# Mapping of biogas methanation potential in Denmark - Based on existing biogas sources

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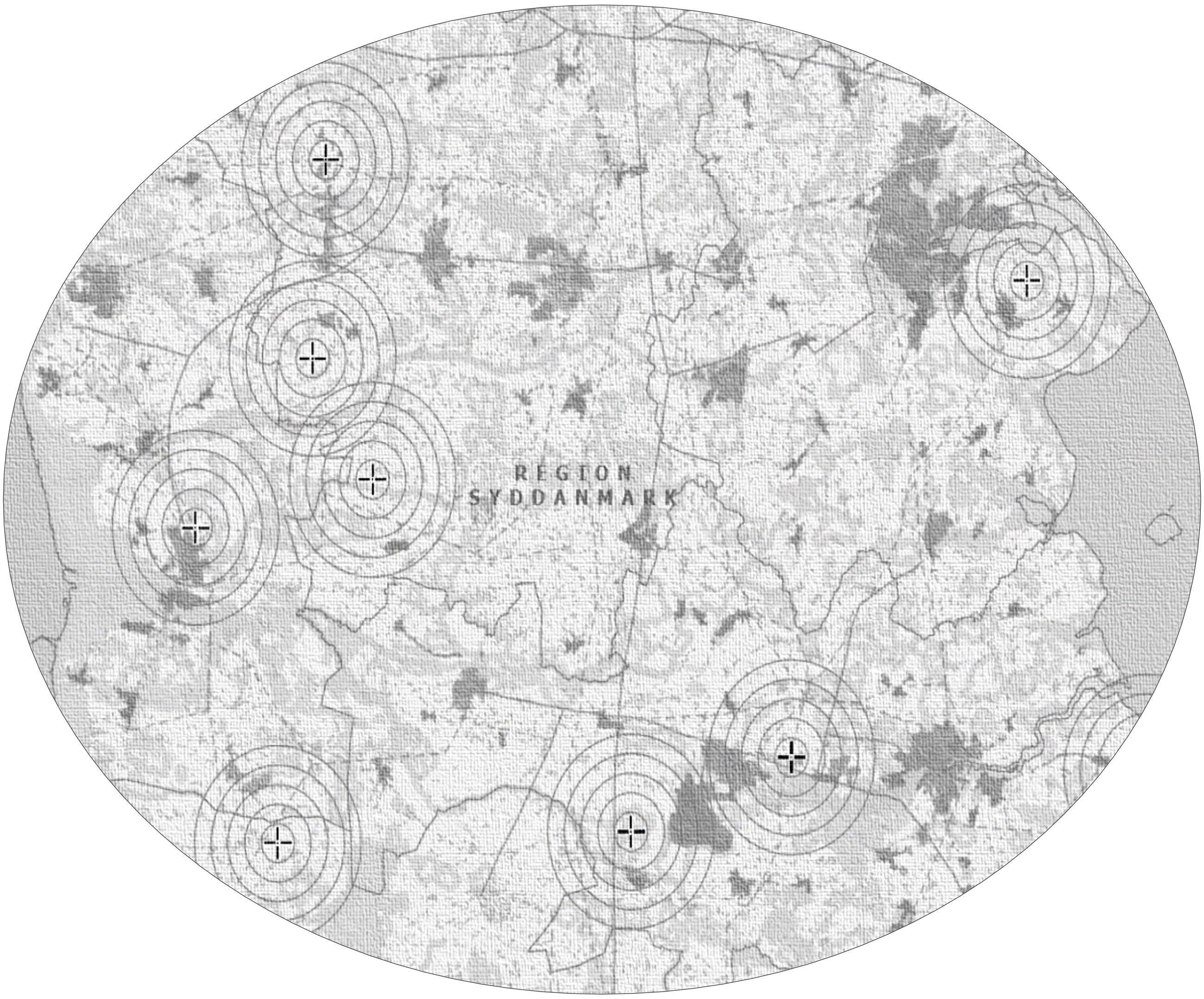

**Mapping of Biogas Methanation Potential in Denmark - Based on Existing Biogas Sources**

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**Abstract**

This report estimates the potential for biogas methanation plants based on a spatial analysis of the existing biogas producers. The analysis evaluates distances to electricity and gas infrastructure, as well as local wind potentials. Furthermore, each location is evaluated in terms of existing gas injection, distance to district heating and to CNG stations.

The results show that the total theoretical production potential of e-methane from biogas is around 6,666 GWh/year. From this potential around half of the locations are suitable for biogas methanation. The report also shows that this conclusion, is highly sensitive to the criteria used, if longer distances to gas and electricity networks is allowed, then the share increases.

**This report is prepared as a part of Task 6.3 in EUDP Biocat Roslev**

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# 1 INTRODUCTION

In recent long-term national energy plans [1–3], power-to-gas technology is seen as a key technology for reaching the 100% renewable energy system. With increasing amounts of fluctuating renewable electricity production, like wind and solar power, it becomes necessary to use the technologies that can exploit the excess electricity production. Some technologies use electricity directly (electric vehicles) while others convert the electricity to other types of energy (heat pumps). In general, these examples are more energy efficient technologies than power-to-gas technology, however by using power-to-gas technologies it is possible to generate green gases that can be used for decarbonising gas network and to generate fuels for heavy industry and transport, where conversion to direct use of electricity is not possible.

Several types of power-to-gas technologies exists, both from numerous carbon sources to several different electrolyser technologies. This report takes a point of the departure in the recent report [4], and quantifies the total potential of biogas methanation and geo-spatially evaluates the existing biogas plants in terms of different criteria. The aim of this report, is to make a broad analysis of the biogas methanation potential based on current infrastructure and physical constraints, without going into regulative barriers or economic considerations.

Additionally, as to enhance the outreach and accessibility of this research, an ArcGIS Web Application has been built up under Open Access agreement making use of the current spatial data available at the moment of the study. The tool facilitates the user to perform personalized modelling for the different biogas methanation potential facilities responding to a set of parameters required as inputs. These parameter inputs are the ones used as selection criteria in section 2.4 and can be modified in the application by the user in order to obtain different analysis. A brief description of the tool’s accessibility and capabilities is presented in this report, specifically in section 3.3.

In 2019, the Danish TSO Energinet.dk published an analysis of different organizational models for power-to-gas plants (including biogas methanation); offsite model, onsite model and the upstream model [5]. Each model differs in the way the plants are connected to the electricity grid, and thus have different possibilities.

In the offsite model all electricity is bought from the national electricity grid, which gives the benefit that the renewable energy production does not need to be placed near the biogas methanation plant. However, the offsite model has a high sensitivity to the tariff and tax structures, and it can be hard to document how much of the electricity, consumed in the electrolyser comes from renewable energy sources (RES). Moreover, it is difficult to guarantee the renewable product due to the electricity mix in the grid, however, this can be solved by power purchasing agreements (PPA) with producers, that then guarantee the renewable electricity.

The second model is the onsite model, where the electrolysis is placed behind the meter, and can use electricity from local RES when available, and the national electricity grid in the rest of the hours. The main benefit of this model, is that it is possible to save the grid tariffs for part of the production, reducing the need for building large electricity infrastructures. Furthermore, with the onsite model, it is easier for the owner to documents the RES share of the production. The weakness of this model is that it is more restricted in terms of potential locations, as the methanation plants must be close to RES production.

The third model is the off-grid model, which is a variation of the onsite model, where the biogas methanation unit is not connected to national electricity grid. In this model, the benefit is that it is easy to document the RES share of the production, but compared to the onsite model, the utilization of the electrolysis will be lower.

It should be noted, that the calculations in the report are rather general and based on specific capacities of biogas methanation and renewable energy plants. However, the knowledge from the report is useful for designing a methodology that evaluates both the best locations and feasible biogas methanation plant sizes. Thus, in this report, the following categories will be used:

a) Far from electricity and gas infrastructure
b) Near electricity and gas infrastructure
c) Near electricity and gas infrastructure and existing wind turbines
d) Near electricity and gas infrastructure and good locations for new wind turbines

It should be noted that the categories are exclusive of each other, so a biogas source can only be in a single category. Using these categories is the next logical step in finding suitable locations for biogas methanation plants in Denmark. Thus, the aim of this report is to both *quantify the potential plant sizes and gas output*, but also *to evaluate how large a share of these plants is within each category*. This can be used as an indicator on where it could be a good place to start the deployment of biogas methanation plants.

