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ORIGINAL ARTICLE

A consolidated potential analysis of bio-methane and e-methane using two different methods for a medium-term renewable gas supply in Germany

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Abstract

Background: The German energy transition has entered a new phase and one important aspect is the question, to what degree the gas sector could be supplied with so-called "green" gases, i.e., gases from renewable sources. This paper focuses on the potential of domestic methane from biological origin (bio-CH_4) until 2030 that is estimated with two different methods. The comparison of the results provides a consolidated estimate.

Methods: In a bottom-up approach, a GIS-based cluster analysis was undertaken to estimate the potential on bio-CH_4 from the existing cogeneration biogas plant (BP) stock. In a top-down approach a meta-analysis of GHG-reduction scenarios with respect to bio-CH_4 was performed. The meta-analysis was also extended to methane from renewable electricity (e-CH_4) since the BP stock may play a role in the provision of CO_2. Further, it included the year 2050 (the target year for most scenario studies) as well as issues like energy imports.

Results: The bottom-up approach yields a potential of 24.9 TWh of bio-CH_4 for 2030. This is well within the range of the top-down analysis of 11–54 TWh (average: 32.5 TWh) for that year. In some scenarios values for e-CH_4 where considerably higher, especially with respect to 2050, but in these studies the sources—including the CO_2 sources—are either not explained at all or they are due to imports of e-CH_4 in combination with direct air capture (DAC) rather than biogenic sources. Concerning the regional dispersion, the bottom-up analysis shows that the largest potentials (53% or 905 of the biogas plants) are located in the northern part of Germany, more particular in Lower-Saxony, Schleswig-Holstein, Mecklenburg-Western Pomerania. These represent 54% or 602 MW of the installed capacity of the clusters.

Conclusion: The consistency of the outcomes of the two methodologically very different approaches may be called the main result of this research. Therefore, it provides a consolidated analysis of the potential for domestic supply of bio-CH_4 in 2030. Furthermore, the amount corresponds to 2.7–3.5% of the German natural gas consumption in 2018. Taken bio-CH_4 and e-CH_4 together it corresponds to 7.2–8.0%.

Keywords: Bio-methane potential, Top-down analysis, Bottom-up analysis, Consolidated estimates, Biogas installation, Retrofit, Biogas bundling, Green gases

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Background

The German energy transition has entered a new phase by the end of the late 2010s. With rising shares of renewable electricity supply the focus has gone beyond decarbonizing the electricity sector and has shifted towards the integration of renewable energy sources (RES) within the larger energy system [1, 2, p. 795]. That is, issues like sector coupling and defossilizing gas supply have gained attention [3, 4]. The latter stems from the insight that (renewable) electricity needs to be complemented by other climate-neutral or defossilized energy carriers for certain applications and uses. These include selected high calorific applications in transport (heavy duty vehicles, sea and air transport) as well as industrial applications such as medium to high temperature processes and basic materials [5, Trend 8]. Further, a medium is required to store large amounts of energy over longer periods (i.e., seasons). Other storage media, like compressed air storage, flywheel generators or pumped hydro storage are meant to store energy for hours or for some days at maximum. Depending on the technical parameter of the site pumped hydro is able to store energy for some weeks. Only large storage lakes with a natural supply may store energy over seasons. [6, pp. 49–51, 7, p. 100].

That is, the role of the German natural gas sector within the energy transition has come under discussion [8]. As of 2018 the German gas storage capacity was 24.3 billion m^3 [9, 10] or 242 TWh (own calculation, see "Methods"), being the highest in Europe. In the same year, the German gas grids had a total length of 551 thousand km and were divided into three broad pressure ratings. High pressure grids (125 thousand km, $p > 1$–120 bar) are used for long distance gas transport. Medium pressure distribution grids (249 thousand km, $p > 0.1$–1 bar) and finally low pressure connection lines (177 thousand km, $p < 0.1$ bar) are used to transport the gas to the consumers [11, p. 350, 12, p. 40]. The consumption of natural gas in Germany was 928 TWh in 2018 [11, figure 148]. The German natural gas supply comes from very different regions: In 2015, the largest import volumes came from Norway and Russia (32% each) and the Netherlands (27%). 7% was due to domestic exploitation [13]. On the one hand, trying to use the existing natural gas infrastructure as a storage and flexibility option also in a climate-neutral energy system has attracted rising attention. On the other hand, it is not yet decided to what degree the gas sector should (and could) contribute to the energy transition. It raises a number of questions on the optimal future size and kinds of infrastructure, e.g., concerning pressure levels, adaptation needs for certain gases, etc. [4, 8].

Technically natural gas consists of fossil methane, i.e., CH_4, and one important aspect of defossilization is the degree the gas sector could be supplied with so-called "green" gases, i.e., gases from renewable sources. These gases are hydrogen from RES (e-H_2) and renewable methane. Since renewable methane, in turn, may be produced in (different) process(es) of methanation from H_2 and CO_2, the origin of these substances is of importance as well. Under the assumption of using e-H_2, this paper focuses on the potential of domestic methane from biological origin (bio-CH_4) until 2030. Due to the technicalities of the production routes, it is necessary to analyze the potential of methane from RES (e-CH_4) as well. It provides two different methods of analyzing these potentials in order to compare the results and provide consolidated estimates. As Fig. 1 shows, there are two broad categories of methanation, namely biological (left hand side) and catalytic (right hand side). Biological methanation may be divided into a process where CO_2 is extracted from the biogas plant (BG) and together with e-H_2 injected into an external reactor. In the in situ process bio-CH_4 may be obtained from the BP directly where it raises the yield of bio-CH_4 (50–75% of the BP's biogas consists of CH_4, see Box in "Methods"). In catalytic methanantion there are different processes that refer to different types of reactors that are not detailed here. However, in terms of e-CH_4 the availability of CO_2 is a key aspect. By definition above, e-CH_4 is based on e-H_2. The source of CO_2, however, may vary as shown on the right-hand side of Fig. 1. It could be taken from point sources of industry or power plants via carbon capture (CC) techniques (far right). However, this is still in an early development stage and meant to sequester carbon from fossil fuels [14, pp. 67–70]. Secondly, it could be taken from ambient air via direct air capture (DAC). However, estimates about the future commercial availability of DAC technologies cannot yet be made [14, p. 113]. Thirdly, CO_2 may also be provided by BP (25–45% of the biogas consists of CO_2, see Box in "Methods"). That is, BP may also play a role in the provision of a climate-neutral CO_2 source for e-CH_4 in catalytic methanation and in estimating its potential in case DAC technologies are not available.

In order to find out the adequate role of these technologies from a system perspective it has been searched whether they have been included in greenhouse gas (GHG) reduction scenarios so far. GHG-reduction and energy scenario analysis are commonly applied tools for the long-term development of the energy system [15, 16]. They have a more strategic approach from the view point of the overall energy system as they try to identify optimal transition paths towards a defossilized energy systems. That is, they try to find optimal combinations of energy inputs, optimal combinations of direct electricity usage vis-à-vis gases usage and the optimal combination of the different gases. In the long-term energy scenarios, renewable gases play an important role [e.g., 17]. From a systemic point of view, all these options have their merits and pitfalls and they have partly been alluded to above. For instance, e-H_2 beyond a certain concentration requires adaption of the grid ("H_2 readiness"), whereas bio-CH_4 and e-CH_4 do not. However, the latter two

