encircled in red, that the shortest connections are not always used. This is due to the iterative approach of the heuristic, whereby one connection is chosen in each step. Previous iterations could have selected connections that would not have been chosen if all connected settlements had been known beforehand. Therefore, the heuristic is extended by a second stage with another target criterion: the costs for the connections outside the settlements. However, the selection of settlement areas in this second stage is limited to those settlements that were connected in the previous stage. This leads to a more economical connection, as shown in the lower part of Fig. 3.

Another problem can be caused by the iterative approach. In case the heat demand is not met to 100%, the last selected settlement will only be partly supplied with heat ($p < 1$). However, this last connected settlement could have a higher heat density than another settlement connected to the DHN. Then it would be reasonable to supply the last selected settlement with more heat. In this case, the settlement with the lowest heat density would be supplied with less heat than in the solution of the second stage. Therefore, the heat supply is reassigned to all selected settlements on the basis of the HDC in the third stage of the heuristic.

Finally, the DH connections and the associated costs and CO_2 abatements per year are given as output. For calculating the CO_2 abatement, the actual heating technologies in the various settlements were determined in Weinand et al. [53].

4. Results

In Weinand et al. [54], the 11,100 German municipalities were clustered into ten groups with regard to their suitability for decentralised energy systems. Two of the 34 socio-energetic indicators in the cluster analysis were used to measure the potential for geothermal energy: the attainable geothermal temperature and the required drilling depth. The municipalities in Germany are suitable for low-temperature GTPs with achievable temperatures up to 190 °C. As case studies for the analysis in this paper, four municipalities are selected from the clusters with the highest potential for geothermal energy (cf. Table 5). Municipalities are selected which differ particularly in the number of settlements, heat demand and the population density. Three of the municipalities are located in the North German Basin (NGB) and Bensheim lies in the Upper Rhine Graben (URG). The parameters of the municipalities important for the following analyses are listed in Table 5.

Firstly, the results and the solving time of the optimisation and the heuristic are compared in section 4.1. The results for the four municipalities from Table 5 are then presented in section 4.2. The results are determined for different levels of heat supply, from 10% in 10% steps up to 100%. The proportion of existing DH systems in the municipalities is subtracted from the heat demand in the settlements.

4.1. Comparison of optimisation and heuristic approaches

The heuristic was executed in Matlab and the optimisation was performed in GAMS using the solver CPLEX. The selected computer has the following performance properties: Intel Xeon E-1650 v2, 12 threads and 128 GB RAM. The results of the optimisation model and the heuristic are compared for the municipalities of Billerbeck, Dümmer and Bensheim, which contain three, five and seven settlements respectively. The optimisation for Groß Kreutz with more than seven settlements was not conducted because time constraints already arose during the optimisation for Bensheim with seven settlements. Thus the optimisation for Bensheim had to be terminated after 7 days in the case of 100% heat

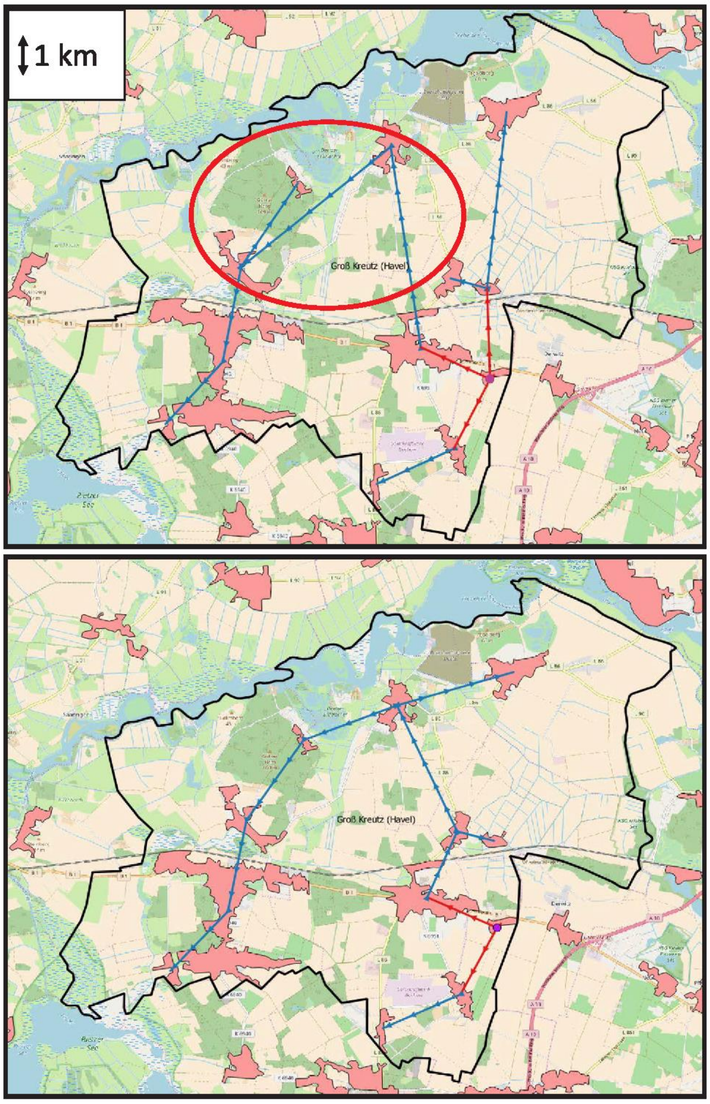


Fig. 3. Location of the GTP (purple circle) and DH pipelines to the settlement areas for the target criteria investment per kW (upper part) and costs for the DH pipelines outside the settlements (lower part).

supply with a MIP gap of 4.8%. Building the equations in Matlab for a municipality with 8 settlements alone would take two hours and the optimisation problem would contain over 1×10^5 binary variables. In the municipalities of Billerbeck, Dümmer and Bensheim, the equations take between 35 s and 12 min to build. The time required to build the equations is not included in the following analysis.

Fig. 5 shows the percentage by which the calculated total costs are lower in the optimisation compared to the heuristic. In the case of 100% heat supply in Bensheim, the result of the lower bound was adopted due to the above-mentioned termination of the optimisation. However, it should be noted that the deviation could actually be much smaller in this case. Therefore, the following analysis will focus on how the deviations in Billerbeck are caused in the 30–70% cases and the deviation in Dümmer is caused in the 50% case.

In Billerbeck up to the 20% case, heat is supplied to settlement 2 in the heuristic as well as in the optimisation cases, since this settlement has the highest building density (for settlement 2 see Fig. 6). In the 30% case, however, there would still be heat remaining, so that another settlement has to be supplied. The error is caused by the fact that with the heuristic, after selecting a settlement, the maximum possible

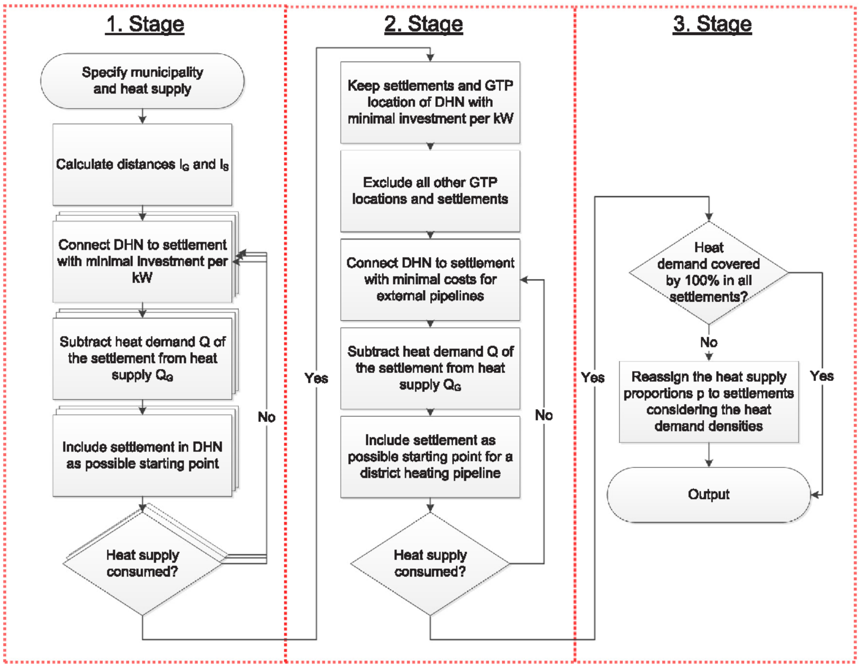


Fig. 4. Heuristic for determining the cost-optimal DH system for an arbitrary municipality considering the heat demand and heat densities of the settlements. The nested illustration of some steps in Stage 1 shows that these steps are executed several times, in this case one iteration per GTP location.

Table 5
Characteristics of the German municipalities Billerbeck, Groß Kreutz, Bensheim and Dümmer.

Municipality	Biller-beck	Groß Kreutz	Bens-heim	Dümmer
Cluster [54]	3	8	3	8
Basin [61]	NGB	NGB	URG	NGB
Area [km^2]	91	99	58	32
Population	11,593	8,133	40,051	1,430
Population density in municipality [1/km^2]	127	82	693	46
Number of Corine settlement areas	3	12	7	5
Average Population density in settlements [1/km^2]	3,000	1,000	3,300	1,300
Yearly heat demand [GWh]	135	55	320	9
Average share of DH in settlements [%]	2	4	2	8

amount of heat is supplied to this settlement. Therefore, in the cases 30–70%, only settlement 3 with a lower building density than settlement 2 is supplied in the case with the heuristic (cf. left part of Fig. 6). By contrast, in the optimisation in these cases, settlement 2 is always supplied entirely with heat and settlement 3 proportionately (cf. right part of Fig. 6). Although this means that the costs for the pipelines outside the settlements are higher, the overall costs are lower. Above the 30% case, the deviation between optimisation and heuristic decreases further, as the proportion of the heat quantity delivered to settlement 2 becomes smaller and smaller in relation to the total heat supply.

The difference in the municipality of Dümmer in the 50% case is due to the same reason as in Billerbeck. The right part of Fig. 7 shows the DHN resulting from the optimisation. Here settlement 4 represents an intermediate station and only 15% of the heat demand is covered. This would not be possible in the heuristic since settlement 4 would have been supplied with the complete remaining heat supply. Therefore, the more favourable solution in the heuristic is to supply settlement 3 and 5 (cf. left part of Fig. 7).

The two discussed examples show that with regard to the amount of heat that is delivered to the settlements, there is still potential for improvement in the heuristic. However, the largest deviation from the optimisation is only 5% and in most cases less than 0.1% of the total investment. If the 100% case in Bensheim is neglected in the calculation due to the termination of the optimisation, a mean absolute percentage error of 0.7% results. As these errors are deemed acceptable for this application, the heuristic can be used for estimating DH costs and for planning the DHN including location planning of the plant.

Nevertheless, the use of the heuristic would not be reasonable, unless the application contains a significant reduction of the solving time. As Fig. 8 shows, the solving time of the heuristic is between 2 and 35 s, depending on the case. Leaving aside the 100% case in Billerbeck, the optimisations take between 5 and 100,000 times longer compared to the heuristic. The more settlements that can be connected in a municipality, the longer the optimisation takes (cf. 80% case and 90% case in Bensheim). Whilst the time increases linearly in the heuristic, an exponential increase can be observed in the optimisation. Billerbeck has the fewest settlement areas and yet in some cases, the calculations/optimisations take longer than in the other municipalities. This is due to the possible locations of the GTP, of which there are about 200 more in Billerbeck compared to the other two municipalities.

Interpreting the fluctuations of the solution time when optimising the different cases is not possible since CPLEX is provided as a black

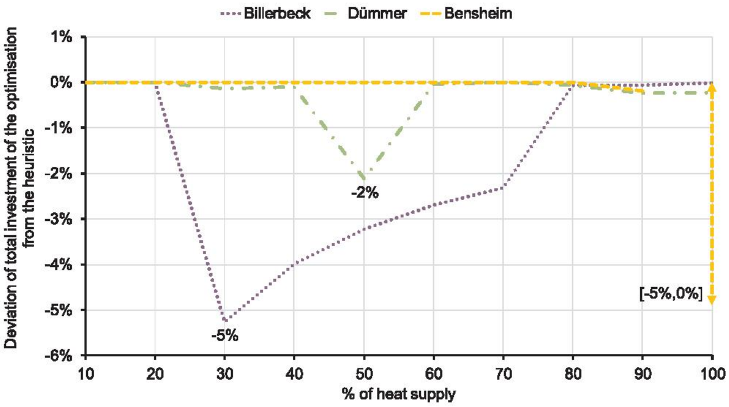


Fig. 5. Deviation of the total investment of the optimisation from the heuristic for the municipalities Billerbeck, Dümmer and Bensheim.

box. However, it is certain that the solution space will become smaller or larger, depending on the specified amount of heat. With a duration of up to 7 days, the optimisation would be quite time-consuming. For municipalities with more than seven settlements, optimisation should be avoided at all due to the computing constraints as stated at the beginning of this section.

In order to show that the heuristic also runs in an acceptable time for larger municipalities, the heuristic was executed for the municipality Gardelegen. This municipality has the eleventh largest number of settlements of all municipalities in Germany with 42 settlements. In total, the calculation of all 10 cases from 10% to 100% took 4 h. The heuristic was not executed for larger municipalities than Gardelegen since in this case, the limitation to only one heating plant would not be appropriate due to district heating pipelines with a length of more than 100 km.

4.2. Resulting costs for district heating networks

Since the employment of the heuristic was evaluated as appropriate in the previous section, it is applied to the four municipalities from Table 5 in this section. Thereby the assumptions from section 3.1 are used. The comparison of the results reveals the following main interdependencies:

- The higher the household density in the settlements, the lower the investment.
- The more settlements in a municipality and the further apart they are, the higher the costs.
- The smaller the largest settlement, the faster the costs increase with the proportion of heat supplied.