## 1.1 DELIMITATIONS

Quantifying biogas methanation sizes and evaluating suitable locations can be done by various methods and detail levels. Chapter 2 explains in detail how the task has been solved in this report, however it is important to be aware of the focus and delimitations, before proceeding with the analysis.

This report only assesses existing biogas plants and not any potential new or planned biogas plants. Thus, it should be noted that future potentials for biogas methanation could be relevant in the long term, in addition to what is assessed in this report. Another key part of the report, is that it focuses on a broad planning level, examining spatial and technical limitations, without going into any economic assessments. The analysis in this report should be seen as an important first step towards making an economic feasibility study of the potentials. Likewise, the report does not consider the operation of the biogas methanation plans or examine e.g. the capacity availability in the various energy infrastructure. The focus is on annual production and capacity of plants, evaluating distances to relevant infrastructure and local renewable energy production. In the same way, the web application responds to the inputs used for this report and therefore possess alike limitations.

# 2 METHODOLOGY AND DATA SOURCES

This chapter introduces the setup of the methodology and the data sources used in the report. Furthermore, it also explains the selection criteria, as well as the sensitivity analysis.

## 2.1 METHODOLOGY

This research methodology employs essentially geospatial analysis performed using ArcGIS Desktop 10.6.1 from ESRI [Environmental Systems Research Institute], which includes a rich analytical toolbox and modelling framework [6]. This tool will allow the geographic identification of potential locations meeting certain parameters for the specific goals set by the study. Further, scripts were used in ArcGIS toolboxes using Python language for the automation of processes and management of geographic data.

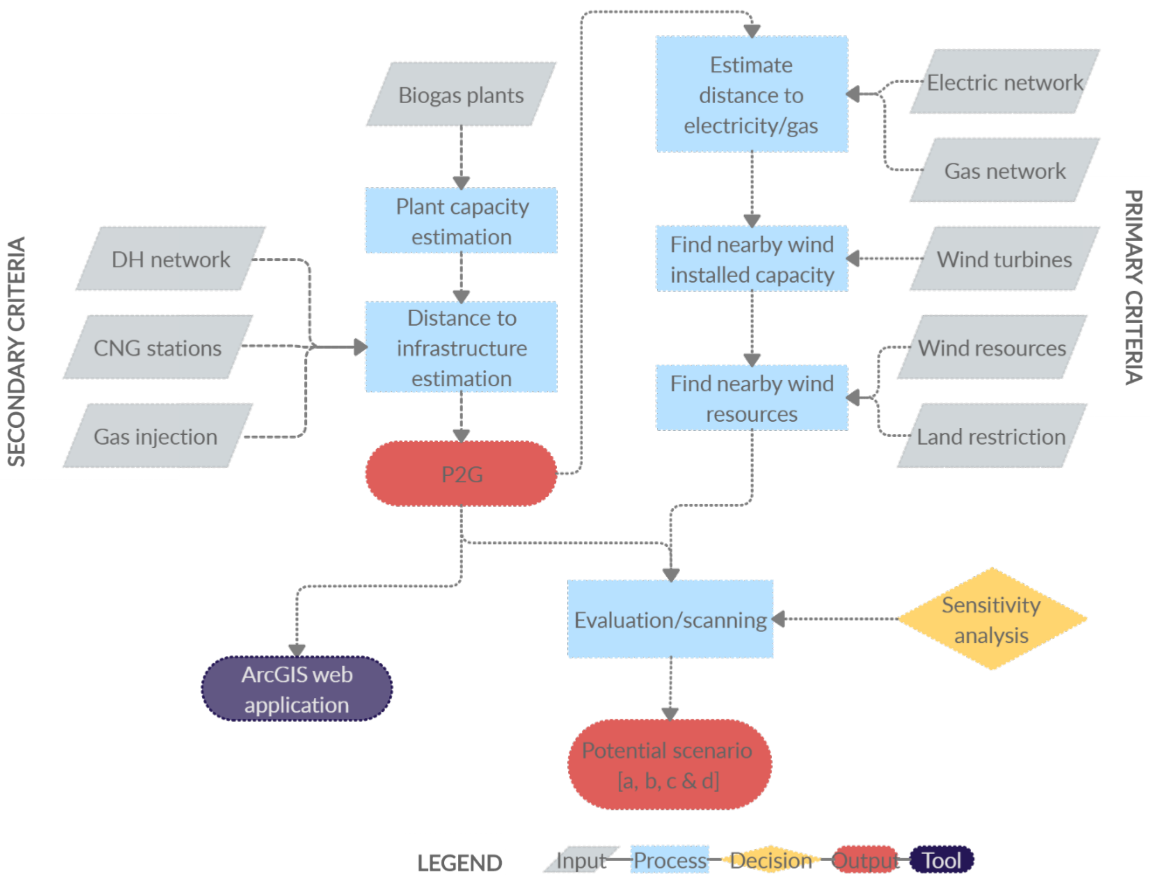



*Figure 1 Methodology set-up flow chart*

Figure 1 schematizes the methodology employed for the development of this report. As illustrated, several inputs were used, both from Danish existing infrastructure and extra useful available databases to help determine primary processes throughout the flow.

In summary, the procedure starts with the Danish biogas plants identification and capacity and production estimation based on each biogas plant annual biogas production. Later, a geospatial *near* analysis tool allows the estimation of distance from biogas plants to existing infrastructure such as electric, gas and district heating [DH] networks and compressed natural gas stations [CNG], likewise.

Once the distances are measured and as the process continues, *buffer* analysis tools contribute with the assessment of existing and potential wind power on the specific region. The potential, available in the zone for wind power deployments, is taken as an output after wind resources and land restrictions assessments and the calculations are made for an array of ratios ranging from 1 to 10 km. Sensitivity analysis is then performed in order to assess the most relevant parameters to be included in the subsequent process which elaborates after this selection criteria.

Biogas methanation prospective plants undergo an evaluation meeting specific conditions. This step assesses feasibility based on the distance and availability of resources of each specific potential biogas methanation plant. The feasibility is then categorized under a four-category structure [a, b, c & d], each category builds up after the previous one and this can be explained as follows:

Categories:

a) **Far from electricity and gas infrastructure**
   Biogas sources that are far from electricity and gas infrastructure. This represents a potential that at present would not be interesting, unless the electricity and gas infrastructure is expanded.
b) **Near electricity and gas infrastructure**
   Distance to transmission networks is used as selection criteria. Both electricity and gas.
c) **Near electricity and gas infrastructure and existing wind turbines**
   Distance to transmission networks and existing wind turbines are used as selection criteria.
d) **Near electricity and gas infrastructure and good locations for new wind turbines**
   Distance to transmission networks and areas with good wind conditions are used as selection criteria.

## 2.2 DATA DESCRIPTION

The following sections, describe the input data used to estimate the potential. All data is obtained and geocoded at source.

### 2.2.1 BIOGAS PRODUCERS

Figure 2 shows a map of the biogas producers in Denmark. The dataset is made by the Danish Energy Agency and was updated in September 2018 [7]. Amongst the most relevant attributes of the geospatial database, for this study, are the type of biogas plant and its yearly biogas production respectively. Data includes 7 industrial plants, 89 agricultural, 28 waste disposal sites and 51 waste water treatment facilities, in total 175 plants. Visually on a Danish national scale, the map shows both the type of plants through a set of colours; and annual biogas production plant size through the usage of proportional symbols. As seen on the map, agricultural biogas type of sources not only represent the majority when it comes to quantity; but statistically, agricultural producers are accountable for circa 87% of the total potential in Denmark (Table 1). Currently, 36 of the current biogas producers are connected to the existing natural gas network [8], this will be included as a secondary evaluation criteria.

