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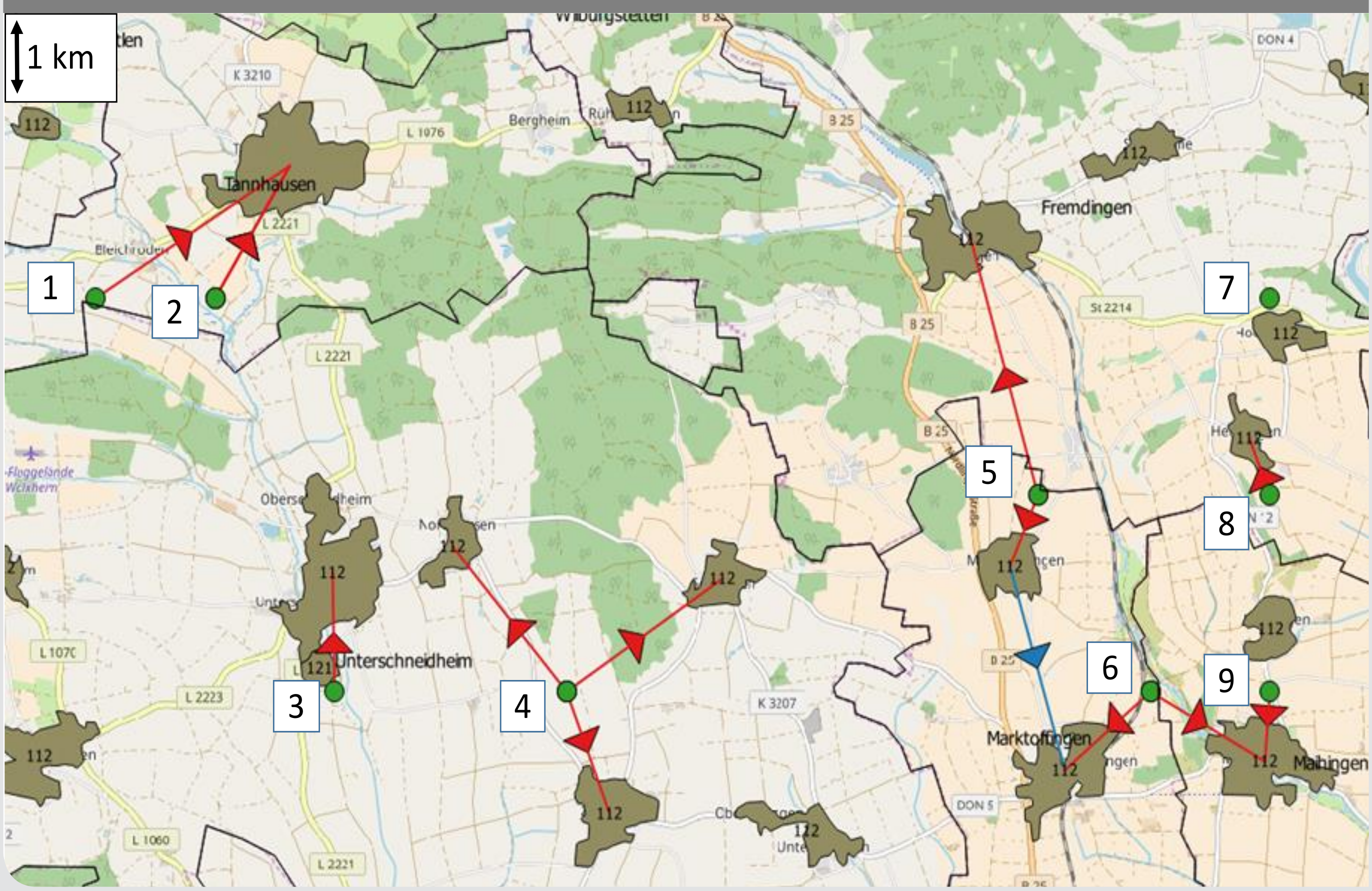

Assessing the potential contribution of excess heat from biogas plants towards decarbonising German residential heating

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This paper analyses the current technical potential for utilising excess heat from German biogas plants, in order to supply local settlements through district heating. Based on a survey of around 600 biogas plant operators, the fractions of excess heat in these plants are analysed. A heuristic is developed to match biogas plants (heat sources) with local settlements (sinks) in order to determine a least-cost district heating supply for residential buildings. Two criteria are employed, namely the CO2 abatement costs and the payback period, which represent the macro- and microeconomic perspectives respectively. Based on the survey, a mean fraction of 40% excess heat is determined, which is in agreement with other empirical studies. Extrapolating this fraction to the German biogas plant stock leads to technically feasible CO2 savings of around 2.5 MtCO2/a. Employing the criteria of CO2 abatement costs and payback period yields about 2 MtCO2/a below CO2 abatement costs of 200 €/tCO2 and below a payback period of 9 years respectively. This represents about 0.25% of the total German CO2 emissions in 2016 or around 2.5% of all CO2 in residential buildings. If threshold values of 80 €/tCO2 and 5 years are employed, to reflect the German government's suggested external cost of carbon and an expected payback period from an investor's point of view respectively, the carbon reduction potential is about 0.5 MtCO2 and 0.75 MtCO2 respectively. These potentials are concentrated in around 3,500 of 11,400 municipalities, where district heating from biogas plants could reduce CO2 emissions per capita by an average of 250 kgCO_2/a and cover 12% of the total heating demand.

Nomenclature

Variable / Parameter	Description	Unit
a	Annuity factor	–
a_{111}	Area size of a “111” area	m^2
a_{112}	Area size of a “112” area	m^2
A_{BC}	Share of brown coal in heat supply for settlement area	%
A_{EL}	Share of electricity in heat supply for settlement area	%
A_{Gas}	Share of gas in heat supply for settlement area	%
A_{HC}	Share of hard coal in heat supply for settlement area	%
A_{Oil}	Share of heating oil in heat supply for settlement area	%
BSA_{SA}	Total building space of a settlement area	m^2
$CO2_{costs}$	CO_2 abatement costs	$€/\mathrm{tCO_2}$
$CO2_{saved,SA}$	Saved CO_2 emissions in a settlement area	$\mathrm{tCO_2}$
$C1$	Construction cost parameter 1 for district heating network	€/m
$C2$	Construction cost parameter 2 for district heating network	€/m^2
CR	Coverage ratio	%
df	Discount factor	%
d_{SA}	Average diameter of the district heating pipelines	m
DIS_{SA}	Distance between biogas plant and settlement area	m
e	Plot ratio	–
EF_{BC}	CO_2 emission factor of brown coal	$\mathrm{kgCO_2/kWh}$
EF_{EL}	CO_2 emission factor of electricity	$\mathrm{kgCO_2/kWh}$
EF_{Gas}	CO_2 emission factor of gas	$\mathrm{kgCO_2/kWh}$
EF_{HC}	CO_2 emission factor of hard coal	$\mathrm{kgCO_2/kWh}$
EF_{Oil}	CO_2 emission factor of oil	$\mathrm{kgCO_2/kWh}$
EH_{BGP}	Share of available excess heat in a biogas plant	%
EH_{used}	Share of already used excess heat in a biogas plant	%
EXP_{SA}	Sum of expenses for the supply of a settlement with district heating	€
F_1	Number of residential buildings in a federal state / municipality with one apartment	–
F_2	Number of residential buildings in a federal state / municipality with two apartments	–
F_3	Number of residential buildings in a federal state / municipality with three or more apartments	–
F_{mean}	Mean living space per apartment in a federal state	m^2
$F_{mean,m}$	Mean living space per apartment in a municipality	m^2
F_{total}	Total living space in a federal state	m^2
hd_{mean}	Mean specific heat demand in a settlement area	$\mathrm{kWh/m^2}$

HD_{SA}	Adjusted total heat demand in a settlement area	kWh
$HD_{SA_{total}}$	Total heat demand in a settlement area	kWh
HDC_{SA}	Specific heat distribution costs	€
$I_{con,SA}$	Investment in the pipeline for connecting the biogas plant and the settlement area	€
$I_{DHG,SA}$	Investment for the building or the densification of the district heating grid	€
I_{SA}	Necessary investment to use the excess heat from the biogas plant to supply the settlement area	€
IR	Investment rate for the district heating pipeline	€/m
LHD_{SA}	Linear heat density	$\mathrm{kWh/m}$
LP_{BGP}	Excess heat profile of a settlement area	–
LP_{SA}	Heat demand load profile of a settlement area	–
LS_1	Living space in a settlement area	m^2
LS_2	Adjusted living space in a settlement area	m^2
LS_{total1}	Calculated sum of the living space over all settlements in a municipality	m^2
LS_{total2}	Measured total living space in a municipality	m^2
n_a	Number of apartments in a settlement area	–
n_b	Total number of buildings in a square kilometre of the census data grid	–
n_{b111}	Number of buildings in a “111” area	–
n_{b112}	Number of buildings in a “112” area	–
NPV_{SA}	Net present value for the supply of a settlement with district heating	€
P	Total population of a settlement area	Inhabitants
PD_{SA}	Population density of a settlement area	$\mathrm{Inhabitants/km}^2$
PP	Payback period	a
P_{th}	Thermal power of a biogas plant	kW
Q_{sell}	Amount of excess heat that is supplied by the biogas plant to the settlement area	kWh
REV_{SA}	Sum of revenues for the supply of a settlement with district heating	€
S_{Bio}	Proportion of heat supplied by biomass	%
S_{DH}	Proportion of heat supplied by district heating	%
S_{GT}	Proportion of heat supplied by geothermal and other environmental heat	%
S_{SE}	Proportion of heat supplied by solar energy	%
S_{WP}	Proportion of heat supplied by wood pellets	%
SLP_{BGP}	Standardised excess heat profile of a biogas plant	–
SLP_{HD}	Standardised heat load profile of a settlement area	–
SR	Supply ratio	%
w	Effective width	m
x	Average number of apartments in a residential building with more than two apartments	–

1. Introduction

The expansion of renewable energy technologies (RETs) in Germany is largely being driven by private individuals, farmers and energy cooperatives in the context of community energy (Klaus Novy Institut e.V. & trend:research 2011, trend:research 2017). This trend involves these actors investing in and/or operating RETs, including wind, solar and bioenergy plants, in some cases also buying the local energy infrastructure (gas, electricity, heating networks) back from the local utility. They are mainly motivated by a desire to 'take control' of their local energy supply (system) and thus become more independent from centralised markets and energy suppliers (Müller et al. 2011, Rae & Bradley 2012, McKenna et al. 2015). Many community energy projects declare an objective of energy autonomy, which they typically define on an annual basis and for electricity alone[1]. Examples in Germany include the 100% Renewable Energy Regions and the Bioenergy Villages (McKenna 2018). The costs of these RETs were historically higher than those of conventional technologies, meaning they relied on subsidies to be economical. But recent rapid reductions in costs for PV and batteries have provided a renewed incentive for attempts to become energy autonomous at a local scale (Nykvist & Nilsson 2015).