As these findings mainly confirm expectations, no detailed

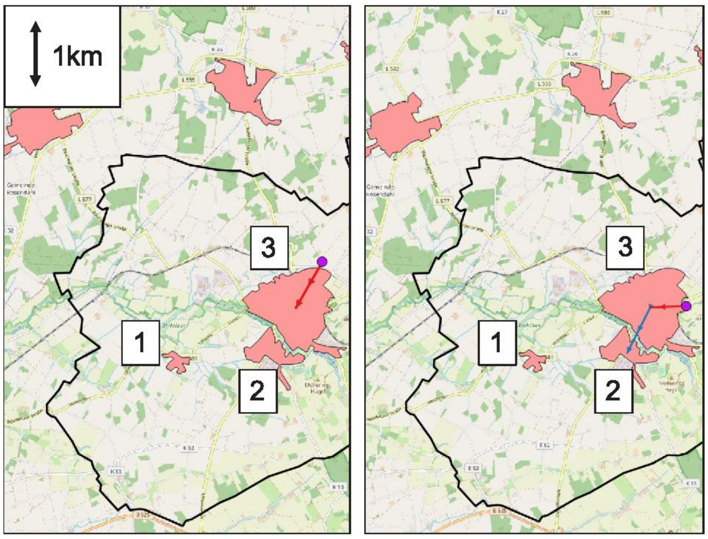


Fig. 6. DHN in the 30% case in Billerbeck with the heuristic (left part) and with the optimisation (right part). The settlements are numbered from 1 to 3.

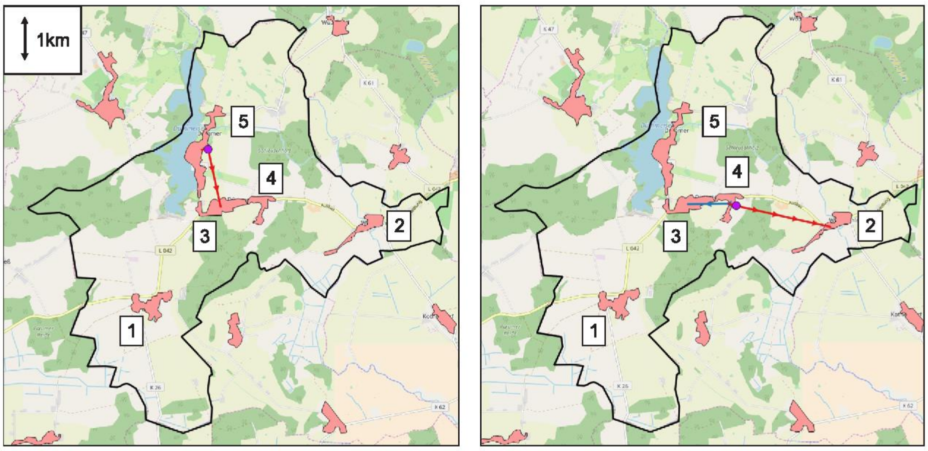


Fig. 7. DHN in the 50% case in Dümmer with the heuristic (left part) and with the optimisation (right part). The settlements are numbered from 1 to 5.

explanation is given in this section, but instead, only a few aspects are discussed. The dependency of costs on household density is clarified in Fig. 9. The figure shows the investment in relation to the connected heat capacity. The specific connection costs are between 500 €/kW and 1,900 €/kW when using the assumptions from section 3.1. Bensheim and Billerbeck with the highest household densities lead to the lowest costs per kW. The specific costs in Bensheim exceed those in Billerbeck in the 100% case in which all settlements are supplied for the first time and thus a long pipeline is built. In Dümmer and Groß Kreutz, the long distances between the settlements play an important role in addition to the low household density, which leads to high specific costs. If the costs increase more rapidly, as in the 50% case in Dümmer, this indicates that more or different settlements are connected to the heating network than in the previous case.

The calculated costs in Fig. 9 are close to the average costs for the DHN of the geothermal projects Grünwald, Unterföhring, Unterhaching and Neustadt-Glewe of 615 €/kW and can therefore be interpreted as plausible [55,56,49,57,58]. Since the percentage of the heat demand satisfied by the geothermal projects in the municipalities is not known, the 615 €/kW is illustrated as a horizontal line. The costs for the municipalities Dümmer and Groß Kreutz are above this average, as these municipalities have a low building and population density. The costs in the municipalities of Billerbeck and Bensheim with higher building and population density are lower, as the maximum length of the DHN outside the settlements in these municipalities is 3 km and 15 km respectively and therefore below the average network length of 38 km in the above mentioned geothermal projects.

The CO_2 abatement cost curves are similar to those in Fig. 9 and lie between 0.7 €/t_{CO2} and 2.4 €/t_{CO2} in the 100% case in Billerbeck and Dümmer respectively. The similar curves result from the fact that the energy mix in the examined municipalities is almost the same, and therefore the amount of CO_2 abatement per kW of geothermal district heating is nearly the same. Therefore, the following sensitivity analysis is performed only with regard to the total costs, since CO_2 abatement would remain constant.

5. Sensitivity analysis and critical discussion

A sensitivity analysis is conducted on the basis of the municipality of Groß Kreutz, which was already used as an example in section 3.

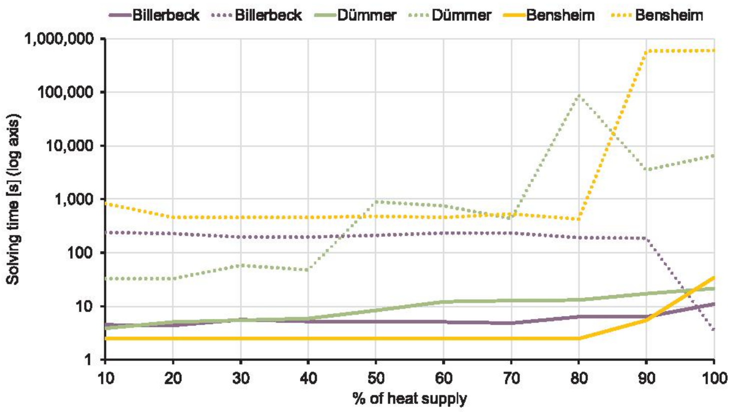


Fig. 8. Solving time of the optimisation (dashed lines) and the heuristic (continuous lines) for the municipalities Billerbeck, Dümmer and Bensheim.

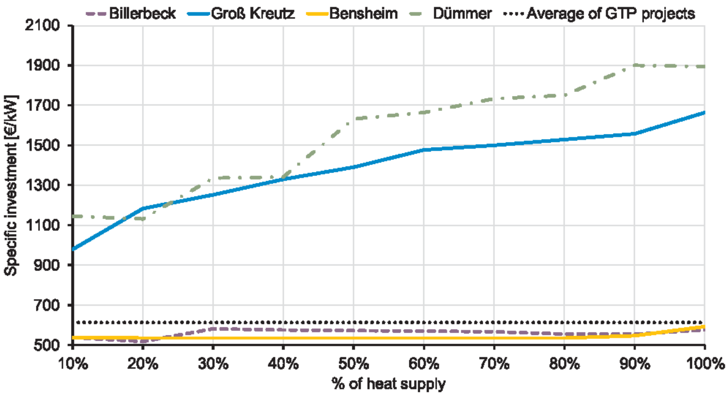
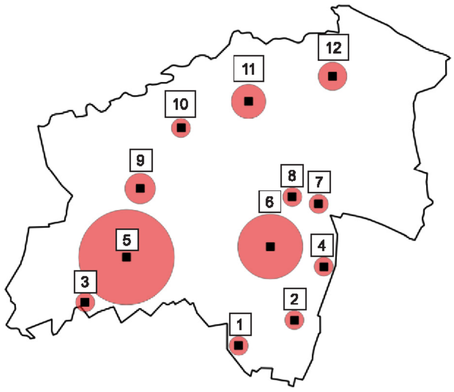


Fig. 9. Specific investment for DH pipelines in the four municipalities depending on the proportion of heat supply compared to the mean value from German geothermal DH projects. The investments are related to the connected nominal capacity of the heating network.



Settlement	Heat demand [GWh]	Heat density [GWh/km²]	Heat demand proportion [%]
1	0.8	4.8	1.4
2	2.2	7.2	4.0
3	1.2	6.3	2.2
4	0.2	1.8	0.4
5	17.7	5.1	32.1
6	12.1	9.6	22.0
7	1.5	10.0	2.7
8	1.0	3.2	1.8
9	5.7	9.4	10.4
10	0.8	6.4	1.4
11	6.6	13.0	12.0
12	5.3	7.7	9.6

Fig. 10. Settlement centroids in the municipality of Groß Kreutz as well as heat demand, heat density and heat demand proportion of the settlements.

Groß Kreutz is shown again in Fig. 10 in reduced form (left side), together with important information in the table on the right side. The black squares represent the centroids of the settlements and above the squares, the numbering of the settlements is shown. The red circles indicate the size of the heat demand in the settlements.

The example presented in section 3 with 497 possible locations for the DH plant as well as the parameters and locations of the settlements shown in Fig. 10 represents the reference case for this section. The costs for the reference scenario are determined using the heuristic developed in this study. Table 6 shows which conditions have been changed as part of the sensitivity analyses in this section. In section 5.1, scenario 1 shows the influence of a modification of the heat density on the solution. The variation regarding the number of possible locations for the DH plant in scenarios 2 to 7 is the subject of section 5.2. Subsequently, section 5.3 explores the impact of the stages of the heuristic using scenarios 8 and 9. Afterwards, the heuristic developed for this study is compared with the Nearest-Neighbour-Heuristic in this subsection. Finally, the methodology developed in this study is subjected to a critical discussion in section 5.4.

Fig. 11 shows the deviation of the total costs in scenarios 1–10 compared to the reference case for 10% heat supply steps. For reasons of clarity, continuous deviations of less than 1.5% have been removed from Fig. 11. Therefore, the curves for scenarios 6 and 9 are not shown at all. In the following sections, the figure is explained in more detail.

5.1. Heat demand and heat density

On the left side of Fig. 12, the reference case with 70% heat coverage is shown. The five settlements 5, 6, 9, 11 and 12 with the highest heat demand are connected to the DH plant in this case. To examine the sensitivity in scenario 1, the heat density is now reduced from 5.1 to 0.5 GWh/km^2 in settlement 5 with the highest heat demand. Settlement 5 must be partially supplied in order to cover 70% of the heat demand in the municipality, as it accounts for more than 30% of the total heat demand (cf. table in Fig. 10). All other settlements, except settlement 4, are now connected to the DHN to ensure that as few households as possible are connected in settlement 5 (cf. right part of Fig. 12). Settlement 4 also has a very low heat density and heat demand, therefore the pipeline to this settlement is not worthwhile.

In the 60% case, settlement 5 is not connected to the DHN at all. In comparison to the reference scenario, the costs increase strongly in scenario 1 if settlement 5 is included in the solution. Thus the total costs increase in the 70% case only by 17%, while in the 100% case the costs increase by over 80% since settlement 5 is completely supplied with

Table 6
Overview of the ten scenarios examined as part of the sensitivity analysis. Changed conditions are shown in italics.

Scenario	Heat density	Number of possible locations for DH plant	Heuristic
Reference	cf. Fig. 10	497	Stages 1, 2 and 3
1	*Reduced to 0.5 GWh/km² for settlement 5, for the other settlements* cf. Fig. 10	497	Stages 1, 2 and 3
2	cf. Fig. 10	*1*	Stages 1, 2 and 3
3	cf. Fig. 10	*9*	Stages 1, 2 and 3
4	cf. Fig. 10	*46*	Stages 1, 2 and 3
5	cf. Fig. 10	*171*	Stages 1, 2 and 3
6	cf. Fig. 10	*1299*	Stages 1, 2 and 3
7	cf. Fig. 10	*2749*	Stages 1, 2 and 3
8	cf. Fig. 10	497	*Stage 1*
9	cf. Fig. 10	497	*Stages 1 and 2*
10	cf. Fig. 10	497	*Nearest-Neighbour-Heuristic*

heat (cf. Fig. 11).

5.2. Number of locations

As already described in section 3, when determining the possible locations of the DH plant, the number of locations between the minimum and maximum coordinates of the municipality is specified. 1, 5, 10, 20, 55 and 80 locations are defined for the scenarios 2 to 7 respectively. The potential locations for the scenarios are illustrated in Fig. 13, with the resulting number of locations shown in parentheses under the scenario names. In cases with a lower percentage of heat supply, the number of locations has the greatest impact on the total costs, as the costs for the pipelines outside the settlements account for a larger share. Thus the costs in the 10% case in scenario 2 are 32% higher than in the reference case with 497 locations (cf. Fig. 11). With a rising number of potential locations from scenario 2 to scenario 5, however, the costs increasingly match with the costs in the reference scenario. In scenario 6 there are only very small deviations, so that the curve is not shown in Fig. 11. A further increase in the number of locations in scenario 7 also reduces the costs only marginally.

As shown, the costs in the scenarios change due to the varying distance of the DH plant to the settlements. Therefore the costs are calculated again for the reference scenario and scenarios 2 to 7, however, this time with costs for the pipelines outside the settlements of 500 €/m instead of 200 €/m. As a result of this adjustment, deviations also occur in the cases with higher heat supply proportions and the other deviations increase strongly. For example, the deviations in scenario 2 increase from 32% to 68% in the 10% case. The cost of pipelines outside settlements now accounts for up to 35% of total costs in scenarios 2 to 7 instead of up to 20% in the case with pipeline costs of 200 €/m. Even with 500 €/m, the costs decrease only slightly in scenarios 6 and 7 compared to the reference scenario. With an increasing number of locations, the time for solving the heuristic increases linearly. Thus the selection of the 497 locations for the municipality Groß Kreutz can be evaluated as reasonable. Therefore, a number of 5 locations per km^2 can be recommended for the study of other municipalities considering the size of Groß Kreutz.

5.3. Number of stages

Section 3 and Fig. 3 have already indicated that an appropriate DHN is not achieved by performing only stage 1 of the heuristic. Since the settlements are iteratively connected to the DHN, the optimal connections rarely arise. This is reflected in the costs of scenario 8, which are at least 5% and on average 12% above the costs of the reference scenario for each case (cf. Fig. 11). Considering the reference scenario and scenario 8 with pipeline costs of 500 €/m instead of 200 €/m, the costs in scenario 8 increase on average by 30%. The omission of step 3 in scenario 9 results in a slight cost increase of no more than 1.3%, so that the curve is not illustrated in Fig. 11. However, the third stage leads to slight improvements and should be executed as it has negligible influence on the solution time.