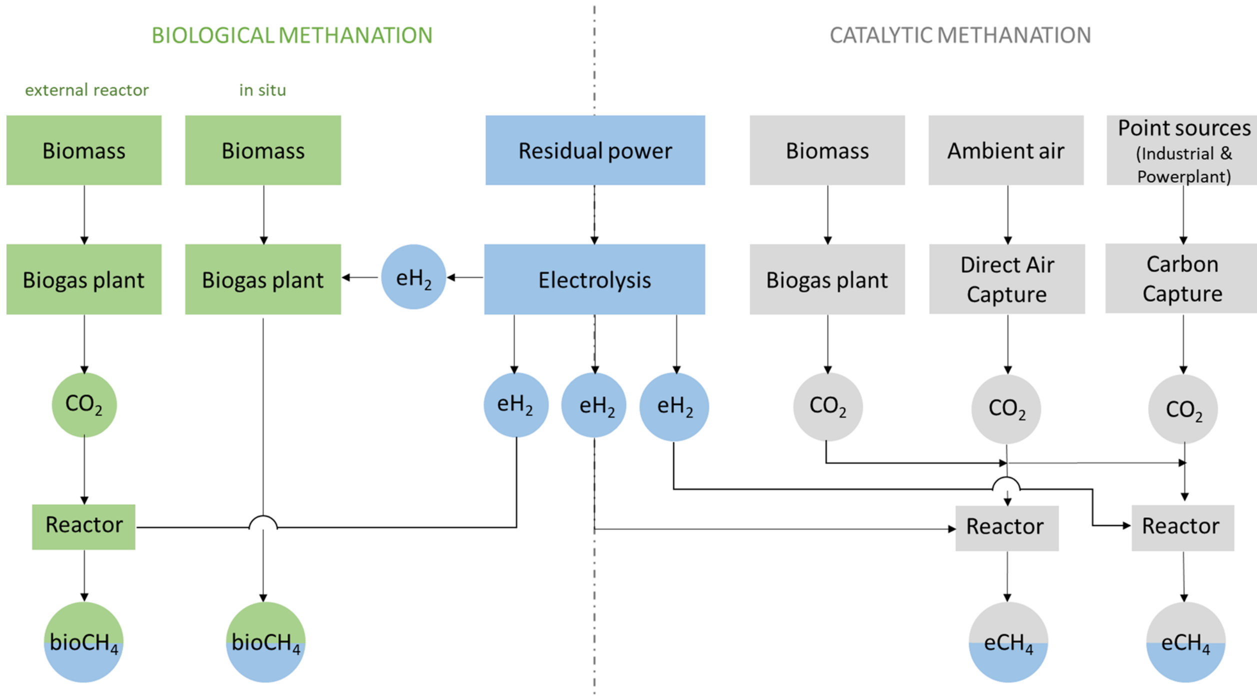

Fig. 1 Production routes of bio-CH_4 and e-CH_4

require higher RES inputs and they require (carbon neutral) CO_2. Furthermore, they have different applications as, for instance, H_2 may be used in fuel cells and CH_4 may be used in CNG cars, etc. [18, p. 150, 19]. Ideally, energy system analysis takes all these aspects into account. Furthermore, energy system analysis may rely on additional options such as energy imports. However, the issue of renewable methane is fairly new and the meta-analysis in this paper may give an overview on the current state-of-the-art with respect to its application in scenario analysis.

Scenario analyses, however, often do not take into account the realities of the German energy transition. With respect to bioenergy, these realities concern the existing German BP capacities and under what circumstances these are able to supply bio-CH_4 to the natural gas grid. That is, in addition to the optimization or greenfield approach of the scenario studies, a complementary brownfield approach needs to estimate the possible bio-CH_4 supply taking the existing BP capacities, adjacent infrastructures and the current regulatory environment into account. Germany has built up a considerable stock of BP within the last 20 years. Almost all of these units have been built and are currently operated under the German Feed-In-Tariff (FIT) scheme. As of 2018 around 10,400 biogas plants with an electrical capacity of 5000 MW where registered under the German FIT scheme. [20, Table 1, p. 21]. In sum the German biogas and bio-CH_4 plants (incl. sewage gas and landfill gas) produced 52.8 TWh gaseous fuels in 2018. This corresponds to roughly 6% of the German natural gas consumption or 22% of the German gas storage capacities [21, own calculations].

That is, the starting point for the transition is the existing stock of biogas capacities, which is spread all over Germany and the existing gas grid on the one hand and changes in regulation on the other hand. In terms of capacities, only a small share of the capacities are bio-CH_4 plants and most of them are cogeneration plants as laid out above. In terms of regulation, however, the 20-year remuneration period under the FIT will end in the 2020s for almost all of these biogas cogeneration units. These so-called "post-FIT units" are in need of a new business model or will have to go out of business [20]. Therefore, under the changing condition of he FIT for the biogas plants, new business models for the plants are necessary and bio-CH_4 provision might become one option. That is, the cogeneration plants may be converted into bio-CH_4 plants and connected to the natural gas grid infrastructure if it seems favorable within infrastructural conditions. In parallel, these units may also play a role for e-CH_4 as they may provide a source of CO_2 for e-H_2 as described above (via injection of e-H_2 into the BP, see e.g., the BioCat Project[1]).

Against this background, the question of this paper is, how much bio-CH_4 can be expected for the renewable gas supply in Germany until 2030. To answer this question the paper combines the two methods above and therefore provides a consolidated estimate. The bottom-up method focuses on the technical, infrastructural and regulatory realities of the existing German BP stock. The top-down approach takes into account overall system considerations such as optimality and additional options such as energy imports. Therefore, the meta-analysis is extended to 2050. Furthermore, biogas plants may also provide biogenic CO_2 for e-CH_4 and therefore e-CH_4 is also taken into account in order to derive a better analysis of the potentials.

Methods

Conversion of energetic values

The different methods apply different units. The scenario studies (top-down) publish the contribution of methane (CH_4) in TWh and the bottom-up approach uses (norm) m^3 of CH_4. Furthermore, the content of (bio-)CH_4 from biogas was calculated, where necessary. Wherever values had to be converted, it is mentioned in the text. The following conversion factors are used:

Energy content of bio-CH_4 [22, p. 68]: 9.97 kWh/Nm^3.

Average composition of biogas [22, p. 19]: 50–75% (bio-)CH23$_4$, 25–45% CO_2, water, other.

Even though it is not always made explicit in the scenario studies, it is assumed that TWh for production of bio-CH_4 and e-CH_4 are of meant as thermal values. Likewise, publications on m^3 gas are always taken as Nm^3 even though this is not always made explicit

Top-down: selection of GHG-reduction scenarios that deploy bio-CH_4 and e-CH_4

In a meta-analysis we examine the role of renewable methane in GHG-reduction scenarios (usually one study contains more than one scenario) on the German energy transition (i.e., the target is reached in 2050). That is, we examine whether these scenarios have published quantitative results on bio-CH_4 and e-CH_4 or where these numbers could be inferred. More explicitly, the selection criteria are as follows:

- Firstly, only scenarios that published quantitative results on both bio-CH_4 and e-CH_4 have been taken into consideration for further analysis. In some cases, additional calculations or measurements within the studies were necessary to infer these numbers [e.g.,]. In other cases, cross-analyses of other studies have been used where the client of some studies has re-examined their own studies later and performed these calculations themselves [e.g., 4].
- Secondly, only scenarios that aim at 95% GHG reduction with respect to 1990 (or higher) have been taken into further evaluation. On the one hand, this is in order to be consistent with the Paris climate change agreement. On the other hand, scenarios that aim at 80% GHG reduction or less usually did not provide quantified data for both bio-CH_4 and e-CH_4. In part, this may be due to the fact that—consistent with their less stringent reduction target—natural gas still plays major role in these scenarios in 2050.
- Thirdly, where studies published several scenarios, sometimes only a reduced number is displayed. That is, when these studies provide the same research framework with regard to bio-CH_4 and e-CH_4 but scenarios differ with regard to other respects, scenarios where chosen that span the range with regard to "green" gas usage [e.g., 24].

Due to better data availability, final energy consumption has been chosen for the meta-analysis. In total, 16 studies containing 48 scenarios where analyzed (see Appendix). The scenarios that match the criteria are displayed in the results section below.

