Plinke *et al. Energy, Sustainability and Society* (2025) 15:7
https://doi.org/10.1186/s13705-024-00505-9

Energy, Sustainability and Society

RESEARCH

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Development of a GIS-based register of biogas plant sites in Lower Saxony, Germany: a foundation for identifying P2G potential

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Abstract

Background Although Germany's biogas capacity accounts for almost 7% of its installed worldwide capacity, the expansion of biogas plants has stagnated owing to the expiry of Germany's Renewable Energy Sources Act *Erneuerbare–Energien–Gesetz* (EEG) subsidies for existing biogas plants. Indeed, without alternative concepts such as power-to-gas (P2G) ensuring their continuing operation, many existing biogas plants must close down to ensure their continuous operation. A detailed spatial register of biogas plant sites must be developed to evaluate the potential for further operation (and thereby promote Germany's sustainable energy transition). In particular, Lower Saxony, a German federal state, was hit hardest by the expiry of subsidies, as there is a lack of spatially high-resolution information to identify which biogas plants have P2G potential as an end-of-subsidy strategy. This study discusses the development of a geographic information system-based register for these plants.

Methods A register was developed using geographic information system (GIS). Spatial data on existing biogas plants in Lower Saxony were selected from the Digital Landscape Model (DLM) data, with additional information coming *inter alia* from the *Marktstammdatenregister*, the Germany-wide core energy market data register. The data were merged into a single register for Lower Saxony, and aerial photographs were used to validate the biogas plant site.

Results A total of 1704 biogas plant sites were identified throughout Lower Saxony. Spatially resolved plant information on production capacity suggests that three quarters are suitable for inclusion in a methanization concept. Because plants at 85% of the sites will no longer be subsidised by 2035, end-of-subsidy strategies will soon become relevant.

Conclusions The GIS-based analysis is a reliable and low-error method for identifying biogas plant sites in Lower Saxony. Almost all plants were included in the registry. The greatest advantages over existing registers and at the same time the unique characteristics of our register were the exact spatial localisation of the plants and the highly up-to-date nature of the data. The register enables the initial (spatial) identification, characterisation, and analysis of potential sites for P2G end-of-subsidy strategies. Overall, the register has significant potential as an advisory basis.

Keywords Sustainable energy transition, P2G, Biogas plant sites, Cadastre, Spatial analysis, QGIS, Geodata

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Background

Biogas plays an important role in transforming a country's energy system into greenhouse gas (GHG)-neutral, because it can be flexibly used in the fuel, electricity, and heating sectors [1]. Bioenergy accounts for a large proportion of renewable energy worldwide [2], half of which is produced in Europe [3, 4]. While countries like

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India and China are focusing on expanding bioenergy use [1], Germany is gradually reducing tender volumes for biogas plants (*Erneuerbare-Energien-Gesetz* (EEG) § 28c [5]), arguing *inter alia* that using biomass for generating energy competes with food production and has potential negative impacts on biodiversity and the environment [6]. Since the EEG came into force in Germany in 2000, biogas plants have been subsidised over a period of 20 years via feed-in tariffs [7]. After the expiry of this subsidy period, revenues fall, resulting in the risk of losing profitability and, ultimately, plant decommissioning [7].

Germany is home to 6.6% of the world's installed biogas capacity [8]. According to the German Biogas Association (*Fachverband Biogas*), 1691 biogas plants, equivalent to almost a quarter of Germany's installed capacity of 1360 MW, will be in Lower Saxony by 2022 [9]. As the second-largest producer of renewable electricity and provides a quarter of the heat generated from renewable sources, biomass plays a central role in Lower Saxony's energy system [10]. Owing to the loss of subsidies, 600 of the state's biogas plants are threatened with decommissioning in the next 5 years, and 80% within the next 10 years [11]. With regard to the goal of achieving climate neutrality by 2040 set out in § 3.1.1 of the Lower Saxony Climate Act (*Niedersächsisches Klimagesetz, NKlimaG*) [12], this potential decommissioning poses major challenges for the federal state. In addition to the loss of renewable energy capacity, agricultural operators of biogas plants are set to suffer financial losses. Therefore, the continued operation of these plants would be advantageous for both energy transition and plant operators. In the interest of sustainable energy transition, appropriate end-of-subsidy strategies must be developed for existing biogas plants.

Daniel-Gromke et al. [13] distinguished two types of biogas production plants in Germany: plants with on-site electricity generation and biogas upgrading plants for the provision of biomethane (an upgraded form of biogas, mainly by removing carbon dioxide (CO_2). In Lower Saxony, only 35 biogas plants can convert biogas into biomethane [11], meaning that most are designed for on-site electricity generation (whereby heat is often generated through combined heat and power generation (CHP)) [10]. Erler et al. [14] describe a progressive end-of-subsidy strategy for these on-site electricity generation plants; instead of using biogas to generate electricity, it can be converted to biomethane using a concept called 'methanization' (power-to-gas, P2G). This utilises the renewable methane contained in biogas and the regenerative CO_2 found therein. In combination with renewable hydrogen (green hydrogen), CO_2 forms the basis for methanization. The electricity required for hydrogen from electrolysis can be generated from the surplus power of many wind turbines in Lower Saxony, close to biogas plants.

Consequently, more renewable gas can be fed into the natural gas grid without utilising additional agricultural land and substrates [14]. In the long term, end-of-subsidy strategies in the context of wider hydrogen transitions are also an interesting option [15]. For example, an electrolyser in a biogas plant can be operated in the stand-alone mode. Steam reforming of prepurified biogas and on-site hydrogen purification is also conceivable [16]. Decentralised hydrogen production can be beneficial, particularly at locations with a demand for hydrogen but no (planned) connection to the hydrogen grid.

However, there is a lack of data to estimate the potential of individual biogas plant sites in Lower Saxony for such subsidy strategies. Any such data must show the exact location of the plant, as well as further attributes, such as the type of plant, its output, and the commissioning date (to determine the end-of-subsidy and potential decommissioning date), for any estimate to be meaningful. The estimated raw biogas and CO_2 outputs were also of interest. The exact location is necessary to estimate the distance to a natural gas or hydrogen grid, water sources for electrolysis, and areas, where renewable energy is available. According to current plans, there will be no comprehensive hydrogen network in many places in the foreseeable future, particularly in rural areas [17], where renewable gases such as hydrogen and biomethane are needed to transition to climate neutrality. Therefore, amping decentralised hydrogen production is crucial. Biogas plant sites already offer important synergies for P2G sites and should be specifically targeted for the decentralised production of renewable gases. Establishing a detailed database of biogas plants, especially with regard to their precise locations, is the first step in any analysis of decentralised production potential.

Although there are already a few registers of biogas plants at various administrative levels in Germany, they do not provide a comprehensive, high resolution, and detailed siting. According to § 5 of the *Marktstammdatenregisterverordnung* (MaStRV), which governs the register of core energy data in Germany, operators must register their systems in this register. While this freely accessible data set contains important attributes such as a system's capacity or commissioning date, the spatial location of the electricity-generating units of biomass plants and the gas-generating units with biomethane generation technology are partly incorrect and unreliable. Detailed district-level data provided by the 3N Centre of Experts—Lower Saxony Network for Renewable Resources (*3N Kompetenzzentrum Niedersachsen Netzwerk Nachwachsende Rohstoffe und Bioökonomie* *e.V., 3N*) on biogas plants in Lower Saxony should also be cited. However, these data are updated every few years, with the most recent data available dating back to 2021.

