

ORIGINAL ARTICLE

Open Access



# Bioenergy plants' potential for contributing to heat generation in Germany

M. Steubing<sup>1\*</sup>, M. Dotzauer<sup>2</sup>, T. Zakaluk<sup>2</sup>, B. Wern<sup>3</sup>, F. Noll<sup>3</sup> and D. Thraen<sup>1,2</sup>

## Abstract

**Background:** The Paris Climate Agreement requires a rapid and efficient shift to renewable energies and a decarbonization of the energy system. Combined heat and power provision from biomass is one way to efficiently provide renewable heat. Despite this, many bioenergy plants in Germany are mainly used to generate electricity and the provision of externally usable heat still has untapped potential. In this study, we investigated gross quantities as well as the economically viable potential of Germany's current bioenergy plant stock in supplying renewable heat.

**Methods:** We used a top-down GIS modeling approach to spatially and explicitly assess the heat demand of three different categories of heat sinks at sub-municipal level. These included residential, commercial, and industrial areas, as well as large individual heat consumers. We then calculated the plant-specific heat sales potential for two different district heating network options. In addition, we developed a method for assessing the economic efficiency of the previously identified technical heat sales volume for a set of 20 different clusters of bioenergy plants.

**Results:** The results show that about 50% of the bioenergy plants have potential heat consumers in their immediate proximity. The overall technical heat sales potential for all three categories totals around 150 TWh<sub>th</sub>/a. However, this potential is not evenly distributed throughout Germany. Certain regions appear to be more favorable for investing in district heating networks powered by heat from biomass. The economically viable heat sales potential related to electrical energy generation ranges from – 0.128 to 0.160 €/kWh<sub>th</sub>.

**Conclusion:** We concluded that, under certain conditions such as location or supply and demand structure, German bioenergy plants have the potential to provide a significant share to renewable energies in the heating sector. In addition, the heat sales potential is highly relevant for plant operators as the importance of heat as a business segment is set to increase. Furthermore, bioenergy plants could contribute 2.1% (16.3 TWh<sub>th</sub>/a) to the total demand for space heating in Germany (765 TWh<sub>th</sub>/a) when considering certain technical and economic constraints.

**Keywords:** Bioenergy CHP, Renewable heat, District heating networks, GIS modeling

## Background

Heat accounts for half of the final energy consumption in Germany, but currently only 13.9 % of heat is supplied by renewable energy sources (RES) [1]. Thus, the share of renewable energy sources in heat supply needs

to increase if the greenhouse gas reduction targets of the Paris Climate Agreement are to be met. In order to achieve this goal, the European Union (EU) intends to analyze different ways to promote a transition towards using RES in supplying heat as part of its strategy on heating and cooling (COM 2016). One option is to decarbonize existing district heating networks (DHNs) and to supply more heat consumers through new, yet-to-be-built DHNs. At the moment, district heating

\* Correspondence: [michael.steubing@ufz.de](mailto:michael.steubing@ufz.de)

<sup>1</sup>Helmholtz Centre for Environmental Research, Permoserstrasse 15, 04318 Leipzig, Germany

Full list of author information is available at the end of the article



© The Author(s). 2020 **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>. The Creative Commons Public Domain Dedication waiver (<http://creativecommons.org/publicdomain/zero/1.0/>) applies to the data made available in this article, unless otherwise stated in a credit line to the data.

provides 9% of the EU's heat [2]. In 2012, fossil fuels were the primary energy sources for heating and cooling in these networks (75%). The most important renewable fuel for DHNs, with a share of 12% in 2015, is heat generated from biomass [3].

In 2012, Germany's share in final energy consumption for heating and cooling supplied by district heating systems was 8–9% [2]. The German district heating system<sup>1</sup> has a connected load of 51 GW and a transformation output of around 470 PJ. The overall fuel input amounts to 522.3 PJ and consists of coal (29%), lignite (11%), mineral oil (1%), natural gas (42%), waste (11%), and biomass (6%) [4]. However, in order to achieve the greenhouse gas reduction targets set by the German government, DHNs supplied by RES will need to provide 23% of the final energy consumption for building heat by 2050 [5]. One reason for this is that regions without a natural gas network and with predominantly decentralized oil heating systems also need to have renewable alternatives for their so far fossil-based heat supply [6]. Furthermore, with the foreseeable shutdown of coal-fired power plants in Germany by 2038 [7], the 50 TWh<sub>th</sub>/a of heat [8] currently produced by this sector needs to be replaced by low-carbon fuels. Fritz and Pehnt [8] recently stated that biomass must also partly contribute to this as well.

The largest share of heat from RES in Germany is generated by biomass (87.3%), mainly in small combustion plants [9]. Additionally, Germany has an installed capacity of 5.6 GW<sub>el</sub> [10] in biogas plants and 1.6 GW<sub>el</sub> [10] in plants using solid biomass fuels, which are currently not utilizing all of the available heat [11].

DHNs are a suitable way of increasing the use of RES in the heating sector, as Lund et al. point out [12]. This particularly applies to biomass. Bio-fueled combined heat and power units (CHPU) can achieve an overall efficiency of up to 90% [13]. The co-generated heat can be used to supply DHNs. In order to fully exploit this potential, however, suitable heat consumers (heat sinks) must be located near the plants; otherwise, the generated heat cannot be supplied properly due to transport-related energy losses. The plant-specific and, consequently, the total heat supply potential of the bioenergy plants (BEPs) in Germany thus crucially depends on plant location.

In current energy scenarios for Germany, there is little information available specifically on local district heating networks and the fuels being used there. Koch et al. [14] stated an overall contribution to the generation of heat of 16 TWh with natural gas being the dominant fuel. Biomass only plays a minor role in the supply of these

networks but with increasing proportions until 2050 [14].

Against this backdrop, the question arises as to the extent to which the current BEP installations in Germany can contribute to the provision of heat to external users by means of district heating networks. In this study, we investigate the gross amount of heat demand and supply of the German BEP stock as well as the economically viable potential. For this purpose, we seek to answer the following research questions:

- How many BEPs have nearby heat sinks suitable for a DHN?
- What is the extent of the technical heat sales potential (tHSP) (in TWh<sub>th</sub>/a) of these BEPs?
- How can the economic viability of tHSP be assessed?
- How high is the economically viable heat sales potential (eHSP)?

To answer these questions, we modeled the heat demand for three different categories of heat sinks at a sub-municipal spatial resolution: the residential sector (1), the industrial sector as well as the sector trade, commerce and services (TCS) (2), and large individual heat consumers (LIHC) such as hospitals and schools (3). We then evaluated which BEPs are capable of delivering heat at all, as well as the plant-specific and overall heat sales potential per category.

Additionally, we developed a method to evaluate the economic viability of the previously assessed technical heat sales for a set of 20 different clusters of BEPs.

In the context of modeling future energy systems, Weinand et al. emphasize the need for data at a high spatial resolution [15]. While the general potential for DHNs in Germany has been analyzed before [16], an investigation into the specific potential of bio-fueled CHPUs has only been carried out in some states, such as Saarland [17]. A Germany-wide assessment has yet to be made.

## Methods

### Modeling scheme

In order to determine the technical heat sales potential (tHSP) for each plant individually, it is necessary to identify suitable heat sinks close to the respective plant. Consequently, the tHSP is defined as the heat demand of suitable heat sinks within a defined maximum distance to the respective BEP. While spatial information on BEPs is available through the bioenergy plant database of the German Biomass Research Centre (DBFZ) [18], the spatially explicit heat demand related to these plants is missing and needs to be identified. The modeling consisted of two separate steps. First, we modeled the heat

<sup>1</sup>Without rural local district heating networks fueled by heat generated from biomass.

demand at a spatial resolution below the municipal level. For the residential sector, this means the level of individual residential blocks and for the industrial sector the level of industrial and commercial areas as recorded in the ATKIS Basis Digital Landscape Model (DLM) [19]. The ATKIS Basis DLM offers a description of these topographic elements in vector data format for all of Germany on a scale of 1:25,000 [19]. For the LIHC, this means their exact geographical location. In a second step, we calculated the tHSP for each plant individually and concluded the overall tHSP.

Based on the tHSP, we developed an estimation approach to assess the economically viable heat sales potential (eHSP, see Fig. 5). The basic method for calculating tHSP as well as the input data used is illustrated in Fig. 1.

Most of the data used in the model is publicly available. The content of the respective datasets, their origin and the latest update are listed in Table 1. Only the municipal level heat demand (later referred to as “IZES heat demand”) and the DBFZ BEP database contain internal data of the respective institutions and are therefore not publicly available.

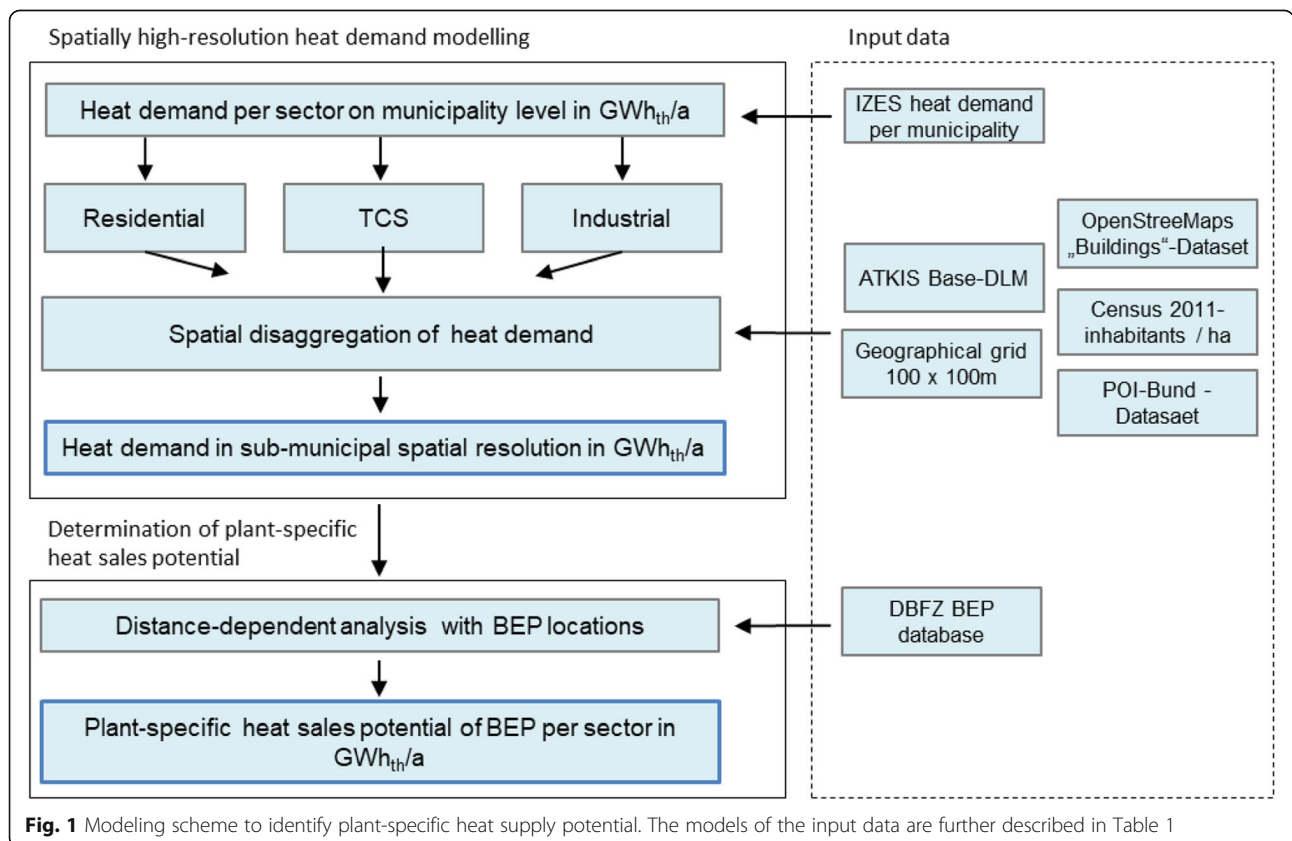
**Modeling the heat demand at a high spatial resolution**

Heat is required and consumed in three different sectors: residential, TCS, and industrial. As the German

Environment Agency states, heat in the residential and TCS sectors is primarily required for space heating, while the industrial sector requires the largest share for process heat [1]. Consequently, the methods for determining the total heat demand per sector and for its spatial modeling vary.

For the residential, TCS and industrial sectors, we followed a top-down modeling approach as described by Fleiter et al. and applied by Baur et al. [3, 17]. The basic principle of this approach is to disaggregate the heat demand from the existing aggregated level into smaller spatial units. In our case, we used data on the heat demand per sector for each municipality, calculated by Baur et al. [20], and allocated it to the residential areas and the commercial and/or industrial areas of each community.

We simultaneously applied a bottom-up approach for LIHCs, such as hospitals, commercial greenhouses, schools, and public outdoor swimming pools, which are particularly suitable for DHNs fueled by heat generated from biomass [26]. This means that we calculated their yearly heat demand on the basis of an object-specific key such as kWh<sub>th</sub>/a/bed (hospitals), kWh<sub>th</sub>/a/student (schools), kWh<sub>th</sub>/a/m<sup>2</sup> (commercial greenhouses), and kWh<sub>th</sub>/a/m<sup>2</sup> water surface (public outdoor swimming pools).



**Fig. 1** Modeling scheme to identify plant-specific heat supply potential. The models of the input data are further described in Table 1

**Table 1** Data used for modeling heat demand

Name	Content	Source	Update
IZES heat demand	Heat demand in GWh <sub>th</sub> /a on a municipal level for the residential, TCS, and industrial sectors	IZES gGmbH, Wuppertal Institut, Fraunhofer UMSICHT [20]	2011
DBFZ BEP database	Locations and technical information on bioenergy plants in Germany, containing approx. 14,000 individual plants	DBFZ	2016
ATKIS basis DLM	Digital landscape model (scale 1:25,000) with spatial and content-related information on land use in vector data format	©GeoBasis-DE/BKG [19]	2012
Administrative areas	Administrative areas of Germany (NUTS 0-3, LAU 1-2) including population figures	©GeoBasis-DE/BKG [21]	2016
Geographical grid	Geographical grid of Germany with a raster cell size of 100 m × 100 m	©GeoBasis-DE/BKG [22]	2018
POI-Bund	Locations and additional information on schools and hospitals	©GeoBasis-DE/BKG [23]	2018
OSM buildings	OpenStreetMap buildings dataset	Geofabrik GmbH, OpenStreetMap, and contributors [24]	2018
Census 2011	Small-scale (raster cells, 100 m × 100 m) population statistics for Germany	Destatis (Federal Statistical Office) [25]	2015

### Residential sector

The heat demand of residential units on a municipal level was assessed using building stock grouped by building type (single family dwelling, townhouse, etc.), year of construction, and municipality. This data was extracted from the 2011 census database [27]. We multiplied the number of buildings, divided into building class and municipality, by the corresponding heat demand in kWh<sub>th</sub>/a and respective residential unit, derived from the German building typology of IWU 2003 [28]. Additionally, we took an average annual domestic hot water demand of 500 kWh<sub>th</sub> per capita into account, based on the municipal population on December 31, 2011 [27]. The overall methodology of assessing the heat demand is discussed in more detail in Baur et al. [20].