Bottom-up: geographic-structural conversion potential of existing BP capacities

Clustering of BP via GIS

To assess the potential for clustering of the existing BP inventory for bio-CH_4 production, a GIS analysis was performed. As a basis for this analysis a digital and geo-referenced map of the natural gas grid of Germany [25][2] and the biogas plant database of the German biomass research centre (Deutsches Biomasseforschungszentrum, (DBFZ)) were used. This database is continuously updated and contains detailed information on biogas plants such as location, installed capacity, full load hours, and commissioning year. It is based on information the Federal Network Agency (Bundesnetzagentur, (BNetzA)) publishes on biogas plants within the German Renewable Energy Act (Erneuerbare Energien Gesetz (EEG)) [26].

This assessment has two main objectives:

[1] http://biocat-project.com/.

[2] Map of German gas grid as of 2010 with last amendments in 2013.

Table 1 Selection criteria for BP clusters

No.	Criterion	Value	Source
1	Minimum installed electrical equivalent capacity (P_{inst}) of each BP in a cluster	≥ 375 kW	[26–28]
2	Distance of all BPs to natural gas grid	≤ 10 km	[27]
3	Distance of BPs to a potential biogas upgrading facility (feed-in point) within a cluster	≤ 10 km	[27]
4	Sum of P_{inst} of all BP within the cluster	≥ 5 MW	[29]

1 Identify biogas plants which could, based on their geographic location, position to the natural gas grid and a defined minimum installed capacity, form a cluster for bio-CH_4 production and

2 Determine the potential amount of bio-CH_4 those plants could technically produce under an economically feasible framing.

The clusters were defined by four spatial and technical boundary conditions. Further physical boundaries like regional and local differences in topography or ground were not taken into account. The criteria for the composition of the clusters are listed in Table 1.

The modeling process itself consisted of several distance-based queries and a subsequent clustering of the biogas plants in question. It can be divided into five steps:

(1) Data selection and preparation.
(2) Selection of BPs that could be considered for a bio-CH_4 production cluster.
(3) Definition of potential feed-in points.

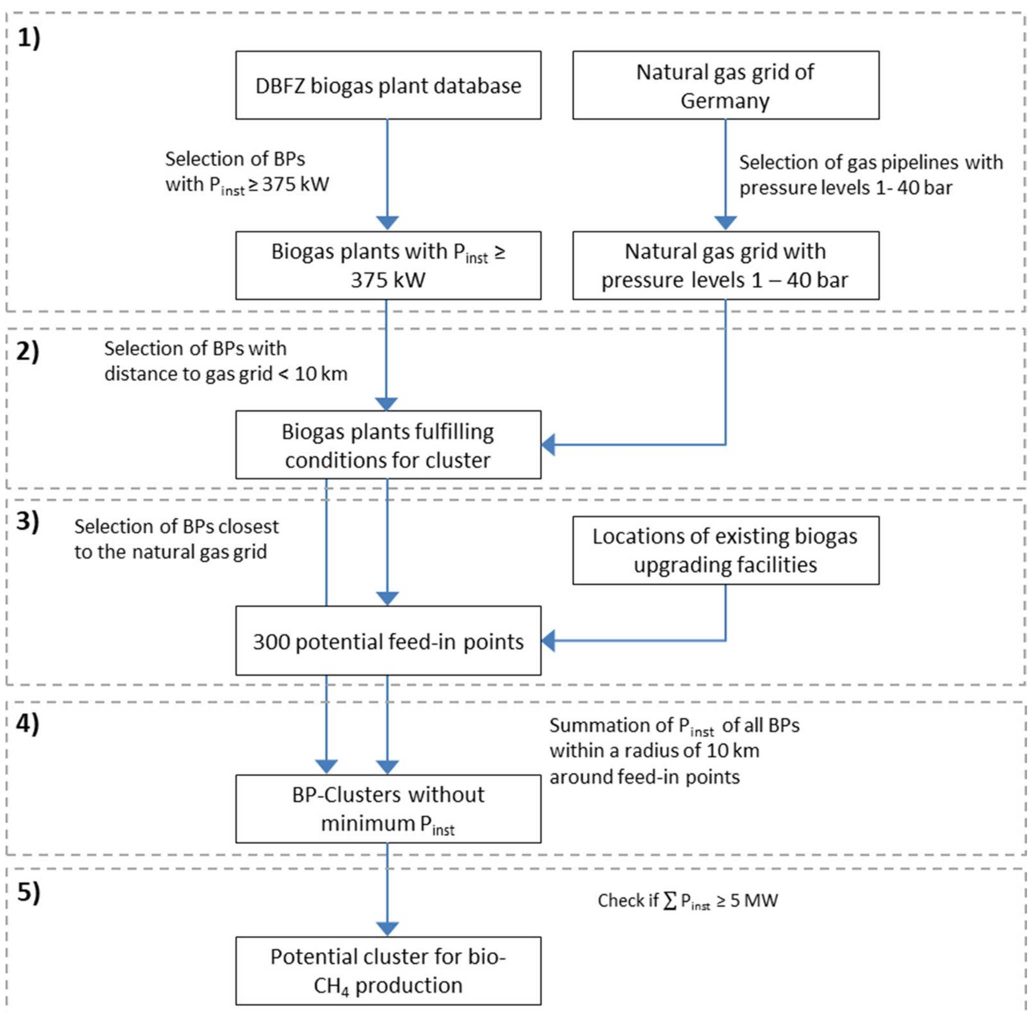

Fig. 2 Flowchart of the GIS-modeling process to identify potential clusters for bio-methane production

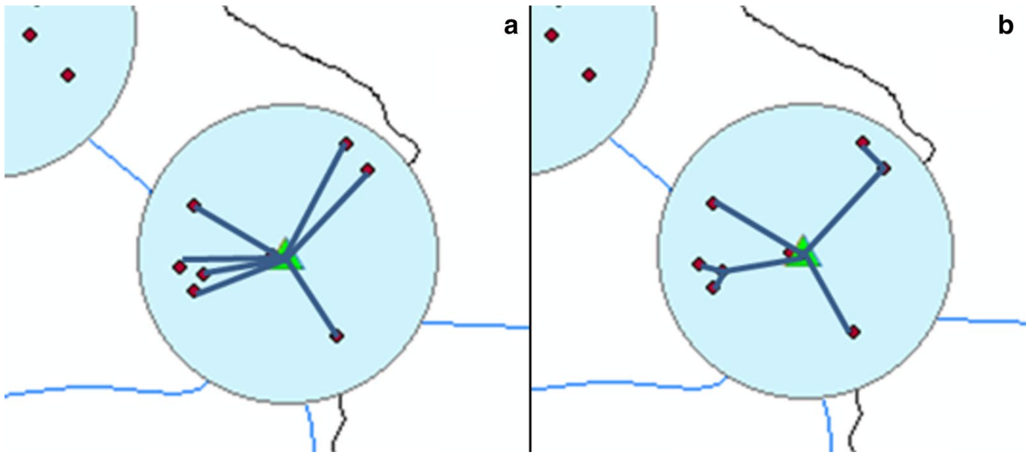

Fig. 3 **a** Star-like pattern: single connection for each biogas plant to upgrading unit. **b** Web-pattern: manually optimized gas grid structure

(4) Allocation of BPs from (2) and to feed-in points.
(5) Selection of clusters with $P_{inst} \geq 5$ MW.

Figure 2 shows the flowchart of the analytical steps.

Initially all biogas plants from the database with a minimum installed electrical capacity of 375 kW were selected. The value of 375 kW for P_{inst} was chosen based on values extracted from comparable studies. It was found that the economic feasibility for a cluster with an average P_{inst} of 368 kW[3] is most likely to be given [27].