Many studies have techno-economically analysed the scope to achieve a local energy supply from renewable sources. Most conclude that a completely autonomous energy supply is only feasible in rural municipalities with large bioenergy resources, and even then, large storage capacities are required which lead to high costs (e.g. McKenna et al. 2015). In the context of decentralised energy supply, a related stream of research is concerned with (industrial) excess heat and the possibilities of utilising this as an energy input, e.g. for space heating. Several studies in this area have analysed the technical and/or economic potential of excess heat from industry, often based on emissions data from individual industrial plants. Noteworthy are the studies McKenna & Norman (2010), Fang et al. (2013, 2015), Brückner et al. (2014), Miró et al. (2015), Miró et al. (2016), Bühler et al. (2017), and the ongoing European Heat Roadmap project (Persson et al. 2014). Amongst other things, the European Heat Roadmap project has produced the European Thermal Energy Atlas, a Europe-wide map of heat demand and industrial excess heat potentials at a spatial resolution up to of 1 km^2. One additional source of excess heat potential are biogas plants, which valorise organic matter into biogas through fermentation (cf. section 2). This biogas is typically combusted in a cogeneration unit, whereby the electricity is typically fed into the grid. A legal requirement was introduced with the Renewable Energy Sources Act (EEG) 2012, that new biogas plants must utilise at least 25% of their excess heat in the first year of operation and 60% thereafter (Mergner et al. 2013). Despite this, there are many operating plants, some of which were commissioned before this time, with much lower levels of heat utilisation.

Against this background of decentralised energy systems, aspirations for local energy autonomy and excess heat potentials, this study analyses the technical and economic potential for recovering excess heat from biogas plants in Germany to supply local buildings with low carbon space heating. The objective is to determine the amount of heat that could technically

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

be recovered as well its associated costs, in order to give indications of promising locations. The paper addresses the following research questions:

- How does the heat from biogas plants in Germany that is not used today match the existing heat sinks?
- What contribution can the use of biogas excess heat make to the autonomy of municipalities?
- In which locations is the utilisation of biogas plant excess heat economically interesting for investors?

The employed methodology involves a combination of input from a survey of around 600 biogas plant operators, a GIS-based analysis of sources and sinks, and a heuristic that matches heat sources and sinks based upon a least-cost approach. The results are therefore of relevance to local decision makers, biogas plant operators and researchers in the field of energy system analysis. In particular the quantitative results offer an indication of the costs and related CO_2 saving potentials on a local level, in order to underpin local decisionmaking in the context of energy and climate plan development.

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

2. Current state of the art in the German biogas branch

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

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

The majority of German plants use the gas onsite to fuel combined heat and power (CHP) units, thus cogenerating heat and electricity. The electricity is fed into the electricity network to receive a feed-in tariff, and heat is used locally if at all feasible. A further around 200 plants (in 2016, around 9 TWh of gas, cf. dena 2016) upgrade the biogas into biomethane or Bio-SNG (Synthetic Natural Gas) and inject it into the public gas grid (cf. Figure 1). Particularly where a local heat sink is lacking, despite additional costs this upgrading can improve the overall utilisation efficiency of biogas valorisation. For example, a typical CHP unit can achieve 40% electrical efficiency, reaching an overall efficiency of up to 80% if all the generated heat can be used locally (Pöschl et al. 2010). In the absence of a local heat sink, biogas upgrading and feed in can result in overall efficiencies of around 75-80%, based on the utilisation of Bio-SNG as a fuel for transport, for heating and/or power generation (Niesner et al. 2013, Köppel et al. 2014).

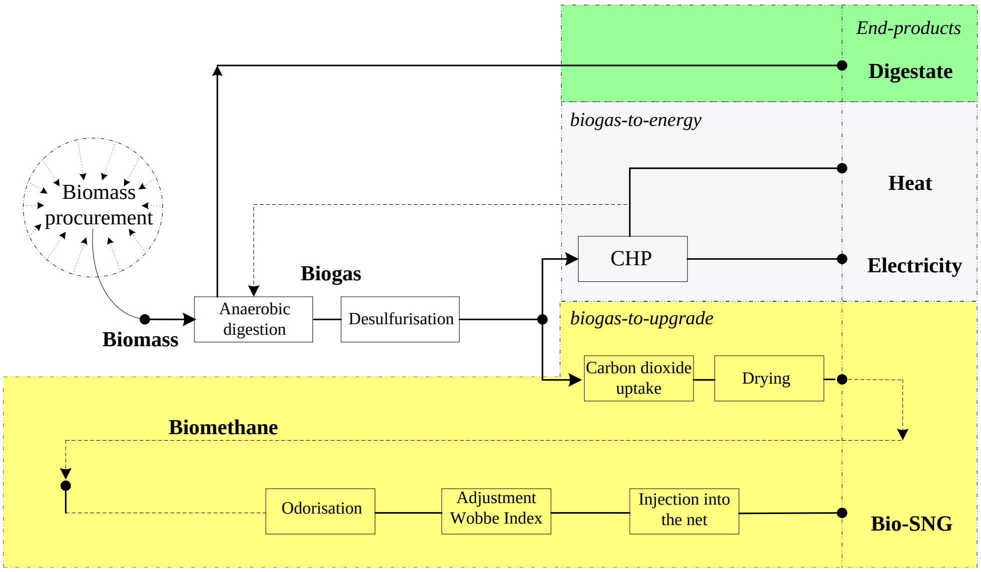

Figure 1: Schematic of biogas plant, showing key valorisation steps and pathways (Figure from Bidart (2013))

3. Method and approach

This study uses different methods in a multi-stage approach. In this section, the developed algorithm is explained, which can also be seen in Figure 2. The boxes with numbers in Figure 2 show in which subsection the respective part of the algorithm is explained. Firstly, the results of an extensive survey of biogas plant operators in Germany are taken into account with regard to their heat utilisation rates (cf. section 3.1, Herbes & Halbherr 2017). Secondly, 10,446 biogas plants as well as the 38,414 CORINE settlement areas in Germany are examined with regard to their technical and geographical characteristics (cf. section 3.2). Subsequently, the local demand for heat in buildings in all German settlement areas and the excess heat availability of biogas plants are calculated (cf. section 3.3). In order to provide a least cost solution, options to integrate the excess heat from the biogas plants into district heating networks are explored. In this context, the distances between the biogas plants and the settlement areas are determined in particular. Based on published methods for district heating systems assessment and dimensioning, the possible CO_2 savings and associated costs as well as the payback periods are determined for combinations of biogas plants and their nearest residential areas. By focussing on the connections with the lowest CO_2-abatement costs/payback period, the most environmentally and economically attractive locations for a district heat network development are identified (cf. section 3.4).

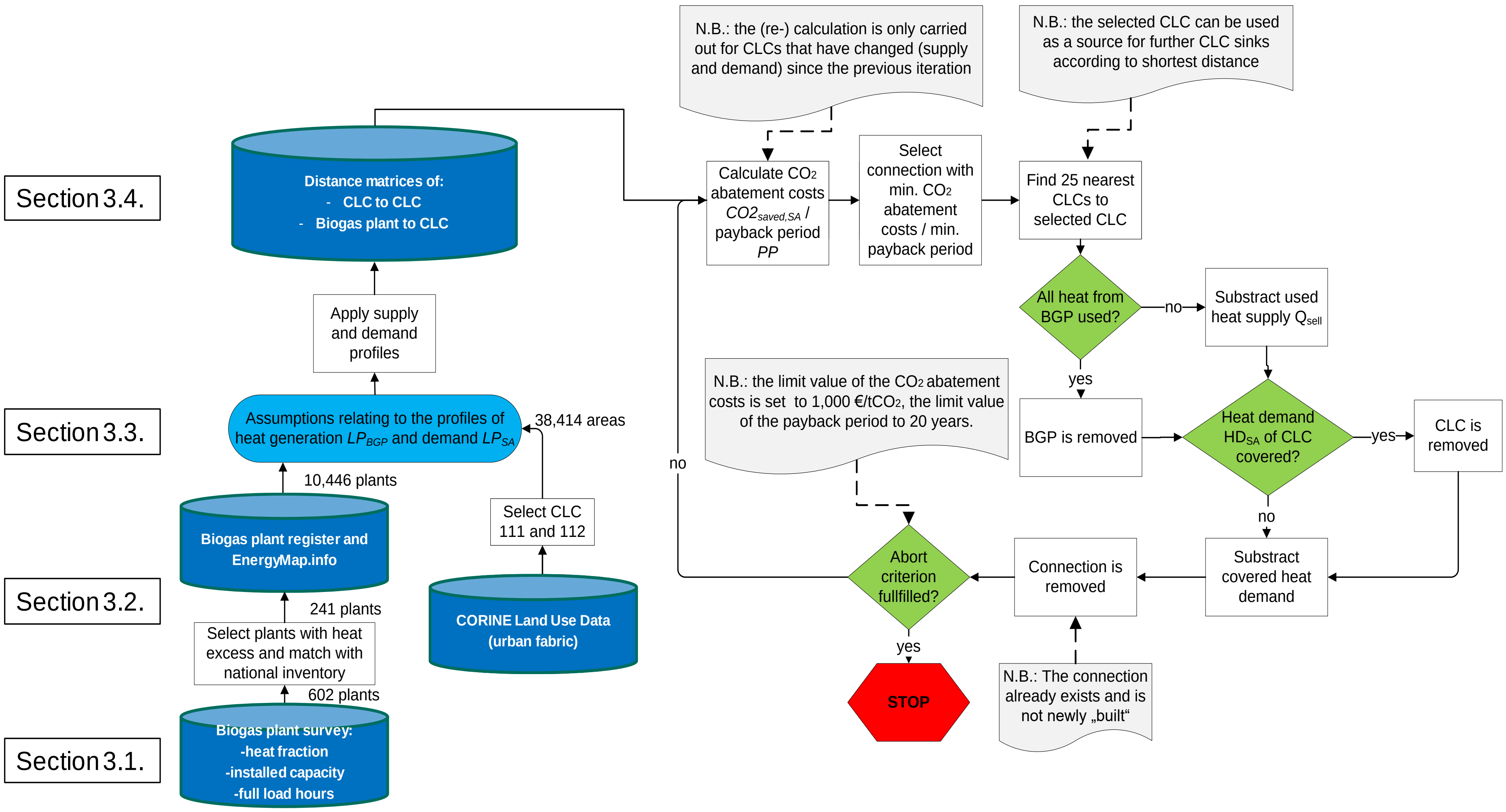

Figure 2: Overview of the algorithm developed and used in this study to select biogas plants (BGP) and settlement areas for district heating supply.

3.1. Biogas plant survey

In the summer of 2016, an online survey of those members of the German Biogas Association that run a biogas plant was conducted, resulting in a gross sample of 2,724 operators (Herbes & Halbherr 2017). After the development of the questionnaire, which was a joint undertaking of Nuertingen-Geislingen University and the German Biogas Association (GBA), extensive cognitive pre-testing with external biogas experts, GBA staff and plant operators was carried out before fielding the survey. To decrease nonresponse bias after the first phase, a telephone campaign in those federal states that were underrepresented in the answers was conducted. These efforts resulted in a final data set of n=602 plant operators, which is equivalent to a response rate of 22% (according to response rate 2 (RR 2), cf. AAPOR (2015)). Regarding the distribution of federal states, the sample shows a small overrepresentation of Bavaria and Baden-Wuerttemberg (cf. Figure 6). Regarding size and commissioning year, the sample is statistically representative of the entire German biogas plant stock. Amongst other things, the data set includes location, plant size, percentage of the already used heat, utilisation paths and various data on prices and price models, which are not relevant for the present study (Herbes & Halbherr 2017).

In the survey, respondents provided information on the percentage share of heat utilisation for different categories such as in schools, hospitals and fish farming. In 262 of the 602 plants, the total shares were above 100% (cf. Figure 3). The plants with a heat utilisation of more than 100% are excluded from the analysis in this study, as it seems the survey participates misunderstood the questions and/or made mistakes in stipulated these shares. In total, this results in an average heat utilisation of 60% and an unused heat fraction of 40%.