Within the ATKIS Basis DLM, the utilization of a given area is defined by unique codes related to object type. Subsequently, we selected all objects that are assigned to the residential sector including the object types 2102 (dwelling), 2111 (residential area), and 2113 (area of mixed use). These objects were then labeled as residential area objects (RAO) and are hereinafter referred to as such. All other objects (e.g., parks, bodies of water, train tracks, and stations) were no longer considered in the model and were therefore removed from our analysis. We then calculated the residential area factor (RAF), which represents the share of each individual RAO in the total residential area of the municipality, with

$$RAF = \frac{A_{RAO}}{A_{\text{total residential area}}} \quad (1)$$

where RAF is the residential area factor, RAO is the residential area object, and  $A$  is the area (m<sup>2</sup>).

Since the heat demand in the residential sector also depends on the number of inhabitants per area, it was

necessary to determine the number of inhabitants for each RAO individually. To do so, we used population data from the 2011 census which is available in a nationwide grid with raster cell sizes of 100 m × 100 m<sup>2</sup> [25]. The geodata for the grid is provided by the German Federal Agency for Cartography and Geodesy (BKG) [22]. We intersected the RAOs with the population data and calculated the population figures per RAO<sup>3</sup>. Subsequently, we determined the population factor ( $PF$ ), which is the ratio of any given RAO to the municipality's total population with

$$PF = \frac{\text{Inhabitants per RAO}}{\text{Inhabitants of municipality}} \quad (2)$$

where  $PF$  is the population factor and RAO is the residential area object.

In the next step, we calculated the RAO-specific heat demand using the heat demand per municipality provided by IZES in combination with the previously introduced factors RAF and  $PF$ . For RAOs containing information on the number of inhabitants, the specific heat demand ( $Q$ ) is

$$Q_{RAO} = Q_{\text{municipality}} \times PF \quad (3)$$

where  $Q$  is the heat demand (GWh<sub>th</sub>/a),  $PF$  is the population factor, and RAO is the residential area object.

For RAOs with missing information on the number of inhabitants it is

<sup>2</sup>To protect privacy, grid cells with one person are identified as grid cells without persons and grid cells with only two persons are identified as grid cells with three persons [29].

<sup>3</sup>75% of the residential area objects are covered by grid cells with more than one inhabitant.



$$Q_{RAO} = Q_{municipality} * RAO \quad (4)$$

where Q is the heat demand (GWh<sub>th</sub>/a), PF is the residential area factor, and RAO is the residential area object.

Finally, the heat density (kWh<sub>th</sub>/m<sup>2</sup>a) was determined for each RAO by dividing the RAO-specific heat demand (GWh<sub>th</sub>/a) by its area.

$$HD_{RAO} = \left( \frac{Q_{RAO}}{A_{RAO}} \right) \quad (5)$$

where HD is the heat density (kWh<sub>th</sub>/m<sup>2</sup>a), Q is the heat demand (kWh<sub>th</sub>/a), A is the area (m<sup>2</sup>), and RAO is the residential area object.

The result is a dataset for the whole of Germany with very detailed spatial information on the heat demand and heat density of residential areas.

#### **TCS and industrial sector**

The heat demand of the industrial sector on a district level (NUTS 3) was estimated by multiplying the number of employees in the manufacturing sector<sup>4</sup> by the corresponding average heat demand per employee and industry derived from the national statistic on industrial energy demand [31, 32]. Due to the lack of corresponding data for the TCS sector, we determined the heat demand of the TCS sector by using the gross added values of the related economic sectors<sup>5</sup> [33]. They were multiplied by the average heat demand of the corresponding sectors derived from the reference scenario, which is described by Kirchner et al. [34]. In order to also determine the heat demand of both the TCS and industrial sector on a municipal level (LAU 2), we multiplied the calculated heat demands by the ratio of the number of employees at a municipal and district level [35].

As with the residential sector, the DLM was the basis for modeling the heat demand for the TCS and industrial sectors. Here, we used the object types “Industrial and commercial area” (2112) and “Area with special functional characteristics” (2114). We recognized that the DLM alone is only partially suitable for spatially modeling the heat demand of industrial and TCS areas. There are numerous objects (areas) assigned in the classification 2112 that have not been developed, as well as objects which do not have actual heat demand, like landfills or substations. To exclude such areas from the assessment, we added the OpenStreetMap (OSM) buildings dataset to the model [24]. During the modeling process, we only considered the DLM objects which

intersect with the OSM buildings dataset. We then created new area objects by calculating minimum boundary polygons around the buildings inside the objects classified as 2112 and 2114 and labeled them as “TCS area objects.” Analogous to the residential sector, we then assessed an area factor for those TCS areas and assigned them their object-specific heat demand (GWh<sub>th</sub>/a) and heat density (kWh<sub>th</sub>/m<sup>2</sup>a).

The quality of the DLM dataset varies strongly for objects within object type 2112. Only the federal states of Brandenburg, Berlin, Saarland and Hamburg provide detailed information about how an area is actually used, e.g., for industrial purposes or for commercial functions like trade or storage. We were only able to distinguish between the heat demand for the industrial sector and the TCS sector in these states. Since no distinction could be made in the other states, we used the combined heat demand of the industrial and the TCS sector to model the heat demand of TCS areas.

#### **Large individual heat consumers**

We identified four categories of LIHC which are particularly suited for DHNs fueled by heat generated from biomass: schools, hospitals, public outdoor swimming pools, and commercial greenhouses [26]. For the categories “schools” and “hospitals,” we used the POI-Bund Dataset which contains both spatial and content-related information on schools and hospitals such as the number of students per school or the number of beds per hospital [23].

For the category “public outdoor swimming pools,” we used the DLM which contains outdoor swimming pools (object type 2345). The values for heat demand per square meter of water surface vary in the literature between 280 kWh<sub>th</sub>/m<sup>2</sup>a and 700 kWh<sub>th</sub>/m<sup>2</sup>a [36, 37]. In order to define an appropriate value for our model, we evaluated municipal energy reports on ten public outdoor swimming pools and used the mean value of 435<sup>6</sup> kWh<sub>th</sub>/m<sup>2</sup>a.

The spatial information for the category “greenhouses” has been extracted from the OpenStreetMap buildings dataset. As this dataset does not contain any information on whether a greenhouse is used commercially, we have set the threshold of 100 m<sup>2</sup> floor space<sup>7</sup> as an indicator for this.

The heat demand for each object of those four categories was determined on the basis of object-specific key figures and object-specific reference units. Those key figures and their respective reference units are

<sup>4</sup>The manufacturing sector includes the economic sectors classified by WZ08-10 to WZ08-33 according to the German Classification of Economic Activities, 2008 edition [30].

<sup>5</sup>Meant here are all economic sectors except the manufacturing sector.

<sup>6</sup>For the original values see [38–45]

<sup>7</sup>We assumed that the floor space of privately used greenhouses does not exceed 100 m<sup>2</sup>.

**Table 2** Heat demand key figures of large individual heat consumers

Type	Count	Reference units for heat demand	Heat demand (kWh <sub>th</sub> /reference unit*a)	Comment
Schools and vocational colleges	33,577	No. of students	Ø 542 [46]	The data on the number of students is incomplete for 4220 objects. In such cases, we used the median heat demand of all schools: 0.116 GWh <sub>th</sub> /a
Hospitals	2217	No. of beds	Ø 27,320 [46]	The data on the number of beds is incomplete for 413 objects. In such cases, we used the median heat demand of all hospitals: 4.99 GWh <sub>th</sub> /a
Public outdoor swimming pools	4803	m <sup>2</sup> water surface	Ø 435	Value for heat demand is taken from municipal energy reports on heat demand of public outdoor swimming pools
Commercial greenhouses	14,868	m <sup>2</sup>	Ø 103 [47]	Minimum floor space of 100 m <sup>2</sup>

shown in Table 2. This enabled us to model the heat demand for a total of 55,465 individual objects.

#### Assessment of the BEP-specific heat sales potential

To determine the BEP-specific heat supply potentials, we looked at two different options on how BEPs can feed heat into a potential DHN. The spatial and technical information needed to do this was taken from the DBFZ bioenergy plant database. This database is continuously updated and contains detailed information on BEPs in Germany. It is based on information which the Federal Network Agency (Bundesnetzagentur, BNetzA) publishes on BEPs as part of the German Renewable Energy Act (Erneuerbare Energien Gesetz (EEG)) remuneration scheme and explained in more detail in Scheftelowitz et al. [18]. It is not possible to derive from the data whether a BEP already feeds into a DHN or not. For the following analyses, this aspect is not taken into consideration. It is also not possible to determine from the BEP database whether a BEP is actually a production unit or if it is a satellite CHPU which cannot be operated independently of its production unit. For this reason, all investigated BEPs are considered to be production units, an assumption which distorts the actual situation.

#### Distance-related heat supply scenarios

To determine the plant-specific tHSP, we looked at two different design options for DHNs: A and B. These are defined as follows: in Option A the heat produced at the BEP site is transported to the consumers via a directly connected local heating network, whereas in Option B biogas is transported via a raw biogas pipeline to a CHPU located directly on the site of the heat sink and the DHN commences at this point. Since the way heat is transported in Option A involves losses of up to 10%, the heat sink must be located in the immediate vicinity of the BEP [48]. The minimum overall heat density for a DHN in year-round operation is defined by the Quality Management (QM) system of the German/Swiss initiative “QM Holzheizwerke” as being 2 MWh/line meter and year [48]. In a comparable calculation for a region in Rhineland-Palatinate made in 2010, IZES and the

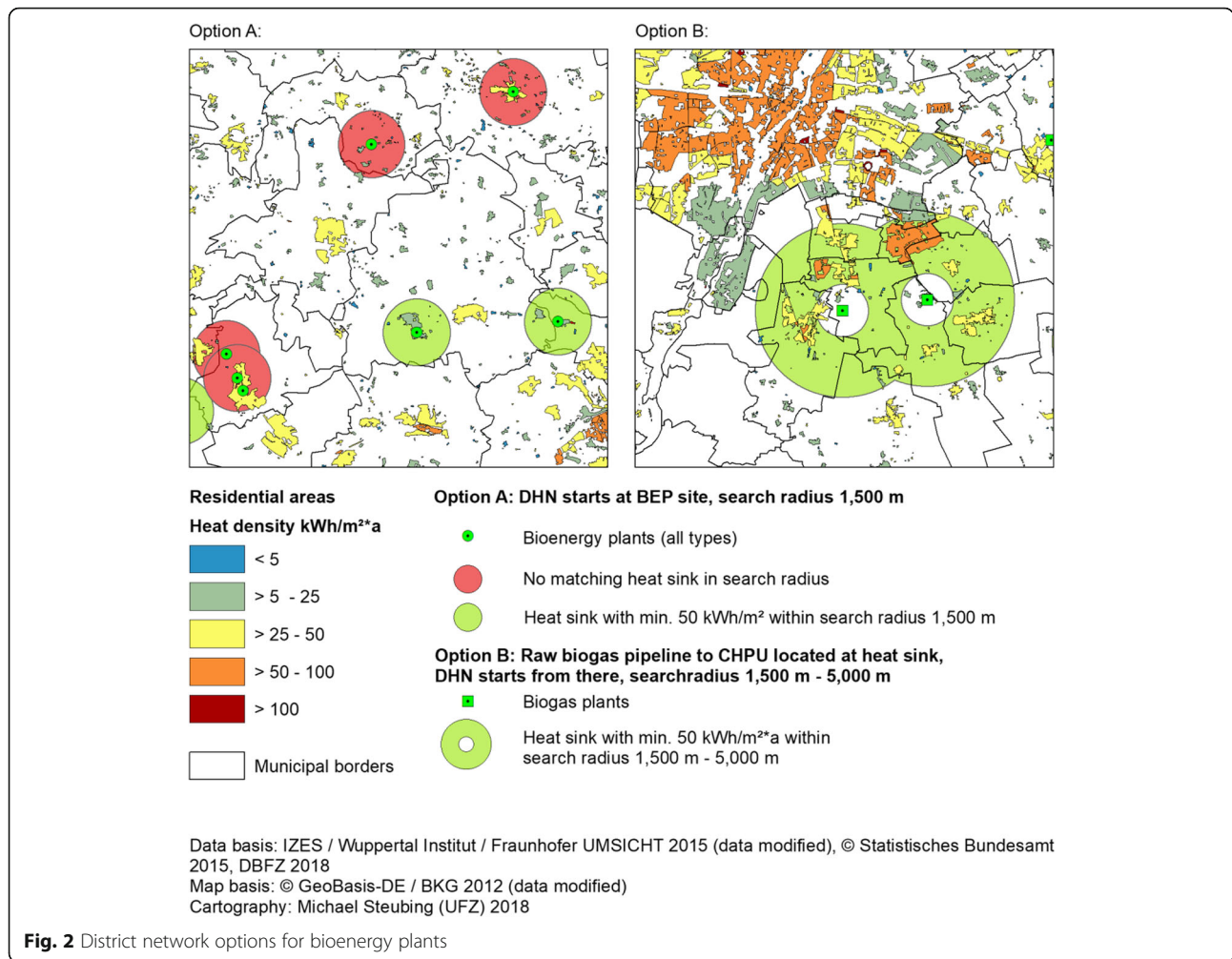
Institut für Energie- und Umweltforschung (ifeu) [49] stated that there should be a heat sink within a radius of 1000 m around a BEP to reach this value. Daniel et al. [50] found a higher figure for the whole grid and concluded that losses must not exceed 20% to ensure sufficient profitability. Losses up to this value occur with total grid lengths of between 1000 m and 5000 m and depend on the capacity of the respective CHPU [50]. Taking this assumption into account, we defined for our model a maximum distance of 1500 m between the BEP and the heat sink. This option is applicable for all BEPs.