In scenario 10, a standard algorithm is used to demonstrate the performance of the heuristic developed in this study. Thereby, the heuristic of this study is applied with a modified target criterion: the Nearest-Neighbour-Heuristic connects the nearest settlement to the DHN in each iteration. The DHN in the reference case on the left side in Fig. 12 could therefore never result with this heuristic. Instead of

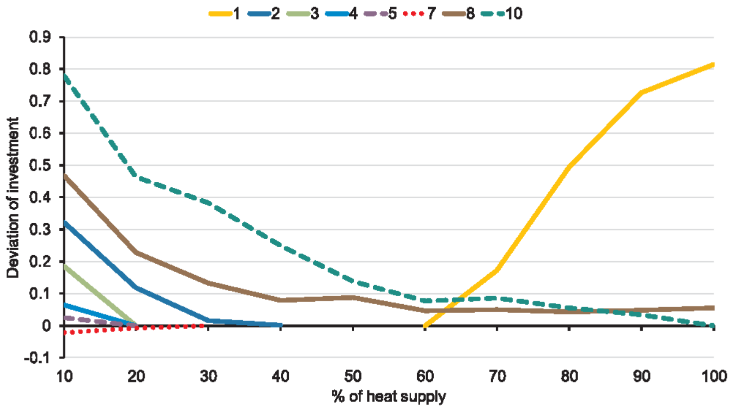


Fig. 11. Deviations in the total costs for scenarios 1–10 in relation to the reference scenario.

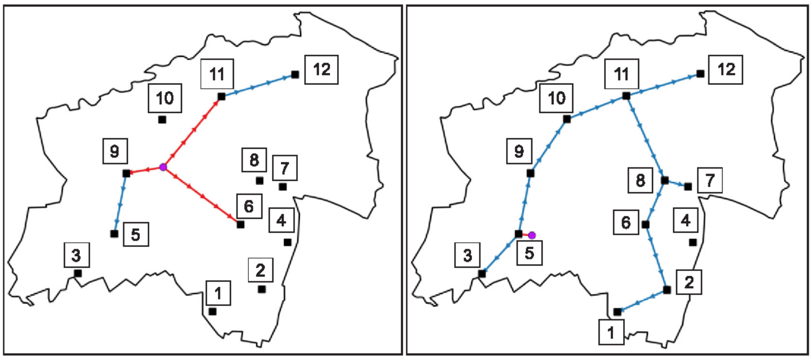


Fig. 12. Location of the DH plant and DHN with a heat supply of 70% of the heat demand in Groß Kreutz in the reference case (left part) and for scenario 1 (right part).

settlement 12, which is the furthest away from all other settlements, the Nearest-Neighbour-Heuristic connects settlements 3 and 10 in the 70% case (cf. Fig. 14). In the next step and if more heat were available, settlement 8 would be connected by the grey dotted line, which is 1.76 km away from settlement 6. The Nearest-Neighbour-Heuristic would be considered if only stage 1 of the heuristic developed in this study would be executed with the target criterion of stage 2.

As shown in Fig. 11, the Nearest-Neighbour-Heuristic results in significantly higher costs than the reference scenario, with deviations reaching values of up to 78%. Obviously, the more heat demand covered in the municipality, the lower the deviations will be until the costs match in the 100% case. The calculation of the nine cases up to the 90% case requires between 50% and 250% more time compared to the reference scenario, as more settlements are connected. The results of this section indicate again that the application of the three-stage heuristic is reasonable.

5.4. *Critical appraisal*

The sensitivity analyses in the previous section revealed that the heuristic developed in this study yields better results than simpler heuristics, especially in the case of low heat coverage in the

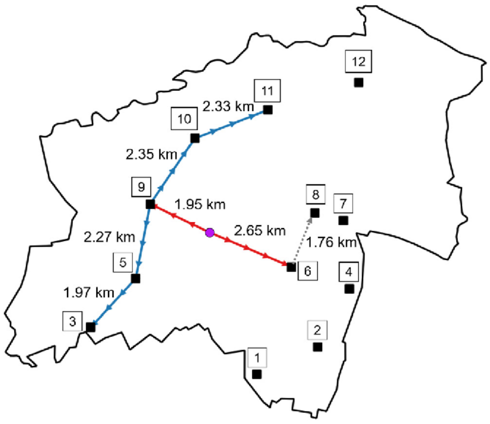


Fig. 14. Location of the DH plant and DHN in the 70% case resulting from the Nearest-Neighbour-Heuristic.

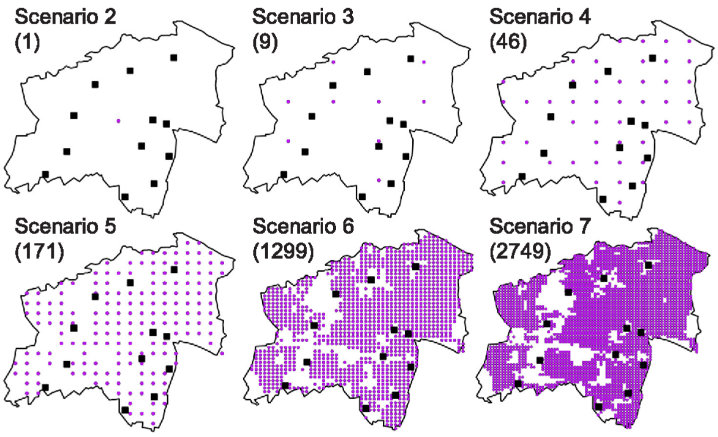


Fig. 13. Possible locations for the DH plant in scenarios 2–7. The resulting number of locations is shown in parentheses under the scenario names.

municipalities. In German municipalities that already have DH systems, the average share of DH in all heating technologies is only 3.5% [30]. Therefore, the municipalities with low heat coverages are of particular importance. This share is lower than the share of district heating in the total German heat supply of 13.8% (cf. section 1), as all municipalities are equally weighted in the calculation. For high heat coverages, e.g. the 100% case, simpler heuristics such as the Nearest-Neighbour-Heuristic are also suitable. However, since this takes more time than the developed heuristic, it is not recommended.

The heuristic can be used in this form or slightly modified for DH plants different to GTPs. This would only require a change in the possible locations of the DH plant. For other plant types, the location could even be within a settlement.

In addition, with the help of the presented approach, DHNs can be designed in holistic energy system analyses. This would be a novelty, as demonstrated in section 2.1, and will be presented by the authors in a forthcoming study. As shown in section 4, the DHNs and the associated costs could be determined for different levels of heat coverage. The results could then be used in the energy system analysis as discrete options, which would enable the optimisation of the DHN. In this study, the developed heuristic was applied to individual municipalities. However, the applicability of the heuristic is not limited to this administrative level. The heuristic can also be used for other regions with little effort. Fig. 15, for example, shows the simultaneous application to four municipalities.

This is an important aspect, since energy system analyses should not be limited to individual municipalities, but should determine the optimal aggregation level for the energy system. In small municipalities, the construction of a GTP would probably not be worthwhile as the fixed costs of these plants are very high. However, if several municipalities are involved in the analysis, the construction of such a plant could become economically viable.

In addition, the heuristic can be applied to other countries. In this case, the heat demand, as well as the population and building density for each settlement, have to be determined as in Weinand et al. [53]. The Corine land use areas are available for 38 other European countries besides Germany and can be used as a basis [59].

For the study presented here, improvements can be made in a couple of areas. First of all, the optimisations in this study do not always yield the realistic optimum. This is due to the fact that, in reality, the pipelines cannot always run straight ahead and no local topographical conditions are taken into account. It is further neglected that a pipeline could be divided into two or more pipelines to connect several settlements with a pipeline starting from one settlement. In order to overcome this problem, many points could be introduced as possible branches in further work, such as the points of the GTPs in Fig. 3, at which pipelines can divide. However, the investment would probably not be significantly reduced. In addition, since the centroids of the settlements are used as connection points and not the border of a settlement, the costs for pipelines outside the settlements are slightly overestimated.

Furthermore, the feasibility of GTPs depends strongly on the local geological conditions. This means that the GTP location determined by the heuristic may not be technically feasible at all. In this case, the location could be excluded and the heuristic could be executed again. On the other hand, a location could also be specified beforehand and the heuristic could be used to only determine the connections of the pipelines. In addition, some locations for the GTP could be manually excluded in advance, as it is clear that these are not optimal due to a high distance to the settlements (cf. Fig. 1). However, due to the short time required by the heuristic, this is not necessary.

The use of a constant heat loss via an efficiency and thus neglecting heat losses per kilometre also means that the optimal location of the GTP and the optimal DHN are not necessarily determined. If the specific heat losses were taken into account, the GTP in Fig. 3 would probably be closer to the largest settlement on the left-hand side of the figure. This is due to the fact that a large amount of heat could then be supplied without a large heat loss occurring before. However, a different location of the GTP than in the optimal case would not increase the costs significantly. Nevertheless, the heuristic should be improved in further work with regard to heat losses. Related to this, pressure losses should also be taken into account in future work. These make further DHN pumps necessary at certain points in the DHN. In the case of an optimisation model, non-linear equations would have to be integrated into the model, to take the properties mentioned in this paragraph into account [29].

It has been described above that the DH share in German municipalities is on average 3.5%, but there are also municipalities with a high DH share of over 90%. In future studies, it is therefore necessary to extend the heuristic in such a way that existing networks can be recognised as well as used to integrate the heat and thus reduce the investment for pipelines. As already explained, the share of existing DH is only deducted from the heat demand in this study. One possibility would be to apply the methodology of Blanco et al. [35] which has been mentioned in section 2.3. Uncertainty about the location of heat consumers could take into account the fact that it is not known where district heating connections already exist and where the greatest heat demand within a settlement exists. However, these approaches would require a significantly higher spatial resolution and the consideration of individual buildings and roads.

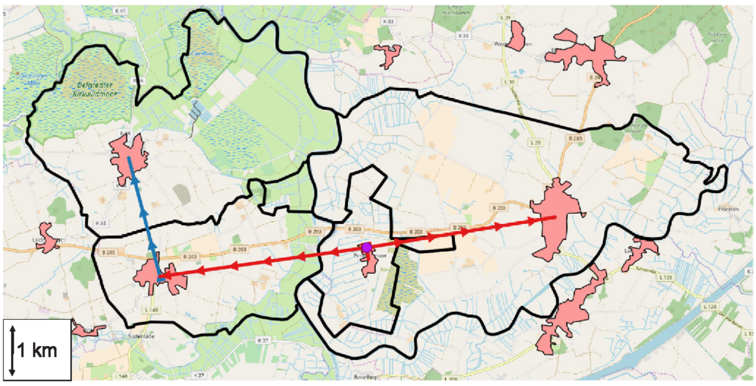


Fig. 15. Resulting district heating network, if the heuristic is applied to several small municipalities.

6. Conclusions

Against the background of a trend towards decentralised and community-owned energy systems, this paper develops a method to set up a minimum-cost geothermal-based municipal district heating system. To this end, two approaches based on combinatorial optimisation were presented, in order to support local planners in the design of geothermal district heating systems. The first approach involves a combinatorial optimisation of the district heating network layout, including geothermal plant location and network topology, which is applicable to municipalities with less than eight discrete settlement areas. The second approach is a three-stage heuristic, which serves the same purpose but can be applied to a much larger number of municipalities with many more settlement areas.

One of the innovations of the developed optimisation model and the three-stage heuristic compared to previous work is the fact that not only the district heating network but also the location of the district heating plant is optimised. Furthermore, the nodes/settlements to be connected are not fixed in advance and do not have to be supplied completely with heat. The two approaches presented in this work can be applied to every municipality in Germany and the methodology could be extended to an arbitrary country with equivalent data. The 38 other European countries are particularly suitable for this extension due to the availability of Corine Land Cover data.

A comparison of optimisation and heuristic for three exemplary municipalities demonstrates the efficiency of the developed heuristic. For municipalities with three, five and seven settlements respectively, the optimisation takes between 500% and 1×10^7% more time than the heuristic. The resulting deviations in the calculated total investment for the district heating from the results of the optimisation are in all cases below 5%, and in 80% of cases below 0.3%. The efficiency of the heuristic is demonstrated by comparison with the Nearest-Neighbour-Heuristic. The latter is not only less efficient, it substantially overestimates the total costs by up to 80% in all cases with less than 100% heat coverage. In addition, the calculated investments in the investigated municipalities ranged from 500 €/kW to 1,900 €/kW, values which could be validated with investments for existing geothermal district heating networks in Germany.

The developed heuristic consistently yields results within acceptable margins of error of its equivalent combinatorial optimisation problem, is efficient and scales well to other regions or contexts. The developed methodology would benefit from some further improvements, for example some of the technical aspects such as heat and pressure losses within the district heating network could be modelled more precisely in the heuristic. This would be particularly important in order to plan the district heating network within the municipality, which is considered beyond the scope of this contribution. Furthermore, additional geological and topographical conditions in the municipalities should be taken into account in order to better identify the optimal location of the geothermal plant and the type of network. Finally, the heuristic should be extended in such a way that the district heating pipelines can also branch off in order to reach several endpoints from one starting point. All of these aspects remain areas for future work and will be the subject of a forthcoming contribution, alongside a more holistic energy system analysis.

Notwithstanding these shortcomings, the developed method, comprising combinatorial optimisation and heuristic, provides a sound basis for decision support for municipal-scale geothermal district heating systems. The heuristic for cost-optimal placement of the geothermal plant (provided as supplementary material) can be extended and should offer useful insights for local planners and authorities when considering the heat source options at their disposal. In addition to supporting the planning of municipal district heating networks, the heuristic can also be used to design district heating networks in holistic energy system optimisations due to the novel possibility of connecting an arbitrary number of buildings to the district heating network.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.113367.

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

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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.

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Geothermal plant
Hydrothermal potential
Variable drilling depth
Energy autonomy

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.

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 [1]. The majority of regenerative plants in Germany are actually owned and operated by private individuals, farmers and communities [2]. 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. [3]). For homeowners, energy autonomy is one of the main factors that drives them to install renewable energies [4].