Simultaneously only sections parts of the gas grid with pressure levels suitable for the feed-in of bio-CH_4 were included in the analysis. Sections of highest (> 40 bar) and low pressure (< 1 bar) were not considered as feeding-in on those pressure levels is not very common at the moment (see step 1 in Fig. 2) [30, 31] or has been found not feasible [32]. Following that all plants with a distance greater than 10 km to the previously selected sections of the natural gas grid were excluded from the model (step 2 in Fig. 2). The next step was the definition of potential feed-in points. To do so, locations of existing biogas upgrading facilities were used and additionally the biogas plants closest to the natural gas grid were selected. As a result, a total of 300[4] already existing (and potential) feed-in points could be defined (step 3 in Fig. 2). Subsequently, the plants from step (2) were assigned to the now defined feed-in points. For this purpose, all plants located within a 10 km radius of a feed-in point were allocated to the respective feed-in point (step 4 in Fig. 2). The 10 km radius is oriented on studies that provide detailed cost–distance analyses of gas piping structures [27, 28]. Finally, all clusters where the combined installed capacity of the BPs reaches a minimum value of 5 MW were selected as potential clusters for bio-CH_4 production. At this point it is important to mention that by the condition that a cluster has to have a cumulated electrical capacity of 5 MW, not all of the existing biogas upgrading facilities are also considered feed-in points for the potential clusters in this assessment.

Gas grid

To assess the availability of the gas grid each biogas plant's linear distance to the biogas upgrading plant was calculated via GIS and then added up. This total reflects the gas grid`s complete length per cluster. However, not every single plant will be connected with the upgrading unit with a separate feed line, which would result in a star-like pattern. In contrast to that, neighboring plants would share sections of pipe connections to lower the overall demand for feed lines, resulting in a web-like pattern pipe grid (see Fig. 3). The adjustment factor (f_{adj}) is the quotient of l_{star} by $l_{web,}$ were l_{star} is the sum length of pipes in a cluster and l_{web} the sum length for web pattern.

To estimate f_{adj}, 11 clusters were chosen (see Table 2), on whose basis a more realistic gas grid was constructed manually. The distance and the course of roads where taken into consideration by a simplified approach. So the length of the gas grid ascertained by this procedure was multiplied by square root of 2 (1.44) to consider infrastructural barriers for pipe routing in the landscape, which should be bypassed by rectangular detours. The realistic gas grids` total and the initially calculated total of the single pipes to the biogas upgrading plant were finally $f_{adj}{'} = f_{adj} \times 1.44$. So $f_{adj}{'}$ serves the conversion of

[3] The analyzed cluster consisted of 8 BPs with values for P_{inst} of 530 kW, 220 kW, 250 kW, 180 kW, 500 kW (2), 400 kW [27].

[4] In 2016, 205 biogas upgrading facilities were in operation. The 300 potential feed-in points would mean an increase by almost 50% of that number [26].

Table 2 Example cluster for calculating the average additional costs of upgrading compared to pure biogas production

Cluster	Power [kW]	Plants	Pipe length "web" [m]	Pipe length “web” x 1.44 [m]	Pipe length "star" [m]
A	8739	13	32,835	47,282	76,307
B	6635	10	41,643	59,966	80,196
C	9210	14	39,592	57,012	86,939
D	5321	10	30,881	44,469	66,336
E	15,591	19	45,989	66,224	113,180
F	8703	12	31,252	45,003	52,609
G	15,930	26	69,337	99,845	159,141
H	11,874	20	52,900	76,176	135,942
I	8645	14	35,344	50,895	71,157
J	18,643	33	63,188	90,991	208,173
K	5654	8	22,719	32,715	36,453
Ø	10,450	16	42,335	60,962	98,767

the gas grid length calculated by GIS into a realistic gas grid length. Furthermore, the realistic gas grid of the 11 clusters served to determine the amount of overbuilt area (i.e., roads, villages, towns, etc.) with the aid of freely available satellite and aerial images. This resulted in the fact that for 15% of the gas grid higher construction costs arise.

Cost of biogas upgrading and clusters

Both the construction and material costs are based on the reference number from 33 [33, pp. 223–235]. Not only the difference between developed and non-developed areas, but also the diameter needed for the pipes was calculated and considered in the material costs and construction costs. As a compensation for crossing developed areas 1 €/m and year was assumed [28] served as a data store concerning the biogas drying and compressors. This leads to costs of between 447 € and 693 € per Nm^3 and hour, depending on the size of the pipe. The annual technical service costs are calculated with 1% of the investment costs. This leads to average gas grid and processing costs of 0.0151 € per produced kilowatt hour (lower heating value).

In order to assume the economical framing of the potential, a cost analysis has to be carried out. To assess the overall costs the cluster of costs was subdivided into the items gas pipe/gas grid and biogas upgrading plant. All cost calculations were based on a fixed interest rate of 5% and a depreciation period of 10 years. The figures of 12 [12] served as a model for the biogas upgrading plants. Regarding the plant's size (>5 $MW_{equ.}$) specific investment costs of 1.000 €/Nm^3 h were assumed. Further, based on the analysis the costs for technical service, overheads and energy costs were assumed to be 220 €/Nm^3 h. The costs, which should borne by the plant operator for the gas grid connection are capped to 250,000 € by the decree on the Gas Grid Access Ordinance (§33 paragraph 1 Gas NZV). If the connection requires larger investments the gas grid operator has to bear these additional costs. This is maintained for all the clusters in order to have a realistic economic estimation/upper cap of the technical potential.

Results

Top-down: deployment of bio-CH_4 and e-CH_4 in GHG-reduction scenarios

The scenarios that match the criteria of the meta-analysis (see “Methods”) are displayed in Fig. 4. Values are displayed for 2030 and 2050. A first result is the selection process itself: Out of 48 scenarios analyzed only ten have met the criteria, i.e., most importantly, have published quantitative results on both bio-CH_4 and e-CH_4. Secondly, with two exceptions only studies from 2019 and 2020 have qualified for the selection. Thirdly, with the exception of the “Ways”-scenarios, all scenarios are based on studies commissioned by the German Federal Environmental Agency (Umweltbundesamt, UBA). Going into more detail the results are as follows:

Bio-CH4

The variability of bio-CH_4 ranges between 11–54 TWh/a in 2030 and 7–113 TWh/a in 2050. The oldest scenario among the ones displayed is “Greenhouse Gas neutral Germany” (THGND). Here biogas use is set at the potential of biogas from waste residues (40 TWh/a in 2050, no value given for 2030) [18, pp. 54–55]. The scenario “Climate protection Scenario 95” (KS95) displays only values for 2050, too, in the original study [34]. Here, values were calculated in the recent roadmap-study by UBA for KS95 (who commissioned the study) and these are displayed here: 53 TWh/a in 2030 and 43 TWh/a in 2050 [4, p. 49]. For both of their own scenarios, Roadmap 95% e-CH_4 and Roadmap 95% e-H_2, a phase out of biogas is assumed, going down to 7 TWh/a in 2050. It is mainly due to the assumption that either e-CH_4 or e-H_2 will be used in all uses where conceivable [4, table 23, p. 112]. The two Scenarios RESCUE GREENLate and RESCUE GREENSupreme are also among the lowest value for bio-CH_4. With value of 14 and 12 TWh/a in 2030 and 2050, respectively, for RESCUE GREENLate and 11 and 8 TWh/a in 2030 and 2050 for RESCUE GREENSupreme, respectively, as well, values are the lowest from the outset. Both scenarios assume that only a certain share of volume of bio-waste and greenery is used for bio-CH_4 production as well as some waste disposal sites [24, pp.