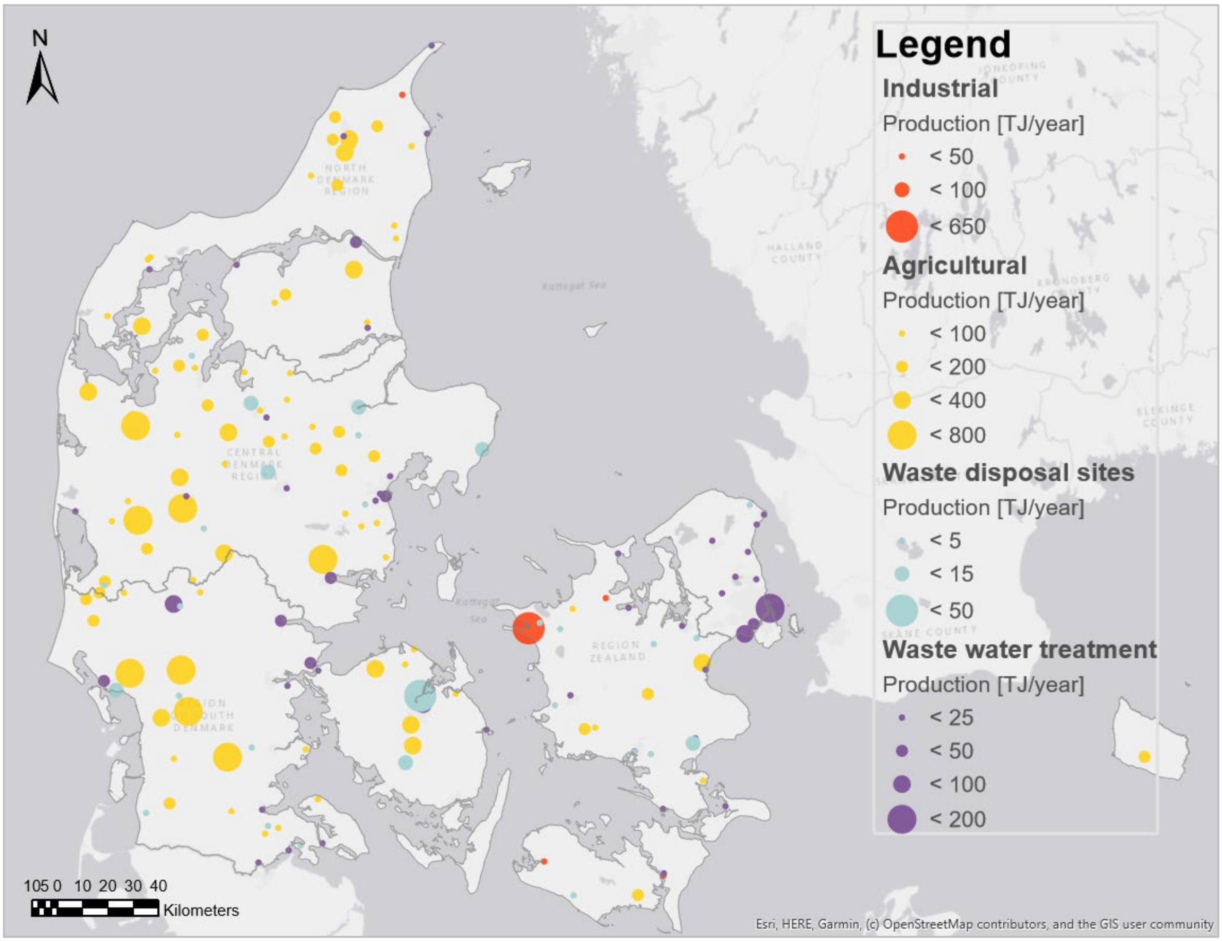



*Figure 2: Biogas producers by type and size*

In Table 1 the same data is shown in tabular form, where the number of plants and the total annual biogas production is shown for the same type and size categories. As explained above, the agricultural plants have a majority of the production with 14,816 TJ/year out of the total 16,985 TJ/year, and also have the majority of producers with more than 50 TJ/year, besides 4 waste water treatment facilities and 1 industrial plant. Even though there are 28 of waste disposal sites, this is the type with lowest production potential.

*Table 1: Count and biogas production by type and size*

| Size category | All plants | | Industrial | | Agricultural | | Waste disposal | | Waste water treatment | |
|---|---|---|---|---|---|---|---|---|---|---|
| TJ/year | Count | TJ/year | Count | TJ/year | Count | TJ/year | Count | TJ/year | Count | TJ/year |
| 0-1 | 9 | 9 | - | - | 2 | 2 | 4 | 4 | 3 | 3 |
| 1-5 | 28 | 90 | - | - | 3 | 10 | 16 | 47 | 9 | 33 |
| 5-10 | 18 | 139 | - | - | 4 | 30 | 5 | 37 | 9 | 72 |
| 10-50 | 51 | 1,343 | 6 | 202 | 16 | 458 | 3 | 71 | 26 | 612 |
| 50-100 | 20 | 1,515 | - | - | 17 | 1,277 | - | - | 3 | 238 |
| 100-800 | 49 | 13,889 | 1 | 650 | 47 | 13,039 | - | - | 1 | 200 |
| **TOTAL** | **175** | **16,985** | **7** | **852** | **89** | **14,816** | **28** | **159** | **51** | **1,158** |

### 2.2.2 DANISH INFRASTRUCTURE

Geographic available documentation on the national framework is also needed. This section includes the existing Danish infrastructure relevant for the analysis, including the following:

- Electricity transmission lines above 50kV from FOT Denmark [9]
- Natural gas (NG) transmission lines estimated based on [10]
- Natural gas (NG) and district heating (DH) distribution networks from Plansystem.dk [11]
- Existing wind turbines from the Danish Register of Wind Turbines [12]
- Compressed natural gas (CNG) stations from the map from CNG Europe [13]

For a visual representation of all the infrastructure databases joined, an example for the Aarhus and neighbouring municipalities, is shown in Figure 3.

Concerning infrastructure data attributes, databases vary in terms of content. Transmission line feature layer can be spotted in the map as doted purplish coloured lines. These lines are sectioned and categorized by type of transmission, status, power tension and time of construction/start of operations. Natural gas and district heating distribution networks are polygon feature layers visualized as ocean blue and dark green coloured areas. Each of these areas pose same attributes since they were acquired from the same root database and filtered by type of distribution network. Their attributes include operations date, grid status, data source, date of distribution initiation. Similarly, ownership and operating company identification data are included.