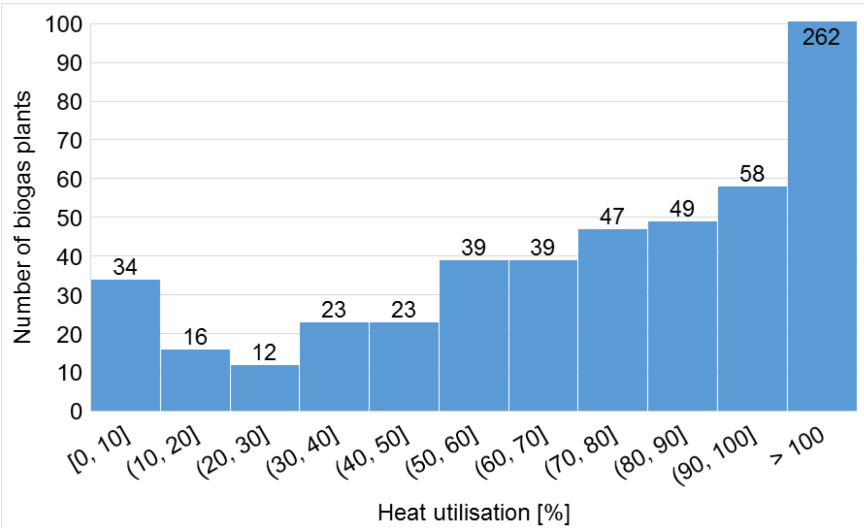

Figure 3: Number of biogas plants surveyed as a function of the specified share of heat that is already being used.

3.2. Biogas plant register and CORINE Land Use Data

Of the 602 biogas plants from the survey, 241 plants (40%) could be identified and mapped in the Energymap plant register (Engel 2015) on the basis of their year of commissioning, postcode and nominal power. Further and more detailed information could then be taken from the plant register, such as the full load hours in recent years. The data from the survey were used for heat utilisation (cf. section 3.1).

The Energymap plant register contains the coordinates of the biogas plants with a maximum error of 3 km. Therefore, the locations of the 10,446 plants in Germany could be mapped with the help of the geoinformation system QGIS. The 241 assigned plants from the survey are a subset of these 10,446 plants. CORINE Land Cover (CLC) data from the European Environment Association (EEA 2016) were used as a source for the settlement areas. The shapefiles of these areas for Germany are provided by the Federal Office of Cartography and Geodesy (Lenk et al. 2017a). Urban areas are distinguished according to the density of the urban fabric, into "continuous urban fabric" (denoted with the number "111") and "discontinuous urban fabric" areas (denoted with the number "112"). The boundary between the 111 and 112 areas is mainly determined by the presence and quantity of vegetation (EEA 1995). Overall, the German settlement areas are divided into 38,414 of these areas. The left part of Figure 4 shows an exemplary section of these areas.

3.3. Heat demand and generation

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

3.3.1. Heat demand

Data on the building stock in Germany were taken from the census of the Federal Statistical Office to determine the heat demand in the settlement areas. For more information on determining the census data, see Statistisches Bundesamt (2015b). The census data include data on building age, building type and share of district heating, and are assigned with the help of the Lambert-Azimuthal-Equal Area Projection (ETRS89-LAEA) into INSPIRE-compliant 1-km² grid cells (Statistisches Bundesamt 2016b). Therefore, the CLC settlement areas must also be assigned to this grid. For this purpose, the CLC settlement areas were intersected with the ETRS89-LAEA grid. The result can be seen on the right part of Figure 4. The black dots in the CLC areas represent the area centroids. The areas without centroids are industrial or commercial areas (denoted with the number "121") which are excluded from this analysis due to the lack of data for industrial heat demand.

Figure 4: Exemplary section of the "111", "112" and "121" CORINE areas (left part) and the intersection with the ETRS89-LAEA grid (right part).

After the allocation of the CLC sub-areas to the square kilometres, the census data were assigned to the CLC areas. The data per square kilometre must be distributed to all CLC sub-areas in the grid. In addition to taking into account the area share, a distinction is also made between 111 and 112 areas (cf. section 3.2). The 111 areas represent settlement areas of which on average 90% are covered with buildings. For the 112 areas, the proportion of building area is on average 65% (EEA 1995). These values are used as building densities. Since the census data is related to buildings, this information can be used to divide the census data into areas. The number of buildings in the 111 areas n_{b111} and the number of buildings in the 112 areas n_{b112} is calculated in equation Eq. 1 and 2 using the total number of buildings in the square kilometre n_b as well as the area sizes of the 111 areas a_{111} and 112 areas a_{112}.

$$n_{b111} = \frac{\sum 0.9 * a_{111}}{\sum 0.9 * a_{111} + \sum 0.65 * a_{112}} * n_b \tag{1}$$

$$n_{b112} = \frac{\sum 0.65 * a_{112}}{\sum 0.9 * a_{111} + \sum 0.65 * a_{112}} * n_b \tag{2}$$

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

In Landesamt für Statistik Niedersachsen (2014), the average living space per apartment can be found for all federal states. For federal states, districts and municipalities, Statistisches Bundesamt (2015a) indicates the number of residential buildings with one apartment (F_1), two apartments (F_2) and three or more apartments (F_3). In addition, the total living space is given in m² (F_{total}). The mean living space (F_{mean}) could be calculated for each federal state using Eq. 3.

$$F_{mean} = \frac{F_{total}}{F_1 + F_2 * 2 + F_3 * x} \tag{3}$$

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

In order to calculate the living space LS_1 on CLC settlement area level, the number of apartments n_a in the CLC area is required. The census data contains the categories "number of buildings with living space" with: 1 apartment, 2 apartments, 3-6 apartments, 7-12 apartments and more than 13 apartments. In the last 3 categories, the average value was estimated so that the sum of the living space in the CLC areas is equal to the total living space in residential buildings in Germany (i.e. 3,670,870,000 m²). For this purpose, an average value of 3-6 apartments was assumed to be 5, for 7-12 apartments 9.5 and for 13 or more apartments 16. The sum of the apartment number (40,411,000) calculated in this way is taken as the number of households in the settlement areas for later calculations. Compared with the actual number of apartments on 31.12.2010 of 40,479,000, the deviation is only -0.15% (Statistisches Bundesamt 2017a). Then the living space per CLC area LS_1 was calculated using the number of apartments n_a and the mean living space $F_{mean,m}$ in the municipality (cf. Eq. 4).

$$LS_1 = F_{mean,m} * n_a \quad (4)$$

Now the sum of the CLC's living space LS_{total1} for each municipality is compared with the measured total living space of this municipality LS_{total2} (for which data are available). If the sum of the living space LS_{total1} deviates from the total living space of the municipality LS_{total2}, the new living space of each CLC area LS_2 will be adjusted accordingly to Eq. 5.

$$LS_2 = LS_1 - \left(\frac{LS_1}{LS_{total1}} * (LS_{total1} - LS_{total2}) \right) \quad (5)$$

As described above, percentages for building age are also given in the census. With the help of these parameters and specific heat demand per year, square meter and building type, the total specific heat demand per settlement area can be determined. For this purpose, the consumption values for single-family houses, two-family houses and multi-family houses are taken from Walberg et al. (2011). The calculation of consumption values in Walberg et al. (2011) also takes into account the modernisation rate for each age group. The building age classes from the census and in Walberg et al. (2011) are not completely identical, as Table 1 shows. The data has therefore been assigned in such a way that a minimal error occurs. The assignment was made according to the colours in Table 1.

Table 1: Comparison of the building age classes from Statistisches Bundesamt (2015b) and from Walberg et al. (2011) as well as the allocation of the classes by colour.

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

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

These total heat demands divided by the number of SFHs/MFHs gives the mean specific heat demand per SFHs or MFHs in a settlement area.

In order to calculate the total heat demand in a settlement area (SA), the share of SFHs or MFHs in the settlement must be known. For this purpose, the mean living space (differentiated by age group, building type and federal state from the building stock model) was multiplied by the number of apartments in SFHs or MFHs in the settlement. In the case of MFHs, the number of apartments x from Eq. 3 was used to determine the number of apartments. The shares of SFHs in the living space were then multiplied by the specific heat demand of the SFHs in the settlement area (MFHs analogously). The two mean specific heat demands are then added together to form the mean specific heat demand hd_{mean} per settlement area. Now the total heat demand per settlement area $HD_{SA_{total}}$ can be calculated according to Eq. 6.

$$HD_{SA_{total}} = hd_{mean} * LS_2 \tag{6}$$

In many settlement areas there are buildings whose heat demand is covered by district heating systems. For these settlements, the heat demand HD_{SA} is deducted from the total heat demand $HD_{SA_{total}}$. Since it is not known which building types have district heating systems, the share of district heating systems S_{DH} in the settlement is deducted from the total heat demand. In addition, the heat demand is reduced by the share of technologies that should not be replaced by district heating with biogas excess heat, such as renewables (cf. Eq. 7).

$$HD_{SA} = HD_{SA_{total}} * (1 - S_{DH} - S_{WP} - S_{Bio} - S_{SE} - S_{GT}) \tag{7}$$

S_{WP} stands for the proportion of heat supplied by wood pellets, S_{Bio} for biomass, S_{SE} for solar energy and S_{GT} for geothermal and other environmental heat. These shares are not to be replaced because the emission factors are lower or not significantly higher than those for district heating from biogas plants (LfU 2016). Apart from the share of district heating (municipality level), all shares are based on figures at federal state level (Statistisches Bundesamt 2016a). Eq. 7 is based on the assumption that the heat demand of buildings which already have a building connection for district heating is completely covered by the existing district heating. With the census of 2011 as a basis, the share of district heating in settlement areas in Germany ranges from 0 to 95% (mean value is 2.65%).

In the next step, a heat load profile LP_{SA} is assigned to each settlement area. For this purpose, a standardised profile of a district heating network SLP_{HD} with an hourly resolution is used, which is adapted according to the previously determined heat demand HD_{SA} (cf. Eq. 8) (for the standardised profile, see Karner et al. (2016)).

$$LP_{SA} = HD_{SA} * SLP_{HD} \tag{8}$$

3.3.2. Heat generation

For each biogas plant, the thermal capacity, the full load hours and the share of already used excess heat EH_{used} are known, as explained above. If the thermal power P_{th} is not given, it is determined with the help of the electrical power and a heat-to-power coefficient of 1 (Klein et al. 2014). In case no full load hours are known, these are determined on the basis of the electrical power and the amount of energy generated per year. On the basis of this data, an hourly load profile SLP_{BGP} can now be assigned to each biogas plant. Biogas plants are typically operated as baseload, but recent changes to the energy-political framework (cf.

section 2) have led to more flexible operation. Since the maximum thermal power requirement is in winter, it is assumed that the biogas plant will be primarily operated during these months. On the basis of the full-load hours, the time window of operation during the winter is extended in both directions until the full load hours are reached (cf. Figure 13). Since excess heat is only generated during operation, the period of electricity production also corresponds to the period during which excess heat is generated. The excess heat profile LP_{BGP} is determined according to Eq. 9.

$$LP_{BGP} = SLP_{BGP} * P_{th} * (1 - EH_{used}) \tag{9}$$

3.3.3. Coverage and supply ratio

Having assigned load profiles to both the biogas plants and the settlement areas, the coverage ratio CR and the supply ratio SR can now be determined. The supply ratio is based on the total amount of available excess heat EH_{BGP} and puts the available excess heat in proportion to the heat demand HD_{SA} of the settlement areas (cf. Eq. 10).