Thus, this study aims to develop a register identifying the P2G potential of existing biogas plants in Lower Saxony, containing the precise spatial location of each biogas plant and its relevant attributes. Methods for updating data must also be considered. This is done within the context of the research project *H2-FEE: Flexible energy carriers for the energy transition* (running from July 2022 to presumably June 2025) funded by the Lower Saxony Investment and Development Bank (Investitions- und Förderbank Niedersachsen, NBank), which provides the basis for identifying the P2G potential for biogas plant sites. Biogas plants, as established energy production sites and CO_2 sources, play an important role as potential P2G sites. Overall, the register is intended to support decision-making regarding possible end-of-subsidy strategies for plants. Identifying suitable biogas plants is not only an important contribution to the energy transition in Lower Saxony but also offers an opportunity to consider environmentally friendly aspects, for example, concerning the cultivation of energy crops. Using existing decentralised plants offers both environmental and economic benefits for their operators. Indeed, the high availability of biogas plants in rural areas can ultimately become a relevant factor in decentralising energy systems.

Methods

The methodological approach for developing a biogas plant register encompasses four steps (Fig. 1).

In the first step, data were selected based on the following criteria: reliability, up-to-date availability, and public availability (open access). The identification of biogas plant locations (spatial analysis) was based on the Lower Saxony Digital Landscape Model (DLM) [18], the Lower Saxony Energy Atlas (*Energieatlas Niedersachsen*, Energy Atlas) [19], the German core energy market data register (MaStR) [11], TenneT EEG plant core and EEG payment transaction data [20] [21] and OpenStreetMap (OSM) [22]. The surface areas of the biogas plant sites were obtained from the DLM (Step 2). Using the DLM's detailed mapping of the Earth's surface, biogas plant sites were directly transferred from the DLM to the biogas plant register. Additional site information was obtained from MaStR, Energy Atlas, and OSM. If a site was found in two of the three sources, its location was verified (Step 2). The plant attributes, core energy, transaction data, and other data from the Energy Atlas were added to the verified biogas plant site attribute tables (Step 3). Finally, to increase and verify the register's validity, the biogas plant sites were manually validated using aerial photographs (Step 4).

Study area

Lower Saxony is the study area in Northwest Germany (Fig. 2). With an area of 47,710 km^2 and a population of over 8 million, Lower Saxony is Germany's second-largest federal state and has the fifth-lowest population density [23]. The state has 45 administrative districts (*Landkreise* and *kreisfreie Städte*) (ibid.).

According to the German Biogas Association [9], 50% of the energy from biogas and biomethane produced in the European Union will be generated in Germany by 2022, and 17% of German biogas plants (1,691) will be located in Lower Saxony (ibid.). This represents a density of approximately 3.5 plants per 100 km^2. Only Bavaria

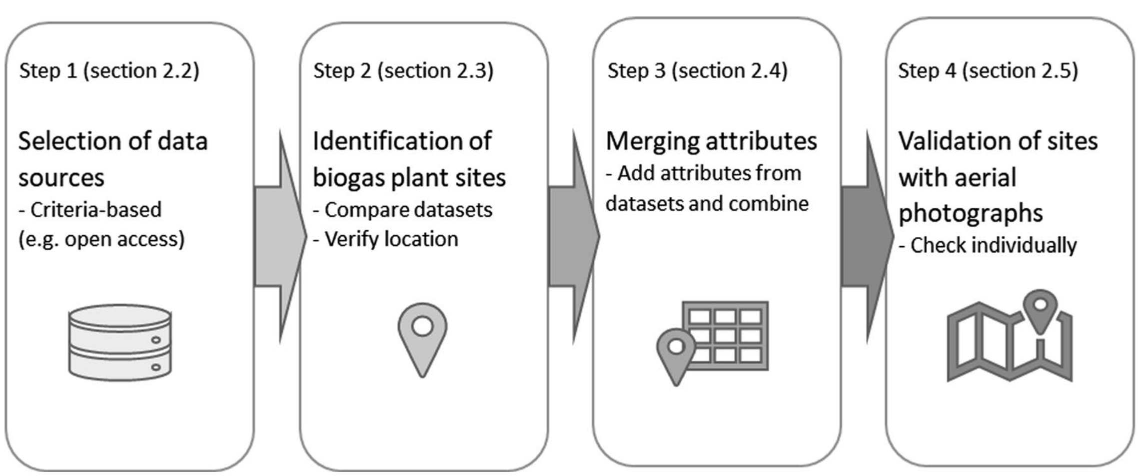

Fig. 1 General methodological approach for developing the biogas plant register

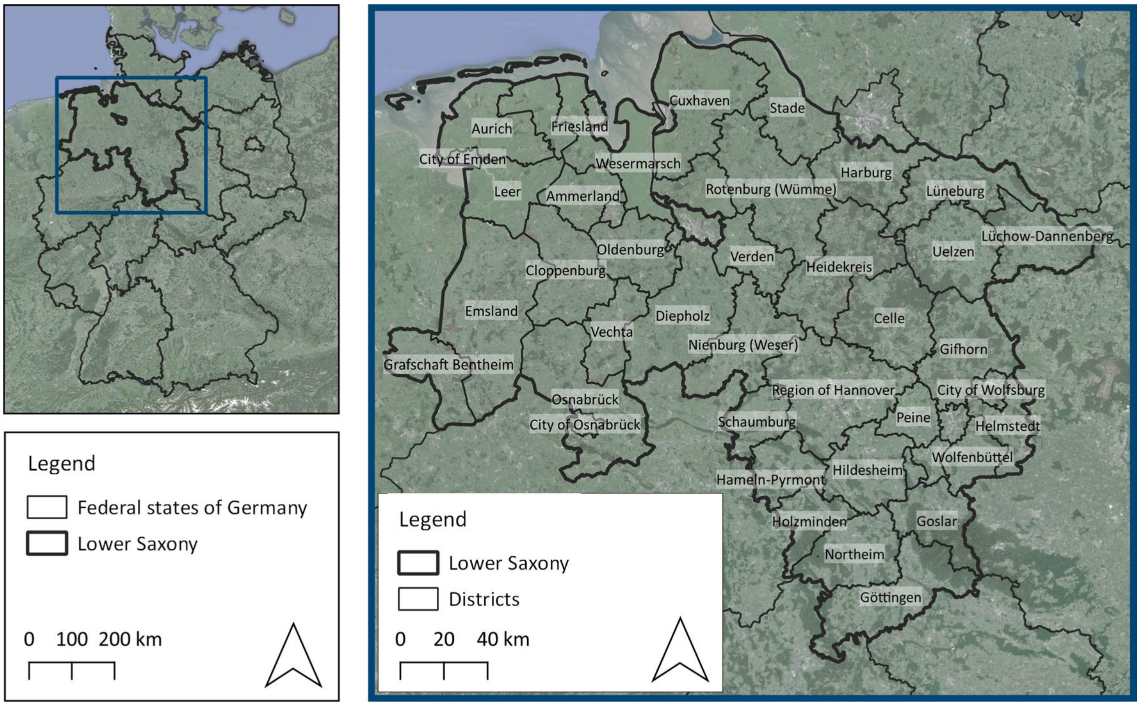

Fig. 2 Location of Lower Saxony in Germany (Geodata basis: [24, 25])

with 2,707 plants (ibid.), had a slightly higher plant density: 3.8 plants per 100 km^2.

Selection of data sources

The biogas plant sites in Lower Saxony were determined by comparing and verifying data from different sources selected using the following criteria: data reliability, up-to-date, and level of detail (including geographic location) to increase the informative value of the data. Furthermore, it is considered a good idea to use freely accessible and free data sets, *inter alia,* to facilitate updates. Wherever possible, the data sets should have been collected independently, allowing data correctness to be verified through comparisons with other data sources. Finally, the data in a data set should cover the entire study area, allowing a standardised method to be used. Regional data sources (e.g., WebMapServices of the geoportals of the districts) were not considered, as they were not available for the entire study and may have been based on the data sources used. Furthermore, the level of detail and up-to-date information varied between districts.

Based on these criteria, the following data sources (Table 1) were selected for Lower Saxony:

Spatial identification of biogas plant sites

To create a coherent and complete data set (Fig. 3) containing the locations and site attributes of the Lower Saxony biogas plants, the data sets were processed using geoinformation software QGIS (version 3.28.11).