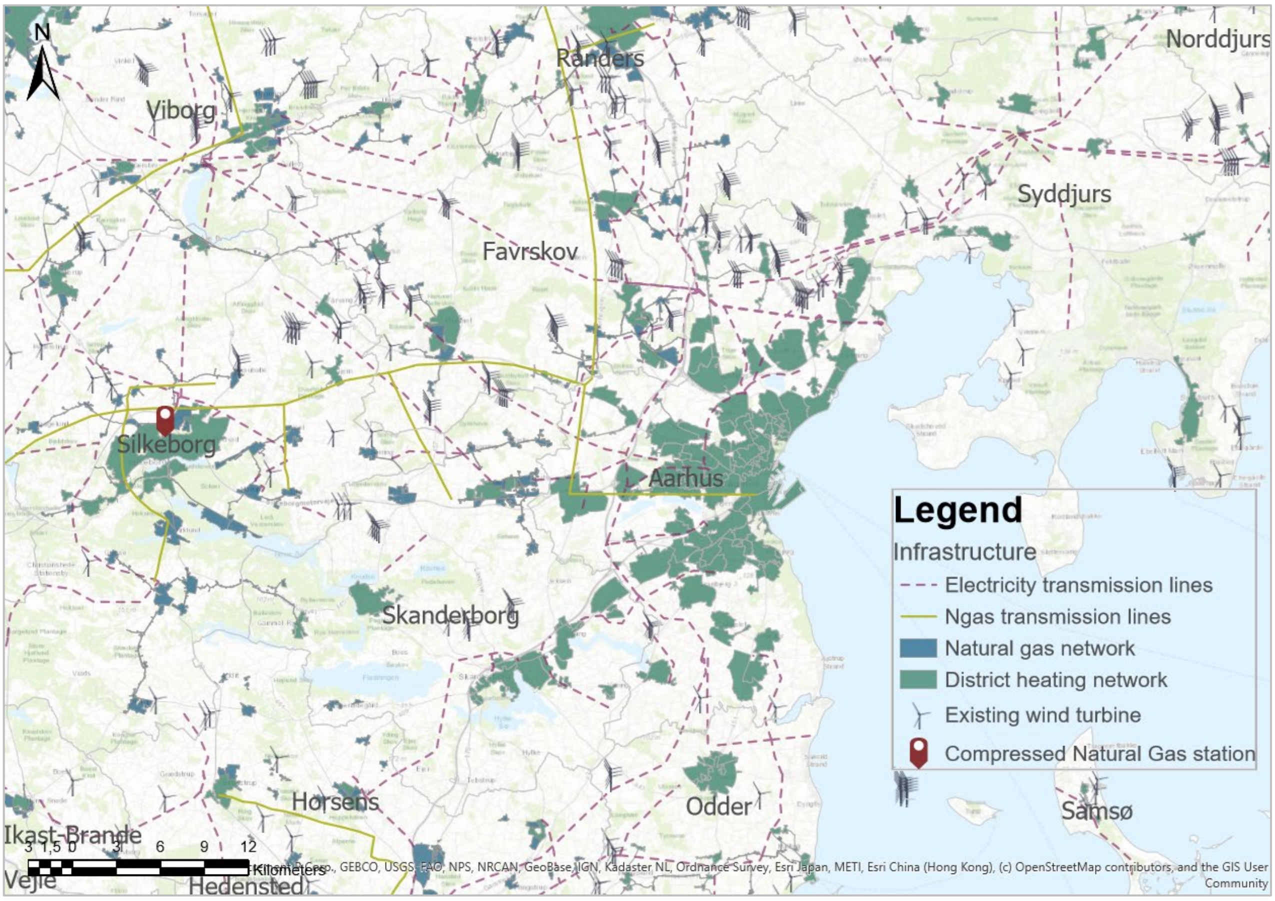



*Figure 3. Existing Danish infrastructure around Aarhus*

Existing wind turbines are extracted from the Danish Energy Agency master data register for wind power plants. Plants shown are above 6 kW and point attributes include location, size and annual production. This dataset is updated every month in line with the network company's reports. CNG stations database denote a fairly limited content when compared to the previous detailed databases. Its attributes solely describe stations location and name, no technical detailing such as sizing is included.

Overall and as seen on the map, databases construct a strong national coverage, features from which biogas methanation potential plants can make use of their specific geographic positioning.

### 2.2.3 WIND MAP AND LAND RESTRICTION FOR NEW WIND TURBINES

In relation to estimating the potential for new wind turbines for the onsite renewable energy capacity, the first step is to use a wind resource map - see Figure 4. The wind resource map shows an estimate of theoretical wind energy potential in kWh/year in 100 m height, for a $m^2$ land area. From the map, it is evident that the best potential areas for wind power is in the western coasts of Denmark. The map will be used together with a cut-off criterion for minimum average kWh/year. The criterion is presented in Section 2.4.3, and further in the sensitivity analysis of selection criteria in Section 2.5.

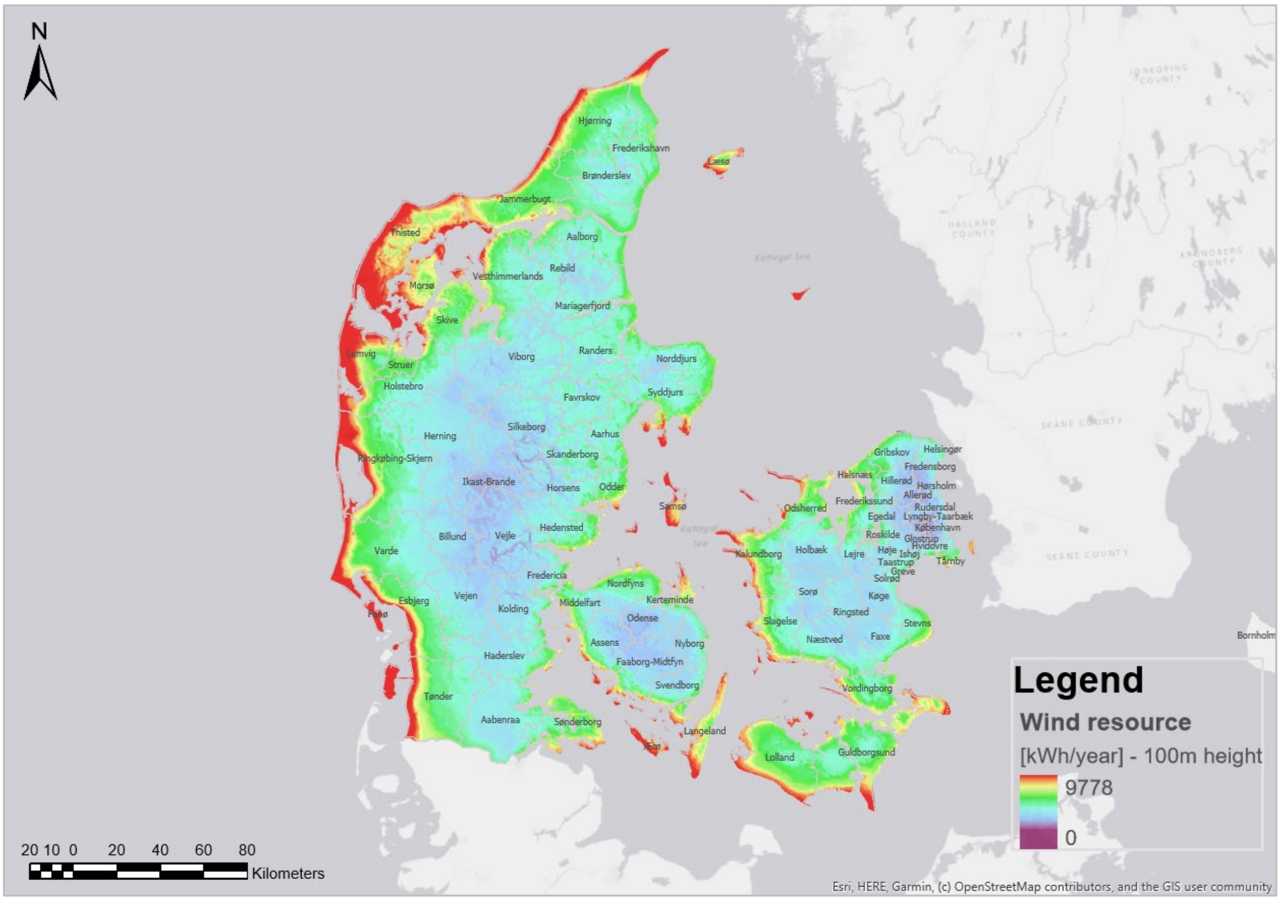



*Figure 4. Danish wind resource map made by EMD International* [14]

Besides knowing the wind resource availability, it is also required to know the land area available for wind turbines. The Danish Wind Association, estimates based on experience that the average land area needed for a single wind turbine is around 5000 $m^2$ [15]. This average will be used as the criteria, in this report, being well aware that it is a simplification, as the land area depends on the specifications of the wind park, such as size of turbines and layout of the wind park.

Another important aspect when looking at possible new wind locations, is restrictions in land use both due to distance to towns, building lines, conservation and nature protection. In terms of determining the distance to towns, an assessment made by The Danish Business Authority [16], where only areas in a distance of 600 m to buildings and 150 m to large infrastructure, is considered. In relation to nature protection and conservations areas, 12 different categories are used. The data is from The Danish Environment Portal [17], which offers national data on natural and environmental conditions. The data includes, building lines to forest, churches, lakes, streams, coasts, protected streams and nature types, conservation areas, game reserves and wetlands. Furthermore, the updated Natura 2000 bird and habitat areas from 2016 were used [18].

Restricting the wind resource areas in terms of distance to buildings and nature protection, makes a considerable reduction in the available land area for wind. Without any restrictions the available area is around 42,798 $km^2$, and when only selecting areas far from buildings this is reduced to around 1,601 km$^2$. But when also introducing restrictions in terms of nature protection and conservation, the available area is reduced to 135 km$^2$. Please, note that this represents the area before considering only good wind resources and distance to biogas methanation locations. Figure 5 is used as aiding visual tool for the presentation of the wind potential restriction described previously. In the map, the restricted areas are summarized into two main ones, nature protection area and built up-areas. When all restriction inputs are analysed conjointly, the output wind potential polygon blue hash area shows the final delimited area.