Option B is applicable for biogas plants only. Since biogas can be transported over longer distances with only minor losses, the distance between the heat source and heat sink can be greater for this option. Obviously, this distance depends again on the capacity of the installation. IZES and ifeu [49] reported that BEPs with an installed capacity of 500 kW<sub>el</sub> can reach a distance of up to 5000 m for raw biogas pipelines without losing their economic feasibility [49]. In our case, we followed the assumption of this maximum distance between BEP and heat sink (5000 m) even though the mean value of the installed capacity of biogas plants throughout Germany is only 435 kW<sub>el</sub> [51]. A visual illustration of the two options for district heating networks under consideration is provided in Fig. 2.

To identify the plant-specific heat sales potential, we then used the spatial information on BEPs from the DBFZ bioenergy plant database and conducted a spatial query into whether there are suitable heat sinks at the respective distances. For residential areas and TCS areas, we defined that the minimum heat density<sup>8</sup> of the nearest heat sink has to be higher than 50 kWh<sub>th</sub>/m<sup>2</sup> × a<sup>9</sup> in order to be suitable for the DHN design options presented above. For the LIHCs, we did not define such a precondition, but instead considered the total heat demand of the respective LIHC.

<sup>8</sup>Heat density is a function of the area (m<sup>2</sup>) of a heat sink and its annual heat demand in kWh<sub>th</sub>.

<sup>9</sup>50 kWh/m<sup>2</sup>a can be regarded as the minimum heat density required for a local heating network [52].



### Categorizing the heat supply potential using line density modeling

So far in the spatial modeling approach, all heat sinks with a corresponding heat density of 50 kWh<sub>th</sub>/m<sup>2</sup>a in the vicinity of the respective BEP are initially selected as potential heat sinks. However, the gross heat demand (in GWh<sub>th</sub>/a) of the heat sink can be insufficient for achieving an economically viable DHN. Therefore, the spatial model required enhancement. To do this, we introduced the line density factor *LDF*. This factor represents the ratio of the heat demand of a heat sink in relation to the total potential network length and the funding conditions of the German Kreditanstalt für Wiederaufbau (KfW) for DHNs in Germany<sup>10</sup> and was calculated as follows:

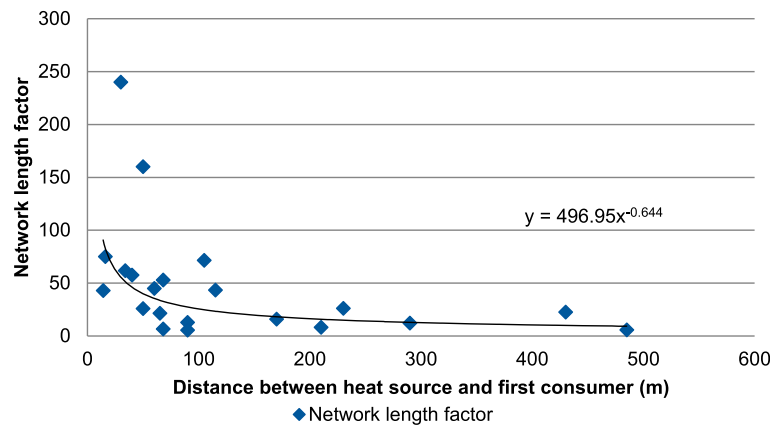
$$LDF = \left( \frac{Q_{RAO}}{D \times NLF} \right) \times 500 \text{ kWh/a} \quad (6)$$

where *LDF* is the line density factor, *Q* is the heat demand (kWh<sub>th</sub>/a), *D* is the linear distance bioenergy plant-heat sink (m), *NLF* is the network length factor, and *RAO* is the residential area object.

We assumed that if the annual heat demand of a given heat sink was unable to generate the required heat turnover of 500 kWh<sub>th</sub> per line meter [53], it was highly unlikely that a DHN would be built. This much more simplified method is a suitable way to eliminate inadequate heat sinks from the model. Values for a line density factor below 1 indicate that the annual heat turnover of a potential DHN would be too low. All heat sinks with a line density factor < 1 were therefore excluded from the model, which subsequently only contained heat sinks suitable for DHNs.

In order to determine the line density factor, it is necessary to know the total length of the DHN. Within the GIS model, however, only linear distances from the heat

<sup>10</sup>The German Kreditanstalt für Wiederaufbau (KfW) is Germany's largest development bank and grants loans to construct DHNs. In return, the bank demands a minimum yearly heat turnover of 500 kWh<sub>th</sub>/a per line meter [53].



**Fig. 3** Network length factor for twenty biomass-fueled district heating networks

source to the potential first consumer are known. The total network length must be estimated. For this purpose, we introduced the network length factor NLF. It describes the ratio of the total network length of a DHN to the distance between the heat source (the BEP) and the initial heat consumer and was calculated using Formula 7.

$$NLF = \frac{L_{tot.}}{D} \quad (7)$$

where NLF is the network length factor,  $L_{tot.}$  is the total network length (m), and  $D$  is the linear distance bioenergy plant to heat sink (m).

The NLF had to be assessed empirically. For this purpose, we analyzed 20 existing biomass-fueled DHNs for which the total network length is known [54–67]. We measured the distance between the heat-generating plant and the potential first consumer of these DHNs and calculated the NLF. Our data on the respective DHNs only includes cases where the distance between the plant and the first consumer is less than 500 m. For these systems, the median value of the NLF is 26.1.<sup>11</sup> For systems where there is a distance > 500 m between the heat source and the initial consumer, which occurs in our GIS data, the NLF was determined with the corresponding regression (see Fig. 3).

Figure 4 illustrates the correction process described above. If heat sink 1 is located within the search radius of 1500 m around a BEP and has a heat demand of 1.9 GWh<sub>th</sub>/a then, to develop the area, the heating network would have to be 6500 m long (assumption). However, to receive financial support, an annual heat turnover of at least 3.25 GWh<sub>th</sub> (6500 m × 500 kWh<sub>th</sub>/a = 3,250,000 kWh<sub>th</sub>/m×a) is required. Heat sink 1 does not have a

sufficient heat demand to operate the DHN economically and can therefore not be considered suitable for a local heating network (line density factor < 1). Heat sinks 2 and 3, on the other hand, have a sufficient heat demand and can therefore be considered for a DHN (line density factor > 1).

#### Economic viability of heat sales potential

This section presents the methodology used for assessing the economic heat sales potential (eHSP), since a second objective of this study was to evaluate the economic viability of the specific heat supply potential of the current German BEP stock. Here, the same dataset for BEPs was used as shown in Table 1.

Even though this study aimed to gain initial insights into the market potential of heat as a by-product of electricity generation, a full techno-economic feasibility assessment was not within the scope of our study. In our approach, economic viability depends on the potential of heat sales (demand/supply) and the associated estimated costs for heat distribution infrastructure (pipelines, peak load boilers, and storage facilities) as well as the earnings from heat sales.

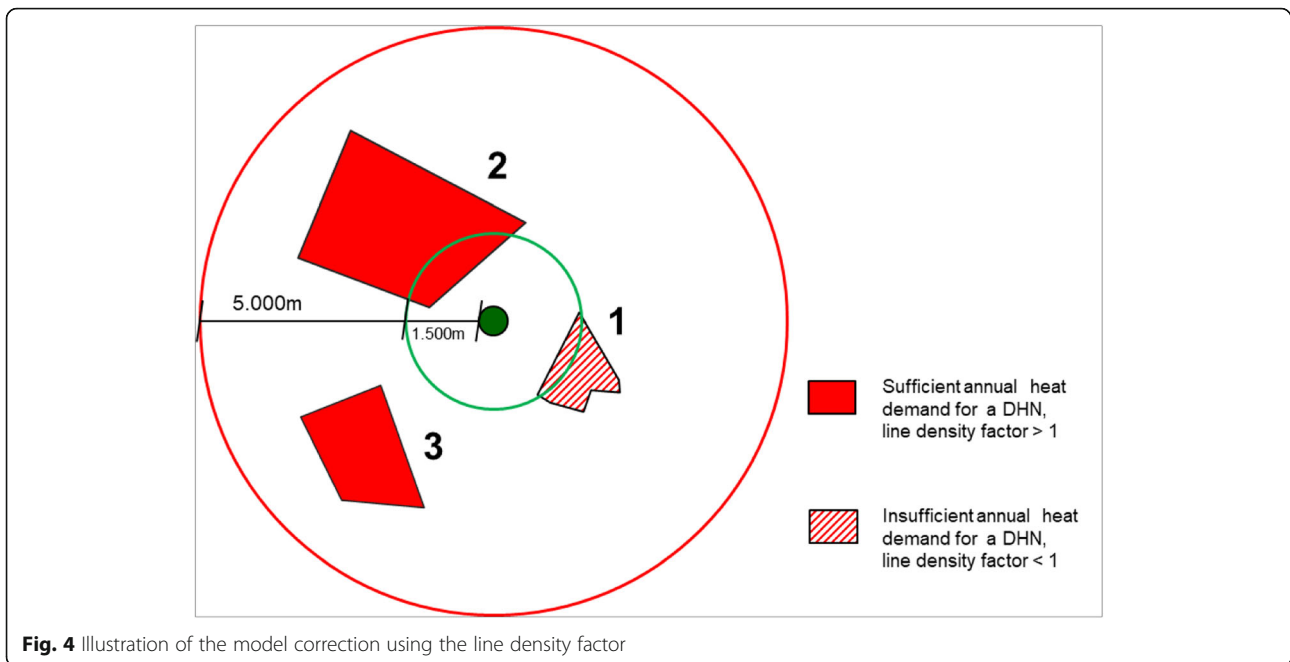
#### Evaluation scheme and main assumptions

In order to assess the eHSP, we developed an evaluation scheme that consisted of four main steps (Fig. 5). We first established individual BEP-heat sink relationships (Step 1) and then derived relevant indicators based on plant-specific data (Step 2). Before transferring all the information onto a bigger scale (Step 3), we grouped all the individual BEPs into clusters according to their EEG remuneration key. This enabled us to obtain the desired overview of the German BEP stock without compromising plant-specific data and provided the basis for the final economic assessment (Step 4).

In addition to the information on location and the related potential heat demand from spatial heat demand

<sup>11</sup>The original values for the total network length, the linear distance from the BEP to the potential first heat customer and the resulting NLF can be found in Table 11 in the Appendix.



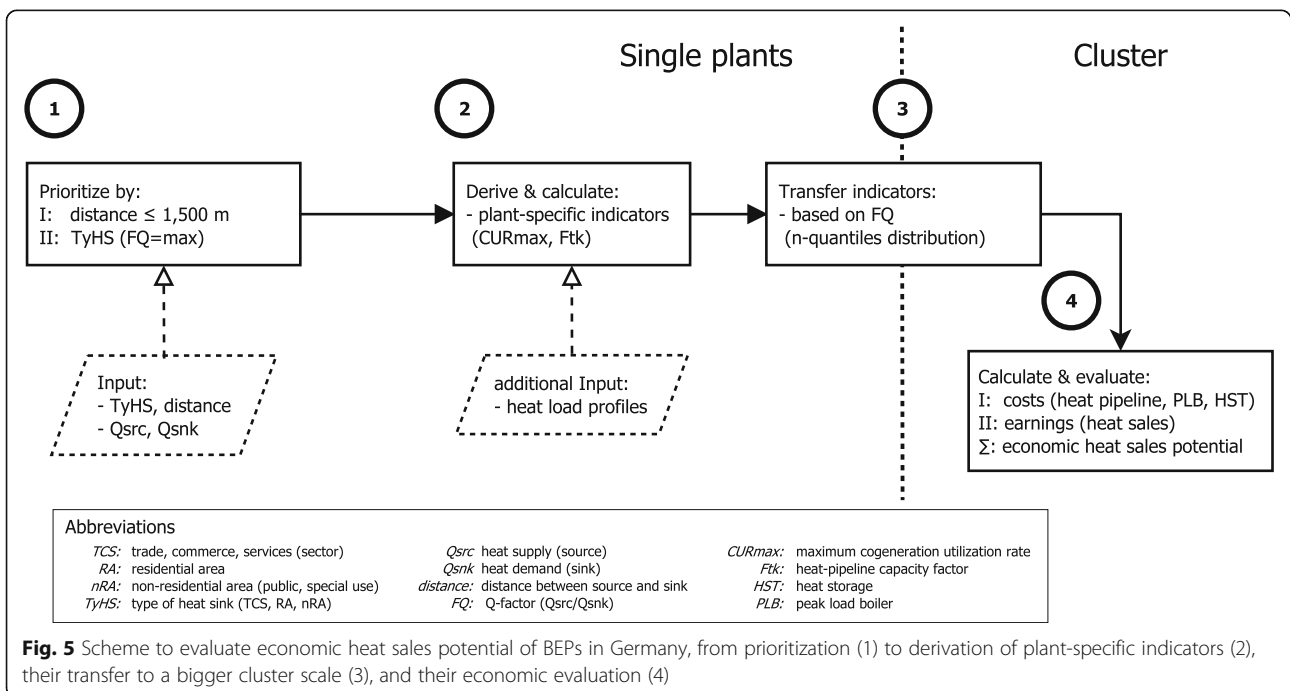


**Fig. 4** Illustration of the model correction using the line density factor

modeling (see above), we used energy-related BEP inventory data (Table 3) obtained from two databases: publicly available data published by the German Federal Network Agency (BNetzA) and datasets retrieved from annual plant operator surveys by the DBFZ (see [51]).

In this approach, we assumed four factors to be determinant for the economic viability of heat sales from BEPs (Table 4). Whereas the distance between the heat sink and the BEP (1), the type of heat sink (2) and the

heat supply-demand ratio (3) all govern the choice and size of the heat distribution infrastructure (pipelines, peak-load boilers, and storage facilities), the heat market price (4) ultimately determines income from heat sales. Other factors (e.g., local conditions underground which influence the excavation costs or regional differences between temperature profiles) may also have an influence on economic viability but their consideration would go far beyond the scope of this study.