Besides energy autonomy for homeowners, the concept of municipal energy autonomy [5] has become established, which is employed here to also include energy autarky [6], self-sufficiency [7] and integrated community energy systems [8]. Alone the number of terms for this concept illustrates the diversity within the literature, which also

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Nomenclature

A_D	area for the well site [m²]
A_{el}	area for the ORC plant [m²]
A_S	area for the 3D seismology [m²]
A_{th}	area for the district heating plant [m²]
$b_{D,1900}$	whether the drilling depth is between 0 m and 1900 m (binary) [–]
$b_{D,3250}$	whether the drilling depth is between 1900 m and 3250 m (binary) [–]
$b_{D,3850}$	whether the drilling depth is larger than 3250 m (binary) [–]
$b_{D,i}$	whether the drilling depth is between (i-1)·1000 m and i·1000 m (binary) [–]
b_{DHP}	whether the district heating plant is built (binary) [–]
$b_{DHP,op}$	whether the district heating plant is in operation or not (binary) [–]
$b_{DH,S,i}$	whether district heating should cover up to i·10% of the heat demand of the municipality (binary) [–]
b_{GP}	whether the geothermal plant is built (binary) [–]
b_{PP}	whether 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 [$\frac{kJ}{kg\cdot K}$]
C_{ST}	costs for stimulation [€]
C_{UP}	costs for the underground planning [€]
d_D	distance between the production and the injection well [m]
D_{el}	electricity demand in the municipality [kW]
$D_{el,total}$	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 [–]

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 [9]. The extensive survey of Engelken et al. [10] 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 autonomy. The exponential development of those projects since 1995 indicates that an increasing number of German municipalities is striving for energy autonomy.[1] The 1300 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 [11]. Another example for complete energy autonomy is the village Feldheim, which is a part of the municipality

[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/.

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 [12]. However, balanced energy autonomy could make network expansion even more essential and also make new allocation systems for grid fees necessary [1]. This could result in economic inefficiencies compared to the established system of centralised generation, transmission and distribution [13]. 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 [14]. In contrast, the proportion of renewable heat supply is much lower at around 13% [15]. The renewable energies include around 55 GW of wind energy (on- and offshore), 42 GW photovoltaic (PV) systems, about 7 GW of bioenergy [16] and 39 MW of deep geothermal energy [15]. 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 of the highest in the world [17]. The currently (2017) installed 30 GTPs in Germany generate about 155 GWh of electricity [15] and 1.3 TWh of heat [18] annually, which is generally used for district heating (DH) applications [19]. The locations of the 30 GTPs are shown in Fig. 2. The electricity generation is still very low compared to the available resources with a technical potential of 4155 TWh per year [20]. This potential is significantly higher than the 654 TWh of gross electricity generated in 2017 in Germany [21].

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 [22].

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 holistic[2] 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).

2.1. 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 [23], Schmidt et al. [24], Peura et al. [25] and Burgess et al. [26]. Scheffer [23] 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. [24] 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. [25] 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. [26] 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 [27], Jenssen et al. [28] and Woyke & Forero [29].The suitability of a rural settlement structure for complete energy autonomy is analysed in Peter [27], who demonstrates that renewable energies could cover the electricity demand of an “example village” with 3850 inhabitants but with tremendous storage costs. Jenssen et al. [28] conclude that complete energy autonomy is technically achievable in an “average” German municipality through the “Bioenergy Village” approach, albeit at high costs. Woyke & Forero [29] assess complete energy autonomy in Pellworm, an island municipality in Germany with 1100 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.

[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.

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. [26]	✓	✓	✓	✓	GHP	Balanced	Region in UK
Jenssen et al. [28]	✓	×	×	×	×	Complete	German "Bioenergy village"
Peter [27]	×	✓	✓	✓	GHP	Balanced and complete	German village
Peura et al. [25]	✓	✓	×	×	×	Balanced	Finnish municipalities
Scheffer [23]	✓	✓	✓	✓	×	Balanced	Rural German region
Schmidt et al. [24]	✓	×	✓	✓	GHP	Balanced	Rural Austrian region
Woyke & Forero [29]	✓	✓	✓	×	×	Balanced and complete	German Island
This study	✓	✓	✓	×	AHP/GHP and GTPs	Complete	German municipalities

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 complete municipal energy autonomy includes a possible contribution from GTPs, which could reduce the high storage costs through base load capacity.

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 A1[3] in the Appendix A). Usually only electricity generation is considered. Van Erdeweghe et al. [30] and Marty et al. [31] alone consider a combined power and heat production, whereby in Van Erdeweghe et al. [30] 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. [32] 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 [33] 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. [34], the municipality of Sønderberg in Denmark is considered, which is aiming for zero net CO_2 emissions by 2029. Exactly as in Østergaard & Lund [33], 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. [31]. 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).
(2) Integration of the GTP model in a holistic and transferable[4] 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).

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 effort[4]. 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

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

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

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 A.1)	Mainly optimisation	Power	×	×	–	GTP
Østergaard et al. [32]	Simulation	DH	×	×	×	Municipality
Østergaard & Lund [33]	Simulation	DH	×	×	×	Municipality
Sveinbjörnsson et al. [34]	Optimisation	DH	×	×	×	Municipality
Marty et al. [31]	Optimisation	Both	×	✓	×	GTP and few consumers
This study	Optimisation	Both	✓	✓	✓	Municipality

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 Fig. 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" (RE^3ASON) model is used and further extended ([35], cf. Fig. 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 RE^3ASON 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 present study, as various municipalities in different locations are investigated. RE^3ASON 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 [36]. 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 72 time slices (4 seasons, 2 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 [37]. 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

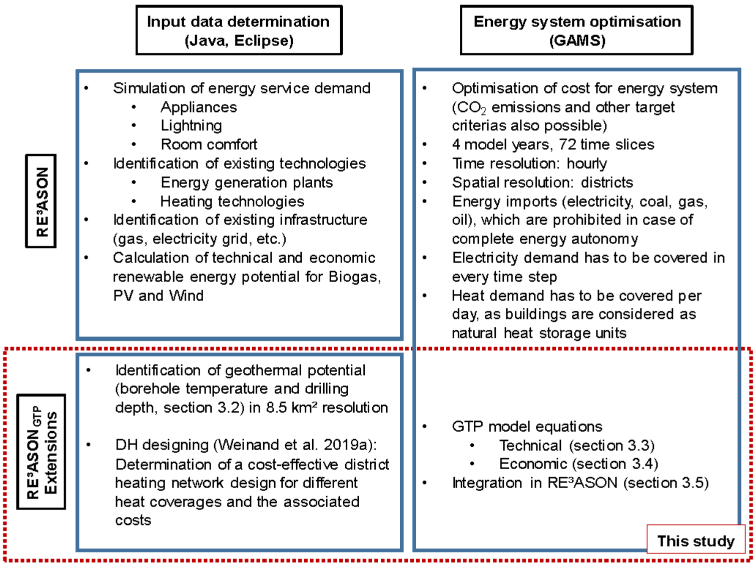

Fig. 1. Overview of RE^3ASON and the extensions developed in the present study.

and no solar radiation or wind is present.

The model can be used to minimise total discounted system costs, CO_2 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. [38] and Mainzer [35]. In order to determine the PV potential, OpenStreetMap is used to identify building data and roof areas [39]. 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. [40]. 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 levelized 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 RE^{3}ASON model extensions shown in Fig. 1 are explained hereafter. The extensions are implemented within the program environment of the existing RE^{3}ASON 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 [41]. For the present study, the data from the geographical map of Germany in GeotIS were transferred to a CSV file in 8.5 km^2 resolution and the vertices of the grid now serve as input for the optimisation model. Fig. 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 km^2 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.

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. [42], 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. [42], especially in the area up to 3 km [43]). MB, NGB and URG are shown in Fig. 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 [44], but adjusted in such a way that the mean value is 43 °C/km. This results in the three temperature sections in Fig. 3. The temperature gradient $\boldsymbol{\Delta} T$ decreases with depth and adapts to the German average. Above 3250 m, a constant temperature gradient is assumed.

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 Fig. 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).

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).

$$\dot{V}_B \cdot \boldsymbol{\rho}_w \cdot c_{p,w} \cdot (\boldsymbol{T}_{PW}(t) - \boldsymbol{T}_{ORC,out}(t)) = \boldsymbol{P}_{el}(t)/\boldsymbol{\eta}_{el} \qquad \forall\, t \tag{1}$$

$$\dot{V}_B \cdot \boldsymbol{\rho}_w \cdot c_{p,w} \cdot (\boldsymbol{T}_{ORC,out}(t) - \boldsymbol{T}_{DHP,return}(t)) = \dot{\boldsymbol{Q}}_{th}(t)/\boldsymbol{\eta}_{th} \qquad \forall\, t \tag{2}$$

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 [45]. 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 kJ·kg^{-1}·K^{-1} at 20 °C to about 4.45 kJ·kg^{-1}·K^{-1} at 190 °C. In the same temperature interval the water density $\boldsymbol{\rho}_w$ decreases from approximately 1 kg/l to about 0.9 kg/l [46]. In this temperature interval, the product of these two coefficients differ by 4%. Therefore, a constant mean heat capacity of 4.31 kJ·kg^{-1}·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

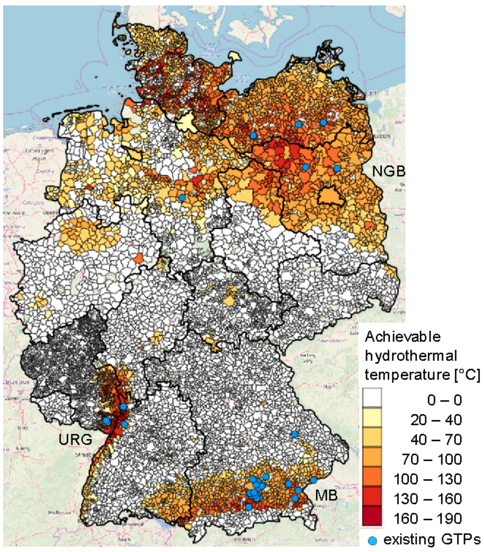

Fig. 2. Achievable average hydrothermal temperature (°C) at a depth of up to 5 km in German municipalities according to Agemar el al. [41] and locations of GTPs in Germany (blue circles). The background map in this Fig. and in all of the following figures with background maps is from OpenStreetMap contributors [39]. For a better analysis of the colours in this figure, please refer to the online version of the paper.

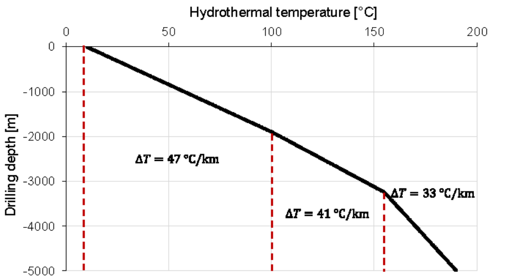

Fig. 3. Assumed temperature sections as a function of the drilling depth in the Upper Rhine Graben.

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% [47]. In accordance with Ozgener and Ozgener [48], 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 [49], 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)).

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

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 [50], 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 °C [51]. 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 °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)).

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

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

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

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 [52], 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)):

$$\textstyle\sum_{i=1}^{5} \boldsymbol{b_{D,i}} \leq 1 \tag{7}$$

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 1000 m.

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

$$\boldsymbol{b_{D,i}}\cdot i\cdot r_z \geq \boldsymbol{z_{D,i}} \qquad \forall\, i \tag{9}$$

$$\boldsymbol{z_D} \leq 5 * r_z \tag{10}$$

For example, if $b_{D,2}$ is set to 1, then the drilling depth is in the range of 1000 m to 2000 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)).

$$\boldsymbol{z_{D,i}} = \boldsymbol{z_D}\cdot \boldsymbol{b_{D,i}} \qquad \forall\, i \tag{11}$$

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:

$$\boldsymbol{z_D} = \textstyle\sum_{i=1}^{5} \boldsymbol{z_{D,i}} \tag{12}$$

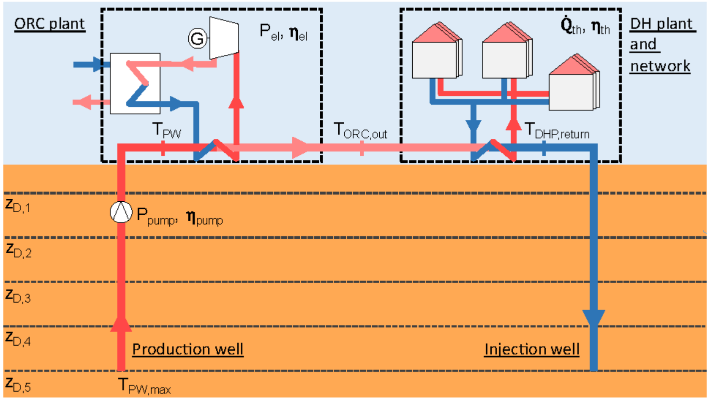

Fig. 4. Schematic illustration of the GTP considered in this study. The heat flow in the condenser of the ORC process could be water or air. For a better analysis of the colours in this figure, please refer to the online version of the paper.

The 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)).

$$\left(\frac{z_{D,1900}}{1900\text{m}}\right)\cdot(100^{\circ}\text{C} - T_{\alpha}) + T_{\alpha}\cdot b_{D,1900} + \left(\frac{z_{D,3250} - 1900\text{m}\cdot b_{D,3250}}{1350\text{m}}\right)\cdot 55^{\circ}C + 100^{\circ}C\cdot b_{D,3250} + \left(\frac{z_{D,3850} - 3250\text{m}\cdot b_{D,3850}}{600\text{m}}\right)\cdot 20^{\circ}C + 155^{\circ}C\cdot b_{D,3850} \geq T_{PW,max} \quad (13)$$

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:

$$T_{PW,max} \leq 100^{\circ}C\cdot b_{D,1900} + 155^{\circ}C\cdot b_{D,3250} + 190^{\circ}C\cdot b_{D,3850} \quad (14)$$

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. [53].

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 [54]. 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, [55]). The cost-functions in this section are mainly based on Schlagermann [56]. 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 A.4.