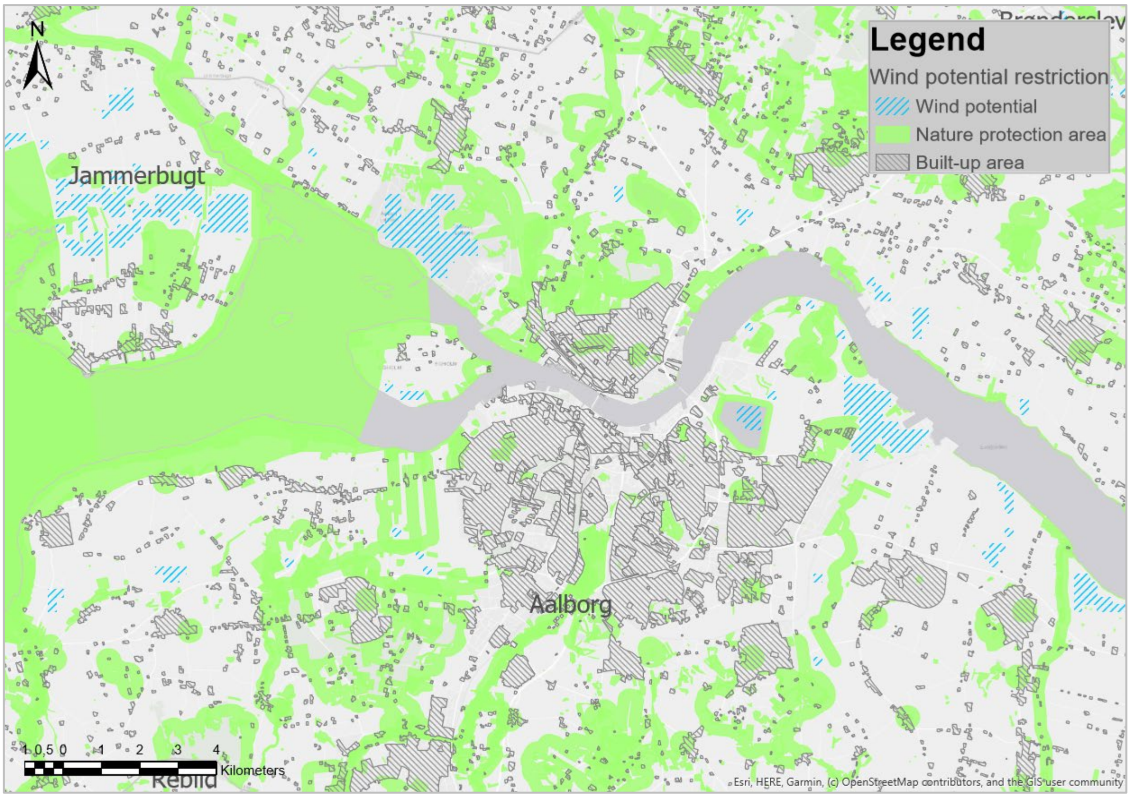



*Figure 5. Wind potential restrictions around Aalborg*

## 2.3 ESTIMATION OF POWER TO GAS CAPACITY AND PRODUCTION

The estimation of biogas methanation capacity and production potential, is made based the biogas available (presented in Section 2.2.1), and assumes a 40% $CO_2$ and 60% $CH_4$ share of biogas. The data is based on an annual biogas production in TJ/year, which is converted to MWh by dividing with 0.0036. From this, the required hydrogen is estimated by multiplying the biogas production with a factor of 0.724 which is based on the hydrogen divided by the biogas input in [4], and the associated electricity consumption for the electrolysis by dividing the hydrogen use with a 0.643 factor, which is based on the efficiency of the alkaline electrolysis in 2020 [19]. The capacity of the plants is estimated based on the biogas production in MWh divided with 7720 full-load hours, giving the capacity in MW. Finally, the e-methane production is estimated multiplying the biogas production with a 1.413 factor, which is based on the e-methane output divided by the biogas input in [4].

## 2.4 SELECTION CRITERIA

As presented in the methodology flowchart in Figure 1, an important part of the analysis is the criteria used to distinguish between the different categories. First, each criterion is presented separately followed by a list of how these will be changed in the sensitivity analysis. It should also be noted, that in the web application (Section 3.3) most of the criteria can be changed by the user.

### 2.4.1 DISTANCE TO ELECTRICITY AND GAS TRANSMISSION LINES

The distance to the electricity and natural gas grids are two of the main parameters in terms of finding suitable locations for biogas methanation. It is quite crucial that the biogas sources are not situated remote from the electricity and gas infrastructure. Thus, a 2 km distance limit is applied to the electricity transmission and the natural gas grids.

### 2.4.2 EXISTING WIND CAPACITY

The next selection criterion is to assess the available existing wind capacity around each biogas producer. Here a buffer of 3 km radius around biogas plants is applied. In the PtX report [5], the example uses a fictional case of 20 MW electrolysis with 75 MW local wind turbines and photovoltaics. This gives a ratio of 3.75 between electrolyser size and local RES. In this report, a 3 ratio will be used as evaluation criteria in the base scenario. Furthermore, this report only considers wind turbines.

### 2.4.3 POTENTIAL NEW WIND AREAS

For the new wind potential, a buffer radius of 3 km around biogas plants is used, similar to the distance of existing wind capacity. To assess the potential for new wind turbines, a short evaluation is made of the existing wind turbines in relation to the wind map. In the evaluation (Figure 6), the wind turbines above 1 MW selected and the mean kWh/year potential within a 1 km buffer around each turbine is evaluated. In Figure 7, the summary of the evaluation is presented as a graph from poorest to best wind locations. Based on the graph, wind conditions where new turbines are feasible will be determined as mean values above 4000 kWh/year or 4 MWh/year.

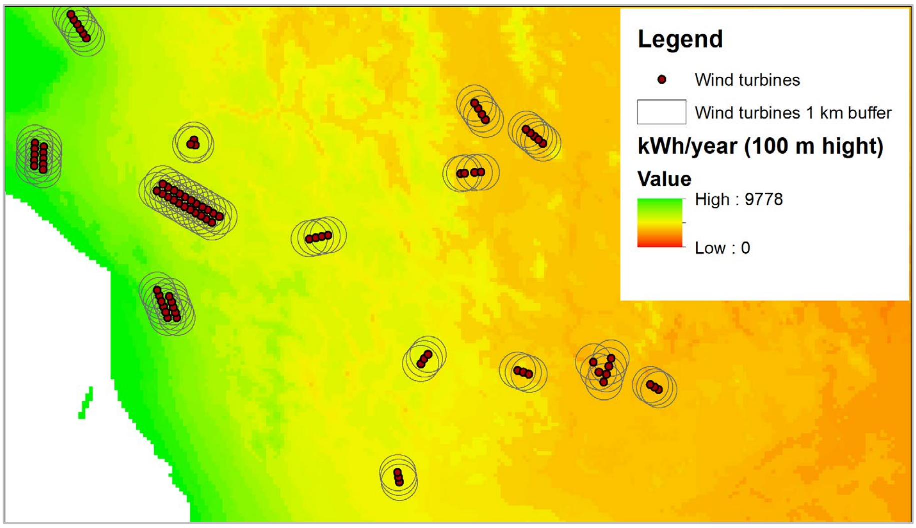



*Figure 6: Wind resource map with existing wind turbines larger than 1 MW with buffer of 1 km*

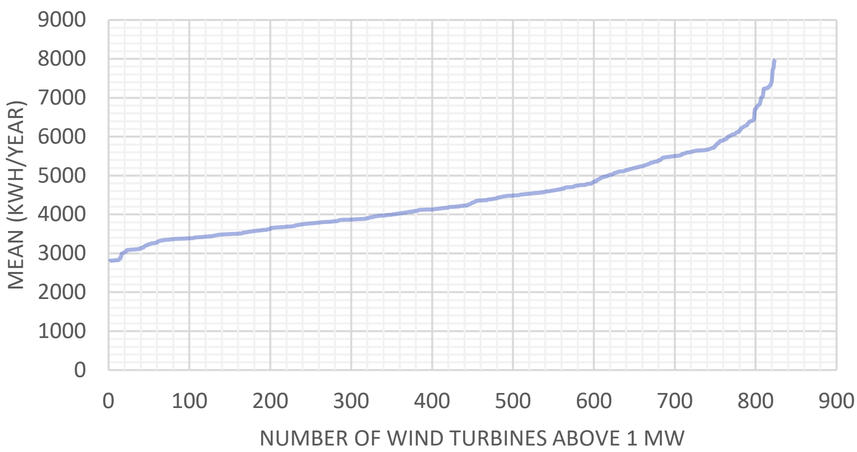



*Figure 7: Mean wind resource values for each 1 km buffer surrounding existing wind turbines above 1 MW. The figure shows how many turbines are located in a certain wind speed. E.g. 300 turbines in 3800 kWh/year or less.*

### 2.4.4 SUMMARY OF BASE SCENARIO CRITERIA

From the above, the criteria values that will be used in the base scenario are the following:

- 2 km distance to electricity and gas networks
- 3 km distance to existing wind turbines
- 3 ratio between biogas methanation capacity and required existing wind capacity
- 3 km distance for new wind potential
- 4 MWh/year for new wind potential

It should be noted, that these are all assumptions used for a general model, and in practise will vary from case to case. Hence, a sensitivity analysis of each criteria is also carried out in Section 3.2.