DLM [18] vector data from ATKIS [29] are available for all Lower Saxony. It is geometrically accurate and has a high information density (data attributes) [30], so it can be used directly in QGIS geoinformation software. This data set provides information on the spatial location of plants using biomass as the primary energy source. The boundaries of the sites were similar to those of the land parcels. However, these sites did not require further examination. Also to be found in the data set, the spatial locations of settlement areas later served as the basis for identifying further biogas plants from other data sets. To avoid confusion between plants and satellite CHP plants, only DLM settlement areas corresponding to the existence of biogas plants were considered (i.e., mixed-use areas as well as industrial and commercial sites), with object types 'AX_FlaecheGemischterNutzung' and 'AX_IndustrieUndGewerbeflaeche' (see object type catalogue [31]) being extracted.

By listing the biomass electricity generation units, the MaStR data [11] provide tabular information on the spatial locations of biogas plants. To display these plants in the GIS spatially, the units were imported into QGIS, wherever possible, using their coordinates. Alternatively, spatially unassignable units could also be identified using the attributes of parcel number (via the property cadastre), plant operator, address, or name of

Table 1 Database for the biogas plant register

Data source	Description
Lower Saxony Digital Landscape Model (DLM) [18]	Vector data of the earth's surface for Lower Saxony from the Official Topographic Cartographic Information System (ATKIS). Four-year update cycle and positional accuracy of ± 3 m [26]
Lower Saxony Energy Atlas (Energy Atlas) [19]	Vector data of renewable energy plants in Lower Saxony. There has been no update since the 2019 spatial localisation of the plants
German core energy market data register (MaStR) [11]	Tabular data on the German electricity and gas market, such as core data on electricity- and gas-generating plants (Appendix MaStRV [27]). The data set is constantly updated, registration is completed by market players (§ 5 MaStRV [27]), and spatial allocation via coordinates is possible
TenneT EEG plant core and EEG payment transaction data [20, 21]	Tabular data of the TenneT EEG plant core and EEG payment transaction data (Pursuant to § 2.3 MaStRV, electricity generation plants classified as an installation pursuant to § 3.1 EEG) for the area of TenneT for 2022
OpenStreetMap (OSM) [22]	Vector data with worldwide data on the earth's surface, including the location of biogas plants. Constantly updated by members of the OSM community [28]

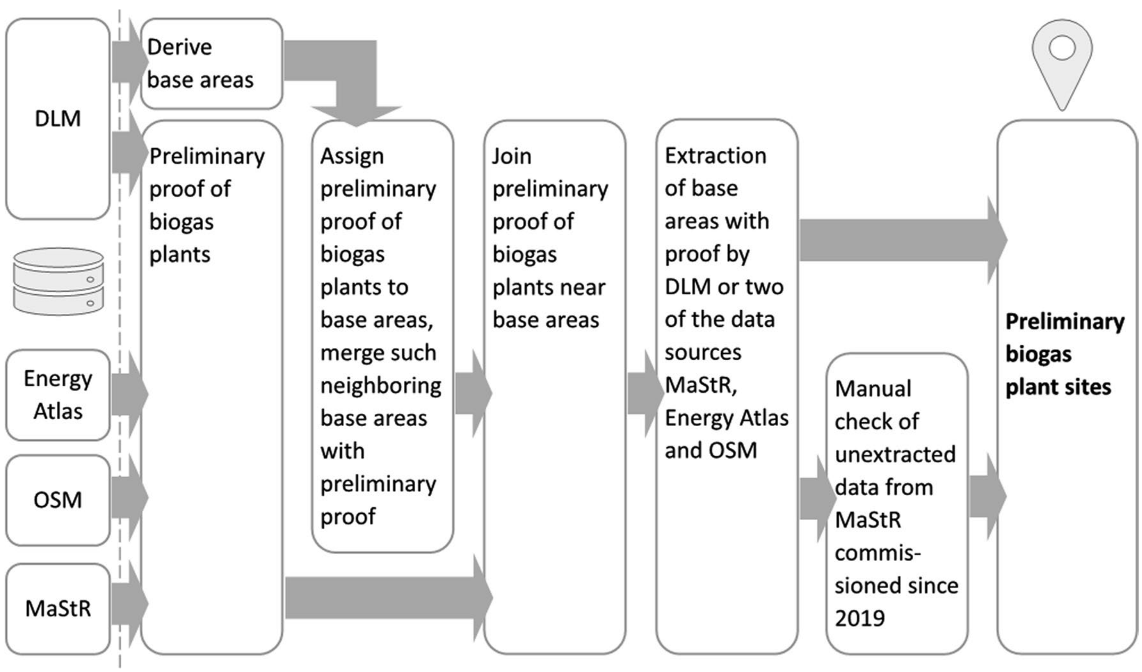

Fig. 3 Methodical approach to the localisation of the preliminary biogas plant sites

the power generation unit (via geocoding) and a supplementary aerial photograph comparison with aerial photographs from ESRI [32] and Google, [24] with the most recent data available dating back to December 2023. However, information regarding the locations of these plants should be used with caution. Although operators of biogas plants in Germany must register their plants pursuant to § 5 MaStRV [27], incorrect data cannot be ruled out. Moreover, satellite CHP systems are also included in the MaStR as biomass electricity generation units, but are not located at biogas plant sites. Wherever possible, these CHP systems were removed from the data set based on the names of the biomass power generation units.

The Energy Atlas [19] provides spatially localised vector data for biogas plants in Lower Saxony. It should be noted that this data had already been cross-checked with data from 3N, from the plant register of the Federal Network Agency (*Bundesnetzagentur*) and from a query by the Regional Development Offices (*Ämter für regionale Landesentwicklung*) as of 2013/2014 [33], revealing a certain dependency on other data sources. It should also be noted that the Energy Atlas data set was last updated in 2019, indicating that the data may be outdated. However, the use of this data source is not only an excellent option for validating biogas plant sites but also for supplementing incomplete information on biogas plants. The Energy Atlas vector data can be used directly in the QGIS.

OSM data for biogas plant sites [22] are also available. Line and polygon vector data mostly map the individual components of the biogas plants. Some of the biogas plants were located using point data. As the OSM community collected the data, incorrect information cannot be ruled out. For example, biogas plants can be confused with slurry tanks in aerial photographs. Nevertheless, OSM was used to validate the positions of the biogas plants. The relevant OSM data were imported into QGIS using the QuickOSM plugin based on the keys and values listed in Table 2 and then prepared as a polygon feature.

No classic neighbourhood analysis was used to validate the biogas plant sites, as their distribution in Lower Saxony was heterogeneous. Such an analysis may result in neighbouring biogas plant sites not being shown separately in areas with higher plant densities. Instead, the settlement areas previously extracted from the DLM were used as potential sites for biogas plants, the so-called base areas. These are considered preliminarily proven sites when a biogas plant is verified using the DLM. To verify the sites found in the MaStR, Energy Atlas, and OSM, a biogas plant had to be validated by at least two data sources to prevent incorrectly located plants from being transferred from their original data sets to our new biogas plant register.

It should be noted that biogas plant sites may extend over more than one DLM base area (see Fig. 4 for an example). Neighbouring base areas with at least one indication of the presence of a biogas plant were identified and merged. At this juncture, we spoke of possible preliminarily validated biogas plant sites, because the neighbouring areas might have only been verified via the MaStR, Energy Atlas, or OSM.

However, it was also possible that biogas plant sites could only be proven by looking at the neighbouring base areas. As already described, verification was required using at least two data sources, the MaStR, Energy Atlas, and OSM. An ID was subsequently assigned to all the

Table 2 Tags in OSM [22] that indicate biogas plant sites

Key	Value
generator: method	Anaerobic digestion, gasification
generator: source	Biomass, biogas

Fig. 4 Example of combining different data sources to a single preliminarily validated biogas plant site (Geodata basis: [11, 18, 19, 22, 24])

resulting preliminary biogas plant sites, allowing them to be clearly distinguished.