$$SR = \frac{EH_{BGP}}{HD_{SA}} \tag{10}$$

By contrast, the coverage ratio is based on an hourly coverage and thus takes into account the time characteristics of supply and demand. As a result, the coverage ratio cannot be greater than the supply ratio. The coverage ratio CR is calculated in Eq. 11 for every hour. If the heat demand HD_{SA} is greater than the excess heat EH_{BGP} in an hour t, the share that can be covered by the excess heat is calculated in Eq. 12. If the share of excess heat is greater, the heat demand can be fully covered (cf. Eq. 13). The hourly coverage ratios are then integrated in order to obtain the overall coverage ratio. The calculation of this indicator allows a statement about the autonomy of the settlement area. By integrating the temporal characteristics, it is not only possible to make a statement on an annual basis (energy autonomy), but also about the temporal characteristics (power autonomy).

$$CR = \frac{100}{8760} * \int_{t=0}^{8760} CR_t * dt \tag{11}$$

$$HD_{SA,t} \geq EH_{BGP,t} \Rightarrow CR_t = \frac{EH_{BGP,t}}{HD_{SA,t}} \tag{12}$$

$$HD_{SA,t} < EH_{BGP,t} \Rightarrow CR_t = 1 \tag{13}$$

3.4. Allocation of the biogas plants to CLC areas

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

Now the loop shown in the algorithm in Figure 2 after determining the distance matrices is explained. In the first step, CO_2 abatement costs/payback periods are calculated for each of the 10,446 biogas plants, which would result from the supply of district heating. This is done for every biogas plant for all 50 of the closest CLC areas. In the next step, the connection is selected from the resulting 10,446x50 connections, which results in the lowest CO_2 abatement costs/payback period. Then the 25 closest CLC areas to the selected CLC area are added to the selected biogas plant because this CLC area can now be considered as the starting point for the heat supply. The amount of heat provided to the settlement is deducted in the next steps from the heat supply of the biogas plant and from the heat demand of the settlement. The maximum possible amount of heat is provided in each step. If there is no heat supply left after this step, the biogas plant will be removed from consideration, otherwise the CLC area. The abort criterion is then checked, and if the last CO_2 abatement costs/payback period are above a predefined limit value, the loop is aborted. The limit values are described in more detail in section 4. Otherwise the loop is carried out again, but the recalculation is carried out only for the biogas plants and CLC areas where the heat supply or heat demand has changed since the last iteration, in order to reduce simulation time. In addition, all variables that change are recalculated, such as *CR* and *SR* from section 3.3.3. All biogas plants that have the selected CLC area among the nearest 50 areas will therefore be included in the new calculation. In each step, for economic reasons it is ensured that the total length of the district heating pipeline does not exceed 50 km (Arbeitsgemeinschaft QM Fernwärme 2017).

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

3.4.1. Calculation of the saved CO_2 emissions

The calculation of the saved CO_2 emissions is based on the allocation of used energy to provide heat to the settlement areas. The emission factors (EF) of the energy sources and their average allocation in Germany are shown in Table 2 (LfU 2016; Statistisches Bundesamt 2016a). The allocation of the energy for the determination in the settlement areas is based on the average values in the respective federal state (Statistisches Bundesamt 2016a). Since the shares of district heating, wood pellets, biomass, solar energy and geothermal and other environmental heat in the total heat demand are deducted from the total heat demand (cf. section 3.3.1), these types of energy are not listed in Table 2.

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

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

The calculation of the saved CO_2 emissions $CO2_{saved,SA}$ in Eq. 14 is based on the calculated coverage ratios per settlement area CR_{SA}. Excess heat replaces part of the fossil energy used to supply the settlement areas. It is assumed that excess heat replaces the existing energy carriers proportionally. The usage of excess heat has an emission factor of 0 kg/kWh (Theissing 2012).

$$CO2_{saved,SA} = \frac{HD_{SA} * CR_{SA} * (A_{Gas} * EF_{Gas} + A_{Oil} * EF_{Oil} + A_{EL} * EF_{EL} + A_{BC} * EF_{BC} + A_{HC} * EF_{HC})}{1000} \quad (14)$$

3.4.2. Determination of the CO_2 abatement costs

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

First, the fraction of the excess heat that is supplied by the biogas plant to the settlement area Q_{sell} is determined using Eq. 15.

$$Q_{sell} = HD_{SA} * CR \quad (15)$$

Another important parameter is the plot ratio *e*. The plot ratio is a city planning parameter that captures the building density within an area. Plot ratio values are used to categorize typical city districts: (A) inner city areas (*e* = 0.5-2.0), (B) outer city areas (*e* = 0.3-0.5) and (C) sparse areas (*e* = 0-0.3). Those parameter ranges are based on Statens Planverk (1985). The plot ratio is calculated with the population density PD_{SA} and the total building space BSA_{SA} of the settlement area divided by the total population of the settlement P. By dividing the calculated residential area per settlement area by the residential area per person of the municipality from Statistische Ämter des Bundes und der Länder (2011), the number of inhabitants per settlement area can be estimated. All in all, Germany will then have a population of 81.711,000, close to the actual population of 2010 (81.750,000, Statistisches Bundesamt 2017b). By dividing the number of inhabitants by the settlement area, the population density can be determined and in the following step the plot ratio *e* (Eq. 16, cf. Persson & Werner 2011).

$$e = PD_{SA} * BSA_{SA}/P \quad (16)$$

The effective width w is a parameter that describes the relationship between a land area and the length of district heat pipelines within this land area. It can also be seen as a correction factor to avoid the overestimation of distribution costs and is based on the plot ratio *e* (Persson, Werner 2011). The effective width is calculated by using Eq. 17.

$$w = 61.8 * e^{-0.15} \quad (17)$$

In order to calculate the investment for heat distribution, the linear heat density LHD_{SA} is necessary. The linear heat density is calculated in Eq.18 based on the effective width, the plot ratio and the specific heat demand.

$$LHD_{SA} = e * w * \frac{HD_{SA}}{BSA_{SA}} \quad (18)$$

Subsequently the average diameter of the district heating grid d_{SA} is calculated as this is one of the major cost influencing factors (cf. Eq.19). The determination of the diameter depends on the linear heat density.

$$d_{SA} = 0.0486 * \log LHD_{SA} + 0.007 \tag{19}$$

Finally, the determined values are used to calculate the specific heat distribution costs HDC_{SA} using Eq. 20. These costs represent the investment for distributing 1 GJ of heat inside a settlement area. The construction cost parameters *C1* and *C2* vary depending on the plot ratio e. *C1* is a base cost that solely depends on the length of the heat pipe, whereas *C2* depends on the pipe diameter d_{SA}. Three district types are considered in this study and for each type there are different cost parameters applied. The higher the plot ratio *e*, the higher are *C1* and *C2*. In Table 3 the values for the construction cost parameters *C1* and *C2* can be found for the according district plot ratio and the district type. Furthermore, an annuity factor a of 0.08 is integrated in the calculation.

$$HDC_{SA} = \frac{a * (C1 + C2 * d_{SA})}{LHD_{SA}} \tag{20}$$

Table 3: Cost parameter values and district type according to plot ratio range (Persson, Werner 2011)

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

The investment $I_{DHG,SA}$ for the building or the densification of the district heating grid (DHG) is determined by the specific heat distribution costs and Q_{sell}. Additionally, the investment in the pipeline for connecting the biogas plant and the settlement area $I_{con,SA}$ has to be calculated. There an investment rate IR of 200 €/m for the pipe is multiplied by the distance DIS_{SA} between biogas plant and settlement area (Fraunhofer UMSICHT 1998; C.A.R.M.E.N. e.V 2012; Pfnür et al. 2016). The relatively low value of 200 €/m is supposed to reflect the fact that biogas plant operators receive a subsidy in the context of the Combined Heat and Power Act (KWKG) amounting to 100 €/m of district heating network built (BMJV 2018). Finally, the investment can be summed up in Eq. 21 and results in the necessary investment I_{SA} to use the excess heat from the biogas plant to supply the settlement area with heat.

$$I_{SA} = I_{DHG,SA} + I_{con,SA} = HDC_{SA} * Q_{sell} + IR * DIS_{SA} \tag{21}$$

In the section 3.4.1, the saved CO_2 emissions were determined. These are now taken into account to calculate the specific CO_2 abatement costs $CO2_{costs}$ (cf. Eq.22).

$$CO2_{costs} = \frac{I_{SA}}{CO2_{saved,SA}} \tag{22}$$

3.4.3. Determination of the net present value and payback period

The net present value (NPV) is used as a further economic criterion. On the basis of this, the payback period PP of the excess heat utilisation can be determined. The present value for a term of 20 years is calculated using Eq.23 and results from the sum of revenues REV_{SA} less expenses EXP_{SA}. Discounting over this period is taken into account by the discounting factor

df of 0.05 (5%), which is intended to represent a compromise between social and commercial discount rates. Finally, the investment I_{SA} is deducted to calculate the NPV_{SA}. Annual costs are caused by maintaining the district heating grid and driving the district heating pumps. As operating power of the pumps, a factor P_p of 10 $\mathrm{kWh_{el}/MWh_{th}}$ is used (Good 2004). This means that 10 $\mathrm{kWh_{el}}$ is required for each $\mathrm{MWh_{th}}$ of district heating transported to drive the pump. Revenue is generated by selling heat to the customers. The used input data is shown in Table 4, which gives the mean heat prices from a random sample of ten district heat providers in Germany.

$$NPV_{SA} = \sum \frac{REV_{SA} - EXP_{SA}}{(1 + df)^t} - I_{SA} \tag{23}$$

Table 4: Input data for economic evaluation, (Statista 2018a, BDEW 2018, SWB 2014)

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

4. Results and discussion

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

4.1. Validation of the algorithm

Figure 5 gives an overview of the possible types of district heating connections that can be created by the algorithm in Figure 2. The red district heating pipelines lead from a biogas plant to a settlement area and the blue ones lead from one settlement area to another. The black lines represent municipal borders. The results shown in this figure were derived from the calculation with all biogas plants in Germany and the CO_2 abatement costs as a selection criterion (cf. scenario A.1 in section 4.3).The first case shows biogas plant 7 (number in box), which has no connection to a settlement area. This can have several reasons. On the one hand, 100% of the excess heat from the biogas plant could already be used. In this case, this biogas plant would be one of the 241 plants from the survey, since only in these plants over

60% heat is used (cf. section 4.3). On the other hand, the settlement area in the vicinity could have no heat demand, e.g. because all buildings are already supplied with heat from alternative technologies. In addition, a district heating supply might not be worthwhile in this case, since the limit values of the target criteria are exceeded in the algorithm. The second case is the one in which a settlement area is supplied with district heating by only one biogas plant, and these biogas plants also supply only one settlement area (biogas plants 3 and 8). If a settlement area is supplied by several biogas plants, this is the third case (biogas plants 1, 2, 5, 6 and 9). The fourth case is the supply of several settlement areas by a biogas plant, as in the case of the biogas plants 4, 5 and 6. Finally, the connections of biogas plant 5 show that the district heating pipeline can also lead from one settlement area to the next, as shown by the blue-coloured district heating pipeline.

The heat demand of the settlement areas from section 3.3.1 can also be validated. The sum for all settlement areas $HD_{SA_{total}}$ results in a heat demand of 576 TWh (cf. Eq. 6). The heat demand for space heating and hot water in private households is subject to large annual fluctuations (mainly gas demand) and ranged from 544 to 578 TWh between 2010 and 2015 (DIW Berlin & EEFA 2017; Umweltbundesamt 2017a; Statista 2018b). In 2010, from when the census data, heat consumption data and renovation data originate, the heat requirement was 578 TWh (Deviation: -0.35%). Thus, the procedure presented in section 3.3.1 can be deemed to be very accurate.