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} [56]:

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

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

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 [57], the distance in the underground, in the area of the working horizon, is usually 1000–2000 m. Therefore d_D is assumed to be 1500 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 1000 m steps. Now the costs can be calculated using the linearised cost functions (cf. Equations in red boxes in Fig. 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} [56]. With a share of up to 70% of the capital costs, drilling costs account for the largest share of the investment for a GTP [58]. The drilling costs are estimated according to the following equation [59]:

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

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 [56]:

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

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

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

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

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

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

3.5. Integration in RE[3]ASON

The entire GTP model presented above is integrated in the optimisation model of the RE[3]ASON 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

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

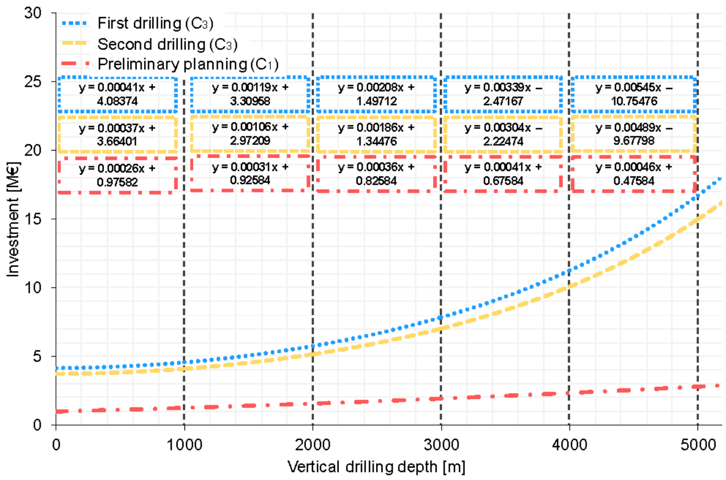

Fig. 5. The costs for the feasibility study and the preliminary planning C_1 (red) and the costs for exploration of the reservoir C_3 as a function of vertical drilling depth as well as linearization of the functions. The costs C_3 are shown for the first (blue) and second (yellow) drilling. For a better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

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 RE[3]ASON 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. (A1)–(A2) in the Appendix A of McKenna et al. [38]).

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. [60]. 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 [61]. 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 RE[3]ASON. 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)).

$$\sum_{i=1}^{10} b_{DH,S,i} \le 1 \tag{23}$$

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)).

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

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 Figs. 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 km^2 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 Fig. 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 A.4.1 of the Appendix A. 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.

Fig. 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 Fig. 6, [62]). 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 Fig. 6. If the ORC efficiency η_{el} is reduced or $T_{ORC,out}$ is increased, the LCOE increase. Thereby the

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

Municipality	Westheim (Pfalz)	Prinzenmoor	Groß Kreutz (Havel)
Cluster [63]	3	4	8
Basin [41]	URG	NGB	NGB
Area [km^2]	7	6	99
Population	1731	179	8133
Population density in municipality [1/km^2]	243	32	82
Number of districts	1	1	12
Maximum hydrothermal temperature [°C]	190	175	80

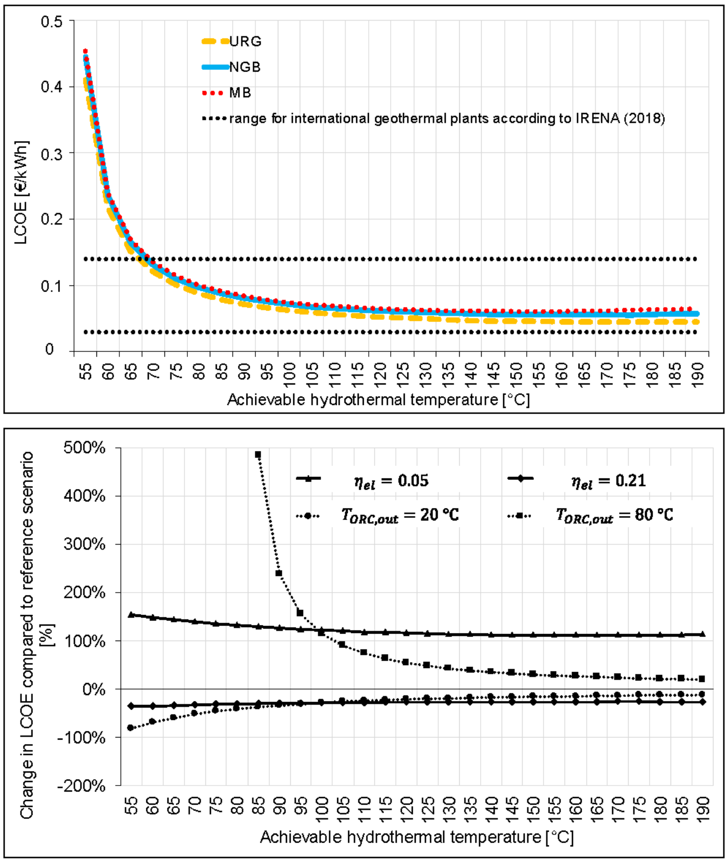

Fig. 6. LCOE of geothermal power plants calculated by the model presented in this study using different achievable temperatures for the three large basins in Germany (upper part). The dotted black horizontal lines mark the area in which the LCOE of real deep geothermal projects fall according to IRENA [62]. 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.

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 (η_{el} = 5% and $T_{ORC,out}$ = 80 °C) is higher due to the high fixed costs of the 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 RE^{3}ASON model can be found in Mainzer [35].

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 [63], 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.

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 renewable 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)).

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 Fig. 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 and 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. Fig. 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. Fig. 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.

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.

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).

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

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	3235	3180	6724
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		

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]	Tempera-ture [°C]	ORC capac-ity [kW]	DH capac-ity [kW]	GTP invest-ment [M€]
Westheim 1 (W1)	×	✓	✓		–	–	–	–	–
Westheim 2 (W2)	✓	✓	✓		1850	98	1100	1970	22
Westheim 3 (W3)	✓	✓	✓	η_{el} = 5%	2130	109	610	1920	22
Westheim 4 (W4)	✓	✓	×	ORC forced	1580	85	1390	–	18
Westheim 5 (W5)	✓	×	×		–	–	–	–	–
Prinzenmoor 1 (P1)	×	✓	✓		–	–	–	–	–
Prinzenmoor 2 (P2)	✓	✓	✓		–	–	–	–	–
Prinzenmoor 3 (P3)	✓	✓	✓	ORC forced	1590	56	230	–	15
Groß Kreutz 1 (GK1)	×	✓	✓		–	–	–	–	–
Groß Kreutz 2 (GK2)	✓	✓	✓		2290	80	1200	–	20
Groß Kreutz 3 (GK3)	✓	×	×		–	–	–	–	–

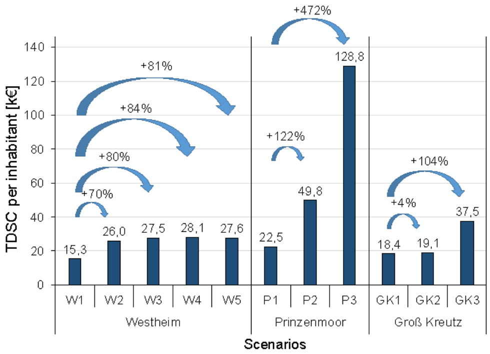

Fig. 7. TDSC per inhabitant for the energy supply between 2015 and 2030 in various scenarios for the municipalities Westheim, Prinzenmoor and Groß Kreutz.

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. Fig. 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. Fig. 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. Fig. 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 1590 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. Fig. 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. Fig. 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 municipality[4], 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

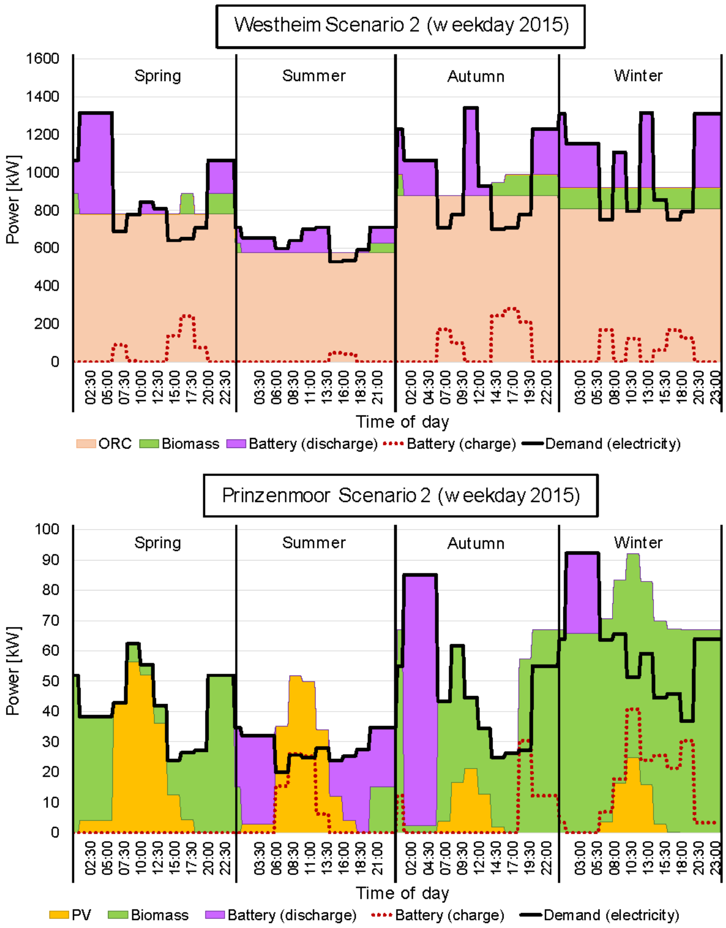

Fig. 8. Optimised energy supply patterns (upper part) - divided into energy supply technologies - on a typical weekday for all seasons in 2015 for the municipalities of Westheim (upper part) and Prinzenmoor (lower part). For a better analysis of the colours in this figure, please refer to the online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

premature replacement [64]. In addition, the scaling reduces the diameter of the pipes and thus increases the total pressure drop and the friction factor in the pipe [65]. 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 [64]. 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 [66].

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 (+6%), 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 [67], which consists of an injection well and two production wells [68]. 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 [69].

Another important issue for future studies is the investigation of the influence of the time series structure on the results. In the RE^3ASON 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 efforts[4].

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 [60], 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. For 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.

Acknowledgements

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Appendix A

A.1. Literature review table

See Table A1.

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. [70]	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. [71]	Optimisation	–	Thermodynamic efficiency	Geothermal plant	Binary ORC	Power	120–180
Budisulistyo et al. [53]	Thermo-economic analysis	Taupo Volcanic Zone (New Zealand)	Plant performance and lifetime	Geothermal plant	Binary ORC	Power	131
Chagnon-Lessard et al. [72]	Thermodynamic numerical simulation and optimisation	–	Specific power output	Geothermal plant	ORC	Power	80–180
Clarke et al. [73]	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 [74]	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. [75]	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 Kalina cycle (CKC)	Heat	170
Ghasemi et al. [76]	Parametric optimisation	–	Net power output	Geothermal plant	Binary ORC	Power	135
Guzović et al. [77]	Optimisation of the main parameters of ORC and Kalina cycle.	Lunjkovec-Kutnajk, 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. [78]	Deterministic global optimisation of component size and operating conditions (Non Linear Program)	–	Net power; LCOE	Geothermal plant	ORC	Power	135.85
Karimi & Mansouri [79]	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
Kolahi et al. [80]	Particle swarm optimisation	Sabalan geothermal power plant (Iran)	Maximum total output power	Geothermal plant	Flash-binary ORC	Power	31–188
Lazzarin et al. [81]	Cycle and turbine re-optimisation on geothermal resources	–	Net electrical output	Geothermal plant	–	Power	145
Liu et al. [82]	Parametric optimisation and performance analysis	–	Net power output	Geothermal plant	ORC	Power	110–150
Liu et al. [83]	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. [84]	Thermo-economic analysis (multi-objective optimisation)	–	Thermal efficiency, exergy efficiency, power output, capital cost	Geothermal plant	Binary ORC	Power	80–95
Lu et al. [85]	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. [86]	Optimisation by an exergy-topological methodology (cognitive thermodynamic tool)		Optimal operating conditions	Geothermal plant	Binary medium grade plant	Power	25–150
	Multi-objective optimisation	–		Geothermal plant	ORC	Power	167.75

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Table A1 (*continued*)

Study	Methodology	Assessment area/ region or plant site	Objective function	Energy system	Plant type	Energy Generation	Brine temperature
Martínez-Gomez et al. [87]			Maximise profit from energy sales, minimise risk and minimise environmental impact (CO_2 emissions)				
Marty et al. [31]	Simultaneous optimisation	–	Net annual profit	ORC plant, district heating plant and a few consumers	ORC	Heat and Power	185
Mohammadzadeh Bina et al. [88]	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. [89]	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. [90]	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
Nakomcic-Smaragdakis et al. [91]	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	Indjija (Serbia)	–	Geothermal plant	–	Heat	–
Østergaard et al. [32]	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 [33]	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. [92]	Optimisation	Dieng Geothermal Power Plant (Indonesia)	Energy exergy flow and efficiency	Geothermal plant	Single flash binary	Power	18–179.9
Pambudi et al. [93]	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. [94]	Optimisation	–	Structure of the cycle, operating conditions and best fluid	Geothermal plant	Binary ORC	Power	164.34–170
Pollet et al. [95]	Optimisation	–	Total energy output	Geothermal plant	ORC	Power	120–150
Shengjun et al. [96]	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. [97]	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. [98]	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

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Table A1 (*continued*)

Study	Methodology	Assessment area/ region or plant site	Objective function	Energy system	Plant type	Energy Generation	Brine temperature
Sun et al. [99]	Thermodynamic optimisation		Evaporation temperature and net power output	Geothermal ORC	ORC	Power	100–150
Sveinbjörnsson et al. [34]	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	–	–	–
van Erdeweghe et al. [30]	Thermodynamic optimisation	–	Electrical power output	Combined heat-and-power (CHP) configurations	ORC	Heat and Power	110–150
van Erdeweghe et al. [100]	Two-step optimisation	Balmatt site, Belgium	Design case: Net present value Off-Design case: Net electrical power output	Geothermal plant	ORC	Power	110–150
Walraven et al. [101]	Optimisation with different types of cooling systems	Belgium	Levelized cost of electricity	Geothermal plant	ORC	Power	100–150
Wu et al. [102]	Thermodynamic analysis and performance optimisation (parametric optimisation via pattern search algorithm (PSA))	–	Turbine inlet temperature, turbine inlet pressure, power output	Geothermal plant	Transcritical Power Cycle (TPC)	Power	100–150
Yang & Yeh [103]	Economic performance optimisation	–	Net power output	Geothermal plant	Transcritical Rankine Cycle (TRC)	Power	44.13–66.02
Yilmaz [104]	Thermo-economic optimisation using genetic algorithm method	–	Cost optimal exergetic efficiency	Geothermal plant	Combined flash-binary	Power	150–159
Zare [105]	Thermodynamic and exergoeconomic optimisation with own models & profitability evaluation	–	Optimisation: total capital investment and payback period	Geothermal plant	ORC-based binary power plant	Power	160–170
Zhao & Wang [106]	Exergoeconomic analysis and optimisation	–	Exergoeconomic: Minimise levelized cost per unit of exergy; Thermodynamic: maximise exergy efficiency.	Geothermal plant	Flash-binary ORC cycle	Power	200

A.2. Data tables on deep geothermal projects

See Table A2.