Furthermore, it cannot be ruled out that the MaStR, Energy Atlas, and OSM data were not true to the location and did not match the base areas extracted from the DLM data (see Fig. 4 for an example). A further possibility is that when biogas plants were only verified using the MaStR, Energy Atlas, and OSM, the DLM base areas did not correspond precisely to the areas of biogas plant sites. Therefore, the MaStR, Energy Atlas, and OSM data were only selected when not previously assigned to a possible preliminary biogas plant site. Data located a maximum of 118 m away from a possible preliminary biogas plant site were considered (118 m was the mean radius of a sample of 30 randomly selected biogas plant sites, measured based on aerial photographs). For data located farther away, the possibility that they do not belong to a plant site is higher. To consider all data of the biogas plants on or near the possible preliminary sites, additional plant data were merged with the preliminary site data set. Finally, sites were rejected when found solely in one of the data sets (MaStR, Energy Atlas, or OSM).

Commissioned biogas plants have not yet been identified. These systems have been added since 2019 and thus are not included in the Energy Atlas (last updated in 2019). To include these newer biogas plants as much as possible, detailed and up-to-date MaStR data were used; in this case, all units and plants commissioned since 2019, located on or near a DLM base area, and not yet assigned to a plant site. These MaStR data were added to the base area and then checked manually using an aerial photograph comparison with aerial photographs from ESRI [32] and Google [24] (the most recent data available dating back to December 2023). Plants were identified in the aerial photographs by the typical shape of the fermenter, whereby any visual confusion of the biogas plants, such as a slurry tank, was unlikely because the plant operators entered the information on the plants themselves in the MaStR. The newly identified biogas plant sites were added to the existing preliminary biogas plant sites, resulting in the registration of all the biogas plants in Lower Saxony.

Merging of biogas plant attributes

To assign attributes to the biogas plant sites, MaStR data (biomass electricity generation units, EEG biomass plants, and CHP plants) [11], TenneT EEG plant core, and EEG payment transaction data [20, 21] were linked. The tabular attributes of the EEG biomass and CHP plants were added to the tabular data for biomass electricity generation units based on their EEG or CHP numbers. The tabular TenneT EEG plant core data were linked to the units via the MaStR number or to the address. The tabular TenneT EEG payment transaction data were added to the TenneT EEG plant core data using an EEG plant key (*EEG-Anlagenschlüssel*). Double-attribute entries in each field are avoided.

The MaStR data described above, TenneT EEG plant core, and EEG payment transaction data were linked to the biogas plant sites using the coordinates of the biomass electricity generation units. This included data localised at a maximum distance of 118 m from the biogas plant sites. Because the attributes of the biomass electricity generation units are listed in a column for each site, they can be viewed separately. Nevertheless, the data were presented compactly and clearly. In the case of EEG plants, care was taken to ensure that they and their associated attributes were not mentioned twice at one site. Like the biomass electricity generation units, the plant attributes are listed separately for each site. The same principle was applied to the core and transaction data and the CHP plants. The units of the gas producers using biomethane technology (MaStR) were then added based on their coordinates. The attributes of the biogas plants from the DLM, the Energy Atlas and the OSM were similarly assigned to the biogas plant sites based on their location. Again, data within a 118 m radius of the biogas plant sites were included. Regarding the Energy Atlas and DLM, the attributes for each site are listed in the columns. Regarding the OSM data, only the location was of interest, as no relevant attributes were available. Therefore, we only checked whether the OSM data provided proof for the plant. A prefix is used to indicate the source of all attributes. The results comprise a data set of biogas plants and plant attributes aggregated for biogas plant sites.

Attributes of interest for the possible future use of biogas plants are highlighted. Specific attributes from the data sources were merged. In addition to the coordinates of each plant site, the MaStR numbers of the biomass electricity generation units, plants, and grid operators were entered. Plant commissioning and decommissioning dates are also provided. The year in which EEG subsidies for the plants were set to expire was also added, with the statutory remuneration period of 20 years (§ 25 (1) EEG [5]) being added to the year of commissioning. This is the point in time when the question of the possible future use of facilities arises. In addition, data on the installed capacity, net rated output, thermal output, and biomethane production at the site are highlighted. When merging the attributes from various data sources, the most recent and detailed data must be highlighted. In general, this is the MaStR data. When these attributes were missing for a site, data were obtained from the master and transaction data. The Energy Atlas was the last option, because it is the least up-to-date, and the data are less detailed. It should be noted that most plant information was only included in some of the data sets MaStR, TenneT EEG plant core data and Energy Atlas (see Table 3).

Validation of biogas plant sites using aerial photographs

Finally, preliminary biogas plant sites were validated using aerial photographs. This enables us to simultaneously test the methodology's suitability and boost the register's quality. A comparison was made between all preliminary biogas plant sites in the register and current aerial photographs from ESRI [32] and Google [24], with the most recent data dating back to December 2023, allowing incorrectly located sites to be removed from the data set. It was assumed that additional biogas plant sites could be derived from the MaStR, as this was the most recent and detailed data source included in the analysis. As some biogas plants were only found in this data set and were, therefore, missed in the previous data analysis, any spatially localisable electricity generation units from the MaStR that were not yet allocated to a plant site were the focus of attention. These included units previously identified as satellite CHP units. Units with incorrect coordinates were also not neglected. As far as possible, they were first matched with their current coordinates using their attributes (address, name, and operator). Those that did not belong to a biogas plant location were checked by comparing the spatially located biomass electricity generation units with aerial photographs. The biomass electricity generation units found at a previously unidentified biogas plant site were then added to the corresponding base areas from the DLM, supplemented by plant attributes. This was performed in the same manner as described above.

Results

By comparing the data sources used and a subsequent aerial photograph crosscheck of the preliminary biogas plant sites (see Fig. 5 as an example), we could locate and validate 1,704 biogas plant sites.

Spatial distribution of biogas plant sites

In the GIS-based analysis, comparing the DLM, MaStR, Energy Atlas, and OSM data sets enabled the spatial localisation of 1858 potential biogas plant sites in Lower Saxony (Table 4). A total of 97.71%, or 1665 of these sites, were confirmed by comparison with aerial photographs. In addition, a comparison between MaStR units not previously assigned to a biogas plant site and aerial photographs revealed an additional 39 sites, 2.29% of the validated biogas plant sites.

More than 90% of existing sites were identified without a final aerial photograph comparison. To (correctly) identify as many sites as possible in Lower Saxony, it is advisable to use the DLM, MaStR, Energy Atlas, and OSM data sources combined with aerial photographs.

The DLM provided information on 1521 of the 1704 biogas plant sites, as validated by aerial photographs. By comparing the MaStR, Energy Atlas, and OSM data sets, we identified 183 additional sites verified by aerial photography (Fig. 6). The Energy Atlas and OSM data were primarily used to validate the MaStR data. However, information on the five sites was not found in either the DLM data set or the MaStR. These sites can only be identified using the Energy Atlas and OSM data.