**Fig. 5** Scheme to evaluate economic heat sales potential of BEPs in Germany, from prioritization (1) to derivation of plant-specific indicators (2), their transfer to a bigger cluster scale (3), and their economic evaluation (4)

**Table 3** Mean cluster-specific energy (supply) capacities based on BEP-specific values from German inventory data

Cluster		Main-Group	inst. cap. (el)	inst. cap. (th)	gross heat p.a.	net heat p.a.
Unit	n	[-]	[kW]	[kW]	[MWh]	[MWh]
biogas plant - slurry 75kW	1	biogas	70	88	672	403
biogas plant - (slurry) 150kW *	2	(slurry)	115	138	866	598
biogas plant - energy crops 250kW	3		215	244	1,712	1,181
biogas plant - energy crops 500kW	4	biogas	493	544	3,854	2,698
biogas plant - energy crops 750kW	5	(energy crops)	726	763	4,737	3,363
biogas plant - energy crops 1,000kW	6		1,315	1,315	5,927	4,446
biogas plant - residues 750kW	7	biogas	461	484	1,976	1,502
biogas plant - residues 1,000kW	8	(residues)	1,140	1,140	4,607	3,455
biogas plant - residues 2,000kW	9		1,500	1,427	5,779	4,276
waste wood power plant 10,000kW	10	CHP (waste wood)	11,727	27,469	172,678	172,678
wood powered CHP 50kW	11		39	94	376	376
wood powered CHP 250kW	12		270	559	2,533	2,533
wood powered CHP 2,000kW	13	CHP (wood)	1,384	4,568	21,928	21,928
wood powered CHP 5,000kW	14		5,233	12,558	69,737	69,737
wood powered CHP 10,000kW	15		11,889	21,796	117,207	117,207
wood powered CHP 20,000kW	16	CHP (paper pulp)	30,216	26,275	117,941	117,941
vegetable oil CHP 250kW	17	CHP (vegetable oil)	124	140	337	337
biomethane CHP 50kW	18		33	59	205	205
biomethane CHP 250kW	19	CHP (biomethane)	272	299	1,482	1,482
biomethane CHP 1,000kW	20		1,192	1,250	5,829	5,829

Net heat production is taking auxiliary power requirements into consideration

\*Cluster 2 does not solely use slurry but a mix of different substrates

### Steps 1-3: assessment indicators

In the first step of this evaluation scheme (Fig. 5), we used the spatial and energy-related information (derived from the above presented assessment of tHSP) to establish single BEP-heat sink relationships. We assumed specific heat delivery costs would decrease (economies of scale) as potential heat demand increased. Therefore, we linked each BEP to a single heat sink within a radius of 1500 m (Option A of the DHN design options) that had the highest potential heat demand (see Fig. 4 for an illustration). Since we expected that heat distribution costs would significantly affect economic viability, we excluded the option of exploring a larger radius or possible connections between multiple producers and consumers. We deliberately excluded biogas plants with potential

heat sinks within a radius of 1500-5000 m and the construction of a raw biogas pipeline from this assessment (Option B of the previously described DHN design options). Also, our methodology is only suitable for a 1:1 ratio between BEP and heat sinks, so we were unable to incorporate cross-linked networks.

We operationalized the BEP-heat sink relationship by introducing the “Q-factor” (FQ) which is heat demand ( $Q_{\text{snk}}$ ) divided by net heat production ( $Q_{\text{src}}$ ) (Formula 8). Furthermore, we decided to use this indicator as a main reference point for the economic assessment.

$$FQ = \frac{Q_{\text{snk}}}{Q_{\text{src}}} \quad (8)$$

**Table 4** Key determinants for assessing the economic feasibility of BEP heat sales potential (eHSP)

Determinants	Effects on the BEP heat sales potential
1 Location (distance)	The distance between a BEP and a potential heat sink determines the required length of heat pipelines (investment costs).
2 Type of heat sink (TyHS)	Seasonal fluctuations and peaks in the heat demand vary depending on the type of heat sink (heat load profiles). Peaks and troughs in heat demand might justify the use of peak load boilers (PLB) and heat storage facilities (HST).
3 Heat supply-demand ratio (FQ)	Heat distribution infrastructure needs to fit the given supply-demand ratio (transmission capacity) which also determines the potential earnings from heat sales.
4 Heat price at the point of sale ( $C_{\text{h@POS}}$ )	The additional income expected from heat sales depends not only on the distribution costs but also on the market price for heat.

**Table 5** Construction of synthetic heat load profiles

Type of heat sink	Type of heat load profile	Description
Residential sector	"Single dwelling", see [68]	Used for settlements
TCS/industrial sector	Weighted average of 10 TCS-load profiles from [68]	Used for TCS heat sinks as a blend of different TyHS
LIHC	"Laundry", see [68]	Used for LIHC like public outdoor swimming pools, greenhouses, schools, and hospitals

where FQ is the heat source-sink-ratio,  $Q_{\text{snk}}$  is the heat demand of a heat sink ( $\text{GWh}_{\text{th}}/\text{a}$ ), and  $Q_{\text{src}}$  is the net heat production of BEP ( $\text{GWh}_{\text{th}}/\text{a}$ ).

To refine this assessment, we considered seasonal fluctuation in heat demand depending on the characteristics of the type of heat sink (*TyHS*). Here, we distinguished between three *TyHS* for which we created synthetic heat load profiles according to a methodology that was presented by [68] (Table 5). For reasons of simplicity, we allocated the annual heat demand over the course of a year (8760 h) and decided not to create regionally explicit heat load profiles but to use only one climate reference dataset (weather station in Potsdam [69]).

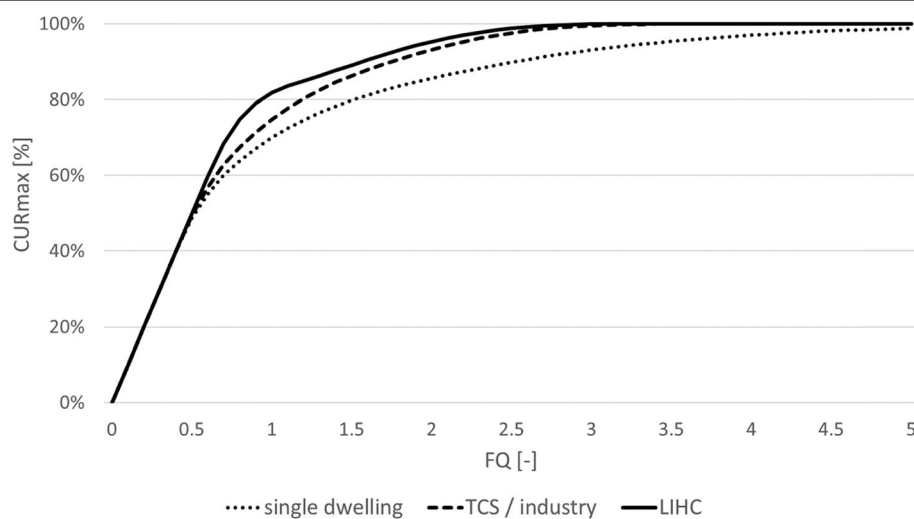
In the second step of the evaluation scheme (Fig. 5), we extended the plant-specific data and derived other indicators that influence the economic viability of heat sales, i.e., the maximum cogeneration utilization rate ( $\text{CUR}_{\text{max}}$ ) and a heat pipe capacity factor ( $F_{\text{tk}}$ ).

The maximum cogeneration utilization rate ( $\text{CUR}_{\text{max}}$ ) indicates how much of the BEP's gross heat generation could be sold on the market, taking into account a seasonal fluctuation in heat demand. For reasons of simplicity, we do not consider flexible operation of BEPs but assume 24-h operations that result in a constant heat supply at full capacity (net heat production) throughout the year. When both power and heat have to be considered at a temporal resolution, the analysis becomes

much more complex. We focused on varying heat demands and used heat load profiles, we had generated previously (Table 5) to calculate the  $\text{CUR}_{\text{max}}$  for each *TyHS* and for the FQ at intervals of 0.1 until a  $\text{CUR}_{\text{max}}$  of nearly 100% was reached (see Fig. 6).

Furthermore, we assumed that the investment costs of heat pipelines depend not only on their length but also on their diameter (heat transmission capacity). When heat storage facilities (HST) and bio-fueled peak load boilers (PLB) were used to supplement cogeneration and maintain heat supply, we also needed to adjust the heat pipeline diameter accordingly. Therefore, we introduced a heat pipe capacity factor ( $F_{\text{tk}}$ ), defined as the ratio of net heat supply to annual peak loads as observed in the generated load profiles (Table 5).

In the third step of the evaluation scheme (Fig. 5), we transferred the single-source sink-related data to the cluster level by aggregating the previously gathered information (FQ,  $\text{CUR}_{\text{max}}$ ,  $F_{\text{tk}}$ ) and the cluster-related information (Table 3). To do this, we divided each cluster into five groups each of which represented 20% of the BEPs in the respective cluster (quintiles) and which referred to equally sized classes of FQ. The FQ values assigned to each previous BEP-heat sink pair (Formula 8) were used for this statistical division. Whereas quintile 1 represents the 20% of BEPs with the smallest FQ values, quintile 5 represents the 20% of BEPs with the

**Fig. 6** Maximum cogeneration utilization rate ( $\text{CUR}_{\text{max}}$ ) in relation to FQ for three types of heat sinks (*TyHS*)

largest FQ values. Using this approach, we then assigned each BEP-heat sink pair to a cluster quintile and calculated the arithmetic mean of the  $CUR_{max}$  and  $F_{tk}$ .

**Step 4: economic assessment**

In the fourth and final step of the evaluation scheme (Fig. 5), we assessed the economic heat sales potential (eHSP) of German BEPs for all cluster quintiles based on the previously generated dataset. The remainder of this section will describe how we calculated the capital expenditures (CAPEX) for the heat distribution infrastructure and how we related these costs to expected earnings from heat sales.

The CAPEX in this assessment included investment costs such as annuities for heat pipelines, peak load boilers (PLB), and heat storage facilities (HST). For all cost calculations, we fixed the interest rate at 5% and assumed no price increase during a depreciation period of 15 years for PLBs and HSTs, and 25 years for heat pipelines. As a requirement for heat sales from BEPs, we first calculated the CAPEX for heat pipelines for all BEP-heat sink pairs. Then, we defined the PLBs and HSTs to those pairs that fulfilled a specific set of criteria (Table 6) and calculated the additional CAPEX from using them (including fuel costs for PLB). Finally, we calculated the mean CAPEX for each BEP cluster quintile and added the expected earnings from heat sales. Hence, we determined the economic viability of heat sales from German BEPs, including additional earnings from using PLBs and HSTs.

To calculate the CAPEX for heat pipelines ( $C_{pipe}$ ), we derived specific pipeline costs and multiplied them by the length of the heat pipelines required to connect each BEP with a heat sink (Formula 9). We introduced a correction factor (CF) to account for the fact that a heat pipeline will need to deviate from a direct line in order to overcome infrastructural barriers like residential areas, roads, or rail lines. We multiplied this CF by the distance between each BEP and heat sink to derive the required pipeline length (Formula 9). However, we did not consider the local distribution and transmission infrastructure that would be required, e.g., for district heating in residential areas [70].

$$L_T = D \times CF \tag{9}$$

where  $L_T$  is the length of a heat pipeline that is equal to the distance between a BEP-heat sink pair (Step 1,

Fig. 5) multiplied by a correction factor (CF). CF is equal to the square root of 2 which results from applying the Pythagorean theorem. Streamlining deviations, we divided the alternative way (the sum of the two legs of a right-angled triangle) by the direct distance between the BEP and heat sink (hypotenuse).

$$C_{pipe} = (C_T + C_c) \times L_T \tag{10}$$

where  $C_{pipe}$  is the cost of the heat pipeline calculated for each BEP-heat sink pair (Step 1, Fig. 5).  $C_T$  is the cost of the heat pipelines per meter (as a function of  $P_{th}$  and  $F_{tk}$ ).  $C_c$  represents other construction-related costs per meter (underground work and planning), and  $L_T$  is the length of heat pipeline (m).

Serving peak loads or storing heat in times of low demand might be economically reasonable if the expected additional earnings outweigh the additional CAPEX for HSTs and PLBs (including fuel costs for a PLB). Furthermore, the use of HSTs and PLBs would have an impact on the CAPEX for heat pipelines, affecting the required heat transmission capacity (diameter). We therefore established a set of rules for three different heat marketing concepts based on the level of FQ (Table 6). According to these rules, we decided whether to use peak load boilers (PLB) and/or heat storage (HST) for each BEP-heat sink pair and adjusted the required heat pipeline capacity accordingly.

Following a “full supply” marketing concept, we used HST and PLB and placed them close to the source (here the BEP). By adapting the pipeline capacity, all peak loads of heat could be potentially served via the heat pipeline ( $F_{tk} \times P_{th}$ ). The “basic supply” marketing concept differs as it prescribes only the use of an HST. Due to periods of peak demand, heat pipelines should be able to transport heat produced by the BEP and discharge the capacity of the storage. We therefore proposed that a heat pipeline’s capacity should be double the value of the BEP’s thermal capacity ( $F_{tk} = 2$ ) while both the charge and discharge rates are equal to the BEP heat capacity. The “full feed-in” option assumes there is no need for a PLB or HST so that we based the transmission capacity of the pipelines solely to the BEP’s capacity ( $F_{tk} = 1$ ).

In addition to considering the use of PLB and HST for the “full supply” and “basic supply” concepts, we

**Table 6** Rules for deciding on the heat sales marketing concept based on the FQ

Range of Q-factors	FQ ≤ 1.5	1.5 < FQ ≤ 5	FQ > 5
marketing concept	full supply	basic supply	full feed-in
heat storage facility	yes	yes	no
peak load boiler	yes	no	no
heat pipeline capacity	Q <sub>snk</sub>	2 * Q <sub>src</sub>	Q <sub>src</sub>



optimized their size aiming to find the most cost-efficient combination of both. For this purpose, we used a cost function (Formula 12) that builds upon an optimization approach which suggests that the investment costs for HST and PLB depend on their volume and power capacity [71].

The optimization approach for an ideal combination of PLB and HST is described in [71]. Here, we only accounted for the different heat load profiles for each quintile in every cluster (based on the previous TyHS and  $CUR_{max}$ ) in order to find minimum overall costs.

$$C_{opt.} = f(V) + f(P) + (C_{fuel} - C_{h@POS}) \times P_{th} \rightarrow \min \quad (12)$$

where  $C_{opt.}$  is the cost optimum,  $f(V)$  and  $f(P)$  are functions of the CAPEX for HSTs and PLBs [71] and  $P_{th}$  is a cluster's power capacity (see Table 3),  $C_{fuel}$  represents fuel costs and  $C_{h@POS}$  is the heat price at the point of sale. For simplification purposes, we fixed the potential heat losses from heat storage at a value of 10%, the PLB efficiency ( $\eta$ ) at 85%, the  $C_{h@POS}$  at 50 €/MWh<sub>th</sub> and the  $C_{fuel}$  at 30 €/MWh<sub>th</sub>.