Table A2
Data on German deep geothermal projects [41,107,59]. If more sources than Agemar et al. [41], Enerchange [107] and Eyerer et al. [59] 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
Poing	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**

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Table A2 *(continued)*

Location	Injection Temperature [°C]	Forward/return temperature [°C]	Volumetric flow rate [L/s]	Nominal power (electrical) [MW]	Nominal 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 [108]
Neuruppin			14	0	2.1		
Neustadt-Glewe		90/60	11-33	0.2	5/6.5		Schallenberg [108]
Waren		70/50	17	0	3.6		
Average NGB			14–20				
Bruchsal	60	90/65	24	0.55	5.5		Eyerer et al. [59]
Brühl							
Insheim	70		85	4.8	0	15	
Landau (Palatinate)	50	70/40	70	3.8	6		Eyerer et al. [59]
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. [42]
Ismaning			85	0	10		
Kirchstockach	45		145	5.5	0	10	
Kirchweidach			50	0.7	12		
München (Riem)			75	0	10		
Poing			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. [59]
Unterschleißheim			90	0	28/8		
Waldkraiburg			65	4.8	14		
Average MB			95			12.5	

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Table A2 (*continued*)

Location	Total investment reality [m. €]	Total investment model [m. €]	Total investment deviation	Investment for drilling [m. €]	Investment distric 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 [109]
Hannover	15	17	+15%					development	1	Bundesverband Geothermie [110]
Neubrandenburg		21						1987	3	Bundesverband Geothermie [110]
Neuruppin		16						2007	2	Bundesverband Geothermie [110]
Neustadt-Glewe	10.8	24	+122%	1.7	1.8	3.2	ORC	2003	2	GTN [111],Enerchange [112]
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. [59]
Landau (Palatinate)	20	39	+93%				ORC	2007	2	
Average URG	19	34	**52%**						**2**	
Aschheim	60	45	−24%					2009	2	Bundesverband Geothermie [110]
Dürnhaar	60	50	−17%					2012	2	Bundesverband Geothermie [110],Eyerer et al. [59]
Erding	18.7	51	+172%					1998	2	Bundesverband Geothermie [110]
Garching		32		13				2011	2	Bundesverband Geothermie [110]
Geretsried								development		
Grünwald	150.4	92	−39%		53.8		ORC	2011	2	Erdwärme Grünwald GmbH [113]
Ismaning	71.6	36	−50%	18	41			2012	3	
Kirchstockach	62	44	−30%	23			ORC	2013	2	Eyerer et al. [59]
Kirchweidach		40						2012	2	Bundesverband Geothermie [110]
München (Riem)		31						2004	2	Bundesverband Geothermie [110]
Poing		30						2013	2	
Pullach		47		9				2005	3	
Sauerlach	90 (initially 25)	62	−31%				ORC	2014	3	Bundesverband Geothermie [110],Zeitungsverlag tz [55]
Simbach-Braunau	21	24	+14%				ORC	2001	2	Bundesverband Geothermie [110]
Straubing	12	16	+33%					1999	2	Bundesverband Geothermie [110]
Taufkirchen	65	78	+20%				Kalina	Testing phase (2014)	2	Bundesverband Geothermie [110], Eyerer et al. [59]
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 [114]
Unterschleißheim	22	44	+99%					2013	2	Bundesverband Geothermie [110]
Waldkraiburg	12	46	+281%					2012	2	OVB24 GmbH [115],Bundesverband Geothermie [116]
Average MB	**55**	**47**	**56%**						**2.3**	

A.3. Model deviation compared to reality

See Figs. A1–A3.

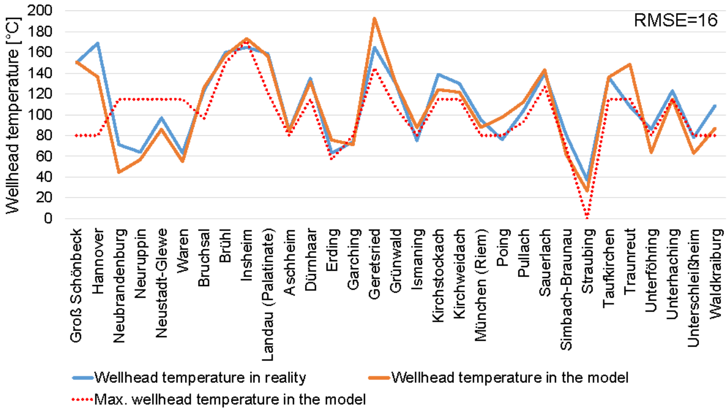

Fig. A1. Wellhead temperature of geothermal projects in reality compared to the model (cf. columns "Wellhead temperature reality", "Wellhead temperature model" and "Max. wellhead temperature model" in Table A2 for precise values). For a better analysis of the colours in this figure, please refer to the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

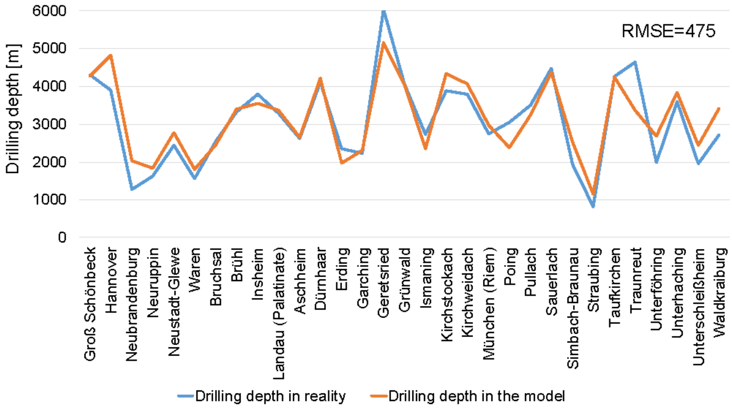

Fig. A2. Drilling depth of geothermal projects in reality compared to the model. (cf. columns "Depth reality" and "Depth model" in Table A2 for precise values). For a better analysis of the colours in this figure, please refer to the online version of the paper.

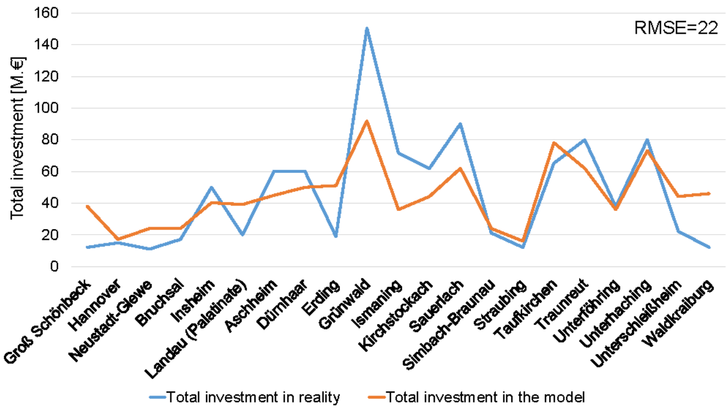

Fig. A3. Total investment of geothermal projects in reality compared to the model. (cf. columns "Total investment reality" and "Total investment model" in Table A2 for precise values). For a better analysis of the colours in this figure, please refer to the online version of the paper.

A.4. Further economic assessment

The purchase values for properties C_P in German municipalities are given in Statistisches Bundesamt [117] 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 [118]. 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. Fig. A4 shows the cost structure of other building land for different municipality sizes [117].

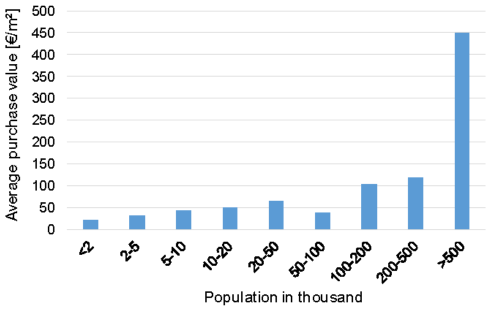

Fig. A4. Average purchase value for other building land for different municipality sizes [117].

The figure shows that the land prices can differ significantly from the 60 €/m² assumed in Schlagermann [56]. 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 [119] 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 [120] 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/km²]	80	170	245	380	565	885	1385	1695	2700
Purchase value [€/m²]	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:

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

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

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 [47,121]. 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 $D_{el,total}$:

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

with

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

As a conservative estimate, the assumption is made that the required amount D_{pump} is not yet included in the calculation to determine $\boldsymbol{\eta_{th}}$ in Ozgener & Ozgener [48]. The nominal power P_{pump} of the pump is determined via Eq. A(4) with a pump efficiency $\boldsymbol{\eta_{pump}}$ of 0.95.

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

Eyerer et al. [59] 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) [56].

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

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 [122]:

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

For the ORC plant and the grid connection, a linear cost function C_6 is assumed according to the values from Jancik & Kupfermann [122], Campos Rodríguez et al. [123] and Rubio-Maya et al. [124]:

$$C_6 = 2,470\frac{€}{kW_{el}}\cdot P_{el,max} + 14,100€\cdot b_{PP} \tag{A7}$$

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 [56]:

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

A.4.1. 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 [122] for the calculation of the total investment in Table A2:

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

The more accurate investment calculation for the district heating plant from Section 3.5 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. Fig. A3). This conservative assessment is taken over for the optimisation.

A.4.2. 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 [56]:

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

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 [59]:

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

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:

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

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:

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

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

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.113824.

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Identification of Potential Off-Grid Municipalities with 100% Renewable Energy Supply

Jann M. Weinand, Sabrina Ried, Max Kleinebrahm, Russell McKenna, Wolf Fichtner

Abstract—**An increasing number of municipalities are striving for energy autonomy. This study determines in which municipalities and at what additional cost energy autonomy is feasible for a case study of Germany. An existing municipal energy system optimization model is extended to include the personal transport, industrial and commercial sectors. A machine learning approach identifies a regression model among 19 methods, which is best suited for the transfer of individual optimization results to all municipalities.**

The resulting levelized cost of energy (LCOE) from the optimization of 15 case studies are transferred using a stepwise linear regression model. The regression model shows a mean absolute percentage error of 12.5%. The study demonstrates that energy autonomy is technically feasible in 6,314 (56%) municipalities. Thereby, the LCOEs increase in the autonomous case on average by 0.41 €/kWh compared to the minimum cost scenario. Apart from energy demand, base-load-capable bioenergy and deep geothermal energy appear to have the greatest influence on the LCOEs.

This study represents a starting point for defining possible scenarios in studies of future national energy system or transmission grid expansion planning, which for the first time consider completely energy autonomous municipalities.

Index Terms—**Energy autonomy, renewable energy, geothermal power generation, electric vehicles, vehicle-to-grid, mixed integer linear programming, regression analysis.**

I. Introduction

THE share of renewable energies (RE) in electricity generation has increased steadily in the past years. In 2018, REs already accounted for a third of the worldwide installed electricity capacity [1]. The planning of RE power plants has to be closely coordinated with power grid planning. By simultaneously considering grid and RE expansion, the costs of using local resources can be weighed against the costs of grid expansion to sites with higher RE potential [2]. However, many studies focus on just one of these aspects. For example, [3] and [4] concentrate on large-scale transmission grid planning with fixed generation capacities. At the same time, studies on transmission grid planning are often based on centralized RE generation [5-7].

However, [8] finds that a decentralised RE expansion could be economically favourable, largely due to higher required grid expansion costs in the centralized case. In fact, the expansion of RE resources is mainly decentralized due to their characteristics. Thus, the vast majority of the installed capacity of RE plants is connected to the distribution grid [9]. Related to this, in many countries, the owner structure of energy plants is changing: for example, the majority of German RE plants are actually owned and operated by private individuals, farmers and communities [10]. In this context, an increasing number of municipalities are striving for energy autonomy due to drivers like tax revenues and environmental awareness [11]. These municipalities mainly focus on *annual municipal energy autonomy (AMEA)*, whereby the local RE generation exceeds the annual demand. In addition, some municipalities strive for *complete municipal energy autonomy (CMEA)*, a state in which no energy is imported (i.e. “off-grid”) [12].

For future power grid designs, the questions of whether, which, how many and at what cost municipalities could become completely energy autonomous is of interest. To this end, the whole energy system with all energy consumption sectors - industrial, commercial, residential and transport - should be considered in municipal energy system analyses. Energy autonomy in municipalities has already been examined in [12–16]. Some of these studies are limited to the residential sector [12, 13]. Others also include further sectors. Thereby, the industrial energy demand is determined by surveys [16], interviews [15] or measurements of actual transformer substations [14]. Therefore, the application of these methods to other municipalities would require considerable effort. Since only individual municipalities or regions are considered in the studies, the results cannot be used to develop scenarios for future national energy systems. Furthermore, none of these studies investigates the impact of the flexibility through electric vehicles (EV) on costs.

This paper aims to address the identified shortcomings of the studies on municipal energy autonomy. To this end, the energy systems of 15 municipalities are first analysed in detail with the

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aid of an optimization model. This model is extended to include the personal transport, industrial and commercial sectors. Thereby, the assumption is made, that all vehicles of the personal transport sector are replaced by EVs. The optimization results are transferred to further municipalities by means of a regression model. Based on the results, energy scenarios could be derived for future planning of electricity grids. At the same time, the following research questions are addressed:

1) How many and which municipalities can become energy autonomous?
2) Which cost increase would be associated with achieving energy autonomy in these municipalities compared to the optimized energy system without energy autonomy?
3) What impact does the consideration of the industrial, commercial and personal transport sector have on costs in off-grid municipalities?

Germany is selected as the case study for this paper since the developments in energy autonomy described in this introduction particularly apply to this country.