The 1,704 biogas plant sites identified were spread across Lower Saxony (Fig. 7), with the

Table 3 Original data sets of the biogas plant attributes of interest

Attributes	Data sets		
	MaStR	**TenneT EEG plant core data**	**Energy Atlas**
The MaStR number of biomass electricity generation units, EEG plants and CHP plants	(1)		
The grid operator MaStR number		(1)	(2)
Year of commissioning	(1)		(2)
	Earliest of all data sets		
Year of decommissioning	The most recent date of all data sets		
Installed power	(1)	(2)	
Nominal net power	(1)		
Thermal performance	(1)		(2)
Biomethane feed-in and biomethane production capacity	(1)		

Depending on availability: first (1) and second (2) choices

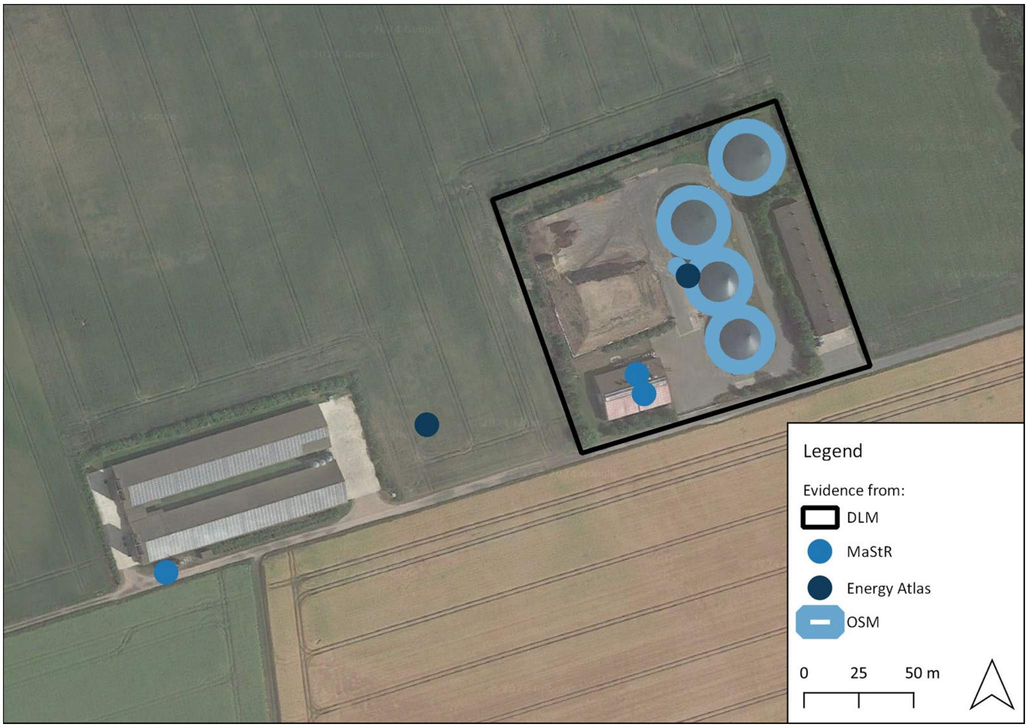

Fig. 5 Example of biogas plant location information from different data sources for a single site (Geodata basis: [11, 18, 22, 24])

Table 4 Process of identifying biogas plant sites

	Biogas plant sites
Identify preliminary sites based on comparison of DLM, MaStR, Energy Atlas and OSM data sets	1858
Not visible in the aerial photograph	−193
Additional sites based on MaStR using aerial photography	+39
Sites after aerial photograph comparison	1704

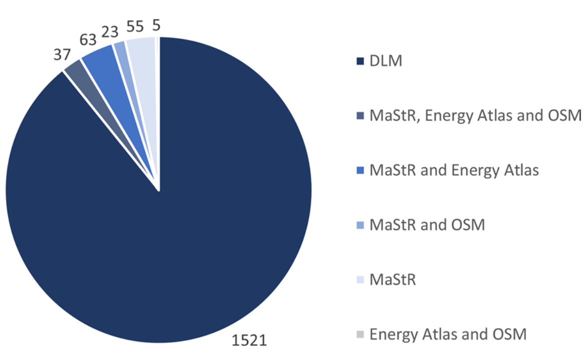

Fig. 6 Biogas plant identification by different data sources

districts of Cloppenburg (118), Oldenburg (82), Rotenburg (Wümme) (140), Emsland (177), Diepholz (115), and Grafschaft Bentheim (56) in the centre, north, and west of the state, respectively, with a comparatively high density of over five sites per 100 km^2. In contrast, south of Lower Saxony as a whole, the districts of Leer (13), Uelzen (28), and Hanover (41) featured densities of fewer than two sites per 100 km^2. Emsland had the most sites (177), whereas Cloppenburg had the highest plant density (8.3 sites per 100 km^2). Braunschweig and Salzgitter had no plants and, therefore, had the lowest density of all districts (0 plants per 100 km^2).

Attributes of lower saxony biogas plant sites

Specific plant information was assigned to identify biogas plant sites using different data sources (Fig. 8). Although almost 90% of the sites were extracted from the DLM, the data set provided no further plant-specific attributes. The MaStR data set, in combination with the master data, proved to be indispensable, listing detailed information on the units and plants. Missing information has been added to the Energy Atlas. Data gaps were filled by merging the plant attributes relevant for further use of the biogas plant sites from these three data sets, and key data such as nominal net power and

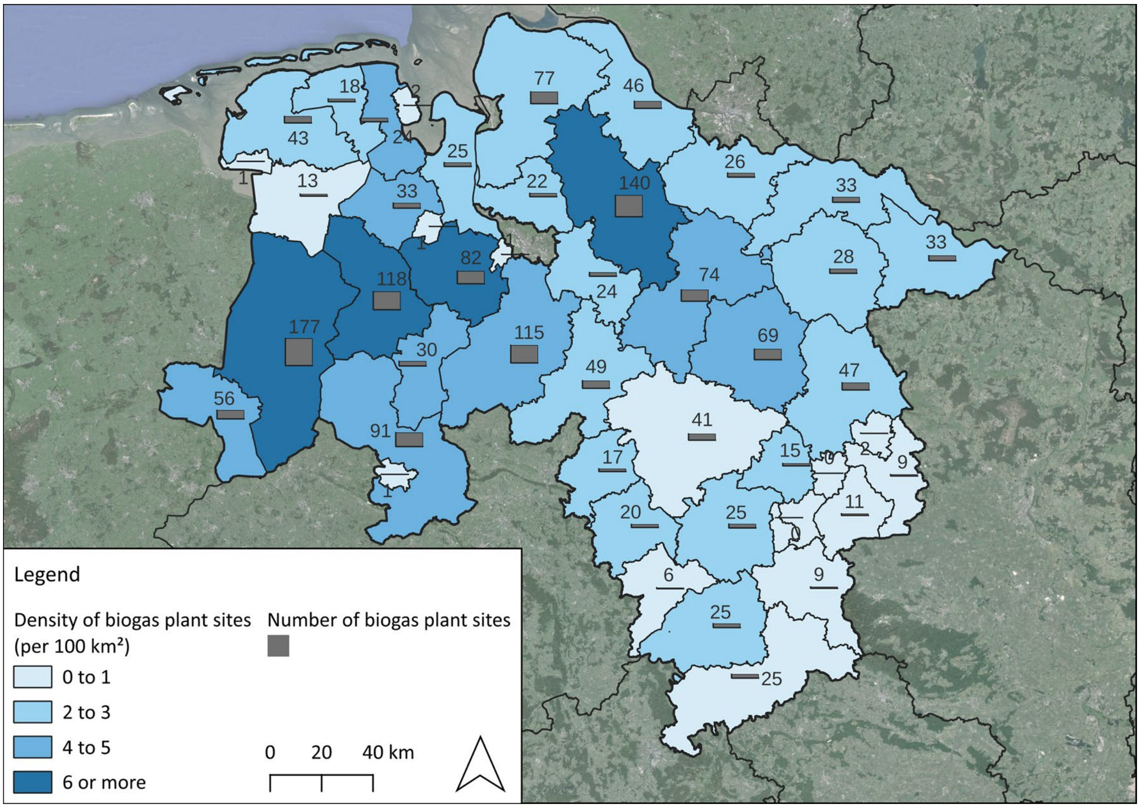

Fig. 7 Spatial distribution of biogas plant sites across the districts of Lower Saxony (Geodata basis: [24, 25])