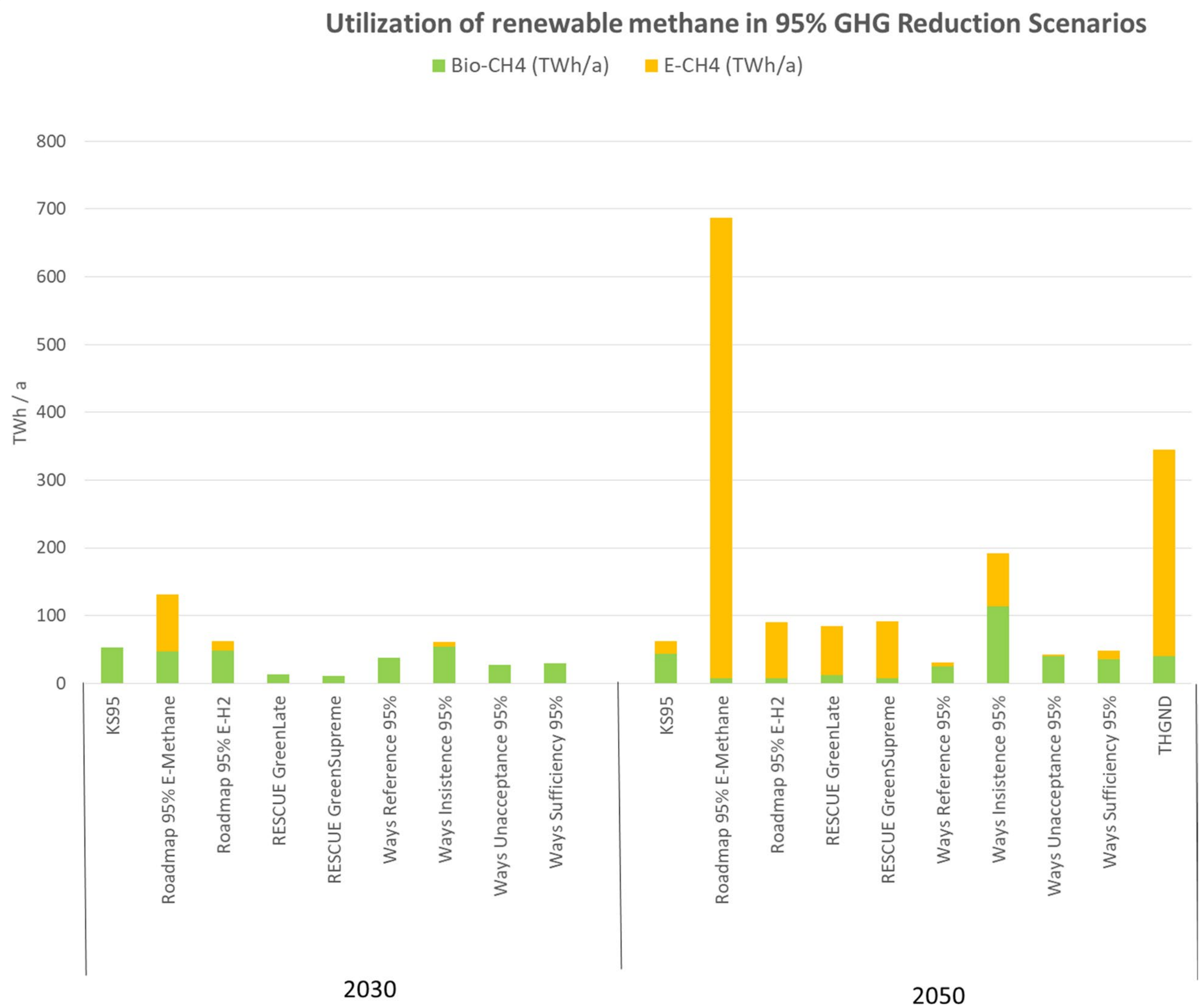

Fig. 4 Utilization of renewable methane in 95% reduction scenarios (source: referenced scenarios; own calculations)

129–130]. The four "Ways"-scenarios of Fraunhofer ISE cover the whole range of bio-methane use. They range between 27–54 TWh/a in 2030 and 25–113 TWh/a in 2050. The span is due to different modeled restrictions with respect to the reference case (the latter develops from 38 TWh/a in 2030 to 25 TWh/a in 2050). This leads to different optimal usage of the different gases. Bio-CH_4 use is the highest over the whole time in Scenario "insistence" (54 TWh/a in 2030 and 113 TWh/a in 2050) where there is less structural change, e.g., in heating systems and building insulation. It is the highest bio-CH_4 use of all scenarios displayed here [23].

e-CH4

The range of e-CH_4 goes from 0 to 83 in 2030 and 3–681 TWh/a in 2050. This raises the question to what degree the usage of e-CH_4 is due to the models optimization logic or simply set as an exogenous assumption. Directly connected with that is the second question of how the availability of CO_2 sources is modeled, in particular whether it is biogenic or by, e.g., DAC technologies? Are there assumptions on imports or domestic production? THGND calculates e-CH_4 use of 306 TWh/a for 2050 [18, Table B-14]. There is no exact information on the CO_2 source or what shares of e-CH_4 are imported in the model. The scenario Roadmap 95% e-CH_4 displays the highest e-CH_4 usage with 83 TWh/a in 2030 and 681 TWh/a in 2050. It is mainly due to the assumption that e-CH_4 will be used in all sectors and uses where conceivable. Further, it is assumed that e-CH_4 will be mainly imported from the MENA-region[5] and CO_2 will

[5] MENA stands for "Middle East and North Africa".

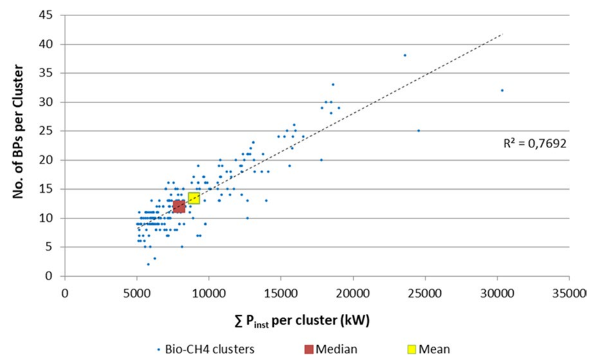

Fig. 5 No. of BPs and combined installed capacity per cluster

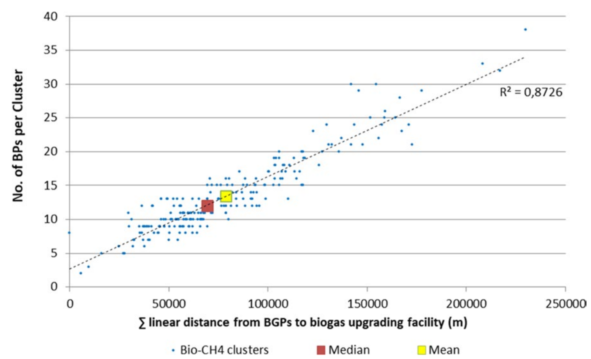

Fig. 6 No. of BPs and linear distances to the biogas upgrading facility per cluster

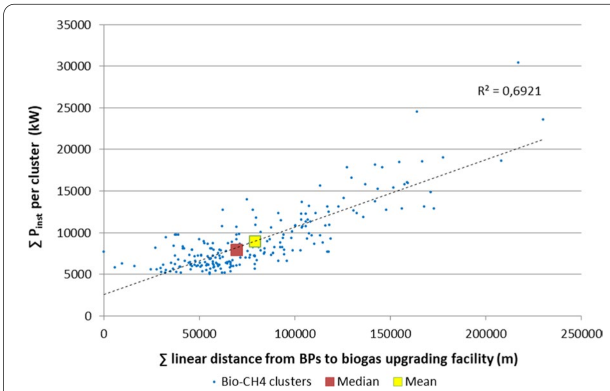

Fig. 7 $\sum P_{inst}$ per cluster and aggregated linear distances from the BPs to the upgrading facility

be obtained via DAC. The scenario Roadmap 95% e-H_2 displays e-CH_4 usage of 14 and 83 TWh/a for 2030 and 2050, respectively [4, table 23, p. 112]. The scenarios RESCUE GREENLate and RESCUE GREENSupreme display medium values of 73 and 84 TWh/a in 2050, respectively (both zero in 2030) for e-CH_4 [24, p. 138].[6] The four "Ways"-scenarios are mostly among the lowest e-CH_4 uses, ranging between 0 TWh/a in 2030 and 3–13 TWh/a in 2050. The exception is, again (like bio- CH_4), the scenario "insistence" with e-CH_4 uses of 7 TWh/a in 2030 and 78 TWh/a in 2050. Here, too, there is no mentioning of the CO_2 source for bio-CH_4. [23].