We are aware of the fact that we created an inherent incentive to use PLB ( $C_{h@POS} > C_{fuel}$ ) and real prices for heat would be influenced by many factors such as the locality, market characteristics, and the type of heat sink. For instance, factors that affect local demand for heat from BEPs include existing access to the gas grid, availability (and abundance) of solid biogenic fuel (from wood), and a fossil-fueled heat source that is already connected to existing heat pipelines. However, due to the scope of this study, we did not specify and adjust the calculations to these factors. Finally, we determined the economic heat sales potential (eHSP) from German BEPs for all the cluster quintiles by calculating the annual heat sales potential in terms of heat earnings ( $E_{sale}$ ) (Formula 13) minus the financial expenditure for heat distribution (PLB, HST, and heat pipelines) (Formula 14).

$$E_{sale} = C_{h@POS} \times W_{th} \times CUR_{max} \quad (13)$$

where  $E_{sale}$  is the annual heat earnings (€),  $C_{h@POS}$  is the price of heat at the point of sale fixed at 50 €/MWh<sub>th</sub>,  $W_{th}$  is the net heat production (Table 3), and  $CUR_{max}$  is the maximum cogeneration utilization rate for each BEP cluster quintile.

$$eHSP = E_{sale} - C_{opt} - C_{pipe} \quad (14)$$

where eHSP is the economically viable heat sales potential,  $E_{sale}$  is the annual heat earnings (€),  $C_{opt.}$  is the cost optimum, and  $C_{pipe}$  is the cost of heat pipeline from BEP to heat sink (€).

Since we considered mainly heat as a by-product of electricity generation, we divided the eHSP (Formula 14) by the current electricity generated by the German BEP stock (as kWh of electrical power per BEP cluster [51]). This enabled us to compare the option of heat sales to other CHP options.

### Results

The outcomes of this study can be divided into three categories. Firstly, the spatially explicit heat demands for different relevant sectors, secondly the heat sales potential of the BEPs as a whole and on a plant-by-plant basis, and finally the estimation of the valuable heat sales potential.

#### Spatially explicit data on heat demand

As a result of the previously described modeling process, spatially explicit data is now available on the heat demand of various types of heat sinks (residential, TCS and industrial, large individual heat consumers) at a sub-municipal level for the whole of Germany. The data includes the type of heat sink (residential area objects, TCS/industrial area objects, LIHC), their gross heat demand in GWh<sub>th</sub>/a and their heat density in kWh<sub>th</sub>/m<sup>2</sup>a. Table 7 lists the residential area objects and TCS/

**Table 7** Number of residential area objects and TCS/industrial area objects classified by their heat density

Residential area objects								
Heat density (kWh <sub>th</sub> /m <sup>2</sup> a)	< 5	> 5-25	> 25-50	> 50-100	> 100	Total	Potential suitability for DHN (> 50 kWh <sub>th</sub> /m <sup>2</sup> a)	
							Count	%
No. of objects in class	93,738	327,011	107,322	25,718	12,669	566,458	38,387	6.8
TCS/industrial area objects								
Heat density (kWh <sub>th</sub> /m <sup>2</sup> a)	< 25	> 25-50	> 50-100	> 100-200	> 200	Total	Potential suitability for DHN (> 50 kWh <sub>th</sub> /m <sup>2</sup> a)	
							Count	%
No. of objects in class	3291	6847	19,086	33,670	43,918	106,811	96,674	90.5

industrial area objects based on their heat density. Here, the data indicates a clear difference between the two types of heat sinks. TCS/industrial area objects show a generally higher heat density than residential area objects. This is particularly noticeable in the number of objects with a heat density higher than  $50 \text{ kWh}_{\text{th}}/\text{m}^2\text{a}$  (the previously defined minimum heat density for a DHN). The vast majority (91%) of the TCS/industrial area objects have a heat density above this value; 41% even exhibit values of more than  $200 \text{ kWh}_{\text{th}}/\text{m}^2\text{a}$ . For the residential area objects, on the other hand, only approximately 7% of all objects have a heat density of  $50 \text{ kWh}_{\text{th}}/\text{m}^2\text{a}$  or higher. Almost 75% exhibit heat density values of less than  $25 \text{ kWh}_{\text{th}}/\text{m}^2\text{a}$ .

A visual representation of this data for the categories residential sector and TCS/industrial sector is presented in Fig. 7. This section of a city depicts how the variations in urban fabric produce different values for heat density, making them either more or less suitable for district heating networks. The inner-city areas show higher heat densities (usually more densely built up, more inhabitants per area) whereas the outer areas exhibit lower values (often residential areas with a less dense development).

## Technical heat sales potential

### Total heat sales potential

Using the previously presented methods, we were able to identify those BEPs which have suitable heat sinks nearby and to quantify the tHSP per category and on the whole. Of the total 14,236 BEPs analyzed, 52% (7383) have tHSP. The category TCS/industrial is most dominant with 5875 BEPs located next to suitable heat sinks, which is about 80% of all plants with tHSP. Two thousand four hundred twenty-nine plants have tHSP in the residential sector and 2,096 plants could serve as heat suppliers for LIHC. The detailed figures are presented in Table 8.

When considering the two different options for DHNs, Option A (DHN commencing directly at the BEP site) is suitable for most BEPs. For the categories TCS/industrial and LIHC, Option A is suitable for 85%, and 91%, of the plants respectively, while Option B is only suitable for 15% and 9% respectively. In contrast, for the residential sector, the ratio between Option A and Option B (DHN starting from the BEP, raw biogas pipeline to CHPU located at heat sink) is more evenly distributed. Forty-one percent of the BEPs with tHSP could theoretically apply Option B. This is conclusive as the previous chapter has shown that TCS/industrial areas are better suited for DHNs or better qualified as heat consumers, as heat demand and heat density are generally higher in these areas.

Looking at the heat sales potential per category, a similar picture unfolds. The overall tHSP is  $153.61 \text{ TWh}_{\text{th}}/\text{a}$  of which more than two-thirds (69% or  $105.94 \text{ TWh}_{\text{th}}/\text{a}$ ) correspond to the category TCS/industrial. The residential sector accounts for 30% ( $46.15 \text{ TWh}_{\text{th}}/\text{a}$ ), and 1% ( $1.52 \text{ TWh}_{\text{th}}/\text{a}$ ) is attributable to LIHC.

The total tHSP of  $153 \text{ TWh}_{\text{th}}/\text{a}$  corresponds to 17% of the final energy demand for heating (only space heating and hot water; reference year 2011, which is the point in time of the IZES heat demand figures).

For the residential and TCS/industrial sector categories, this results in a proportion of final energy consumption in the heating sector of 7% and 38% respectively.<sup>12</sup>

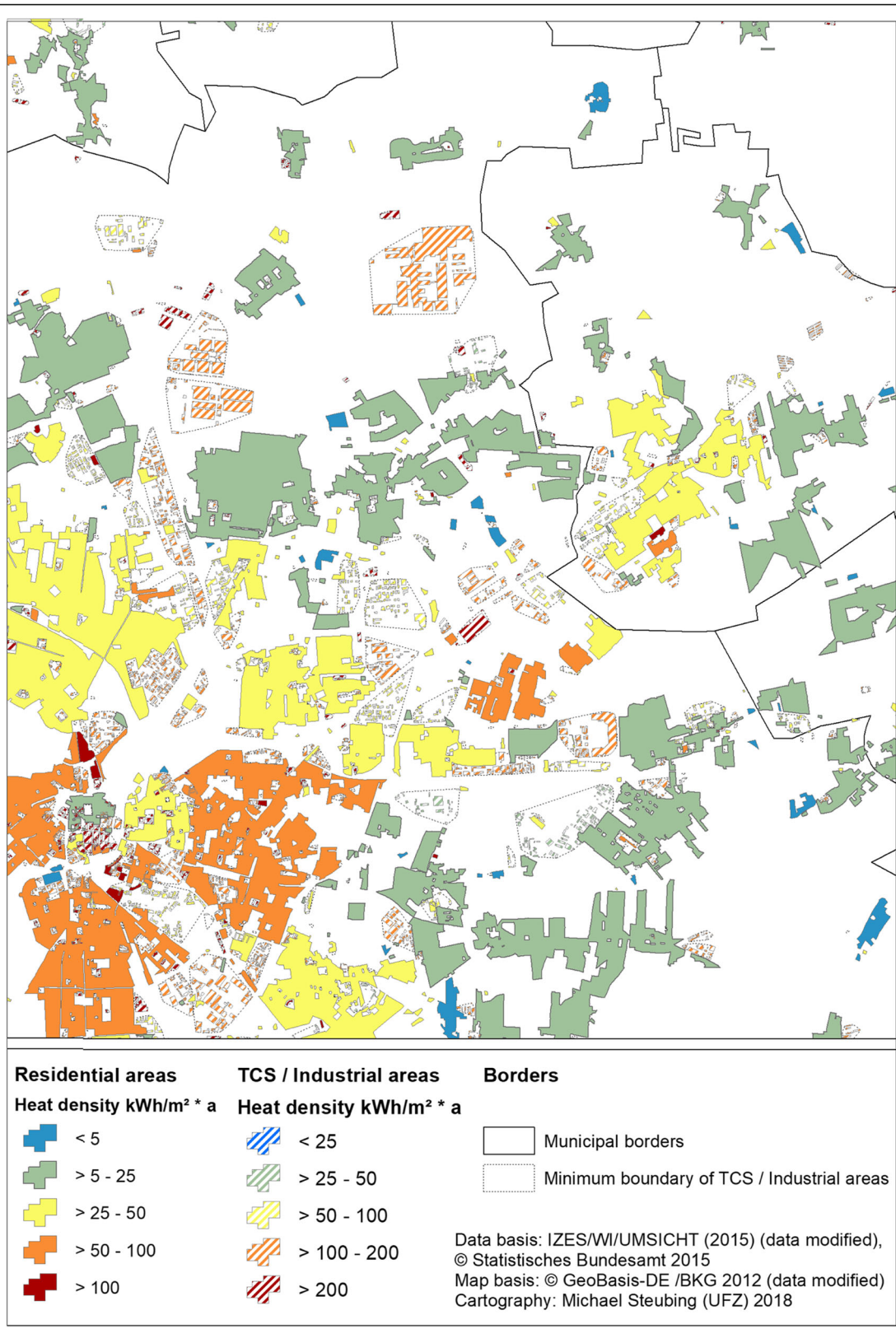
However, this potential is not evenly distributed among all BEPs with a DHN option. Taking into account all BEPs for which we could determine sufficient tHSP, and using the heat density of the respective heat sinks as an indicator for the feasibility of a DHN, it is possible to identify statistical hot and cold spots. The hot spots represent plants whose heat sinks have heat densities that have a high statistical significance and are surrounded by plants whose heat sinks have equally high heat densities. For the cold spots, the opposite is true. Consequently, it is possible to identify spatial clusters of plants which could be preferable for a heating network. Figure 8 shows all BEPs with tHSP for each category as well as statistical hot and cold spots.

The identified hot spots point to conditions in the corresponding regions that tend to be advantageous for DHNs. In the residential sector, these include a high population density and corresponding housing typologies (i.e., multi-story buildings) [73]. For the category TCS/industrial, we observed hot and cold spots. The hot spots indicate that the BEPs are close to commercial or industrial areas with a high heat demand, whereas the cold spots imply that the heat demand in the areas under observation is low in comparison to surrounding areas.

## Economic heat sales potential

As described in the methodology section, we analyzed the German BEP inventory data to estimate the economic heat sales potential (eHSP) in a step-by-step process (see Fig. 5). Since we limited the scope of this study to looking at the bigger picture, we did not conduct regionally explicit assessments. Therefore, we aggregated single plant data into a set of 20 BEP clusters and further refined the view by splitting each cluster into 20% shares (quintiles) based on a heat source-sink-ratio

<sup>12</sup>The final energy consumption in the heating sector for space heating and hot water (2011) was  $916.1 \text{ TWh}_{\text{th}}/\text{a}$  of which  $631.6 \text{ TWh}_{\text{th}}/\text{a}$  were consumed by the residential sector and  $281.4 \text{ TWh}_{\text{th}}/\text{a}$  by the TCS and industrial sectors [72].



**Fig. 7** Example of the heat demand of residential area objects and TCS/industrial area objects modeled at a sub-municipal level

**Table 8** Number of BEP with option for district heating networks and heat sales potential per category

	Residential	TCS/Industrial	Large individual heat consumers (LIHC)	Total
Analyzed BEP				14,236
BEP without district heating network option				6853
BEP with district heating network option				7383 <sup>a</sup>
Option A	1435	4993	1916	--
Option B	994	882	180	--
Total	2429	5875	2096	--
Heat sales potential [TWh <sub>th</sub> /a]				
Option A	34.99	94.05	1.23	130.27
Option B	11.16	11.89	0.29	23.34
Total	46.15	105.94	1.52	153.61

<sup>a</sup>Some of the BEPs have a heat sales potential in more than one category (residential, TCS/industrial, LIHC) and are suitable for Options A and B. The number of plants per category and option can therefore not be added up

(FQ). This ratio represents the available heat generated by an operating BEP divided by the potential heat demand of a heat sink within a maximum distance of 1500 m.

The results for all clusters and their quintiles ( $Q_n$ ) are presented in Table 9 and show that for some of the quintiles the costs for heat distribution exceed the net earnings and vice versa. The results are quite heterogeneous with deficits reaching 12.8 eurocents per kWh of electricity produced by BEPs (Cluster 18,  $Q_2$ ) and potential earnings of up to 16 eurocents per kWh (Cluster 10,  $Q_5$ ). Heat sales could be economically viable for 78% of the assessed BEPs but would generate deficits in 13% of the cases. Nine percent of the BEP quintiles would not be considered for heat distribution since they only contain BEPs with no potential heat customer in their vicinity (1500 m). Furthermore, heat sales seem to be economically more viable for the upper quintiles in each cluster (highest FQ).

One of the reasons why the eHSP in the upper quintiles is higher, it is due to the fact that these mostly contain BEP-heat sink-pairs with higher FQ values. Since the quintile distribution was based on the FQ, the proportion of salable heat from BEPs (waste heat) is therefore higher in the upper quintiles and affects the eHSP. Once the FQ exceeds a value of 5, we assumed the maximum cogeneration utilization rate ( $CUR_{max}$ ) to be 100% (Fig. 6). In Table 10, we can observe that the 4th and 5th quintiles show values from 92–100% for  $CUR_{max}$  in all the clusters. This indicates that at least 40% of the BEPs within each cluster can possibly supply all, or nearly all, of their net heat production to nearby heat sinks.