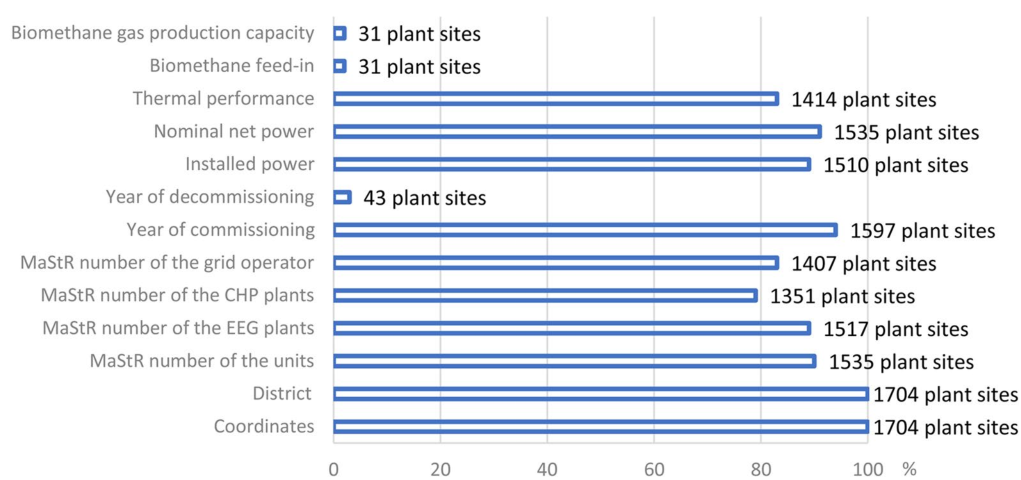

Fig. 8 Availability of attributes relevant to the potential further use of biogas plant sites

biomethane feed-in were highlighted (Fig. 8). Note that not all attributes are available for all sites. For example, biomethane processing only occurs at a few sites, whereas information on plant decommissioning is only found at sites, where plants have already been decommissioned.

The biogas plant register allowed us to analyse biogas plant sites based on the selected attributes and spatial location. The proximity of individual biogas plants to one site led to their bundling. For example, Fig. 9 shows four biogas plants (as defined in § 3.1 EEG [5]) in the immediate vicinity of a livestock fattening plant.

Fig. 9 Example of a biogas plant site with four EEG plants (Geodata basis: [11, 18, 24])

Looking at the number of EEG plants at any one site, we found 163 sites with two plants, 29 with three plants, seven with four plants, and one with seven plants; 200 of the 1704 sites featured more than one biogas plant. The plant attributes at these sites were bundled.

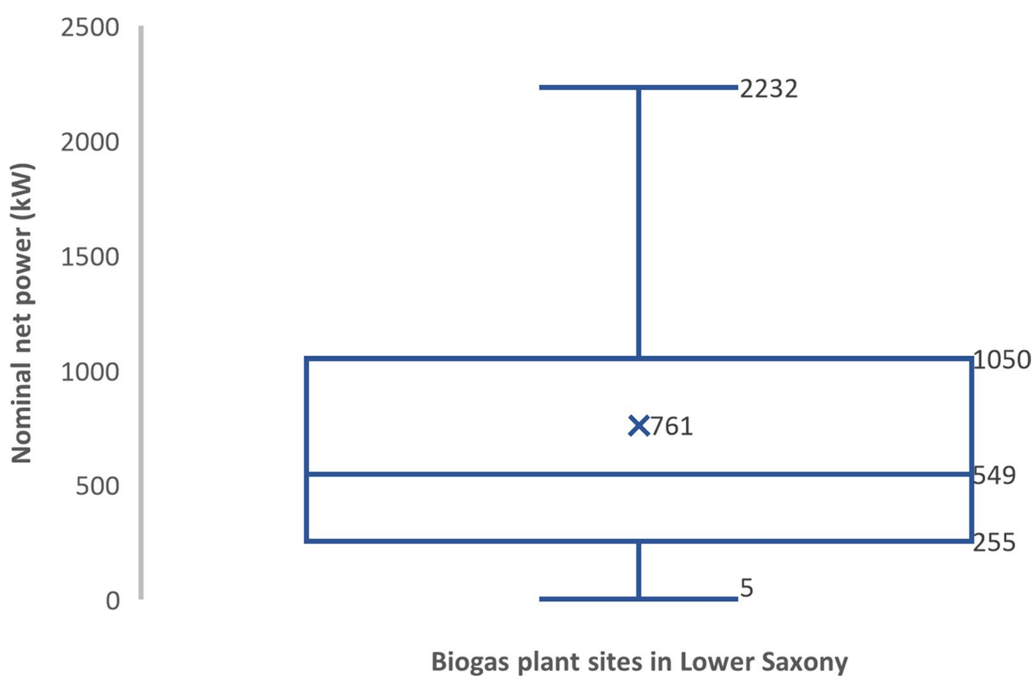

Fig. 10 Distribution of the nominal net power in kW of all biogas plant sites

Statements on plant performance at each site can be made regarding the nominal net power. In Lower Saxony, this varies between 5 and 2232 kW (Fig. 10), excluding the outliers. Fifty per cent of the sites had capacities between 255 and 1,050 kW. However, at 51 sites, the bundled nominal net power exceeded 2232 kW, with values of up to 11,348 kW recorded.

The register also provides information on the spatial distribution of biogas plants based on their output. One example is the installed power. This is an initial indication of a site's suitability for a P2G end-of-subsidy strategy [14]. According to Erler et al. [14], sites with conventional on-site electricity generation plants with an installed capacity of 250 kW or higher are P2G candidates. The register shows that 73.7% (1255) of all Lower Saxony biogas plant sites are candidates (Fig. 11), many located in the centre and west of the state. Of those unsuitable for P2G (26.3%), most were located in the north and west of Lower Saxony (shown in white in Fig. 11).

The installed capacity allows conclusions to be drawn regarding a plant's suitability for upgrading raw biogas to biomethane. According to Scherzinger [34], biogas plants with installed 500 kW or higher capacities are economically suitable for such upgrades. Plants featuring this capacity can be found throughout Lower Saxony, with the majority in the north and west (Fig. 11). When the installed power is insufficient, using collection pipelines is an option to make the upgrade feasible. According to Erler et al. [14], these pipelines bundle and transport small quantities of raw biogas to central locations for upgrading and feeding. The proximity of suitable biogas plants was obtained from the registry.

Furthermore, initial statements could be made about the location and suitability of Lower Saxony biogas plants for end-of-subsidy strategies as part of decentralised P2G systems. Forecasts related to the upcoming expiration of a 20-year EEG biogas plant subsidy are of particular interest. The year of commissioning was used for the forecasts (Fig. 12).

At 179 (10.5%) of the identified sites, subsidies had expired by the end of 2025. Between 2026 and 2030, an additional 727 or almost 42% of all sites with plants currently operating will suffer from this fate, as will 539 (31.6%) from 2031 to 2035, 126 (7.4%) by 2040, and 27 (1.6%), the last of today's operating plants, by 2045. Plant decommissioning was particularly noticeable in northern and western Germany (Fig. 12), where high plant densities prevail.