### 2.4.5 DISTANCE TO DISTRICT HEATING AND CNG STATIONS

As secondary criteria, the distance to district heating areas and to existing CNG stations are calculated. Furthermore, it is evaluated if the biogas producers already have an injection point to natural gas network. The distance to district heating is carried out due to the synergies in utilizing the excess heat production from the biogas methanation process, while the distances to existing CNG stations are calculated because these are possible user of the e-methane. These secondary criteria are not deemed crucial in finding the suitable locations for biogas methanation stations, but are positive features for a location, as they can contribute to the economic feasibility of the biogas methanation plant.

## 2.5 SENSITIVITY ANALYSIS SELECTION CRITERIA CHANGES

As most of the criteria presented in the base scenario are assumed, and not based on e.g. specific planning experience with biogas methanation plants. It is relevant to examine how the results change if any of these criteria were more or less strict, this is done in the sensitivity analysis. Table 2 present the changes that will be applied to each criterion.

*Table 2: Selection criteria changes for the primary criteria. Values for the base scenario are shown in bold.*

| Criteria | Unit | Values | | | | |
|---|---|---|---|---|---|---|
| Distance to elec. and gas networks | km | 1 | **2** | 3 | 4 | 5 |
| Distance to existing wind turbines | km | 1 | 2 | **3** | 5 | 10 |
| Requirement for wind capacity | ratio | 1 | 2 | **3** | 4 | |
| Distance for new wind potential | km | 1 | 3 | **3** | 5 | 10 |
| Requirement for new wind potential | MWh/year | 3 | **4** | 5 | | |

The distance to electricity and gas infrastructure is set to 2 in the base scenario, in the sensitivity this is analysed from 1-5 km. For the distance to existing and new wind turbines the base scenario used 3 km radius as a standard, however this is changed from 1-10 km in the sensitivity analysis. The requirement of a 3 ratio between biogas methanation and wind capacity is also changed from 1-4. Finally, the last parameter is the wind speed for new wind potential, as presented in Figure 7, this could be both more or less strict, thus a change from 3-5 is analysed.

# 3 RESULTS OF THE MODELLING

This chapter presents the results of the modelling, the chapter begins with the base scenario and continues to the sensitivity analysis. Overview of the categories is illustrated in Figure 8 for easier understanding of the modelling results. The discussion of the results will be presented in Chapter 4.

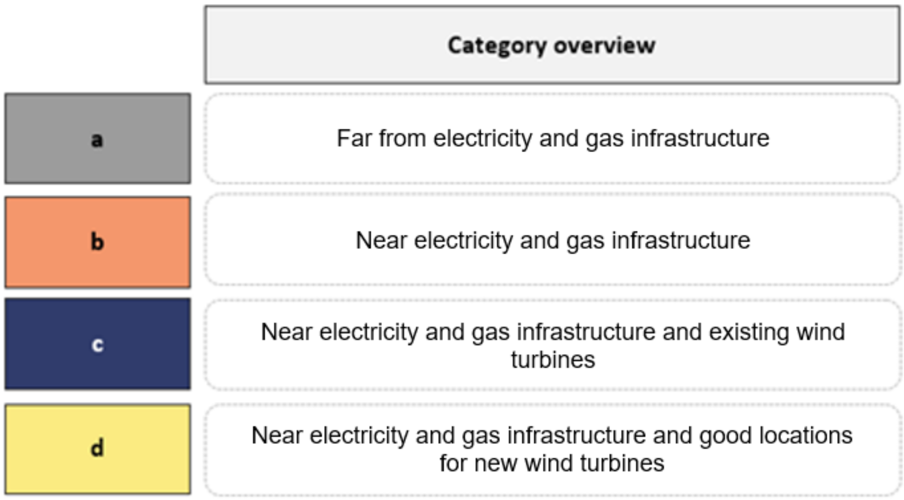



*Figure 8. Overview of different categories modelled*

## 3.1 BASE SCENARIO

The results of the base scenario are illustrated in the map in Figure 9, and shows the different biogas sources in relation to the four categories. When summarizing, the output mapping yields that 104 biogas sources are in category [a], and are thus too far from gas and electricity infrastructure. Further, 53 sources are in category [b], only fulfilling the distance to gas and electricity infrastructure requirement, while 16 are in category [c] (existing wind turbines available) and only 2 in category [d] (potential new wind locations available).