Table 9 and Table 10 also display the actual supply potential of the German BEP stock. The overall exhaust heat amount of all 20 clusters totals to a gross value of

37.7 TWh<sub>th</sub>/a (Table 9). Taking into consideration the different ratios for  $CUR_{max}$ , the externally usable heat amounts to 19.1 TWh<sub>th</sub>/a (Table 10) of which 16.3 TWh<sub>th</sub>/a could be identified economically viable heat sales potential (Table 9).

## Discussion

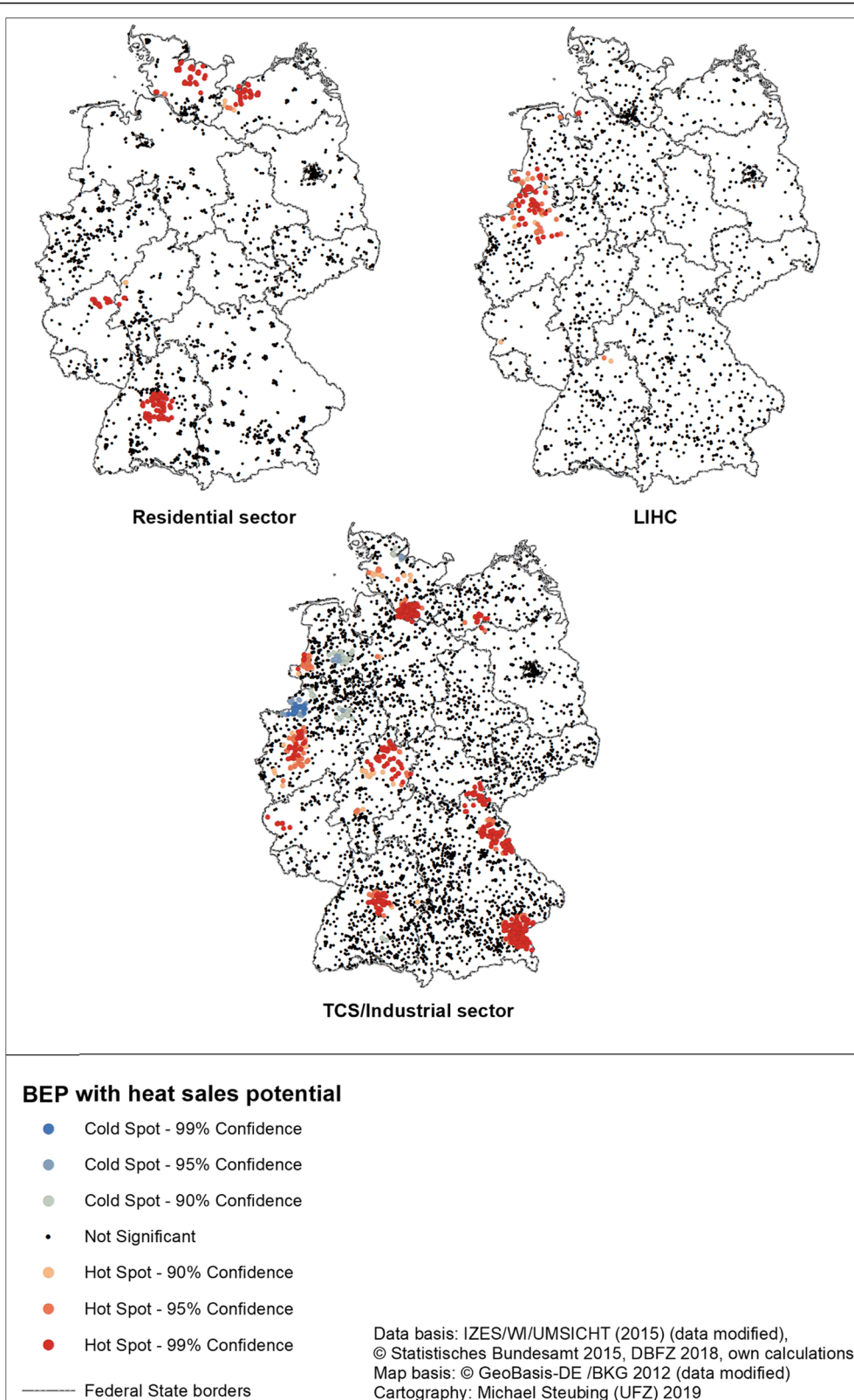
As the results indicate, the presented methods are a suitable approach for determining the BEP-specific tHSP and subsequently for estimating the eHSP. The required data could be generated by mostly publicly available data sources as described in the method section. The data indicates that there is currently unused potential especially with regard to tHSP but for eHSP too. Most of the BEPs display positive values concerning this matter, especially in the quintiles Q4 and Q5 of the 20 BEP-clusters.

The total tHSP of 153 TWh<sub>th</sub>/a corresponds to 17%<sup>13</sup> of the final energy demand for space heating [72]. Bioenergy plants in contrast, generate a gross heat amount of 37.7 TWh<sub>th</sub>/a, of which 19.1 TWh<sub>th</sub>/a could be used externally (net heat amount). Our results show, that the economically viable supply potential of 16.3 TWh<sub>th</sub>/a (see Table 9) almost covers the net heat generation.

According to most recent energy statistics, biogas plants already generate heat in an order of 15.5 TWh<sub>th</sub>/a [10]. We estimate that the economical heat sales potential for those clusters of plants would be about 11.2 TWh. Thus, assuming that co-generated heat is not solely used for space heating, the order of the calculated potential is closely related to the recent amount. The

<sup>13</sup>As previously mentioned, this is the figure for 2011. Latest energy statistics (2018) state an energy demand for space heating and hot water of 764.4 TWh<sub>th</sub>/a [74]. In this case tHSP corresponds to 20%.





**Fig. 8** Statistical hot and cold spots of bioenergy plants with tHSP in relation to the heat density of their nearest heat sink

**Table 9** Annual heat sales potential: net earnings minus annuity of distribution costs

Cluster		Specific heat sale balance [Ct/kWhel]					Cluster		Economic heat sale potential (eHSP) [GWh]				
n		Q1	Q2	Q3	Q4	Q5	n		Q1	Q2	Q3	Q4	Q5
1*		0.0	1.0	-2.0	-0.6	-1.5	1*		0	51	0	0	0
2*		0.0	0.5	4.0	-4.4	0.4	2*		0	0	0	0	1
3*		0.1	-0.6	1.4	2.1	2.3	3*		69	0	1,969	1,880	953
4*		-0.4	0.3	1.9	2.9	3.1	4*		0	521	1,217	1,489	786
5*		-0.3	0.3	2.3	3.0	3.0	5*		0	198	478	457	271
6*		-0.4	0.6	2.8	3.2	3.3	6*		0	110	220	256	117
7*		0.2	1.0	2.4	2.0	2.8	7*		5	24	24	25	12
8*		0.0	0.2	3.2	3.2	3.2	8*		0	3	15	4	3
9*		0.8	1.9	2.1	2.1	1.9	9*		18	10	2	1	1
10		0.4	7.3	11.5	11.6	11.6	10		33	201	250	50	45
11		0.0	1.7	-9.9	-5.2	2.7	11		0	25	0	0	24
12		0.0	-1.1	3.6	7.4	9.1	12		0	0	83	110	62
13		0.0	3.6	13.6	15.6	16.0	13		0	187	229	346	104
14		0.4	4.5	10.9	11.9	11.9	14		10	37	82	42	13
15		0.0	4.6	8.6	9.1	9.2	15		0	9	11	14	8
16		0.0	3.3	3.9	4.3	4.3	16		0	2	1	1	2
17		0.0	1.4	-2.3	5.7	5.7	17		0	246	0	457	56
18		1.2	-12.8	9.0	9.0	9.0	18		96	0	388	77	14
19		0.3	2.5	4.0	3.8	4.1	19		22	414	264	161	59
20		0.9	4.3	4.7	4.9	4.9	20		104	297	215	198	45
		Σ Q1-Q5							Σ Q1-Q5				
Σ <sub>net</sub> [TWh]	0.5	4.0	6.2	5.7	2.6	19.1	Σ eHSP [TWh]	0.4	2.3	5.5	5.6	2.6	16.3
*biogas [TWh]	0.3	1.9	4.0	4.2	2.2	12.5	*biogas [TWh]	0.1	0.9	3.9	4.1	2.1	11.2

official energy statistics [74] do not contain disaggregated data for plants fueled by solid biomass, so a similar comparison is not possible here.

These numbers exceed the figures which have been found in energy scenarios for heat supply by local district heating networks in Germany [14]. However, it also

displays the high potential of biomass fueled cogeneration plants, which could also provide a noteworthy contribution to renewable heat in Germany.

To unlock this currently unused potential, further investigations on specific constraints are necessary, because the input dataset has some weaknesses. First,

**Table 10** Results for the gross exhaust heat amount, the individual CUR<sub>max</sub> of the 20 BEP plant clusters

Cluster		Exhaust heat amount [GWh]					Cluster		Maximum cogeneration utilization rate (CUR <sub>max</sub> ) [%]				
n		Q1	Q2	Q3	Q4	Q5	n		Q1	Q2	Q3	Q4	Q5
1*		191	195	95	69	26	1*		0%	26%	82%	100%	100%
2*		1	3	0	0	1	2*		0%	10%	100%	100%	100%
3*		2,815	3,034	2,445	1,889	953	3*		2%	32%	81%	100%	100%
4*		2,511	1,874	1,668	1,517	786	4*		4%	28%	73%	98%	100%
5*		1,367	715	633	462	271	5*		5%	28%	76%	99%	100%
6*		256	355	269	256	117	6*		4%	31%	82%	100%	100%
7*		91	42	26	25	12	7*		5%	58%	96%	100%	100%
8*		12	12	17	4	3	8*		0%	27%	91%	100%	100%
9*		34	11	2	1	1	9*		54%	98%	100%	100%	100%
10		915	358	253	50	45	10		4%	56%	99%	100%	100%
11		189	182	227	103	24	11		0%	14%	64%	99%	100%
12		139	120	152	119	62	12		0%	10%	55%	92%	100%
13		184	717	291	352	104	13		0%	26%	78%	98%	100%
14		254	94	102	42	13	14		4%	40%	81%	99%	100%
15		65	17	12	14	8	15		0%	52%	95%	100%	100%
16		79	2	2	1	2	16		0%	75%	89%	100%	100%
17		593	967	628	457	56	17		0%	25%	89%	100%	100%
18		716	765	388	77	14	18		13%	86%	100%	100%	100%
19		377	595	265	161	59	19		6%	70%	100%	100%	100%
20		417	327	215	198	45	20		25%	91%	100%	100%	100%
		Σ Q1-Q5							Σ Q1-Q5				
Σ <sub>gross</sub> [TWh]	11.2	10.4	7.7	5.8	2.6	37.7	Σ <sub>net</sub> [TWh]	0.5	4.0	6.2	5.7	2.6	19.1
*biogas [TWh]	7.3	6.2	5.2	4.2	2.2	25.1	*biogas [TWh]	0.3	1.9	4.0	4.2	2.2	12.5

The clusters are divided into 5 quintiles according to the FQ distribution and the resulting accumulated net heat amount

the heat demand was estimated using primary data representing the status quo in 2011. For modeling the heat demand, influencing factors such as regional climate differences, the refurbishment status of the buildings, or the impact of demographic change were not taken into account. In particular, the latter is likely to have an impact on settlement structures and, as energetic refurbishment progresses; the heat demand in the building sector will decrease. However, the stagnating energy demand for heating and hot water [74] shows that energetic refurbishment of buildings (existing stock and new constructions) is progressing slowly. The impact of this on the model results should be low. Second, data for the TCS/industrial sector does not include the sector-specific demand pattern (temperature level, daily and seasonal demand patterns). In order to assign the exact heat demand to each individual industrial or commercial area, it would also be necessary to know exactly what kind of companies (in terms of industry) are located in a specific area. Detailed feasibility studies, in which the heat demand of the consumers is precisely determined, are always necessary in order to make concrete investment decisions in heating networks. Furthermore, there are a number of hard and soft conditions that a municipality must fulfill in order to ensure that the prerequisites for the economic operation of a DHN are met. These include setting the right regulatory framework, e.g., securing areas in spatial planning or requiring connection to the DHN in certain areas [6].

Third, temperature level constraints, in terms of both the forward and backward flow of potential DHNs, were not considered during the modeling process. This is due to the fact that the DBFZ BEP plant database does not include technical specifications of the respective CHPUs or the temperature levels they are able to provide. Thus, it cannot be assumed that the heat demand of heat consumers requiring higher temperature levels (e.g., process heat for industrial processes) can be completely covered by the heat generated by the corresponding BEP. Nevertheless, the analyzed BEPs should at least be able to contribute to the generation of the required space heating or domestic hot water.

With these uncertainties in mind, the previously stated tHSP for BEP is over- rather than underestimated.

When discussing the results for estimating economic viability, some inadequateness of the methodology should first be clarified. It is important to mention that the described approach for calculating the heat sales potential for all BEP in Germany is based on spatial information, which shows some unavoidable blurring. For example, the location of biomethane CHPs and their corresponding heat sinks may produce results (Q1-Q3)

which imply that a significant proportion of that cluster cannot ensure a  $CUR_{max}$  of 100%. However, it is assumed that all biomethane-CHPs utilize all of their heat, since the remuneration scheme they use within the EEG demands complete cogeneration utilization. It is also important to keep in mind that the results presented here represent mean values calculated for the specific quintiles and therefore only describe the conditions for a group of BEPs. This does not necessarily mean that each individual plant in a cluster can be precisely characterized by the values for the quintiles. Also, the assumption of a direct link between the heat source and the heat sink underestimates real world conditions. Usually, there would be many barriers which lead to additional demands for a heat pipeline. Up to this point, we do not have a suitable approach for identifying empirical data for the extra distance needed. In order to interpret the tHSP results, it needs to be mentioned that we did not include competing heat providers in our analysis. This must be especially taken into account for the TCS/industrial category where the calculated heat demand is likely to be met by other sources such as excess industrial heat.