Further attributes listed in the biogas plant register are of interest for possible strategies for plants with expired subsidies, for example, which plants are already producing biomethane. They, therefore, may already be connected to a gas grid. According to the register, methane is

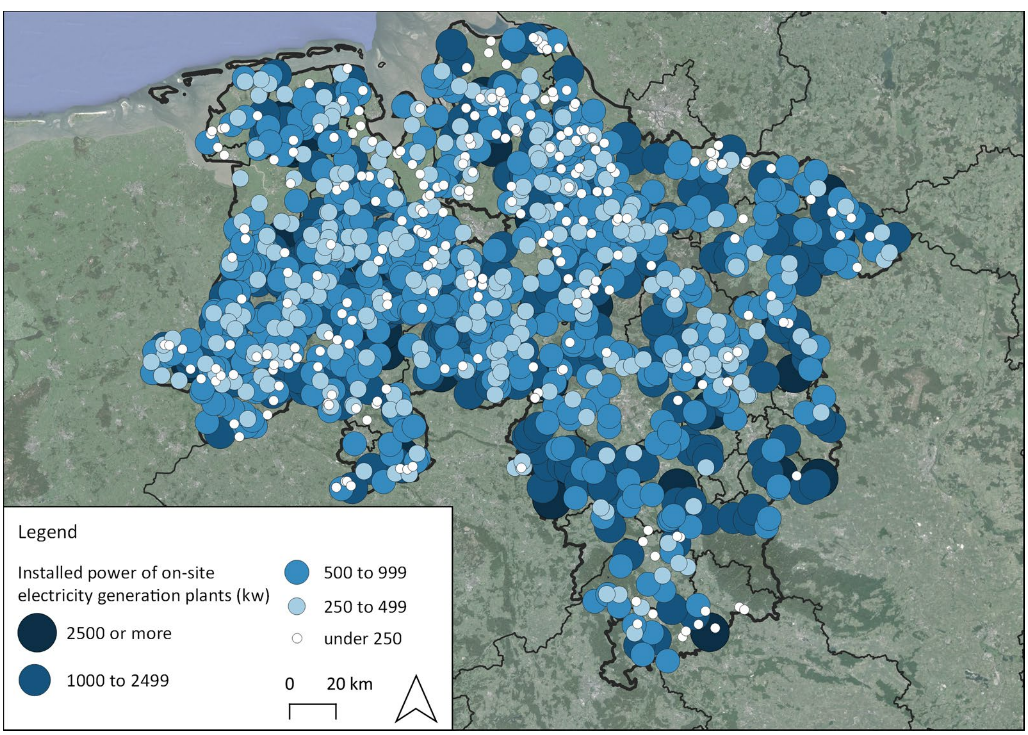

Fig. 11 Spatial distribution and installed power of the on-site electricity generation plants in Lower Saxony (Geodata basis: [24, 25])

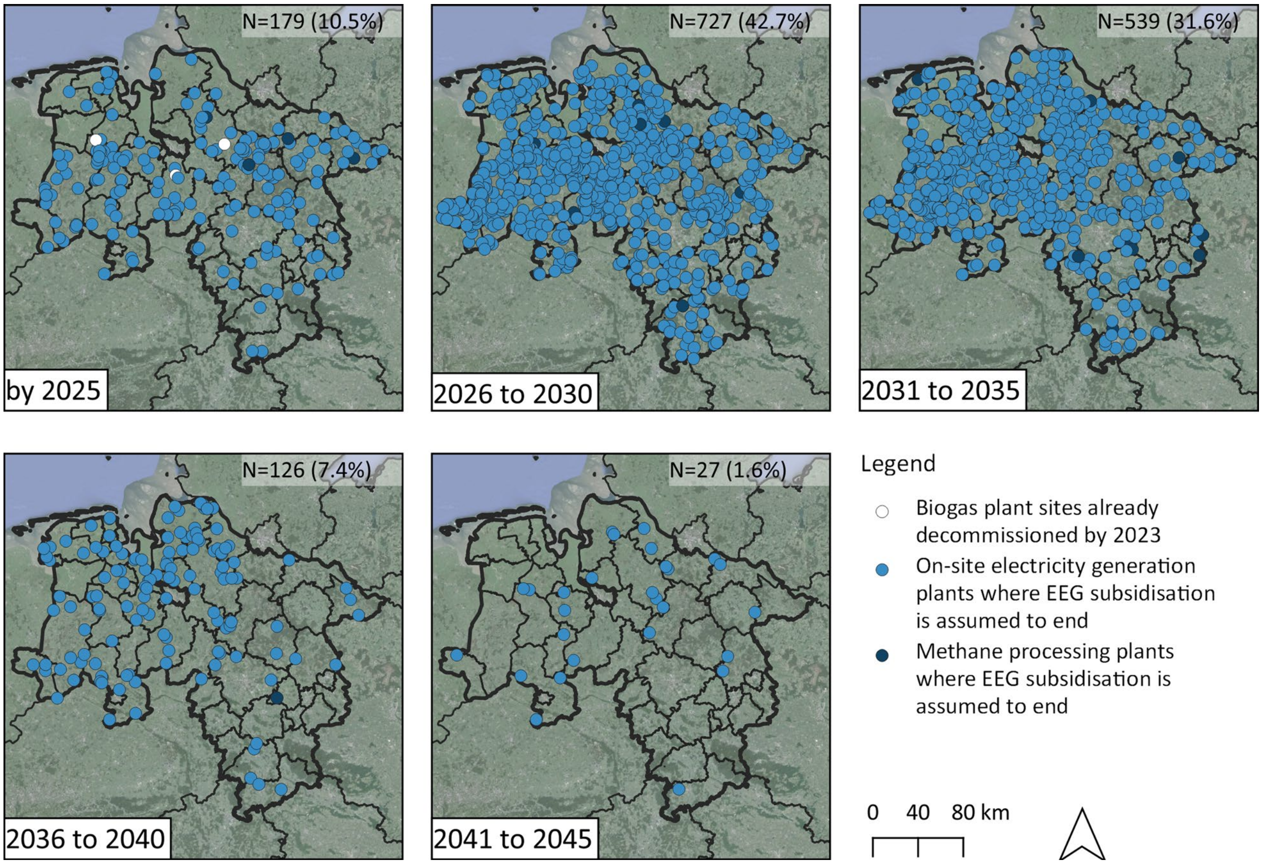

Fig. 12 Spatial and temporal resolution of EEG subsidy expiry dates for Lower Saxony biogas plant sites (Geodata basis: [24, 25])

already being produced at 31 locations in Lower Saxony (Fig. 13).

Discussion

Using GIS-based analysis and subsequent comparisons with aerial photographs, 1,704 biogas plant sites in Lower Saxony were spatially localised. In addition, up-to-date attributes relevant to assessing potential plant end-of-subsidy strategies were assigned to each site.

GIS analysis is a reliable and relatively error-free method for identifying biogas plant sites. Almost all biogas plants built up to December 2023 in Lower Saxony were included in the register. By way of comparison, 3N [10], commissioned by the Lower Saxony Ministry of Food, Agriculture and Consumer Protection (*Niedersächsisches Ministerium für Ernährung, Landwirtschaft und Verbraucherschutz*), identified 1,676 plants in 2021, 28 fewer than in our study. As our register includes only 12 plants commissioned after 2021, some of the sites identified in our study were not identified in the 3N study. Moreover, the register revealed 200 sites with more than one plant, resulting in an even higher total number of individual plants. The significant difference in the number of plants between those in our register and those identified by 3N was not due to incorrect localisation of biogas plant sites in the register, as site locations were validated using aerial photographs. However, there is a potentially small margin of error in the aerial photograph comparison, as it cannot be ruled out that the fermenter, a characteristic feature of a biogas plant, was mistaken for a slurry tank which looked similar to the aerial photograph.

By contrast, according to Manske et al. [35], there are a total of 3,943 biogas plants using biogas or biomethane as the main type of biomass in Lower Saxony. To enable a comparison between our register and the data set established by Manske et al., the biogas plants identified by Manske et al. [35] were clustered by location. This entailed a simplified procedure, whereby all plants within a 236 m circle (118 m radius, as in the cadastre developed above) were merged as a single site. This resulted in 2,313 sites, 35% more than in our register. The difference is probably due to Manske et al. [35] relying primarily on MaStR data. Sites and satellite CHPs incorrectly located in the MaStR could not be reliably extracted. Moreover, not all biogas plants in our register were included in the