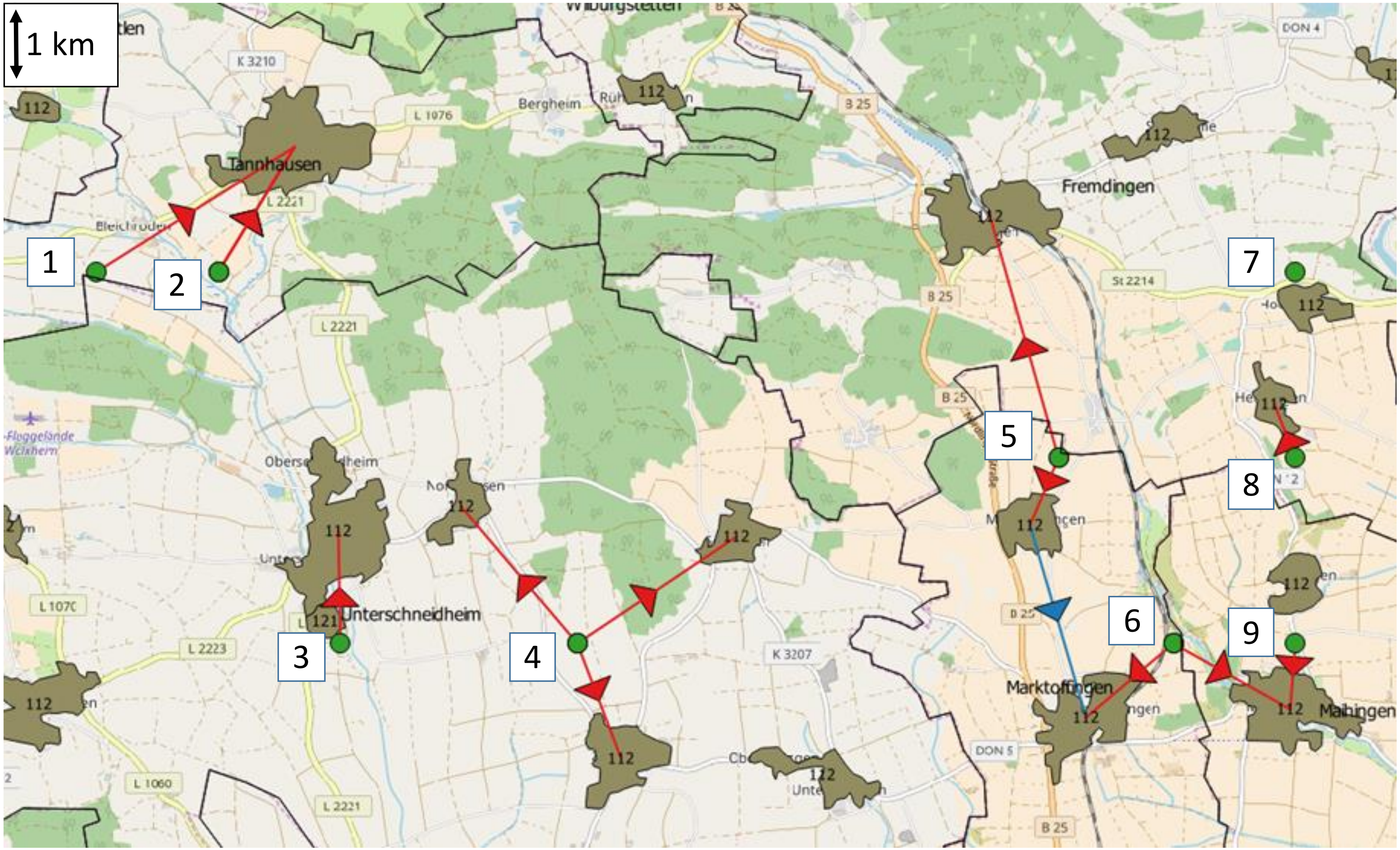

Figure 5: Exemplary illustration of resulting district heating pipelines for the use of excess heat from biogas plants in several municipalities in Baden-Württemberg. The background map is from OpenStreetMap contributors (2018).

4.2. Results from the survey

As the left part of Figure 6 shows, the majority of the 241 biogas plants (green circles) identified are located in the federal state of Bavaria (143 plants ≙ 59%). This also corresponds to the distribution of the responses from the survey (cf. section 3.1).

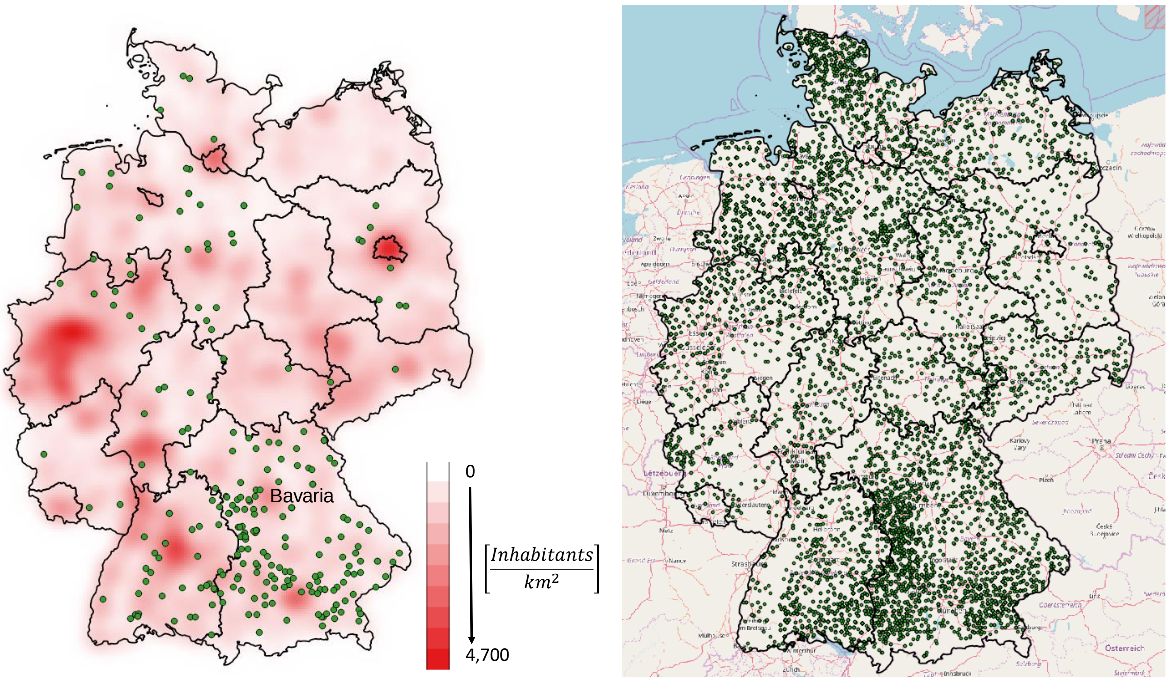

Figure 6: Location of the 241 biogas plants identified among the plants surveyed in Germany and a heat map showing the population density in the settlements (left part). Location of all biogas plants in Germany (right part) (Engel 2015; Statistisches Bundesamt 2017c).

The heat map on the left side of Figure 6 shows the population density. White areas mark settlements with a low population density and the population density then rises to dark red. The heat map shows that the calculation with only 241 plants does not take into account the settlements with the highest population densities. A comparison of the 241 plants with all plants in Germany (cf. right part of Figure 6) shows that the latter are clearly more evenly distributed across Germany. Of the 241 biogas plants allocated, only 121 plants still have unused heat. The remaining 120 plants already use 100% of their excess heat.

First of all, the results of the calculations with CO_2 abatement costs as a decision criterion are presented in section 4.2.1, followed by the results of the calculations with payback period as a decision criterion in section 4.2.2. A sensitivity analysis is performed for both cases to show how some key parameters affect the results. The values of the parameters were changed in 10% steps from -50% to +50%. The only exception is the distance of the biogas plant from a specified location. As described in section 3.2, the location of the biogas plant can have a maximum uncertainty of 3 km. The smallest distance between a biogas plant and the centroid of a settlement area is 10 metres, which lies far below this maximum uncertainty. However, it can also be a so-called satellite CHP unit located within the settlement area (Rutz & Güntert 2012). After all, 17% of the biogas plant operators in Germany have a satellite CHP unit (Liebetrau et al. 2017). To cover this uncertainty, the distance of the plants to the settlement areas was varied between -3 km to +3 km. Since this parameter is shown together with the other parameters in Figure 7 below, - 3 km corresponds to -50% and +3 km to +50% and the change of 10% corresponds to 600 meter steps. A further examination of over 700 plants in the most recent EEG biogas plant register from Bundesnetzagentur (2018) enabled them to be matched to their records in Energymap (Engel 2015). The average distance between the matched plants was 1.5 km, which corresponds to a range in Figure 7 of +/- 25%, but it is unclear which of these two sources is more accurate.

4.2.1. CO_2 abatement costs as decision criterion

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

Figure 7 shows the mean CO_2 abatement costs resulting from the sensitivity analyses. The strongest deviation occurs when the coordinates of the biogas plants are changed (distance of biogas plant from specified location). The mean CO_2 abatement costs change by -41% if the biogas plants are 3 km closer to the settlement areas and by +97% if the biogas plants are 3 km further away from the settlement areas. The deviation for the 3 km closer plants is smaller, since some plants are already less than 3 km away from the settlement areas. The gradient of the curve becomes more constant the less the distance is reduced. Nevertheless, the curves do not have constant gradients. This is related to the abort criteria, as a result of which more and more connections between plants and settlements are excluded from the analysis or included in the analysis when parameters are changed. This will be further explained in section 4.2.2. If the biogas plants deviate 1.5 km from their location as described above, the costs could change between -31% and +52%.

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

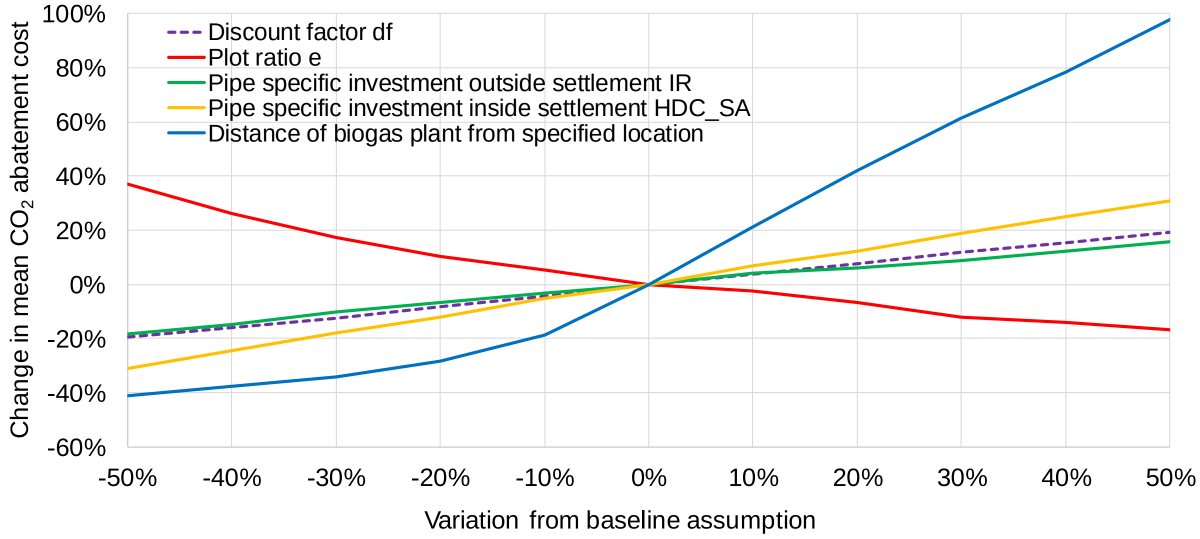

Figure 7: Change in the mean CO_2 abatement costs of the reference scenario when changing specific parameters

As illustrated in Figure 8, the variation of the parameters does not have a large influence on the total CO_2 abatement. The change in total CO_2 abatement of the reference scenario (41,483 $\mathrm{tCO_2/a}$) varies only between -1.5% and +0.5%. The greatest influence has once again the variable "distance of biogas plant from specified location".