The methodology was developed within the project "Bioenergy - potentials, long-term perspectives and strategies for power generation plants after 2020 (BE20plus)" which pursues the aim of evaluating the economic viability of BEPs after they drop out of the EEG's first remuneration period after 20 years. Subsequently, we will use these results to establish which proportion of the recent BEP-portfolio can achieve profitability in a (potentially) second operational period. The findings show that heat sales are not a worthwhile option for some quintiles of the BEP clusters. This is partly due to the fact that there are no suitable heat sinks within the search radius (1500 m) and that the estimated costs for heat distribution exceed the assumed earnings from heat sales. This applies to cases where the heat demand of a heat sink is insufficient and the distance between BEP and heat sink is too far.

In general, even though decreasing electrical efficiency would increase eHSP, power plant operators would not compromise their electricity generation for greater (or exclusive) heat production, since the economic value of heat<sup>14</sup> is lower than that of electricity within the EEG remuneration scheme.

## Conclusion

In our study, we analyzed the heat sales potential of BEPs within the EEG remuneration scheme in Germany. The results show that, based on our assumptions, 52% of the BEPs are suitable for distributing heat through a

<sup>14</sup>Biogas plant operators received 2.6 ct/kWh<sub>th</sub> on average [75].

DHN. The overall technical heat sales potential for these BEPs is approximately 153 TWh<sub>th</sub>/a. About two-thirds of this is attributed to the TCS/industrial sector and about one-third to the residential sector. The share of large individual heat consumers in this potential is only about one percent. This total technical heat sales potential is equivalent to almost 12% of the final energy consumption in the German heating sector. However, this analyzed technical heat sales potential of 153 TWh<sub>th</sub>/a cannot be fully covered by the BEPs identified with the potential for a DHN option. Their gross supply potential for externally usable heat adds up to 19.1 TWh<sub>th</sub>/a and an economically viable supply potential of 16.3 TWh<sub>th</sub>/a. The figures on heat sales potential reveal two different aspects. On the one hand, it becomes clear that, in a best-case scenario, only half of the existing BEPs in Germany have the possibility of distributing heat by means of a DHN and generating revenues by doing so. This must be especially taken into account when looking at future possible business segments for BEPs after their EEG remuneration period ends, since those plants are not competitive by generating power only. On the other hand, we identified considerable potentials for DHNs for those BEPs which have heat sinks nearby. These networks can either be fully supplied with biomass or supplemented with other technologies suited for grid-bound heat supply (e.g., larger heat pumps). We conclude that biomass has further potential as a renewable fuel in supplying district heating networks and that the current BEP stock can contribute to increasing the share of RES in the heating sector. Decisive factors in this context are the BEP's relationship to potential heat customers and their specific requirements for heat supply. In order to fully exploit this potential, the BEPs have to be embedded in local or regional heating strategies which take local conditions into account.

With regard to economic viability, it can be concluded that even if there are potential heat consumers within an acceptable distance to the BEP, heat sales are often not an attractive opportunity for all of them since the costs for distributing the heat can exceed the potential earnings. This might change in the medium term with the obligation to include RES into new heating systems, the introduction of CO<sub>2</sub>-prices and the ban of oil-fired heating systems from 2026 on [76]. These measures are included in a law passed by the German Federal Government at the end of 2019 [77] to achieve its Paris Climate Agreement goals.

The question of heat sales potential is crucial for future business concepts of BEPs, since heat is the most valuable by-product for most of those plants. We are looking forward to integrating the results of this work in a wider approach to cover all factors relevant for BEP profitability.

## Appendix

**Table 11** Total network length, distance of BEP to first potential customer and resulting network length factor of 20 existing DHNs fueled by heat generated from biomass in Germany

Number	Reference	Total network length ( $L_{tot}$ ) (m)	Linear distance of BEP to first potential customer (D)(m)	Network length factor (NLF)
1	[61]	600	14	42.86
2	[54]	1200	16	75.00
3	[62]	7200	30	240.00
4	[64]	2100	34	61.76
5	[65]	2300	40	57.50
6	[56]	1900	434	4.37
7	[60]	1300	50	26.00
8	[58]	1400	65	21.54
9	[66]	450	68	6.62
10	[67]	3600	68	52.94
11	[58]	1160	90	12.89
12	[58]	505	90	5.61
13	[65]	7500	105	71.43
14	[57]	5000	115	43.48
15	[59]	2700	70	38.57
16	[55]	1700	210	8.10
17	[65]	6000	230	26.09
18	[65]	3500	290	12.07
19	[63]	9720	430	22.60
20	[67]	3500	485	7.22
NLF = $\frac{L_{tot}}{D}$			Mean	41.83
			Median	26.1

## Abbreviations

ATKIS: Amtliches Topographisch-Kartographisches Informations System; BEP: Bioenergy plant; CHP: Combined heat and power; CHPU: Combined heat and power unit; CUR<sub>max</sub>: Maximum cogeneration utilization rate; DHN: District heating network; DLM: Digital landscape model; eHSP: Economical heat sales potential; FQ: Heat demand-supply factor; HS: Heat storage; OSM: OpenStreetMap; PF: Population factor; Ph@POS: Heat price at the point of sale; PLB: Peak load boiler; Q: Annual heat demand of a heat sink; QF: Q-factor (ratio of heat demand and gross heat supply of a given source); RAF: Residential area factor; RAO: Residential area object; TCS: Trade, commerce and services; thSP: Technical heat sales potential; TyHS: Type of heat sink

## Acknowledgements

Joint research on this paper has been undertaken by the institutions UFZ, DBFZ, and IZES in the context of the project "Bioenergy - potentials, long-term perspectives and strategies for power generation plants after 2020 (BE20plus)".

## Authors' contributions

Several authors drafted the different parts of the initial version of this manuscript. All authors contributed to the revising and finalizing of the article. All authors read and approved the final manuscript.



**Funding**

This research received funding from the Agency for Renewable Resources e.V. (FNR) and the Federal Ministry for Food and Agriculture (BMEL). The funding bodies had no influence over the design of the study, the interpretation of the data, or the writing of the manuscript.

**Availability of data and materials**

The datasets generated and/or analyzed as part of the current study are not publicly available due to the privacy policy of the institutions involved, but are available from the corresponding author upon request.

**Ethics approval and consent to participate**

Not applicable

**Consent for publication**

Not applicable

**Competing interests**

The authors declare that they have no competing interests.

**Author details**

<sup>1</sup>Helmholtz Centre for Environmental Research, Permoserstrasse 15, 04318 Leipzig, Germany. <sup>2</sup>Deutsches Biomasseforschungszentrum gGmbH (DBFZ), Torgauer Strasse 116, 04347 Leipzig, Germany. <sup>3</sup>izes gGmbH – Institut für ZukunftsEnergie- und Stoffstromsysteme, Altenkesseler Strasse 17, Geb. A1, 66115 Saarbrücken, Germany.

Received: 16 April 2019 Accepted: 26 February 2020

Published online: 16 March 2020

**References**

- UBA [German Environment Agency] (2018) Energieverbrauch für fossile und erneuerbare Wärme. <https://www.umweltbundesamt.de/daten/energie/energieverbrauch-fuer-fossile-erneuerbare-waerme#textpart-1>.
- European Commission [EC] (2016) Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions. An EU Strategy on Heating and Cooling. COM(2016) 51 final on 16.2.2016. EC, Brussels
- Fleiter T, Elsland R, Rehfeld M, Steinbach J, Reiter U, Catenazzi G, Jakob M, Rutten C, Harmsen R, Dittmann F, Rivière P, Stabat P (2017) Heat roadmap Europe. A low-carbon heating and cooling strategy. Profile of heating and cooling demand in 2015. Fraunhofer Institut für System- und Innovationsforschung (ISI), TEP Energy GmbH, University Utrecht, ARMINES, Karlsruhe
- AGFW [Der Effizienzverband für Wärme Kälte und KWK e.V.] (2018) AGFW - Hauptbericht 2017. AGFW, Frankfurt am Main
- Gerhardt N, Sandau F, Becker S, Scholz A, Schumacher P, Schmidt D (2017) Wärmewende 2030. Schlüsseltechnologien zur Erreichung der mittel- und langfristigen Klimaschutzziele im Gebäudesektor. Studie im Auftrag von Agora Energiewende. Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES), Fraunhofer-Institut für Bauphysik (IBP), Berlin
- Baur F, Noll F, Vogler C, Wern B, Mees M, Steinert M, Wiedemeyer N, Beyer S, Hill A, Gebauer M, Pasuchinger T, Kormann A, Menke C, Barton M (2016) Wärmestudie Region Eifel und Trier. Studie im Auftrag des Ministeriums für Wirtschaft, Klimaschutz, Energie und Landesplanung des Landes Rheinland-Pfalz. IZES gGmbH, SWT Stadtwerke Trier AöR, Energieagentur Region Trier GmbH, Kompetenzzentrum Solar der Hochschule Trier, ECOSCOPE Gesellschaft für Umweltberatung und -recherche mbH Trier, Solites -Steinbeis Forschungsinstitut für solare und zukunftsfähige thermische Energiesysteme (Zuständigkeit Wärmenetze), Saarbrücken
- BMWi [Federal Ministry for Economic Affairs and Energy] (2019) Kohleausstieg und Strukturwandel. BMWi. <https://www.bmwi.de/Redaktion/DE/Artikel/Wirtschaft/kohleausstieg-und-strukturwandel.html>. Accessed 22. 09.2019
- Fritz S, Peht M (2019) Der Kohleausstieg und die Auswirkungen auf die betroffenen Wärmenetze. Kurzstudie im Auftrag des Bundesministeriums für Umwelt, Naturschutz und nukleare Sicherheit. ifeu, Heidelberg
- BMWi [Federal Ministry for Economic Affairs and Energy] (2018) Erneuerbare Energien in Zahlen. Nationale und internationale Entwicklung im Jahr 2017. BMWi, Berlin
- Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland unter Verwendung von Daten der Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat). (2019) [https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/zeitreihen-zur-entwicklung-der-erneuerbaren-energien-in-deutschland-1990-2018.pdf?sessionid=906F1084ED959B25AC4C4B27C0C43A70?\\_\\_blob=publicationFile&v=22](https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/zeitreihen-zur-entwicklung-der-erneuerbaren-energien-in-deutschland-1990-2018.pdf?sessionid=906F1084ED959B25AC4C4B27C0C43A70?__blob=publicationFile&v=22).
- Hoffstede U, Stelzer M, Hahn H, Beil M, Krautkremer B, Kasten J, Beyrich W, Holzhammer U (2018) Vorbereitung und Begleitung bei der Erstellung eines Erfahrungsberichts gemäß § 97 Erneuerbare-Energien-Gesetz. Teilvorhaben II a: Biomasse. Zwischenbericht. Erstellt im Auftrag des Bundesministeriums für Wirtschaft und Energie. Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik (IEE), Kassel
- Lund R, Østergaard DS, Yang X, Mathiesen BV (2017) Comparison of low-temperature district heating concepts in a long-term energy system perspective. International Journal of Sustainable Energy Planning and Management 12:5-18. doi:[dx.doi.org/10.5278/ijsepm.2017.12.2](https://doi.org/10.5278/ijsepm.2017.12.2)
- FNR [Fachagentur Nachwachsende Rohstoffe e.V.] (2019) Biogas: Faustzahlen. FNR. <https://biogas.fnr.de/daten-und-fakten/faustzahlen/>. Accessed 19.08.2019
- Koch M, Hennenberg K, Hünecke K, Haller M, Hesse T (2018) Rolle der Bioenergie im Strom- und Wärmemarkt bis 2050 unter Einbeziehung des zukünftigen Gebäudebestandes. Öko-Institut e.V, Freiburg, Darmstadt
- Weinand JM, McKenna R, Fichtner W (2019) Developing a municipality typology for modelling decentralised energy systems. Util Policy 57:75–96. <https://doi.org/10.1016/j.jup.2019.02.003>
- Esch T, Taubenböck H, Geiß C, Schillings C, Nast M, Metz A, Heldens W, Keil M (2011) Potenzialanalyse zum Aufbau von Wärmenetzen unter Auswertung siedlungsstruktureller Merkmale. Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Deutsches Fernerkundungsdatenzentrum (DFD), Oberpfaffenhofen
- IZES gGmbH [Institut für ZukunftsEnergie und Stoffstromsysteme] (2017) Wärmekataster Saarland. Abschlussbericht im Auftrag des MWAEEV des Saarlandes. IZES gGmbH, Saarbrücken
- Scheffelowitz M, Becker R, Thrän D (2018) Improved power provision from biomass: a retrospective on the impacts of German energy policy. Biomass and Bioenergy 111:1-12. doi:<https://doi.org/10.1016/j.biombioe.2018.01.010>
- BKG [Federal Agency for Cartography and Geodesy] Digitale Landschaftsmodelle und Landbedeckungsmodelle von Deutschland. Digitales Basis-Landschaftsmodell (Basis-DLM). <https://www.bkg.bund.de/DE/Produkte-und-Services/Shop-und-Downloads/Digitale-Geodaten/Landschaftsmodelle/landschaftsmodelle.html>. Accessed 21 Aug 2019
- Baur F, Noll F, Wern B, Vogler C, Weiler K, Arnold K, Carpentier R, Pietzner K, Samadi S, Wane S, Hiebel M, Dresen B, Nühlen J (2015) Nachhaltige Integration von Bioenergiesystemen im Kontext einer kommunalen Entscheidungsfindung (KomiInteg). Abschlussbericht. Institut für ZukunftsEnergie und Stoffstromsysteme (IZES gGmbH), Wuppertal Institut für Klima, Umwelt und Energie GmbH, Fraunhofer UMSICHT, Saarbrücken, Wuppertal, Oberhausen
- Verwaltungsgebiete 1:250 000 mit Einwohnerzahlen (Ebenen), Stand 31.12. (VG250-EW 31.12.) (2018) BKG [Federal Agency for Cartography and Geodesy]. Accessed 10.06.2018
- Geographical Grid of Germany in Lambert-Projection (2015) BKG [Federal Agency for Cartography and Geodesy]. [http://www.geodatenzentrum.de/geodaten/gdz\\_rahmen.gdz\\_div?gdz\\_spr=deu&gdz\\_akt\\_zeile=5&gdz\\_anz\\_zeile=1&gdz\\_unt\\_zeile=31&gdz\\_user\\_id=0](http://www.geodatenzentrum.de/geodaten/gdz_rahmen.gdz_div?gdz_spr=deu&gdz_akt_zeile=5&gdz_anz_zeile=1&gdz_unt_zeile=31&gdz_user_id=0).
- Points of Interest (POI-Bund/POI-BPol) (2018) BKG [Federal Agency for Cartography and Geodesy]. Accessed 21 Aug 2019
- OpenStreetMap data for Germany - Buildings (2018) Geofabrik GmbH and OpenStreetMap Contributors. <https://download.geofabrik.de/europe/germany.html>.
- Ergebnisse des Zensus 2011: Bevölkerung im 100 Meter-Gitter (2015) Destatis [Statistisches Bundesamt]. <https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html?nn=3065474>.
- Gaderer M, Lautenbach M, Fischer T, Ebertsch G (2007) Wärmenutzung bei kleinen landwirtschaftlichen Biogasanlagen. Bayerisches Landesamt für Umwelt (LfU), Bayerisches Zentrum für Angewandte Energieforschung e. V. (ZAE Bayern), Augsburg
- Ergebnisse des Zensus 2011: Bevölkerung nach Jahren und Geschlecht für Gemeinden. (2014) Destatis [Statistisches Bundesamt]. <https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html>.