The organization of this paper is as follows: In section II, the methodology for optimizing energy systems in municipalities and transferring the results is presented. The results are then explained and discussed in section III and IV respectively, before the study concludes in section V.

II. Methodology

In this section, a method for determining the energy demand of the industrial, commercial and residential sector (cf. section II.A) as well as the RE potential (cf. section II.B) is presented. Section II.C explains how relevant municipalities for this study are identified using these demands and potentials. Subsequently, the RE³ASON model for energy system analysis is explained (cf. section II.D), which is extended by the industrial and commercial sectors (cf. section II.E) as well as personal transport sector (cf. section II.F). Finally, section II.G presents the methodology for transferring results of the RE³ASON model to other municipalities.

A. Demand of Energy Consumption Sectors

The assessment of the electricity demand for the residential, commercial and industrial sector is based on [17]. The assumption is made that the electricity demand of a municipality correlates with selected socio-economic indicators. Since the electricity demand and the corresponding indicators are known on a national level [18], the municipal electricity demand can be downscaled from the national level on the basis of the relative ratio of these indicators ("top-down scaling"). Based on the assumption that the significance of an indicator as a measure of size can be different for each sector, a weight matrix is used to indicate how strongly each indicator is weighted (cf. Table I). The weightings are determined by minimizing the mean square error in comparison to measured consumption values. For this purpose, 17 German municipalities are considered for which the annual electricity consumption is measured and published by sector [19–21].

The non-dimensional parameter *sector size* ($ss_{m,s}$) indicates the size of the respective sector s in the municipality m under consideration in relation to its size in Germany. The sector size is calculated on the basis of the weight matrix $w_{s,i}$, as well as the municipal ($IV_{m,i}$) and national ($IV_{N,i}$) values of all indicators I by means of the weight matrix:

$$ss_{m,s} = \sum_{i \in I} w_{s,i} \cdot \frac{IV_{m,i}}{IV_{N,i}} \quad (1)$$

The electricity demand ED in the municipality m and sector s is thus calculated by applying the sector size as a scaling factor for the corresponding national electricity demand ED_N:

$$ED_{m,s} = ED_{N,s} \cdot ss_{m,s} \quad (2)$$

TABLE I
Weight Matrix $w_{s,i}$, for Assigning a Weight to each Indicator i to Calculate the Size of the Sector s. Sources of Indicators: [22–24].

Indicators	Residential sector	Commercial sector	Industrial sector
Area	0.075	0.000	0.787
Population	0.925	0.958	0.168
Number of industrial companies	0.000	0.000	0.015
Number of industrial employees	0.000	0.000	0.010
Gross salaries in industry	0.000	0.000	0.012
Number of employees with social security contributions	0.000	0.042	0.008

B. Renewable Energy Potential

The determination of the RE potentials in this section serves to select the municipality population to be investigated in this study (cf. section II.C). In [25], the potentials of residential rooftop photovoltaics [26] and wind energy [27] in Germany have been allocated at municipal level. As further potentials, the bioenergy and the deep geothermal energy potential in German municipalities are considered in this study using the methods from [17] and [12]. The bioenergy includes wood combustion plants and biogas plants. The data for forest area and agricultural land in the specific municipalities is taken from [24]. Furthermore, the fraction of the usable area is assumed to be 33% according to [28]. The hydrothermal temperatures for calculating the deep geothermal potential are taken from an open data set [29].

C. Selection of Municipality Population

By means of the methods in sections II.A and II.B, the annual electricity demand and potential RE electricity supply can be determined for each municipality in Germany. If the demand exceeds the supply, the respective municipality cannot achieve AMEA and thus especially not CMEA. Therefore, these municipalities are excluded from the municipality population beforehand. This calculation of AMEA neglects imports from neighbouring municipalities, which would be excluded anyway for CMEA.

The energy consumption patterns in the industrial sector show a high variety (cf. section II.D). Therefore, a standard load profile cannot adequately represent this sector. To minimize the impact on the results when using a standard load profile, only micro and small enterprises as defined by the European Commission [30] are taken into account. Therefore, municipalities with medium-sized and large industries (i.e. enterprises with more than 50 employees) are excluded from the present analysis. When excluding the municipalities, the manufacturing industry serves as a representation for all economic sectors, since this branch accounts for the largest proportion of energy consumption [31] and the employment figures are only available for this sector at municipal level [32]. However, even small enterprises can be energy-intensive. Therefore, municipalities with companies from the *European Pollutant Release and Transfer Register* (PRTR) are additionally excluded. European companies must declare their emissions in this register, if the emission level exceeds certain thresholds [33] (100,000 tCO_2/a for greenhouse gases [34]).

D. RE³ASON Model

After determining the municipality population, the costs for achieving CMEA can be determined for these municipalities. The "Renewable Energies and Energy Efficiency Analysis and System OptimizatioN" (RE³ASON) model is used to calculate these costs, as it can be applied to any municipality in Germany without additional data collection. This is related to the fact that the model uses publicly available data to determine energy demand and potential energy supply. The optimization minimizes the total discounted system costs over the whole model horizon. Thereby, the types, dimensions and dispatch of the energy technologies and measures are optimized. The optimization takes a macroeconomic perspective and optimizes four years with 108 time slices each. The time horizon of the optimizations reaches until 2030 and the years 2015, 2020, 2025 and 2030 are optimized. Except for district heating, no explicit network infrastructure is considered in the model. Detailed information about the actual state of the model can be found in [17] and [13]. In the present study, the model is extended by the electricity demand of the commercial and industrial sector (cf. section II.E). Furthermore, EVs are implemented to represent the personal transport sector (cf. section II.F).

E. Implementation of Industrial and Commercial Sectors

Electricity load profiles enable to scale the calculated energy demand $ED_{m,s}$ to one year. For the commercial sector standard load profiles are used [35]. The electricity demand of the commercial sector c in a municipality m at hour t ($E_{m,c,t}$) is calculated as follows:

$$E_{m,c,t} = E_{c,t} * \frac{ED_{m,c}}{E_{c,sum}} \quad (3)$$

$E_{c,t}$ is the electricity demand at time t and $E_{c,sum}$ the annual electricity demand of the standard load profile. The data set with industrial load profiles used in [36] contains three load profiles for small enterprises, which are used in the present study. The mean profile of the companies for *Shipping*, *Shaping of sheet* and *Iron casting* is used in this study as load profile for the industrial sector. Equation (3) can then be used to scale the demand profile analogously to the commercial sector.

F. Implementation of the Personal Transport Sector

This study assumes that all vehicles of the personal transport sector in a municipality are replaced by EVs. Thereby, the flexibility potential of the EV fleet is derived as follows. In a first step, flexibility potentials of single vehicles are generated with a model developed in [37]. The model uses representative mobility data of conventional vehicles in Germany [38] and simulates two extreme charging scenarios for each of them, given the assumption that an EV would replace them. The results include one-week time series for an as-soon-as-possible (ASAP) and an as-late-as-possible (ALAP) charging scenario, which can be considered as flexibility potentials for each vehicle. We assume that every vehicle has the possibility to charge both at home and at work, and that it is connected to the charging station throughout the parking duration.

The next step aims at aggregating the single vehicle flexibility potentials to a flexibility potential of one hypothetical battery which represents the municipality's EV fleet (cf. (4)). Therefore, we add the single vehicles' battery capacities C_{EV} to the fleet's battery capacity C_f. $N_{EV,m}$ is the number of EVs in a municipality, available from [39].

$$C_f = C_{EV} \cdot N_{EV,m} \quad (4)$$

In (5), the upper boundary for the fleet's battery state of charge $SoC_t^{max,f}$ in a time slice t is derived by totaling the single EVs' $SoC_{t,v}^{max,EV}$ which results when the vehicle is charged according to the ASAP-strategy. The single vehicle v is part of the total number of simulated EVs (V). In order to account for the representativeness of the vehicles in the dataset, the time series for $SoC_{t,v}^{max,EV}$ are weighted by the vehicle weightings w_V. By dividing them by the sum of all weightings, the resulting weighted time series represents the average of the fleet. Finally, the flexibility potential is scaled on municipality level with the number of EVs in the municipality.

$$SoC_{t,m}^{max,f} = \sum_{v=1}^{V} \left(SoC_{t,v}^{max,EV} \cdot w_V\right) \cdot \left(\sum_{v=1}^{V} w_V\right)^{-1} \cdot N_{EV,m} \quad (5)$$

$SOC_t^{min,f}$ is calculated accordingly based on the simulated ALAP-strategy. The power discharged from the EV battery by driving $P_t^{dr,f}$ and the available charging power $P_t^{max,f}$ are also determined analogously. The latter depends on the power of the charging station and whether the vehicle is parked at one of its charging locations or not.

As shown in [37], the driving and charging patterns vary for different degrees of urbanization. Since most municipalities from the preselected population are located in rural areas (cf. section III.A), the mobility data is preselected by geographic criteria. The data of vehicles in rural areas with higher and lower density, according to the municipality grouping by BBSR [40], are considered. The resulting flexibility potential pattern of the fleet is used for each municipality and varies by scaling with the number of EVs per municipality. Further assumptions are listed in Table II. The mean value of 3.7 – 22 kW charging power in low-voltage grids is used as available charging power.

Controlled bidirectional charging is selected as charging strategy for the EVs [42]. Therefore, the charging process is controlled by the municipal energy management system with regard to load, time and limitations by the mobility patterns. In addition, the battery can be discharged to feed electricity into the municipal grid, known as *vehicle-to-grid* (V2G). The main modelling aspects of the EVs are listed below, for further information please refer to [42]. The SoC of the EV batteries (SoC_t^f) depends on the previous SoC (SoC_{t-1}^f), the (dis-)charging efficiency (η_{EV}), the charge power ($P_t^{ch,f}$) as well as discharge power ($P_t^{V2G,f}$) and the power required for driving ($P_t^{dr,f}$) [42]:

$$SoC_t^f = SoC_{t-1}^f + \frac{(P_t^{ch,f} \cdot \eta_{EV} - P_t^{V2G,f}/\eta_{EV} - P_t^{dr,f}) \cdot dt}{C_f} \quad \forall t \epsilon T \quad (6)$$

At a SoC above 75%, the charging power reduction ($P_{t,max,red}$) increases linearly according to (7) [41]. P_{SE} is the available charging power of the supply equipment.

$$P_{t,max,red} \geq P_{SE}\left(4 \cdot SoC_t^f - 3\right) \quad (7)$$

Equation (8) ensures that for each day d the EVs are charged with the energy required for driving $P_t^{dr,f}$. This implies that the load shift potential can only be exploited within one day and thus limits the usage of EV flexibility to a more conservative range.

$$\sum_{t=1}^{24}\left(P_t^{ch,f} - P_t^{V2G,f}\right) \cdot dt \geq \sum_{t=1}^{24} P_t^{dr,f} \cdot dt \quad \forall d \epsilon D \quad (8)$$

As in [42], the investment in EVs is assumed to be personal, preference-driven and for mobility reasons only. Therefore, this investment is not considered in the optimizations.

G. Transfer of Results

The RE³ASON model is applied to determine the cost-minimal energy system for preselected municipalities as case studies. On the one hand for the reference case without autonomy and on the other hand for the case with CMEA. In the reference case, the energy system is optimized without restricting imports and exports. Subsequently, the *Levelized Cost of Energy* (*LCOE*) are calculated for both cases and all preselected municipalities (cf. (9), [43]). Thereby the conversion factor for electricity into heat is assumed to be the heat pump's coefficient of performance (3.5) as in [43], since the heat load is taken into account for the residential sector.

$$LCOE = \frac{\sum_{y=1}^{Y} \frac{CAPEX_y + OPEX_y}{(1+r)^y}}{\sum_{y=1}^{Y} \frac{E_{m,total,y}}{(1+r)^y}} \quad (9)$$

The LCOEs are calculated depending on the investments (*CAPEX*), the operational and maintenance costs (*OPEX*), the total energy demand ($E_{m,total}$) and the year y. The interest rate r is assumed to be 5%.

A regression is used to transfer the results of the case studies to the entire municipality population. The dependent variable is the difference between LCOEs in the autonomous and in the reference case (*ΔLCOE*). In the selection of the independent variables, those that correlate with other variables are eliminated. Therefore, for all correlations above |0.9| one variable is excluded.

To avoid an overfitting in the regression, a *k-fold cross-validation* is applied [44]. Since our sample is small (n = 15), the *leave-one-out cross-validation* is used, with k = n = 15. 19 different methods are applied, ranging from linear regression models and support vector machines to Gaussian Process Regression models. From these methods, the model that results in the lowest root mean squared error is selected.

TABLE II
Assumptions for Modelling EV Flexibility.

Parameter	Value	Unit	Source
Battery capacity (C_{EV})	50	kWh	[40]
EV energy consumption	10.2	kWh/100 km	[40]
EV battery efficiency (η_{EV})	90	%	[41]
Number of simulated EVs (V)	229		[36, 37]
Available charging power ($P_{t,v}^{max,EV}$)	13	kW	Assumption
SoC-range during operation	5-100	%	Assumption

III. Results

In section III.A, the municipality population examined in this study is presented. In addition, case studies are selected for investigation in the RE³ASON model. Subsequently, the optimization results of these case studies (cf. section III.B) as well as sensitivity analyses (cf. section III.C) are explained. Finally, section III.D presents the results of the regression.

A. Case Studies

The methodology described in section II.C results in an exclusion of 3,120 municipalities that are not suitable for AMEA, 2,656 municipalities with large industries and 616 municipalities from the PRTR Register (grey area in Fig. 4). The remaining 6,314 municipalities correspond to 56% of the municipalities, 14% of the population, 40% of the land area and 23% of the annual electricity consumption of Germany.

As case studies, municipalities which differ particularly with regard to the independent variables from the regression are selected from the municipality population. For each indicator, one municipality is selected that has the maximum or minimum value for this indicator. As for some indicators the municipalities are the same, a total of 15 different municipalities remain for examination, which are geographically distributed across Germany.

B. Energy System Optimization Results

For one of the 15 investigated municipalities, Prinzenmoor, the resulting LCOEs are shown in Fig. 1, for the reference case without CMEA (P1) and with CMEA (P2). Results of other scenarios (P3 to P6) are explained in section III.C.

Prinzenmoor is a small municipality with only 179 inhabitants. The electricity demand in the industrial, commercial and residential sectors is 2.9 GWh/a, 0.3 GWh/a and 0.2 GWh/a respectively.