Bottom-up: geographic-structural conversion potential of existing BP capacities

According to the previously presented method and the therein made assumptions, 225 potential clusters for bio-CH_4 production could be identified. Those clusters consist of a total of 1681 biogas plants with a combined installed electrical capacity of 1.1 GW. In relation to the number of all biogas plants in Germany, this corresponds to a share of 16% and a share of 22% of the total installed capacity, respectively. Assuming that all of the biogas plants within the identified clusters would actually shift their mode of operation from on-site cogeneration to bio-CH_4 production, these plants could produce approximately 2.5 bn Nm^3 bio-CH_4 annually. The values of P_{inst} of the clusters range from 5.0 to 30.4 MW, almost three-quarters (73%) of the clusters have a cumulated installed electrical capacity of less than 10 MW. Figures 5, 6 and 7 present a more detailed view on the composition of the individual clusters. Here we put descriptive parameters such as number of BPs per cluster, cumulated installed capacity per cluster and the sum of distances from the BPs to the potential upgrading facilities (star-pattern) into relation.

The values for sum of the distances from the BPs to the upgrading facilities in Figs. 5 and 6 represent linear distances in a star-shaped network configuration which is why such high values can be seen. In reality, a network configuration combining individual pipelines to manifolds is more likely to be used, as the total network length can be reduced significantly. Figure 3 visualizes the difference between these network configurations.

We also compared the total network length of the star-shaped network configuration with the previously described (and assessed) web network configuration. We found that the linear distances of the star-shaped network configuration are significantly longer than the measured web network configurations. The differences in length are in a range from 11% up to 129% longer.

From all the previously described assessments of the clusters, it can be seen that they are very heterogeneous. Table 3 depicts the broad range of values which can be observed within the clusters.

[6] However, these values do not appear to be entirely consistent with the values in table 5-2 of the study itself.

Table 3 Composition of the identified bio-CH_4 clusters

Category	Minimum	Maximum	Mean	Median
No. of BPs per cluster	2	38	13	12
Combined installed electrical capacity [MW]	5.034	30.385	8.966	7.903
Total network length—star-shaped [m]	5754	230,008	78,972	69,507
Total network length—measured length × 1.44 (web) [m][a]	32,715	69,337	60,962	57,012

[a] The measured network lengths refer to the previously described 11 example clusters, only

With regard to the regional dispersion of the clusters, it can be seen from Fig. 8 that the largest potentials are located in the north and north-west of Germany and in the middle of southern Germany. Most clusters can be found in the federal states of Lower-Saxony and Bavaria. Regarding the number of plants within the clusters, 53% (905) are located in the northern part of Germany (Lower-Saxony, Schleswig-Holstein, Mecklenburg-Western Pomerania) representing 54% (602 MW) of the installed capacity of the clusters. The federal states in central Germany (Saarland, Rhineland-Palatinate, North Rhine-Westphalia, Hesse, Thuringia and Saxony) on the other hand show comparably little potential for clustering existing biogas plants with local cogeneration for bio-CH_4 upgrading. Since the radius of the clusters was set to 10 km there are BPs which could theoretically be allocated to more than one feed-in point which causes overlapping of the clusters in certain regions. A final decision which BP should be allocated to which feed-in point cannot be made for each plant individually at the scale of this analysis.

Discussion

Top-down analysis: consistency of scenarios

The paper makes different attempts to estimate potentials of renewable methane from top-down as well as from a bottom-up perspective using different methods. For the top-down approach, the meta-analysis of GHG-reduction scenarios has shown that only a few models have taken up the issue of bio-CH_4 and e-CH_4 and that this has only happened quite recently. It may be due to the fact that the more recent studies have integrated the more stringent targets of the Paris agreement and these require green gases for, e.g., defossilizing industry or transport. Furthermore, even in those studies the numbers were not always clearly given and sometimes had to be inferred otherwise. So they were sometimes difficult to retrace.

Generally speaking, the range for e-CH_4 is larger than for bio-CH_4 and going further into the future (i.e., 2050 instead of 2030) the range opens up even more. Furthermore, the numbers for bio-CH_4 sometimes appear to be exogenously set by assumption (without always making this explicit though). This seems to be true for THGND [18] that sets the potential of biogas from waste residues without much further explanation. It also seems to be true for the RESCUE-Study [24] by dedicating a certain share of volume of bio-waste and greenery as bio-CH_4. Similarly, the utilization of e-CH_4 seems to be set exogenously at least in some studies. In the Roadmap-study [4] it appears that the assumption of a maximum use of e-CH_4 (and e-H_2, respectively) lead to a phase out of biogas. The Ways-Study [23] does not mention any restriction of bio-CH_4 potential and the range of usage is the broadest in the scenarios. Therefore, in this study bio-CH_4 usage actually appears to be due to model optimization. In most studies analyzed here, however, the number of potential appears to be a bit ad hoc. There is even less information on the usage of (domestic) biogas as a CO_2 source for e-CH_4. None of the studies explicitly mentions this path. Only the Roadmap-study [4] displaying by far the highest amount of e-CH_4 explicitly mentions imports of e-CH_4 and DAC for e-CH_4 rather than using biogenic sources for CO_2. So taken together, despite a number of methodological disclaimers the amount of bio-CH_4 use appears to stay in a certain range, at least for 2030. The results only start to diverge significantly where the production of methane does not depend on biogenic source any more, in particular with respect to 2050. Here, too, the models appear even more ad hoc. That is, they do not mention the sources at all or they mention imports of e-CH_4 or non-biogenic CO_2 sources (DAC) or both.

Bottom-up: geographic-structural conversion potential

In the bottom-up approach, the starting point of the assessment was rather the existing biogas inventory in Germany. Therefore, a GIS analysis was carried out to estimate the short-term geographic-structural conversion potential of this existing inventory into bio-CH_4 production. Within this, first of all, we ask for economic obstacles that could have an impact on the realization of the core concept of clustering existing BP for retrofitting from cogeneration to bio-CH_4 upgrading. It turns out, that 1681 plants (16%) representing 1.1 GW (22%), respectively, can be retrofitted until 2030. However, a caveat has to be made to the analysis as well: Instead of analyzing the economics of every single cluster,