28. IWU [Institut für Wohnen und Umwelt] (2003) Deutsche Gebäudetypologie: Systematik und Datensätze. IWU, Darmstadt
29. Zensusdatenbank - Einwohnerzahl je Hektar. Ergebnisse des Zensus am 09. Mai 2011 pro ha (2015) Destatis [Statistisches Bundesamt]. <https://ergebnisse.zensus2011.de/#StaticContent:00,...>
30. Destatis [Statistisches Bundesamt] (2008) Klassifikation der Wirtschaftszweige. Mit Erläuterungen. 2008. Destatis, Wiesbaden
31. Destatis [Statistisches Bundesamt] (2008) Bruttoinlandsprodukt/ Bruttowertschöpfung – Jahressumme – regionale Tiefe: Kreise und kfrf. Städte. Regionaldatenbank Deutschland der Statistischen Ämter des Bundes und der Länder. Destatis, Wiesbaden
32. Destatis [Statistisches Bundesamt] (2011) Sozialversicherungspflichtig Beschäftigte am Arbeitsort nach Geschlecht und Nationalität – Stichtag 30. 06. – regionale Tiefe: Gemeinden, Samt-/Verbandsgemeinden. Regionaldatenbank Deutschland der Statistischen Ämter des Bundes und der Länder. Destatis, Wiesbaden
33. Destatis [Statistisches Bundesamt] (2010) Bruttoinlandsprodukt/ Bruttowertschöpfung – Jahressumme – regionale Tiefe: Kreise und kfrf. Städte. Regionaldatenbank Deutschland der Statistischen Ämter des Bundes und der Länder. Destatis, Wiesbaden
34. Almut Kirchner, Schlesinger M, Weinmann B, Hofer P, Rits V, Wunsch M, Koepp M, Kemper L, Zweers U, Straßburg S, Matthes F, Busche J, Graichen V, Zimmer W, Hermann H, Penninger G, Mohr L, Ziesing H-J (2009) Modell Deutschland. Klimaschutz bis 2050. Vom Ziel her denken. Endbericht. Im Auftrag des WWF Deutschland. Prognos AG, Öko-Institut e.V., Basel, Berlin
35. Destatis [Statistisches Bundesamt] (2011) Verarbeitendes Gewerbe, Bergbau u. Gewinnung von Steinen und Erden: Betriebe u. Beschäftigte nach Wirtschaftsabteilungen – Stichtag 30.09. – regionale Tiefe: Kreise u. kfrf. Städte. Regionaldatenbank Deutschland der Statistischen Ämter des Bundes und der Länder. Destatis, Wiesbaden
36. VDI [Verband Deutscher Ingenieure] (2014) Richtlinie VDI 3807: Verbrauchskennwerte für Gebäude. Blatt 2: - Verbrauchskennwerte für Heizenergie, Strom und Wasser. vol 3807. VDI, Düsseldorf
37. Schlesiger G (2001) Energie- und wassersparende Maßnahmen in Bädern. 2001 edn. BfSp [Federal Institute for Sports Science], Bonn
38. Merker H-J, Nißen S (2006) Energiebericht der Stadt Voerde für das Jahr 2006. Kommunalbetrieb Voerde - Gebäudemanagement, Voerde
39. Stadt Dinslaken (2014) Energiebericht. Stadt Dinslaken Dinslaken
40. Kerpern S (2012) Energiebericht 2012. Stadt Kerpern, Kerpern
41. Stadt Rheinfelden (Baden) (2016) Energiebericht 2016. Stadt Rheinfelden (Baden), Rheinfelden (Baden)
42. Stadt Wiesloch (2005) Energiebericht. Kommunale Liegenschaften. Berichtsjahr 2005. Stadt Wiesloch, Wiesloch
43. Stadtverwaltung Paffenhofen a. d. Ilm (2014) Energiebericht 2014. Stadtverwaltung Paffenhofen a. d. Ilm, Paffenhofen a. d. Ilm
44. Oertli Rohleder Wärmetechnik GmbH (2010) In Sachen Technik. Planungsanleitung Gas-Schwimmbadheizung GX 01 150 – 800. Oertli Rohleder Wärmetechnik GmbH, Möglingen
45. Innovations- und Transferinstitut Bingen GmbH (2002) Wärmeversorgung für das Freibad und die Sporthalle in Maikammer. Forstliche Versuchs- und Forschungsanstalt Bingen
46. Blesl M, Kempe S, Ohl M, Fahl U, König A, Jansen T, Eltrop L (2009) Wärmeatlas Baden-Württemberg - Erstellung eines Leitfadens und Umsetzung für Modellregionen. Universität Stuttgart - Institut für Energiewirtschaft und Rationelle Energieanwendung (IER), Stuttgart
47. Energieagentur Weststeiermark (2003) Energiebedarf der Gartenbaubetriebe – Auswertung der Gartenbaubetriebe. Zusammenfassung. Basierend auf der Projektstudie: Grundlagen für den Einsatz von erneuerbaren Energieträgern wie Biomasse und Solarenergie zur Beheizung und Trocknung im Gartenbau (Endbericht 31. Oktober 2003). Energieagentur Weststeiermark, Stainz
48. Arbeitsgemeinschaft QM Holzheizwerke (2004) Q-Leitfaden. Checkliste Standard, MS1 – MS5. 2004. Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk e.V. (C.A.R.M.E.N. e.V.), Straubing
49. IZES gGmbH [Institut für ZukunftsEnergie und Stoffstromsysteme], ifeu [Institut für Energie- und Umweltforschung GmbH] (2010) Nachhaltige Biogasnutzung im Raum Trier. Abschlussbericht für die Stadtwerke Trier. IZES gGmbH, ifeu, Trier
50. Daniel J, Scholwin F, Vogt R (2008) Materialband D. Biogasnutzung, im Rahmen des BMU Forschungsvorhabens „Optimierung für einen nachhaltigen Ausbau der Biogaserzeugung und –nutzung in Deutschland, FKZ: 0327544. Heidelberg
51. Scheffelowitz M, Rensberg N, Denysenko V, Daniel-Gromke J, Stinner W, Hillebrand K, Naumann K, Peetz D, Henning C, Thrän D, Beil M, Kasten J, Vogel L (2015) Stromerzeugung aus Biomasse (Vorhaben Ila Biomasse). Zwischenbericht Mai 2015. DBFZ [Deutsches Biomasseforschungszentrum gemeinnützige GmbH], Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES), INL GmbH, Helmholtz-Zentrum für Umweltforschung - UFZ, Leipzig
52. C.A.R.M.E.N. e.V. [Centrales Agrar-Rohstoff Marketing- und Energie-Netzwerk e.V.] Nahwärmenetze und Bioenergieanlagen. Ein Beitrag zur effizienten Wärmenutzung und zum Klimaschutz. C.A.R.M.E.N. e.V., Straubing
53. KfW [Kreditanstalt für Wiederaufbau] (2018) Merkblatt: Erneuerbare Energien Premium. Finanzierung von Maßnahmen zur Nutzung Erneuerbarer Energien im Wärmemarkt. KfW, Frankfurt am Main
54. Ökoprojekte Gronbach GmbH (2019) Nahwärme: Wärmenetz Uttenhofen. <http://www.oekoprojekte-gronbach.de/index.php?id=79>.
55. Gemeinde Buttenwiesen (2019) Das Gute liegt so nah: Nahwärme Buttenwiesen. Gemeinde Buttenwiesen. <https://www.buttenwiesen.de/de/leben-wohnen/energie/nahwaermeversorgung/>.
56. Fachzentrum für Energie & Landtechnik (2016) Nahwärmeversorgung Kastl. Gemeinde Kastl. [https://www.kastl.de/cms\\_showpdf.php?pdfname=Nahwrmenetz\\_Kastl](https://www.kastl.de/cms_showpdf.php?pdfname=Nahwrmenetz_Kastl).
57. Fachverband Biogas e.V. (2019) Bioenergiedorf Reiffenhausen – Gemeinsinn als Schlüssel zum Erfolg. [https://www.biogas-kanns.de/downloads/Interview\\_Hartmut\\_Berndt\\_Biogas\\_Journal.pdf](https://www.biogas-kanns.de/downloads/Interview_Hartmut_Berndt_Biogas_Journal.pdf).
58. Energievision Frankenwald e.V. (2019) Technische Daten zum Nahwärmenetz in Gössersdorf. Energievision Frankenwald e.V. <http://www.energie-frankenwald.de/1338887389-technische-daten-nahwaermenetz.html>.
59. EnergieAgentur.NRW GmbH (2012) Biogas von Stadtteil zu Stadtteil – neues Nahwärmenetz in Schmalleben. EnergieAgentur.NRW GmbH. <https://www.energieagentur.nrw/eanr/ea/biogas-von-stadtteil-zu-stadtteil-neues-nahwaermenetz-in-schmalleben>. Accessed 13.11.2019
60. DVL [Deutscher Verband für Landschaftspflege e.V.] (2019) Biogasanlage Ribbeck, Brandenburg. DVL [Deutscher Verband für Landschaftspflege e.V.]. <https://mulle.lpv.de/praxis-forschung/datenbank/projektetails/id/biogasanlage-ribbeck-brandenburg.html>. Accessed 13 Nov 2019
61. Dorfgemeinschaft Ebbinghof (2019) Nahwärmenetz. Dorfgemeinschaft Ebbinghof. <http://www.ebbinghof-live.de/energiedorf/nahwaermenetz.php>.
62. Bioenergiedorf Oberrospe eG (2019) Bioenergiedorf Oberrospe eG. Bioenergiedorf Oberrospe eG. <http://www.bioenergiedorf-oberrospe.de/>. Accessed 13.11.2019
63. Berghamer O (2013) Nahwärmeversorgung in Mardorf. [http://www.amoeneburg.de/eigene\\_dateien/aktuell/2013/pdf/12-043\\_nahwaerme\\_in\\_mardorf\\_-\\_bericht\\_zur\\_buergerversammlung\\_am\\_18\\_juni\\_2013.pdf](http://www.amoeneburg.de/eigene_dateien/aktuell/2013/pdf/12-043_nahwaerme_in_mardorf_-_bericht_zur_buergerversammlung_am_18_juni_2013.pdf).
64. Krah A (2017) Bebauungsplan mit integriertem Grünordnungsplan: SO Biogasanlage Oberindling. Pocking
65. Kompetenzzentrum HessenRohstoffe (HeRo) e.V. (2009) Bioenergiedörfer in Hessen – mit Erneuerbaren Energien in die Zukunft. Kompetenzzentrum HessenRohstoffe (HeRo) e.V., Witzenhausen
66. Fuchs G (2013) Praxisbeispiel - Satteliten BHKW: Abwärme für Wohnhäuser und für einen Gasthof. Lengdorf
67. Agentur für Erneuerbare Energien e.V. (2018) Energie vom Land hält Warm. Agentur für Erneuerbare Energien e.V., Berlin
68. Ahlers E, Seidel M, Burg C, Huber R, Hügging T, Ketrup H, Makrlík N, Renken A, Sachse U, Straub F, Sztochaj T, Geiger B, Kleeberger H, Pätzold K (2007) Abwicklung von Standardlastprofilen. BGW [Bundesverband der deutschen Gas- und Wasserwirtschaft], Bonn
69. Aktualisierte und erweiterte Testreferenzjahre (TRY) von Deutschland für mittlere und extreme Witterungsverhältnisse (2019) BBSR [Bundesinstitut für Bau-, Stadt- und Raumforschung im Bundesamt für Bauwesen und Raumordnung]. Accessed 13 Sep 2019
70. Fallahnejad M, Hartner M, Kranzl L (2018) Fritz S (2018) Impact of distribution and transmission investment costs of district heating systems on district heating potential. Energy Procedia 149:141–150. <https://doi.org/10.1016/j.egypro.2018.08.178>
71. Dotzauer M, Lauer M, Schneider J (2016) Trade-offs for agricultural biogas plants between flexible power generation and heat cogeneration. In: 24th European Biomass Conference and Exhibition, Amsterdam, 2016. doi:10.5071/24thEUBCE2016-5A0.9.1

72. AGEB [AG Energiebilanzen e.V.] (2013) Anwendungsbilanzen für die Endenergiesektoren in Deutschland in den Jahren 2010 und 2011, Studie beauftragt vom Bundesministerium für Wirtschaft und Technologie Projektnummer: 23/11. AGEB, Berlin
73. Wolff D, Jagnow K (2011) Untersuchung von Nah- und Fernwärmenetzen. Überlegungen zu Einsatzgrenzen und zur Gestaltung einer zukünftigen Fern- und Nahwärmeversorgung, Wolfenbüttel, Braunschweig
74. Zahlen und Fakten. Energiedaten (2019) BMWi [Federal Ministry for Economic Affairs and Energy]. <http://www.bmwi.de/Navigation/DE/Themen/energiedaten.html>.
75. Herbes C, Halbherr V, Braun L (2018) Preise für die Abgabe von Wärme von Biogasanlagen an Dritte. *Agrarbetrieb* 2018(1):12–15
76. The German Federal Government (2019) Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050. The German Federal Government.
77. The German Federal Government (2019) CO<sub>2</sub>-Ausstoß verbindlich senken. The German Federal Government. <https://www.bundesregierung.de/breg-de/themen/klimaschutz/klimaschutzgesetz-beschlossen-1679886>.

### Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Ready to submit your research? Choose BMC and benefit from:**

- fast, convenient online submission
- thorough peer review by experienced researchers in your field
- rapid publication on acceptance
- support for research data, including large and complex data types
- gold Open Access which fosters wider collaboration and increased citations
- maximum visibility for your research: over 100M website views per year

**At BMC, research is always in progress.**

Learn more [biomedcentral.com/submissions](https://biomedcentral.com/submissions)