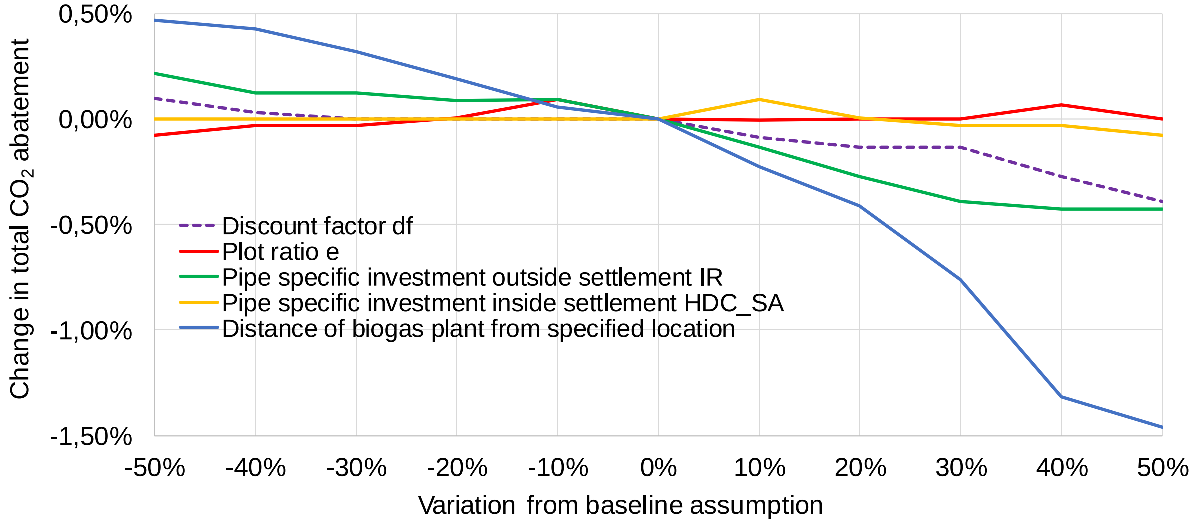

Figure 8: Change in the total CO_2 abatement of the reference scenario when changing specific parameters

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

for 345 €/tCO_2 (cf. left part of Figure 9). In the case of +50%, the CORINE area 8876 will be selected directly with 522 tCO_2/a for 105 €/tCO_2 (cf. right part of Figure 9).

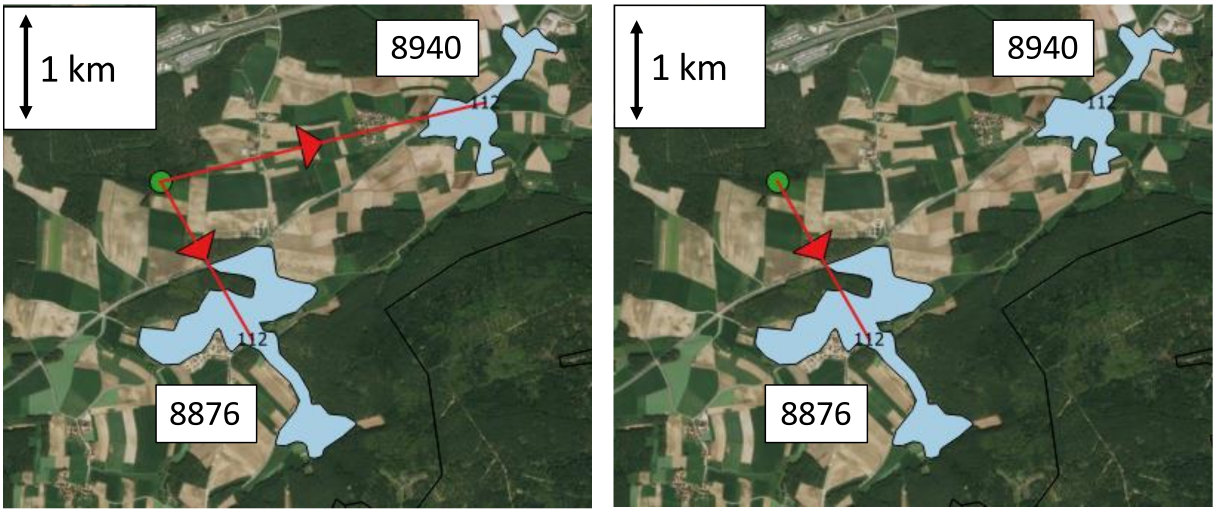

Figure 9: District heating network for the utilisation of the excess heat from a biogas plant in a municipality in Bavaria. The left part of the figure shows the connections that result in the case where plot ratio e is increased by 40%, in the right part e is increased by 50%. The background map is from Microsoft (2018).

In the first case, CORINE area 8876 is also supplied, since approx. 14% of the excess heat in the biogas plant remains after supplying CORINE area 8940. In the second case, however, only 7.4% excess heat is left after supplying CORINE area 8876, so that the supply of area 8940 is no longer worthwhile (CO_2 abatement costs of 1,180 €/tCO_2 ≥ 1,000 €/tCO_2). The reason for the fact that settlement area 8940 is supplied before area 8876 (up to case +50%), although in settlement area 8876 there is more heat demand, is, among other things, the almost twice as high population density in settlement area 8940 (3,400 persons per km² compared to 1900 persons per km²). In order to avoid fluctuations in the curves of the total CO_2 abatement costs in Figure 8, the total CO_2 abatement costs would have to be used as a decision criterion in the algorithm. In this case, however, the CO_2 abatement costs involved could be excessively high in some cases.

4.2.2. Payback period as decision criterion

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

The mean payback period increases the most when HS decreases (+69%) and is the lowest when the distance of biogas plant from specified location decreases (-44%, cf. Figure 10). If HS decreases, only a lower profit can be achieved by selling the heat. Since the variation of District heating pump power P_p has exactly the same effect on the payback period, only the electricity price EP is shown in the figure (cf. section 3.4.3). If EP increases, the costs for driving the district heating pumps and thus the payback period increase. P_a has an opposite effect on the payback costs, since the rate at which the heat is delivered, and hence the amount of heat sold, depends strongly on this parameter. The distance, *e*, *df*, HDC_{SA} and IR have almost the same effect on the mean payback period as on the mean CO_2 abatement costs (cf. section 4.2.1).

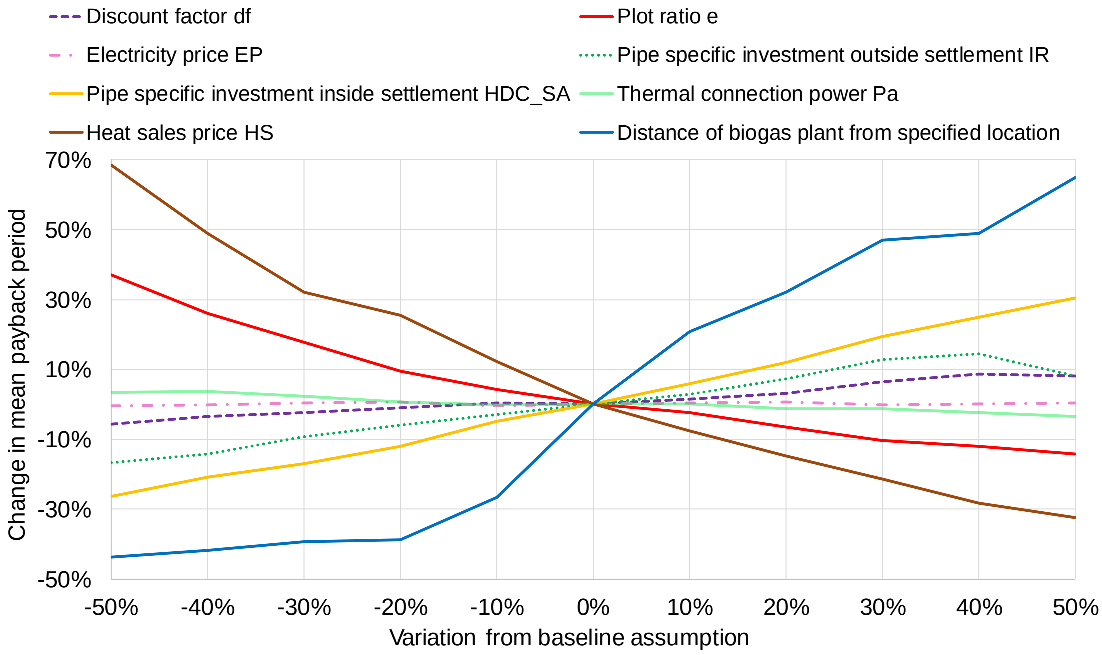

Figure 10: Change in the mean payback period of the reference scenario when changing specific parameters

However, the declining mean payback period with a change from IR from +40% (8.3 years) to +50% (7.8 years) is remarkable. The other non-linearities in the curves in Figure 10 can also be explained using the following example: Figure 11 shows the change in the number of district heating pipelines when increasing IR from -50% to +50%. The number of connections is reduced from 132 at -50% to 107 at +50%. In each step, the changes are within a range of one to three no longer existing connections. However, in the last step from +40% (115 connections) to +50% (107 connections), eight connections no longer exist due to a payback period of more than 20 years. As a result, many of the connections with a long payback period will be eliminated in this step. Therefore, the mean payback period decreases in this case. This can be proven by repeating the calculation in the case of +50%, and this time not using the payback period as a criterion for aborting the algorithm, but by aborting at a number of 115 district heating pipelines as in case +40%. This would result in a mean payback period of 8.8 years, which is higher than in the case of +40%.

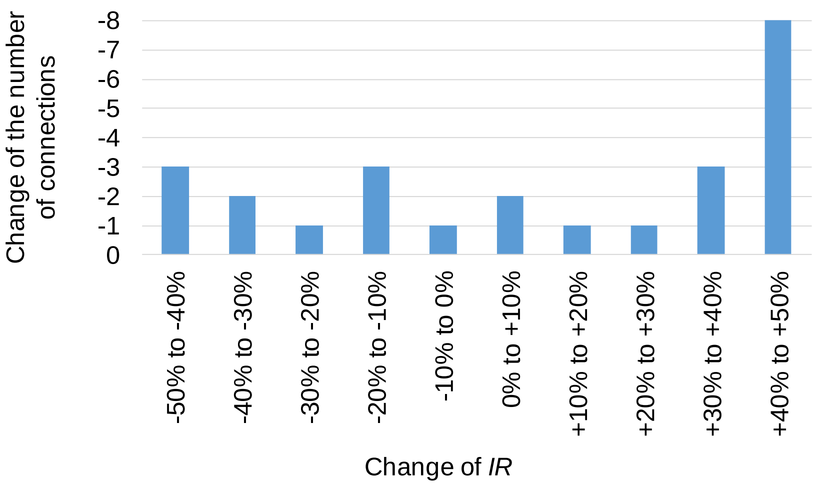

Figure 11: Change in the number of district heating pipelines when changing IR

4.3. Results for all German biogas plants

The analysis with all 10,446 biogas plants assumes an average value of 40% unused heat in the biogas plants that were not part of the survey (cf. section 3.1). Whilst there will obviously be deviations in individual cases, the assumption of 40% excess heat seems reasonable and is verified by other studies (e.g. DBFZ 2015). Table 5 shows the various scenarios developed with all biogas plants.