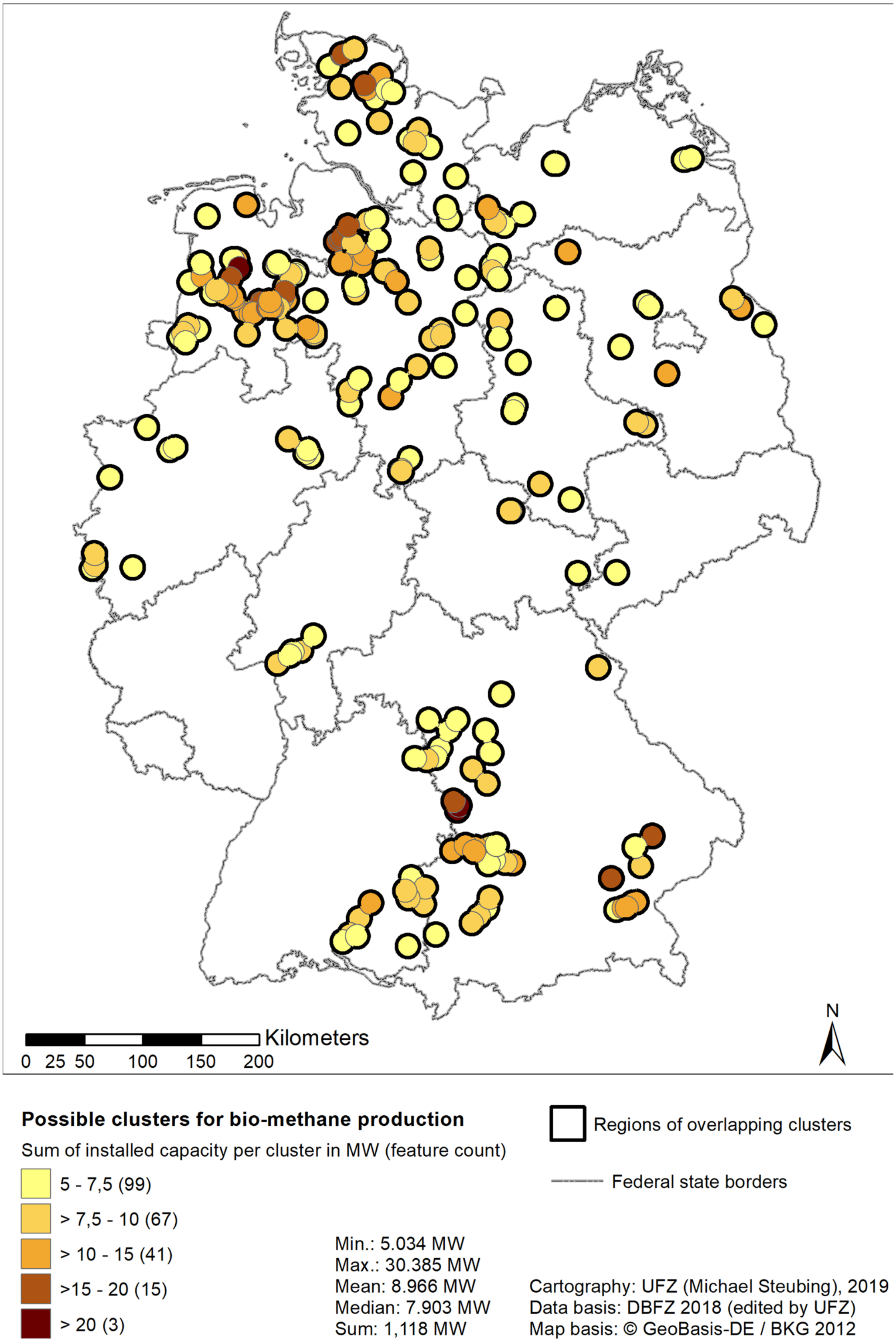

Fig. 8 Regional distribution of potential clusters for bio-CH_4 production, classified by the combined installed capacity of biogas plants with a cluster

assumptions on the necessary minimum size of the BPs and on costs of retrofit and construction costs of the cluster where made resulting in the minimum size of the cluster in the sense of an economical upper cap. That, in turn, was the basis for the GIS analysis. That is, the analysis is mainly geographical and structural and economic aspects came in only indirectly into the analysis.

Furthermore, another caveat has to be made on a temporal issue: as it was mentioned in the background, this upgrade may provide the necessary business model for the considerable share of "post-FIT"-installations, i.e., those capacities whose FIT-remuneration phases out. However, it has to be kept in mind that in reality the "post-FIT"-phase begins at different points in time for different BP. From an investors point of view it seems to be very ambitious to find the best point in time to build up or extend the central upgrading unit. In a worst case the entire capacity could only be reached after several years. But if the decision is delayed until the last plant of the cluster will drop out of FIT, the plants that reach their remuneration period earlier, would face a temporal gap without a proper business model. As we did not explicitly analyzed the age structure of the clusters, we suggest to look for that issue within subsequent investigations. Furthermore, the e-CH_4 should be analyzed by a bottom-up analysis in a further investigation to underpin these findings. Another issue regarding the "post-FIT"-phase is the question of whether a retrofitting to bio-CH_4 production would be the most profitable choice. Other potential business models, such as heat, could eventually generate comparatively higher revenues and many biogas plants have considerable potential in this segment [35]. In order to identify the plant-specific favorable option the relevant opportunity costs need to be assessed in more detail.

On a spatial scale, we already identified the main issues that would have an impact on hindering optimal grid-layouts for the clusters. Since the real world is much more complex, especially regarding spatial planning [36, pp. 32–42], topographic conditions [28] or legal issues [37, pp. 51–52, 38], it seems very likely, that we still underestimate the efforts and so the expenses for creating the needed pipe-infrastructure to transport the raw gas to the central upgrading unit. Another technical point, which we did not consider, is the question of how the BP preserve their process heating. In the current setup, plants utilize the raw gas to convert it in a cogeneration heating and power unit (CHPU) and use some of the heat (depending on feedstock and fermenter design 5–50%) for the substrates and fermenters. If all of the raw gas is delivered to the upgrading unit, the question arises, how to maintain the fermenter heating. One but here excluded option would be to use a partial flow of the raw gas to utilize in small CHPU, which is dimensioned

Table 4 Ranges of bio-CH_4 and e-CH_4

TWh	2030		2050	
	Min	Max	Min	Max
Top-down analysis				
bio-CH_4	11	54	7	113
Average bio-CH_4	32.5		60	
e-CH_4	0	83	3	681
Average e-CH_4	41.5		342	
SUM bio-CH_4 + e-CH_4	11	137	10	794
Average bio-CH_4 + e-CH_4	74		402	
Bottom-up analysis				
bio-CH_4	24.9		–/–	

to the maximum heat demand of the fermentation process. Another solution could be the use of other renewable heat sources like a biomass boiler or solar thermal energy. One way or another, all of these options will lead to additional costs; either by losing some of the raw gas capacity and additional investments for auxiliary CHPU or for other heat sources.

Last but not least, a number of additional regulations are required to make the conversion of BP capacities as a business model work. These include an economic level playing field, certification on meeting technical requirements of bio-CH_4 as products [39].

Comparing top-down and bottom-up: consolidating results

In order to compare the results of the bottom-up and top-down analysis (for 2030), the result of the former may be converted into TWh: applying the lower heating value of 9.97 kWh/Nm^3 CH_4 [22, p. 68] to 2.5 bn Nm^3 bio-CH_4 yields 24.9 TWh. The results are summarized in Table 4. The ranges for bio-CH_4 and e-CH_4 from the scenarios are given for 2030 and 2050. Furthermore, the averages are calculated. In addition, the result from the bottom-up analysis is displayed as well.

That is, the result of the bottom-up analysis lies well within the range the top-down analysis of 11–54 TWh that was found for bio-CH_4. Furthermore, it lies even rather close to the average of 32.5 TWh (see Table 4). In addition, the results between bottom-up and top-down analyses not only appear with each other but also with further results from the literature: one of the very few other bottom-up analyses that are available found 2.6 bn Nm^3 for the potential of clusters [40] or 25.9 TWh (own calculation, see Box in "Methods"). Furthermore, the values for 2030 (the time frame, for which the bottom-up analysis is also made) the range of bio-CH_4 appears rather consistent with two of the oldest studies

Table 5 Shares of renewable methane to current natural gas demand in Germany

	Averages supplies from bottom-up and top-down analyses	Share of 2018 natural gas consumption (928 TWh)
Bio-CH_4	24.9–32.5 TWh	2.7–3.5%
e-CH_4	41.5 TWh	4.5%
Total	66.4–74.0 TWh	7.2–8.0%

of biomass potential that are still used in many scenario studies: For 2030, 41 [41, pp. 89–91] assumes 12–20 TWh[7] bio-CH_4, depending on scenario. However, this is primary energy potential but even when subtracting, e.g., another 10–30% losses it would be mostly within range 42 [42, pp. 131, 149] calculated roughly 20–31 TWh[8] of bio-CH_4 for the same year. This, too, is primary energy but even when calculating efficiency losses it may still be considered well within range.

The potential contribution to gas supply

In order to put the magnitude of the results in perspective, the averages of the bottom-up and top-down analyses may be compared with the current consumption of natural gas in Germany, which was 928 TWh in 2018 [11, figure 148]. The results are shown in Table 5. It can be seen that the average supply of bio-CH_4 represents a bit less than roughly between 3 and 4% of today's natural gas consumption.

Considering that the average of e-CH_4 in 2030 would add another 4.5% to the total average of renewable methane, it will then represent between 7 and 8% of today's natural gas consumption.

Taken together, supplying renewable methane could be one of the business models for "Post-FIT" biogas capacities. As it was shown here and mentioned elsewhere, a significant share of these capacities will have to be decommissioned in the 2020s if no business model is found for them [20, 39].