The value range of the y-axis in Fig. 1 contains negative values (up to -0.1 €/kWh), since exports result in a small negative contribution to the LCOEs in P1. In the autonomy case P2, the energy system of Prinzenmoor changes greatly. Whereas in P1 the energy is provided by wind turbines and power grid, in P2 the entire energy is provided by deep geothermal energy. The geothermal plant is used for base load operation, while the EV batteries in the municipality are discharged to cover peak loads.

For P2, the electricity supply and demand for a typical weekday in 2015 are given in Fig. 2. The high electricity demand of the residential sector at night is remarkable. This is due to the fact that buildings are considered as daily energy storages in RE³ASON. Therefore, during the night hours, when the electricity demand of the other sectors is low, a large part of the heat demand is covered by electric storage heaters and heat pumps. Due to the base load operation of the geothermal plant, electricity surpluses occur in time steps with low electricity demand. Parts of the surpluses are used to charge the batteries of the EVs. A comparison of the power from charging ($P_t^{ch,f}$) and V2G ($P_t^{V2G,f}$) with the maximum available charging or discharging power P_{SE} shows that no more than 60% of the battery flexibility is exploited in the various time steps of the optimization.

CMEA is associated with a high increase in LCOEs in Prinzenmoor (ΔLCOE = 0.45 €/kWh, cf. Fig. 1). In all 15 examined municipalities, the increase in LCOEs range between 82% and 487%, which corresponds to ΔLCOE between 0.19 €/kWh and 0.55 €/kWh. Biomass and additional battery storages are installed in almost every municipality. Geothermal plants are built in 10 of the 15 municipalities, partly supported by biomass, wind and solar energy.

In most municipalities and if CMEA has to be achieved, surplus electricity occurs in hours in which the generation exceeds the demand (cf. Fig. 2 for Prinzenmoor). The surpluses range from 0 to 4 GWh/a. In P2 the surpluses amount to about 50% of the total energy demand of the municipality, which is the highest share among all 15 municipalities. Between 2015 and 2030, the average surpluses are reducing from around 2 GWh to 1 GWh in all municipalities. This is due to the fact that several volatile generation technologies, which are installed in the municipalities in 2015, are replaced over time. The average CO_2 abatement costs for the 15 municipalities are around 3.7 k€/tCO_2. For a detailed discussion of RE³ASON model results, including demand and generation patterns, please refer to [13].

C. Sensitivity Analyses

In the sensitivity analyses (cf. Table III), the reference scenario for the autonomy case P2 is changed in order to examine the influence of model extensions and assumptions (P3, P5 and P6). Secondly, the influence of geothermal plants is investigated, as in many German municipalities no geothermal potential exists (P4).

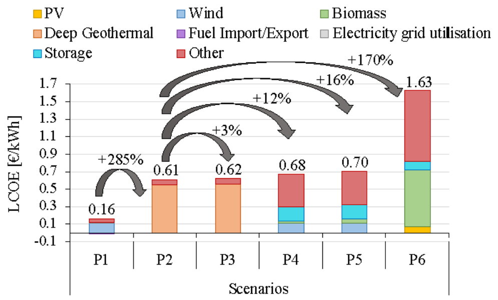

Fig. 1: Technology-specific LCOE contributions for the optimal energy systems in the municipality Prinzenmoor for six different scenarios. The share "Other" includes costs for insulation, heating systems, appliances and lighting in the residential sector.

In order to quantify the uncertainty resulting from the chosen industrial load profiles (cf. section II.E), in scenario P3 the mean profile is replaced by the load profile of the *Iron Casting Company*, which shows higher peaks. The maximum peak is 105% higher than in the mean profile. Consequently, the LCOEs increase by 3% (cf. Fig. 1). In Prinzenmoor, the industrial sector accounts for about 80% of the energy demand. The change in the industrial load profiles therefore has a rather small influence on the results.

If no geothermal plant may be built in scenario P4, the energy is provided by wind and biomass (cf. Fig. 1). Due to the volatile wind energy production, additional storages are required. In addition, more efficiency measures are implemented, such as more efficient household appliances and the insulation of buildings. Especially the efficiency measures and further storages are responsible for the LCOE increase of 12% compared to P2. However, the low increase in costs shows that even municipalities without a large base load potential can become autonomous at comparable costs. Compared to P2, the electricity surpluses are 80% lower. This is because there is less base load in operation in P4 and therefore not so many time

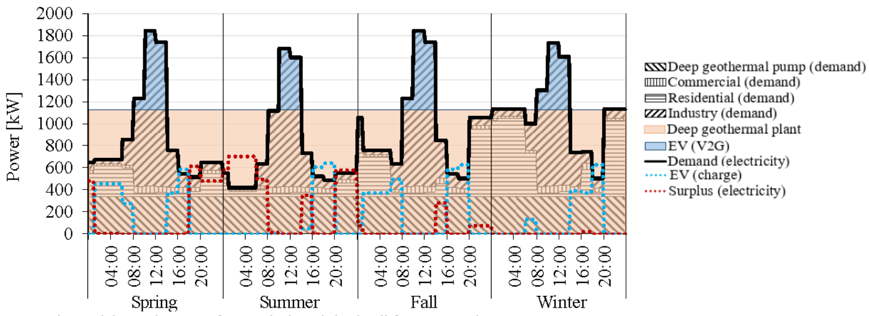

Fig. 2: Electricity generation and demand patterns for a typical weekday in all four seasons in 2015.

steps with surplus electricity as in P2 (cf. Fig. 2).

Due to the electricity surpluses from the geothermal plant in P2, the storage capacities of the EVs are beneficial. However, if a scenario without EVs (P5) is considered, the construction of the geothermal plant is no longer economical. In this case, additional storages have to be installed in order to use much energy from the geothermal plant. Alternatively, the geothermal plant could be dimensioned smaller. However, this type of plant incurs very high fixed costs, and therefore this would not be economical either. This shows that, depending on the conditions of the energy system, the storage capacities of the EVs can moderately reduce costs (by 16% compared to P2). In an energy system without deep geothermal potential, though, the costs would increase only slightly (comparison between P4 and P5).

Due to the consideration of the industrial and commercial sectors in addition to the residential sector, energy autonomy is not feasible in every municipality (cf. section III.A). However, at the same time, the LCOEs for achieving autonomy are greatly reduced (comparison of P2 and P6), since fixed costs of the system are related to a significantly larger amount of energy. Prinzenmoor is an extreme case, due to the small size of the municipality. However, to a lesser extent, this statement can be applied to other municipalities as well.

TABLE III
Scenarios of the Sensitivity Analysis in Prinzenmoor.

Scenario	Differences to reference scenario P2
P3	Load profile of industrial companies (Iron Casting)
P4	Without geothermal plants
P5	Without EVs
P6	Without industrial and commercial sector

D. Regression Results

After the correlation analysis, the following six indicators remained for the regression: industrial electricity demand, residential electricity demand, population density, technical geothermal potential, technical wind energy potential and technical bioenergy potential. From the 19 models of the 15-fold cross validation, *stepwise linear regression* proved to be the best method. The model whose results are shown in Fig. 3 yields the error measures in Table IV.

The technical bioenergy potential and the products of residential electricity demand and population density as well as residential electricity demand and technical geothermal potential are selected as features for the regression. The fact that the industrial electricity demand and the technical wind potential are not used in the regression could be related to the correlation above 0.8 with the technical bioenergy potential.

After applying the regression model to all 6,314 municipalities, 155 outliers downwards (ΔLCOE≤0.02 €/kWh) and 31 upwards (ΔLCOE≥1.50 €/kWh) are eliminated. This is done due to the high R^2 (0.86) as this could indicate a slight overfitting of the model. A lower bound of 0.02 €/kWh was chosen as this corresponds to a cost increase of about 5% in relation to the LCOEs of the 15 investigated municipalities. Fig. 4 shows the 6,128 remaining municipalities and the distribution of ΔLCOE. Among these municipalities, the mean value of ΔLCOE is 0.41 €/kWh. The data of municipalities with ΔLCOE, demand of the sectors and RE potential can be provided upon request.

When distributing the regression results according to the ten German municipality clusters from [26], the results seem plausible: The highest mean ΔLCOE is reached in cluster 2 (0.578 €/kWh), which mainly contains cities with low RE potential. On the other hand, the lowest mean ΔLCOEs are achieved in clusters 3 (0.350 €/kWh), 4 (0.349 €/kWh) and 8 (0.379 €/kWh), which contain mainly rural municipalities with particularly high potential for RE and especially deep geothermal energy.

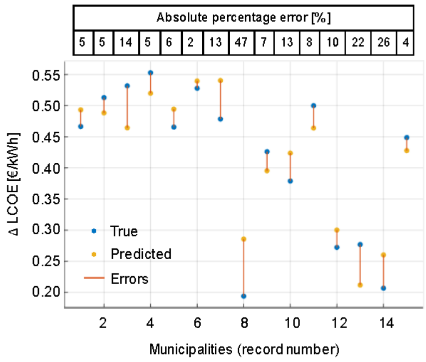

Fig. 3: Results of the stepwise linear regression. The error margins between the results from the optimizations (true) and the predicted values from the regression are shown.

TABLE IV
Resulting Error Measures of the Stepwise Linear Regression.

Root mean squared error	0.047
Mean absolute percentage error	0.125
R-squared	0.860

IV. Discussion and Critical Appraisal

In this study, a methodology for determining LCOEs for achieving energy autonomy in all municipalities of a country was presented. Germany was used as a case study, but the general methodology can also be applied to any other country.

The study has shown that achieving CMEA is associated with large additional costs of 0.41 €/kWh on average. Thus the costs per kWh are more than doubled compared to an optimized energy system without autonomy. Therefore, future studies at a national level should investigate whether and where CMEA is worthwhile if grid expansion is taken into account. Thereby, the results of the present study can serve as a scenario in the design of transmission networks. For example, the assumption could be made that all municipalities with ΔLCOE less than the mean value (0.41 €/kWh) will become autonomous. Then the demand and feed-in from these municipalities could be excluded from the analyses. Furthermore, simultaneous optimization of transmission grid expansion and selection of autonomous municipalities could be performed to determine the optimal future national energy system.

The LCOEs and ΔLCOEs have probably been overestimated in this study. Firstly, due to the separate consideration of individual municipalities. The municipal boundaries represent administrative units that do not necessarily have to represent optimal boundaries for energy systems. In addition, the simultaneous optimization of neighbouring municipalities could lead to lower LCOEs than in individual cases. Instead, the electricity surpluses which could be used in neighbouring municipalities to cover parts of the demand are curtailed. Also, the reference case for the determination of the ΔLCOE is an optimized energy system without autonomy, which in reality does not exist in most municipalities. Furthermore, the expression of these costs in absolute terms, irrespective of the municipality size or energy system structure, could be misleading. An improvement could be to redistribute these costs per final consumer, in order to give a more meaningful and comparable indicator.

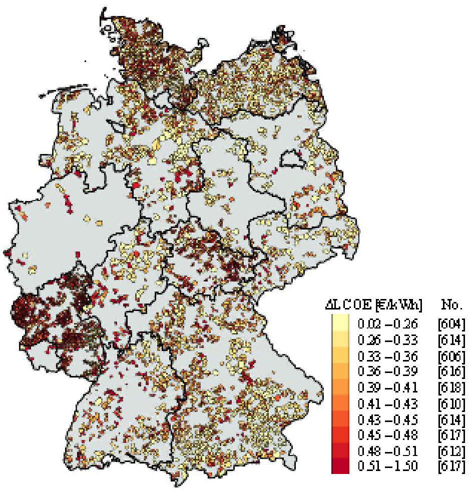

Fig. 4: Illustration of 6,128 [55%] German municipalities that can become completely autonomous and the associated ΔLCOE.

In addition, part of the costs could be underestimated as no grid infrastructures in or outside the municipality were considered. Also, a standard load profile was used to include the electricity demand of the industrial sector. The sensitivity analysis showed that a different structure of the load profile does not have a large influence on the costs. However, the load profiles in individual municipalities could differ greatly from those used in this study. Furthermore, the modelling of EVs could also be improved. Instead of an aggregated driving profile, individual or clustered driving profiles could be used. The computing time of the energy system model would then be a particularly restrictive factor. All of these improvements should be explored in future studies.

Moreover, the regression was used to transfer the results to a large number of municipalities whose individual analysis would not be possible in a single study. However, optimization and subsequent regression do not replace detailed planning of the energy system of a single municipality.

V. CONCLUSIONS

In the present study, a methodology was developed to determine the feasibility and costs for complete municipal energy autonomy. First, methods for estimating the energy demand and potential for renewable energies were proposed. On this basis, municipalities in which complete energy autonomy is not feasible could be excluded. Subsequently, an energy system optimization model was extended to include the personal transport, industrial and commercial sectors and applied to a number of municipalities in order to determine the costs for complete energy autonomy. In a final step, the results were transferred to further municipalities using selected indicators in a regression model.

In this paper, Germany has been selected as case study, where 6,314 (56%) municipalities were identified, in which complete energy autonomy could be technically feasible. Of these municipalities, 15 were selected as case studies, which differ greatly in terms of the indicators used in the regression analysis. The results of the optimizations showed the influence of individual technologies and measures on the levelized cost of energy (LCOE). Thereby, it became apparent that complete energy autonomy is always associated with a high cost increase. Furthermore, the integration of the industrial and commercial sectors has a reducing effect on the LCOEs, since fixed costs are distributed across a larger amount of energy. In addition, the flexibility of electric vehicles can moderately reduce LCOEs. Using a stepwise linear regression model (mean absolute percentage error = 12.5%), the results of the optimizations could finally be transferred to the 6,314 municipalities. On average, the additional LCOEs, which have to be paid in the autonomous compared to the reference (minimal cost) case, amount to 0.41 €/kWh. Apart from energy demand, base load capable bioenergy and deep geothermal energy appear to have the greatest influence on the LCOEs.

The main areas for improving the methodology include the consideration of grid infrastructures and surplus electricity from neighbouring municipalities, as well as more detailed modelling of industrial demand. The method of calculating and comparing the costs of energy autonomy should be improved to express these costs per municipal end user. In future studies in which the national energy system or transmission grid expansion is planned, the results of this paper can be used as a possible scenario.

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