Table 5: Overview of the scenarios carried out with all biogas plants.

Number	Decision criterion	Adjustment
A.1	CO_2 abatement costs < 1,000 €/tCO_2	-
A.2	CO_2 abatement costs < 1,000 €/tCO_2	Not considering Eq. 7
A.3	CO_2 abatement costs < 1,000 €/tCO_2	New excess heat profile, cf. Figure 13
B.1	Payback period < 20 years	-
B.2	Payback period < 20 years	Considering the cogeneration bonus of 3 €-ct/kWh for district heat from biogas plants

When using the CO_2 abatement costs as a decision criterion in scenario **A.1**, the excess heat from 9,790 different biogas plants is used. A total of 10,989 district heating pipelines are built in this case and 2.55 $MtCO_2/a$ can be saved (cf. yellow line Figure 12). This corresponds to 0.3% of the amount of CO_2 emitted in Germany in 2015, equivalent to 792 $MtCO_2/a$ (Umweltbundesamt 2017c). 85% of the 2.55 $MtCO_2/a$ can be saved with CO_2 abatement costs below 200 €/tCO_2. The first 78 tCO_2 are saved at a minimum cost of 13.5 €/tCO_2, which is 41.5 €/tCO_2 less than the best connection in the case of the 241 plants. The reason for this is that this biogas plant is located only 70 metres from the settlement area centroid. In total, around 8 TWh of heat demand in German households are covered by the biogas plants.

Scenario **A.2** assumes that the biogas plant can replace all forms of existing heat supply (i.e. neglecting Eq. 7, so $HD_{SA} = HD_{SA_{total}}$). In this case, the CO_2 abatement is only 5 $ktCO_2/a$ higher at almost the same cost. This can be explained as follows. At the beginning of the calculation with all plants, approx. 10 TWh of excess heat are available from all biogas plants. In the end of calculation A.1 above, only 0.22 TWh (2%) remain at the end. This shows that there is scarcely any potential for an increase and that there is a bottleneck on the supply side of the biogas plants, rather than on the demand side in the existing heat supply systems. For the second scenario (without Eq. 7) only 0.03 TWh more heat is used, due to the small amount of non-fossil-fuel-based existing heating that is replaced in this case. Since the CO_2 abatement cost curve does not change significantly, the curve for A.2 is not shown in Figure 12.

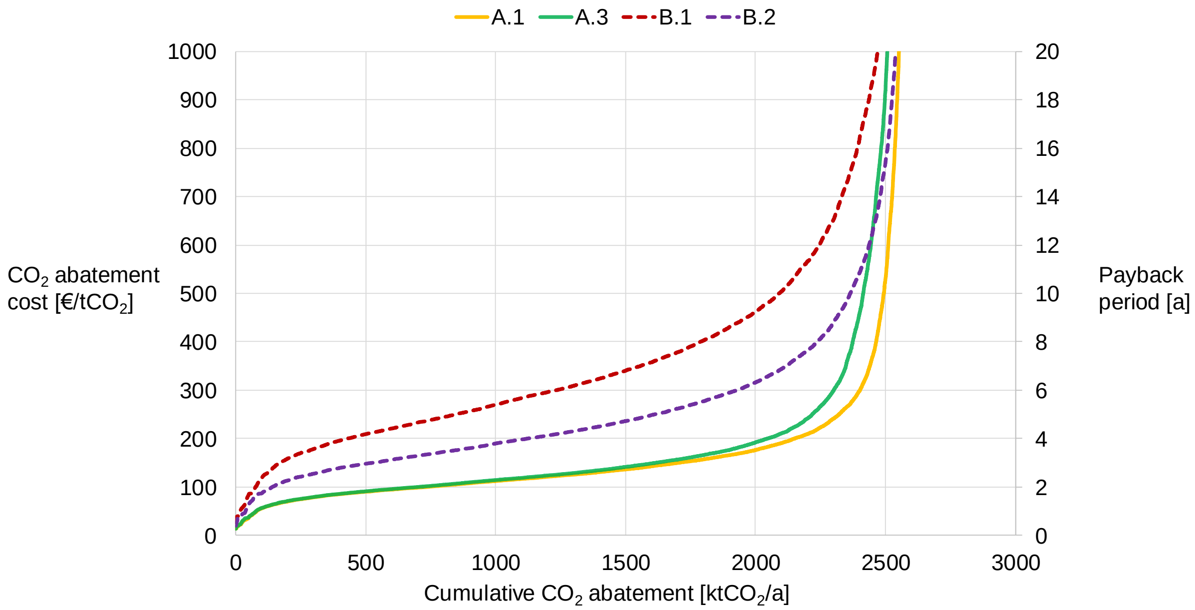

Figure 12: Cumulative CO_2 abatement in the scenarios with CO_2 abatement costs or payback period as the decision criterion

As explained in section 3.3.2, a constant load profile for the excess heat from the biogas plants was assumed. However, this profile could look different in reality, since the digester or residential buildings that are already supplied with heat require more heat in the colder months (Rutz et al. 2015). Based on the values from Rutz et al. (2015), the load profile of a biogas plant that supplies residential buildings and the digester with excess heat is changed in scenario **A.3** according to Figure 13. The short period in summer, in which the load is 0 kW, is due to the fact that the biogas plant shown as an example has full load hours of less than 8760.

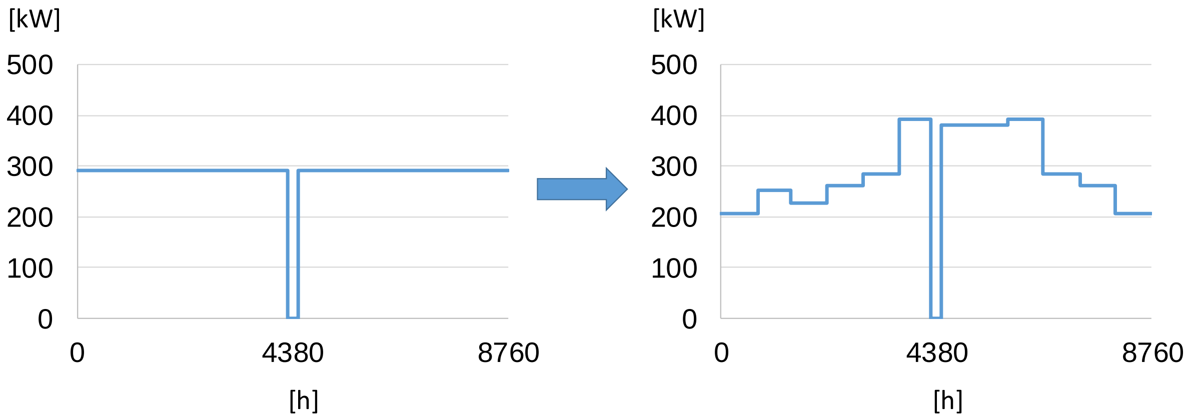

Figure 13: Change in excess heat load profile, without (left) and taking into account monthly differences in heat utilisation (right)

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

Compared to scenario A.1 with CO_2 abatement costs as a decision criterion, if the payback period is used as a decision criterion in **B.1**, the number of biogas plants whose heat is used decreases by 835 to 8,955 plants and 344 district heating pipelines fewer are built (10,645 pipelines). Overall, 0.08 $MtCO_2/a$ less than in scenario A.1 is saved (2.47 $MtCO_2/a$). The first 85% CO_2 can be saved with a payback period of fewer than 10 years (cf. Figure 12). Only 0.53 TWh (5%) of excess heat remains unused in this calculation.

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

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

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

Figure 14 shows the share of residential heat demand in German municipalities that can be covered by the excess heat from biogas plants with the help of district heating. The calculation **A.1** serves as a basis for the figure, and district heating connections where the payback period is longer than 20 years were not taken into account. The figure shows that especially in the southern (Baden-Wuerttemberg and Bavaria) and northern federal states (Schleswig-Holstein, Mecklenburg-Western Pomerania, Lower Saxony, Saxony-Anhalt and Brandenburg), the most heat demand per municipality can be covered. In total, there is a potential in 3,591 (32%) of the 11,400 German municipalities, in the other municipalities the value is 0%. The mean value in the 3,591 municipalities is 12% and the CO_2 emissions per capita are reduced by an average of 250 $kgCO_2/a$. Some of the municipalities can cover almost all of their heat demand with district heating from the biogas plant(s). More than 85% of the heat demand is met in 21 municipalities, while a maximum value of 98% is reached in the municipality of "Bresegard bei

Eldena" (200 inhabitants) in Mecklenburg-Western Pomerania. These results at the municipal level can be found in the online supplementary material.