Conclusion

The paper has applied two different methods to assess the potential of bio-methane (denoted bio-CH_4) and methane from renewable energies (denoted e-CH_4). In a top-down approach a meta-analysis of models with respect to bio-CH_4 and e-CH_4 was performed. From a bottom-up perspective a GIS-based cluster analysis was undertaken to estimate the potential on bio-CH_4 from the existing cogeneration biogas plant (BP) stock. Even with respect to the methodical limitations discussed, the main result may be the consistency of the outcome of the two approaches even though these are methodologically very different. The bottom-up approach yields a potential of 2.5 bn Nm^3 or 24.9 TWh of bio-CH_4 for 2030. That lies well within the range the top-down analysis of 11–54 TWh (average of 32.5 TWh) bio-CH_4 for the same year. These values are also consistent with other values in literature both with "old" values that have been the foundation for model analyses for a long time and with recent bottom-up analysis. The focus of the analysis is on bio-CH_4 from convertible German cogeneration stock until 2030. However, additional questions where how models take into account the need of e-CH_4 for a—possible biogenic—CO_2 source. Furthermore, models aim for 2050 and take into account other options like energy imports, therefore these issues where taken into account as well. It turned out that in some scenarios values for e-CH_4 where considerably higher but in these studies they are either not explained at all or they are due to imports in combination with direct air capture (DAC) rather than biogenic sources of CO_2.

Compared with today's consumption of natural gas in Germany (2018: 928 TWh) the average amount of bio-CH_4 in 2030 corresponds to 2.7–3.5% of that use. Taken bio-CH_4 and e-CH_4 together it corresponds to 7.2–8.0%. Concerning the regional dispersion, the bottom-up analysis shows that the largest potentials (53% or 905 of the plants) are located in the northern part of Germany, more particular in Lower-Saxony, Schleswig-Holstein, Mecklenburg-Western Pomerania. These represent 54% or 602 MW of the installed capacity of the clusters.

We therefore conclude on the grounds of the improved empirical basis that the technical potential for additional bio-CH_4 from existing BP is significant. Depending on the priorities for the ongoing energy transition existing biogas infrastructure could be used to increase the production of "green" gas, for applications, which are hard to decarbonize, while the use of high calorific fuels is hard to substitute. In particular, bio-methane may be used in applications which should be otherwise powered by synthetic fuels or e-methane. As was shown in the model analysis, these energy carriers often need to be imported as they have the drawback, that they often need disproportionate amounts of renewable electricity, due to efficiency losses, especially if methane is needed instead of hydrogen. So it seems to be worth further investigations, to figure the marginal prize and benefit to mobilize the existing technical potential. We expect, that like for many other bioenergy applications,

[7] The study calculates 23–26 TWh biogas, depending on scenario; assuming 50–75% methane content (see Box in methods) implies the range as the minimum value of the lowest and the maximum value of the highest scenario.

[8] The values for biogas are 42 TWh for the technical potential and 39 TWh when concerns of nature protections are taken into account. Conversion to methane as in footnote 6.

there is a cost–supply curve, where "low hanging fruits" can be harvested easily and on the long end of that curve some of technical potential is "trapped" by cost driving conditions. Trapping factors would be expected for unfavorably age structures within clusters or multiple infrastructural barriers for the gas grid; both will substantially increase costs.

Abbreviations

BP: Biogas plant; BNetzA: Federal Network Agency (Bundesnetzagentur); CAPEX: Capital expenditures; DAC: Direct air capture; DBFZ: German Biomass Research Centre (Deutsches Biomasseforschungszentrum); EEG: Renewable Energy Law (Erneuerbare-Energien Gesetz); f_{adj}: Adjustment factor for web-pattern grid layout from star-pattern grid layout; f_{adj}': Modified f_{adj} with consideration of spatial barriers by rectangular detours; FIT: Feed-in tariff; GIS: Geographical Information System (here ArcGIS); IZES: Institute for FutureEnergy- and MaterialFlowSystems (Institut für Zukunftsenergie- und Stoffstromsysteme); Nm^3: Norm cubic meter; OPEX: Operational expenditures; UBA: Federal Environmental Agency (Umweltbundesamt); UfZ: Helmholtz Centre for Environmental Research (Helmholtz-Zentrum für Umweltforschung.

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Authors' contributions

BW: review, drafting; DT: review; JP: bottom-up approach (cost estimates, drafting); MD: review, drafting; MS: bottom-up approach (GIS analysis, drafting); PM: overall conceptualization and drafting, top-down approach; YZ: top-down approach. All authors read and approved the final manuscript.

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Availability of supporting data

All data from top-down analysis (scenario studies) are publicly available. The datasets generated and/or analyzed as part of the bottom-up GIS analysis 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.

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Appendix

Studies	Scenarios	Selected for display	Selection criteria				Note
			> 95%-target	Bio-CH_4	e-CH_4	e-H_2	
Benndorf et al. (2014)	THGND 2050	√	+	/+	/+	/+	data from Wachsmuth et al. (2019)
Repenning et al. (2015)	Current Measures Scenario		-	-	-	-	
	Climate protection scenario 80 (KS80)		-	/+	/+	/+	data from Wachsmuth et al. (2019)
	Climate protection scenario 95 (KS95)	√	+	/+	/+	/+	data from Wachsmuth et al. (2019)
Nitsch (2016)	SZEN-16 Trend		-	-	-	-	
	SZEN-16 Climate 2050		+	+	+	+	
	SZEN-16 Climate 2040		+	+	+	+	
Nitsch (2017)	Trend-17		-	-	-	-	
	Climate-17 MEFF		+	+	-	-	
	Climate-17 HEFF		+	+	-	-	
Nitsch (2019)	Trend-19		-	-	-	-	
	Climate-19 PLAN		+	+	-	-	
	Climate-19 OPT		+	+	-	-	
Bothe et al. (2017)	Only electricity		+	-	-	-	
	Electricity and gas storage		+	-	-	-	
	Electricity and green gas		+	-	-	-	
Klein (2017)	Maximum electrification 2050		+	+	-	-	
	Optimized system 2050		+	+	-	-	
Pfluger et al. (2017)	Reference scenario		-	-	-	-	
	Baseline scenario		-	-	-	-	
Bründlinger et al. (2018)	Reference scenario 2050		-	+	+	+	only data for primary energy
	Electrification scenarios 2050 - 80		-	+	+	+	only data for primary energy
	Technology mix scenarios 2050 - 80		-	+	+	+	only data for primary energy
	Electrification scenarios 2050 - 95		+	+	+	+	only data for primary energy
	Technology mix scenarios 2050 - 95		+	+	+	+	only data for primary energy
Gerbert et al. (2018)	Target- 80		-	+	-	-	
	Target- 95		+	+	-	-	
Wachsmuth et al. (2019)	Roadmap 80% Gas mix		-	+	+	+	
	Roadmap 95% E-Methane	√	+	+	+	+	
	Roadmap 95% E-H2	√	+	+	+	+	
Wietschel et al. (2019)	Climate protection scenario 80		-	+	-	-	
	Climate protection scenario 95		+	+	-	-	
Robinius et al. (2019)	Scenario 80		-	-	-	-	
	Scenario 95		+	-	-	-	
BBH et al. (2019)	Scenario "S85"		-	-	-	-	
	Scenario "S95"		+	-	-	-	
Purr et al. (2019)	RESCUE GreenEe1		+	+	+	+	result similar to GreenSupreme
	RESCUE GreenLate	√	+	+	+	+	
	RESCUE GreenEe2		+	+	+	+	result similar to GreenSupreme
	RESCUE GreenMe		+	+	+	+	result similar to GreenSupreme
	RESCUE GreenLife		+	+	+	+	result similar to GreenSupreme
	RESCUE GreenSupreme	√	+	+	+	+	
Sterchele et al. (2020)	Ways Reference 95%	√	+	+	+	+	
	Ways Insistence 95%	√	+	+	+	+	
	Ways Unacceptance 95%	√	+	+	+	+	
	Ways Sufficiency 95%	√	+	+	+	+	
	Ways Reference100 100%		+	+	-	-	
	Ways Sufficiency2035 100%		+	+	-	-	

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