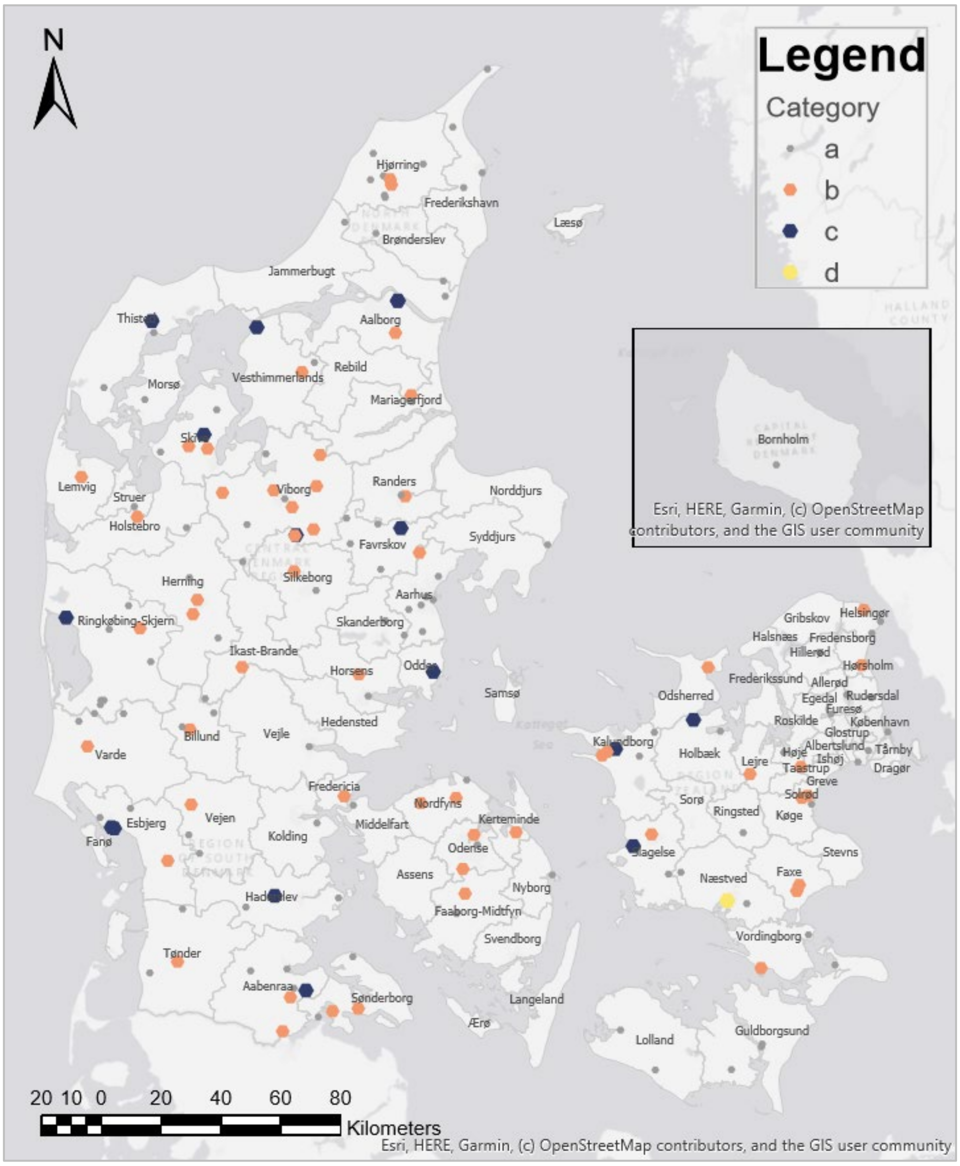



*Figure 9: Map of base scenario result*

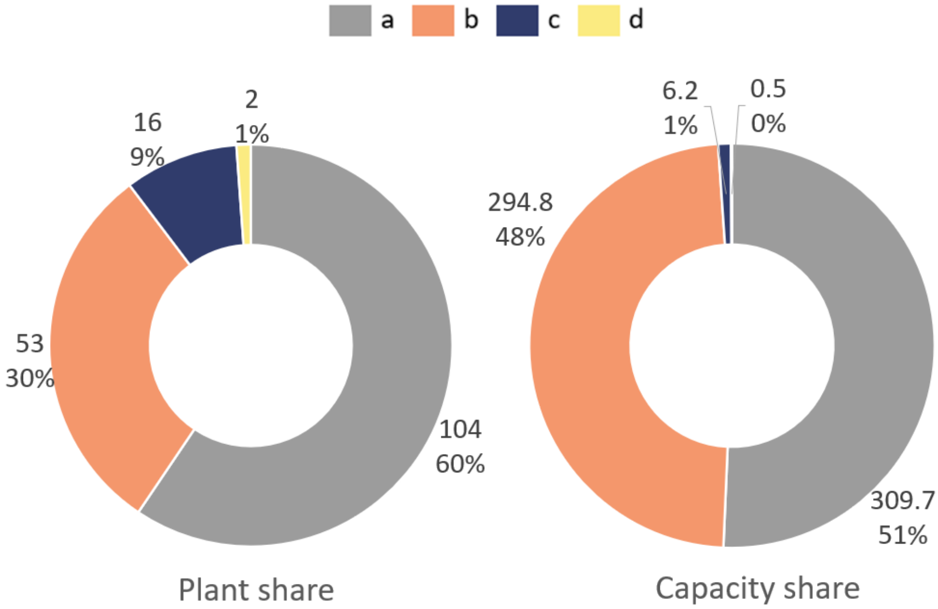



*Figure 10: Number of plants and share of capacity in MW*

Figure 10 shows two pie charts of the same base scenario result, illustrating the difference between the number of plants and the capacity. A focus on number of plants shows that 90% is in category [a] or [b], while 10% is in category [c] or [d]. However, when considering the size of the plants, the share for group [c] and [d] drops to around 1%. Furthermore, the share of group [a] is also reduced to 51% and the share of [b] is increased to 48%. This indicates that the plants in category [b] in general have a larger capacity than the other categories.

Table 3 shows a more detailed overview of the result, indicating both the categories, but also the type of biogas source, as well as various production and consumption data.

Starting from the bottom, category [d] shows that it is only a single waste disposal and a single waste water treatment facility, with a total production of around 5.1 GWh/year. Category [c] shows a production potential of around 67.9 GWh/year and includes all four plant types, with waste water treatment and agricultural being the largest. Category [b] is much larger with a production potential of 3,215.4 GWh/year, with agriculture being the main plant type. Finally, category [a] shows a production potential of 3,378.3 GWh/year, also with agriculture being the main plant type. Furthermore, category [a] and [b] differ in terms of the second largest plant types. In category [b] the second largest plant type are industrial plants and in category [a] waste water treatment plants.

*Table 3: Summary of mapping results into category and type*

| Criteria | Number of plants | Biogas [MWh/year] | Electrolysis Capacity [MW] | E-methane production [MWh/year] | Hydrogen production [MWh/year] | Electricity consumption [MWh/year] |
|---|---|---|---|---|---|---|
| Category [a] | 104 | 2,390,838 | 309.7 | 3,378,258 | 1,730,973 | 2,692,029 |
| Industrial | 3 | 30,555 | 4.0 | 43,174 | 22,122 | 34,404 |
| Agricultural | 55 | 2,093,337 | 271.2 | 2,957,884 | 1,515,579 | 2,357,043 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Waste disposal | 12 | 14,168 | 1.8 | 20,022 | 10,259 | 15,958 |
| Waste water treatment | 34 | 252,778 | 32.7 | 357,178 | 183,013 | 284,624 |
| Category [b] | 53 | 2,275,553 | 294.8 | 3,215,357 | 1,647,498 | 2,562,209 |
| Industrial | 3 | 202,778 | 26.3 | 286,526 | 146,812 | 228,324 |
| Agricultural | 30 | 2,007,497 | 260.0 | 2,836,593 | 1,453,427 | 2,260,386 |
| Waste disposal | 9 | 22,223 | 2.9 | 31,401 | 16,089 | 25,022 |
| Waste water treatment | 11 | 43,055 | 5.6 | 60,837 | 31,170 | 48,477 |
| Category [c] | 16 | 48,056 | 6.2 | 67,906 | 34,793 | 54,112 |
| Industrial | 1 | 3,333 | 0.4 | 4,710 | 2,413 | 3,753 |
| Agricultural | 4 | 14,722 | 1.9 | 20,803 | 10,659 | 16,578 |
| Waste disposal | 6 | 6,946 | 0.9 | 9,816 | 5,030 | 7,823 |
| Waste water treatment | 5 | 23,055 | 3.0 | 32,577 | 16,691 | 25,958 |
| Category [d] | 2 | 3,611 | 0.5 | 5,102 | 2,614 | 4,066 |
| Waste disposal | 1 | 833 | 0.1 | 1,177 | 603 | 938 |
| Waste water treatment | 1 | 2,778 | 0.4 | 3,925 | 2,011 | 3,128 |
| **TOTAL** | | **4,718,058** | **611.1** | **6,666,623** | **3,415,878** | **5,312,416** |

Table 4 shows the number of plants and e-methane production for the same result, divided into three different size categories of electrolyser capacity. The size categories are relevant because the size determines the economic feasibility of plants, and under the current frameworks, mainly larger plants are attractive. In general, the table shows that a majority of the plants have a capacity less than 4 MW with around 20% of the total e-methane production potential. Furthermore, the plants larger than 4 MW are only present in category [a] and [b], while none are in category [c] and [d], indicating that most of the larger plants have a limited local wind potential.

*Table 4: Summary of mapping results into category, type and electrolyser capacity.*

| | **< 4 MW** | | **4-10 MW** | | **>10 MW** | |
|---|---|---|---|---|---|---|
| | **Number of plants** | **E-methane production [MWh/year]** | **Number of plants** | **E-methane production [MWh/year]** | **Number of plants** | **E-methane production [MWh/year]** |
| Category [a] | 78 | 848,592 | 22 | 1,528,790 | 4 | 1,000,876 |
| Industrial | 3 | 43,174 | - | - | - | - |
| Agricultural | 30 | 506,719 | 21 | 1,450,289 | 4 | 1,000,876 |
| Waste disposal | 12 | 20,022 | - | - | - | - |
| Waste water treatment | 33 | 278,677 | 1 | 78,501 | - | - |
| Category [b] | 32 | 379,938 | 7 | 452,943 | 14 | 2,382,476 |
| Industrial | 2 | 31,400 | - | - | 1 | 255,126 |
| Agricultural | 10 | 256,300 | 7 | 452,943 | 13 | 2,127,350 |
| Waste disposal | 9 | 31,401 | - | - | - | - |
| Waste water treatment | 11 | 60,837 | - | - | - | - |
| Category [c] | 16 | 67,906 | - | - | - | - |
| Industrial | 1 | 4,710 | - | - | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| Agricultural | 4 | 20,803 | - | - | - | - |
| Waste disposal | 6 | 9,816 | - | - | - | - |
| Waste water treat-ment | 5 | 32,577 | - | - | - | - |
| Category [d] | 2 | 5,102 | - | - | - | - |
| Waste disposal | 1 | 1,177 | - | - | - | - |
| Waste water treat-ment | 1 | 3,925 | - | - | - | - |
| **TOTAL** | **128** | **1,301,538** | **29** | **1,981,733** | **18** | **3,383,352** |

As described in Section 2.4.5, the results are also compared to the secondary criteria, distance to district heating, distance to CNG stations and whether the plant already has gas injection point to the natural gas network. The latter is presented in Table 5, showing the plants with and without gas injection and by category. In total around 36 plants have gas injection, and they are either in category [a] or [b]. But when examining the size of the plants, in terms of electrolysis capacity, the plants with gas injection have most capacity with 351.4 MW as opposed to 259.8 MW without gas injection. It can also be observed that none of the injection plants are in category [c] and [d], and thus they are not close to neither existing nor potential wind turbines.