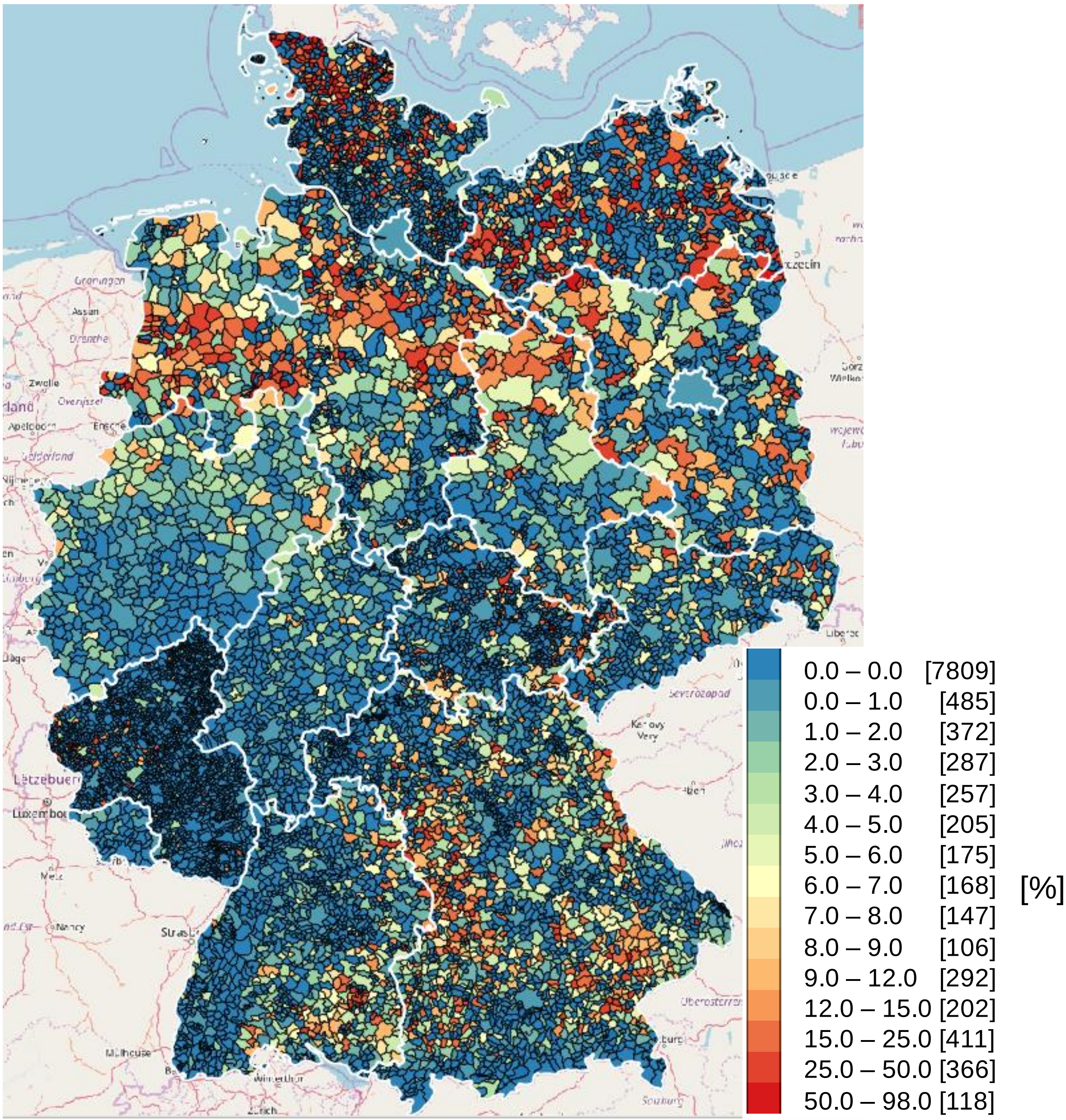

Figure 14: Share of heat demand that can be covered by district heating from biogas in German municipalities. The numbers in brackets represent the number of municipalities to which the shares can be allocated. The background map is from OpenStreetMap contributors (2018).

4.4. Critical appraisal of the methodology

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

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

In addition, the profiles for heat supply and demand were assumed. On the one hand, it is not certain that the biogas plants will actually be operated in the periods in which the heat demand in the settlements is highest (winter). On the other hand, the standard load profile SLP_{HD} from Eq. 8 can only be accurately be applied in municipalities with several hundred households. In the smallest settlement area, there are only three households with a total of five inhabitants. However, the influence of this uncertainty is low, since in the calculations only 7% of the connected settlement areas have less than 100 households.

In some cases the costs are overestimated, however, as the following example illustrates. Figure 15 shows the district heating network for using the excess heat from a biogas plant in the municipality of Cavertitz in Saxony. The problem lies in the fact that the algorithm iteratively selects the optimal connection in each step. The result is that the blue-coloured district heating pipeline furthest to the left is selected before the red coloured district heating pipeline furthest to the left. If the red district heating pipeline had been "built" first, there would have been a shorter distance to the settlement area in the bottom left, which is supplied by the blue district heating pipeline. This uncertainty has a low impact on costs, due to the fact that this phenomenon only occurs very rarely. In scenario A.1, for example, only 6% of district heating connections start in settlement areas. Of this 6%, only a few connections will show this fault, in Figure 15 it is only one connection of five.

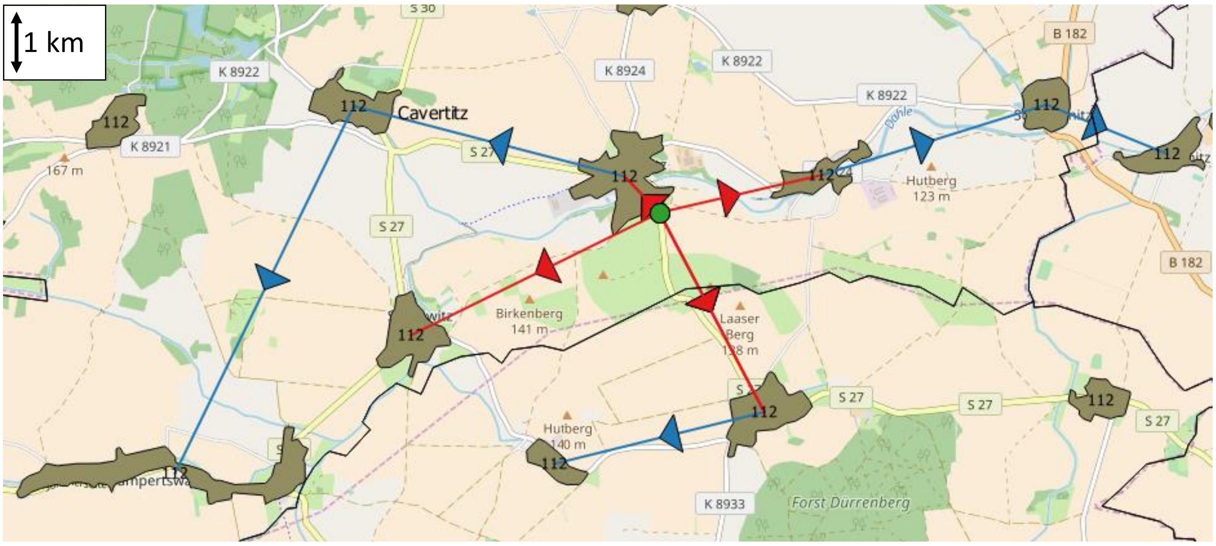

Figure 15: District heating network for the utilisation of the excess heat from a biogas plant in the municipality of Cavertitz in Saxony. The background map is from OpenStreetMap contributors (2018).

Figure 15 also shows that the selection of the area centroid for distance measurement overestimates the length of the district heating pipelines from the biogas plants to the settlement areas in this case. Actually, only the distance to the border of the settlements should be measured here. However, this determination was not possible since the distance calculation is only possible with point coordinates. This could lead to a moderate increase in costs. For example, the settlement area at the bottom left of Figure 15 has a width of 4.2 kilometres. In extreme cases, the length of the district heating pipelines could therefore be overestimated by around 2 km.

Additionally, an existing district heating supply can be deducted from the heating demand of the settlements, but no existing district heating grid can be taken into account due to a lack of data. If these data were available, the length of the district heating pipelines to be built could be reduced, as they would no longer have to lead to the settlement, but only to the nearest connection point of the existing district heating grid. A further overestimation of costs results from the fact that only residential areas are considered and not industrial or commercial areas. Some promising progress in this area has been made by the Pan European Thermal Atlas (PETA) in the context of the Heat Roadmap Europe project[2]. Within the PETA urban areas are considered as "coherent urban areas", including industry and commercial sector, and existing district heating networks are considered on a detailed level. But at the time of carrying out this study, this data was not publicly available. In addition, PETA uses a resolution of 1 km², the resolution in the study carried out here is higher in some parts (e. g. 0.05 km² for CLC data, cf. EEA (2017)). The impact on costs is therefore estimated to be negligible.

Figure 16 shows the municipality of Leutenbach in Baden-Württemberg. Blue surfaces are used here to represent the CLC areas. Red areas are individual buildings from Geofabrik (2018). The figure shows that the CLC data do not cover all existing settlement areas (cf. red circles in the Figure 16), as there is a minimum threshold for the size of an urban area to be differentiated in the CLC data (0.05 km²) and the data are from 2012 (so do not consider newer buildings). In the example shown in Figure 16, the excluded settlement areas are relatively small, so the implications for the results are likely to be only marginal.

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

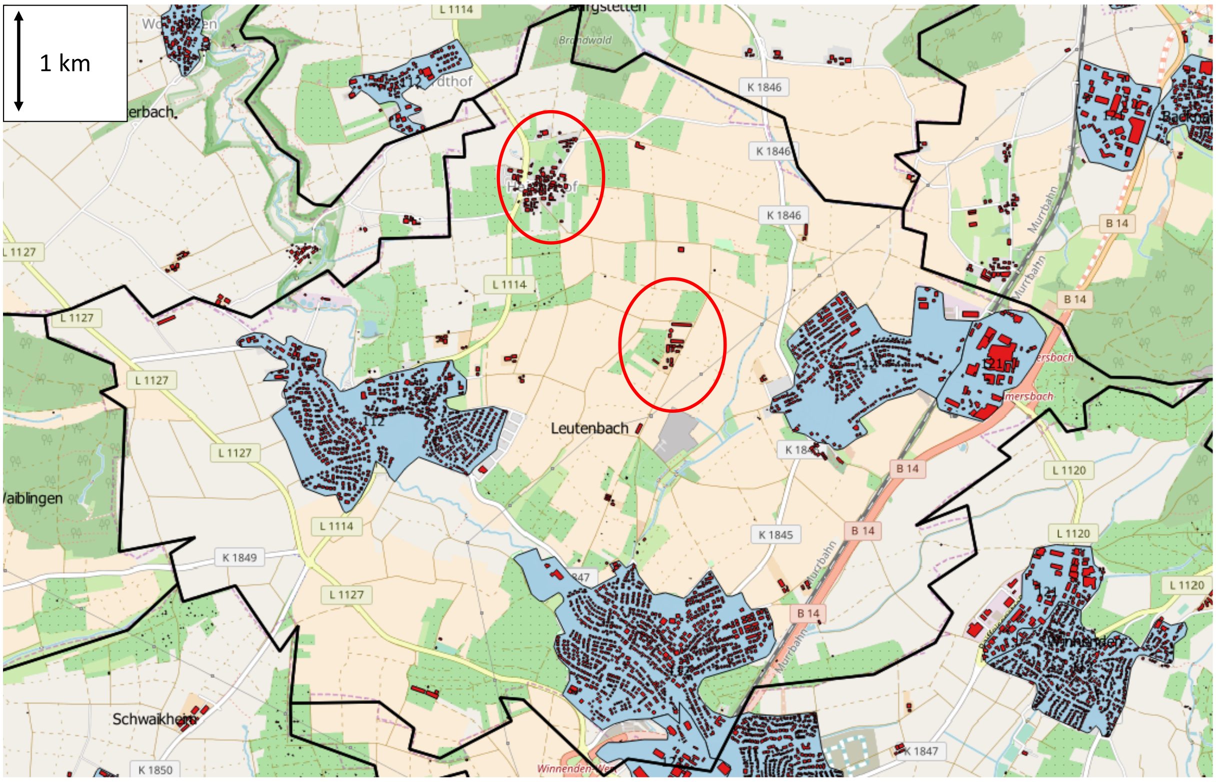

Figure 16: Settlement areas from the CLC data set and buildings in the municipality of Leutenbach in Baden-Württemberg (Geofabrik 2018). The background map is from OpenStreetMap contributors (2018).

A further uncertainty arises from the age of biogas plants. It is impossible to estimate how the plants will continue to operate when the Renewable Energy Sources Act ends after twenty years. The age profile of the existing plants means that some of these plants will cease to benefit from the feed-in tariffs upon which they rely to be economical. After this time, their continued operation is uncertain. The plants should already have broken even after twenty years, as studies have shown payback periods in the region of 7-12 years depending on the substrate and the output (Balussou et al. 2011). Hence the plant may continue to operate, but the negative impact on the economics of losing the FITs could force the operators to seek other business models such as biomethane uprading and feed in (cf. section 2). In the absence of new business models, the plants might be forced to close, which would mean the excess heat considered here is no longer available. However, this study aimed to assess the current technical potential for excess heat use from biogas plants, and there are always future uncertainties associated with such analyses. Potential future business models for biogas plant operators in a post-EEG context will be the subject of a future contribution.

5. Conclusions

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

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

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

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