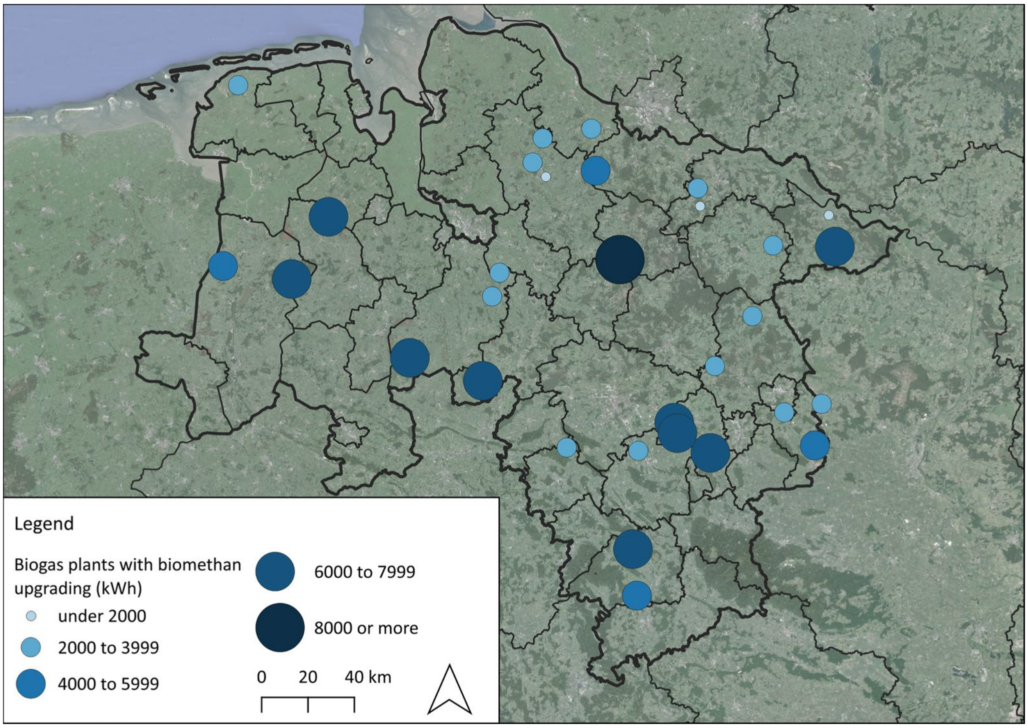

Fig. 13 Spatial distribution and biomethane gas production capacity of methane processing plants in Lower Saxony (Geodata basis: [24, 25])

Manske et al. data set, because 163 of the sites identified were not in the MaStR. Finally, the use of multiple independent data sources contributes to the establishment of a reliable biogas register. Although MaStR data [11] are important, they must be critically reviewed and validated against other reliable sources.

In addition to the high level of localisation reliability of the biogas plant sites in our register, a further advantage is the wide range of plant attributes derived from different data sources. These attributes are easily accessible to sites, can be used for further (spatial) analyses, and combined as required (those particularly relevant to P2G-based end-of-subsidy strategies have already been combined). Not only does the hierarchisation of attributes from different data sources result in attributes being available for as many sites as possible, but the most accurate and up-to-date plant information can also be extracted from the data sources. Nevertheless, it should be noted that there was no further correction for relevant attributes other than their hierarchisation. Future consideration should be given to the adjustment of incorrect attributes, as already practiced by Manske et al. [35].

It is not advisable to summarise plant information based on site register data, such as installed capacity at the district level. MaStR information and master and transaction data were added to the site based on the MaStR number of an EEG site and not based on its address or geocoordinates. Summarising plant information within an area may thus lead to the inclusion of a plant's attributes several times. However, this does not detract from the quality of the register, as the focus is on localising the biogas plant sites. Data such as the installed capacity and number of biomethane-processing plants in Lower Saxony have already been regularly published by 3N [10].

Another benefit of the register is that it can be updated without additional effort. The GIS model upon which the register is based can be reused using the current data sources. Basic GIS knowledge, in combination with a user manual for the model, is sufficient for integrating the latest source data into the GIS model. A subsequent comparison of aerial photography is only necessary for newly added biogas plant sites. This approach offers advantages over the existing biogas plant registers. For instance, Manske et al. [35] (data collected in 2021) or the Energy Atlas [19] (data collected in 2019) constitute snapshots; that is, they are either not updated or irregularly updated. Any later updates constitute a major effort for those not involved in register development. Another advantage of our methodology is that it can be applied to other spatial data acquisition procedures. However, suitable data sources must first be identified for the area in question, and the GIS model must be adapted. Advanced GIS knowledge is a prerequisite to this procedure.

The information in the register can be used for analyses and decision-making processes regarding possible end-of-subsidy strategies for biogas plants. Where are these facilities located? Which sites do biomethane processing occur? Possible future paths for biogas plants with expiring EEG subsidies can also be determined. Is a plant's continued operation economical even after subsidence has expired? Should alternative use be considered? Our register was developed to address the spatial questions surrounding potential P2G-based end-of-subsidy strategies. In the context of Lower Saxony's goal of achieving CO_2 neutrality by 2040 (§ 3.1.1 NKlimaG) and the aspired hydrogen transition, the register can determine which biogas plant sites are best suited for the decentralised production of hydrogen or methane. Which plants are the EEG subsidies set to expire in the short or medium term? What are the technical characteristics? Which sites already process biomethane and, consequently, are connected to the gas grid?

One of the main aims of our biogas plant register is to serve as a basis for decision-making processes regarding P2G-based end-of-subsidy strategies for biogas plants. Thus, they contain plant information and site parameters relevant to such strategies. The consortium of the NBank-funded research project *H2-FEE: Flexible energy carriers for the energy transition* (duration from July 2022 to June 2025) is currently working on supplementing the register, for example, assessing the extent to which large quantities of renewable energy needed for P2G are already or potentially available [36] in the vicinity of the plant. Information on the transport and storage of hydrogen or biomethane produced on-site is highly relevant to these end-of-subsidy strategies. The distance between unconnected biogas plant sites and the nearest gas grid is being analysed in response. Identifying potential gas customers is also of interest.

Furthermore, the CO_2 potential is of great importance for the methanization process (P2G) at biogas plant sites and has already been investigated by Locker [37] as part of the H2-FEE research project. Concerning the near-term implementation of methanization concepts, CO_2 captured by methane-processing plants is already available. The aim is to integrate the CO_2 potential into the registry. The biogas plant register also provides relevant information for local heat planning, because future P2G locations are an option for district heating systems [38]. In addition, future P2G locations are of interest for integration into municipal heating planning. According to the NKlimaG (§ 20), the medium-sized and regional centres in Lower Saxony are obliged to draw up municipal heating plans by the end of 2026. Even if it is still difficult to integrate heat planning into the biogas plant register owing to the current planning, (municipal) heat planning should be considered in the future.

Conclusion

Our biogas plant register provides a comprehensive and up-to-date overview of biogas plant sites and attributes in Lower Saxony based on available public data. Its greatest advantages and, at the same time, unique characteristics are the exact spatial localisation of the plants and the up-to-date quality of the data. The register enables initial (spatial) analyses of potential sites for end-of-subsidy P2G strategies. This register provides a basis set that can be expanded in future. In particular, the integration of the performance potential of neighbouring renewable energy facilities, information on the connection to infrastructure relevant for P2G, and the possible uses of the plants in connection with municipal heat planning will be helpful in the future or are already being dealt with in the H2-FEE research project. Finally, the register has the potential to serve as an advisory basis for small- and medium-sized enterprises, local authorities, and districts, as well as for policy advice.

Acknowledgements
The authors thank Dominik Locker, Sarah Brandtner, and Ines Lüdders for their support during this study. The authors thank Richard Lomax and Elsevier Language Services for linguistic corrections. The authors acknowledge using DeepL Write for text editing assistance and take full responsibility for any remaining errors.

Author contributions
MP developed the method, generated the resulting dataset, and wrote a large part of the manuscript. JB corrected the coordinates of the biogas plants and added them to the manuscript. JH advised on the development of the method and was actively involved in further development of the manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL. This article results from the NBank-funded research project H2-FEE: Flexible energy carriers for the energy transition (from July 2022 to June 2025).

Availability of data and materials
The data with the DOI https://doi.org/10.25835/in90p55t are available at https://data.uni-hannover.de/dataset/gis-basedregister-of-biogas-plant-sites-in-lower-saxony-germany.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 5 April 2024 Accepted: 26 December 2024
Published online: 24 January 2025

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