*Table 5: Number of plants based on where existing gas injection is installed*

| Injection | Number of plants | Electrolysis Capacity [MW] | E-methane production [MWh/year] |
|---|---|---|---|
| **Yes** | **36** | **351.4** | **3,832,766** |
| a | 20 | 186.6 | 2,035,117 |
| b | 16 | 164.8 | 1,797,649 |
| **No** | **139** | **259.8** | **2,833,857** |
| a | 84 | 123.1 | 1,343,141 |
| b | 37 | 130.0 | 1,417,708 |
| c | 16 | 6.2 | 67,906 |
| d | 2 | 0.5 | 5,102 |
| **TOTAL** | **175** | **611.1** | **6,666,623** |

The subsequent secondary evaluation criterion is the distance to existing district heating grids, which is shown in Table 6. The reason for this criterion is the synergies of excess heat production, from the biogas methanation plants that could be used in district heating systems. The result in this table shows that around 114 plants are within 2 km distance to district heating, out of which 76 plants are less than 1 km to district heating. This indicates, that there is a potential for connecting some of the biogas methanation plants to district heating areas. Another point is that around 10 plants in category [c] and two plants in category [d], are also close to district heating areas, which is interesting because these could be economically more attractive locations, as opposed to locations without access to local wind and district heating.

*Table 6: Number of plants based on distance to district heating (DH)*

| Criteria | Number of plants | Electrolysis Capacity [MW] | E-methane production [MWh/year] |
|---|---|---|---|
| **< 1 km to DH** | **76** | **196.0** | **2,137,553** |
| a | 45 | 72.1 | 786,178 |
| b | 25 | 120.4 | 1,313,696 |
| c | 6 | 3.5 | 37,679 |
| **< 2 km to DH** | **38** | **169.7** | **1,850,643** |
| a | 21 | 93.6 | 1,020,505 |
| b | 11 | 74.1 | 808,157 |
| c | 4 | 1.5 | 16,879 |
| d | 2 | 0.5 | 5,102 |
| **< 5 km to DH** | **46** | **181.6** | **1,980,951** |
| a | 27 | 85.0 | 927,481 |
| b | 16 | 95.9 | 1,046,404 |
| c | 3 | 0.6 | 7,066 |
| **> 5 km to DH** | **15** | **63.9** | **697,476** |
| a | 11 | 59.0 | 644,094 |
| b | 1 | 4.3 | 47,100 |
| c | 3 | 0.6 | 6,282 |
| **TOTAL** | **175** | **611.1** | **6,666,623** |

The final secondary criterion is shown in Table 7, which is the distance to existing CNG fuelling stations. This criterion, is interesting due to the possibility of using produced e-methane for transport, rather than selling it to the natural gas grid. However, as there are currently only 17 CNG fuelling stations, this potential is at the present stage limited. Only a single plant is within 2 km distance to CNG fuelling stations, 10 plants are within 5 km distance and the rest are more than 5 km from CNG fuelling stations.

*Table 7: Number of plants based on distance to CNG stations*

| Criteria | Number of plants | Electrolysis [MW] | E-methane production [MWh/year] |
|---|---|---|---|
| **< 2 km to DH** | **1** | **1.3** | **14,130** |
| b | 1 | 1.3 | 14,130 |
| **< 5 km to DH** | **10** | **35.7** | **389,360** |
| a | 5 | 12.8 | 139,730 |
| b | 3 | 20.7 | 226,079 |
| c | 2 | 2.2 | 23,551 |
| **> 5 km to DH** | **164** | **574.2** | **6,263,133** |
| a | 99 | 296.9 | 3,238,528 |
| b | 49 | 272.7 | 2,975,148 |
| c | 14 | 4.1 | 44,355 |
| d | 2 | 0.5 | 5,102 |
| **TOTAL** | **175** | **611.1** | **6,666,623** |

### 3.1.1 LOCAL MAP OF THE BASE SCENARIO

To illustrate the level of detail of the model, Figure 11 shows a map with an example from a local area, where all four categories are represented.

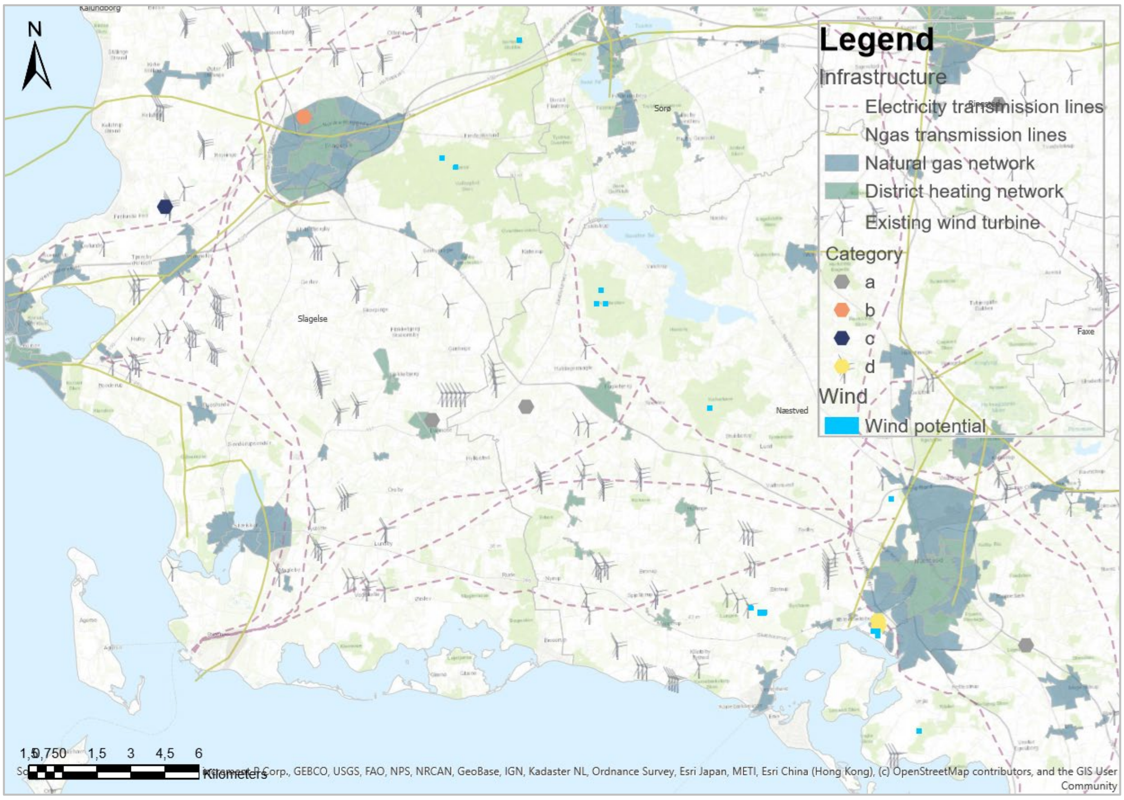



*Figure 11: Local example of the base scenario result*

In the lower right side of the map, an example of category [d] is present. This shows that the biogas source is both close to electricity and gas network as well as local wind potential. On the opposite side of the map, in the top left corner, an example of category [c] is present, with existing wind turbines, electricity and gas infrastructure close by. Category [b] is also present, which is only close to electricity and gas infrastructure, while we see several category [a] plants, which are not close to electricity and gas networks.

## 3.2 SENSITIVITY ANALYSIS

The base scenario is based on set of selection criteria, where the cut-off values can change under various circumstances, as the values are assumed based on estimates by the authors. Therefore, it is important to show how sensitive the results are if the selection criteria had different cut-off values, e.g. what if the distance to electricity and gas networks could be 3 km instead of 2 km. Thus, the sensitivity analysis examines all 5 main selection criteria: distance to electricity and gas grids, distance to existing wind turbines, ratio between electrolysis and wind capacity, and distance to potential wind resources and requirement for wind resources.

The first sensitivity is the distance to electricity and gas grids, this is shown in Figure 12. In the sensitivity, the distance is changed from 1 km to 5 km, where in the base scenario the distance was 2 km. Reducing the distance to 1 km, significantly reduces the amount of plants in category [b], [c] and [d], to less than 25 from around 70 plants in the base scenario. Increasing the distance shows a linear tendency to 3 and 4 km, where it seems to flatten out at 5 km. With a 3 km distance, around 100 plants are in category [b], [c] and [d], and at 4 km 129 plants are in the same categories. This indicates, that many of the plants that in the base scenario are considered far away from electricity and gas network, are actually within 4-5 km of networks and could in certain cases be considered. Thus, for larger plants the distance might not be an issue, and they could be in a more attractive position for biogas methanation than initially expected.

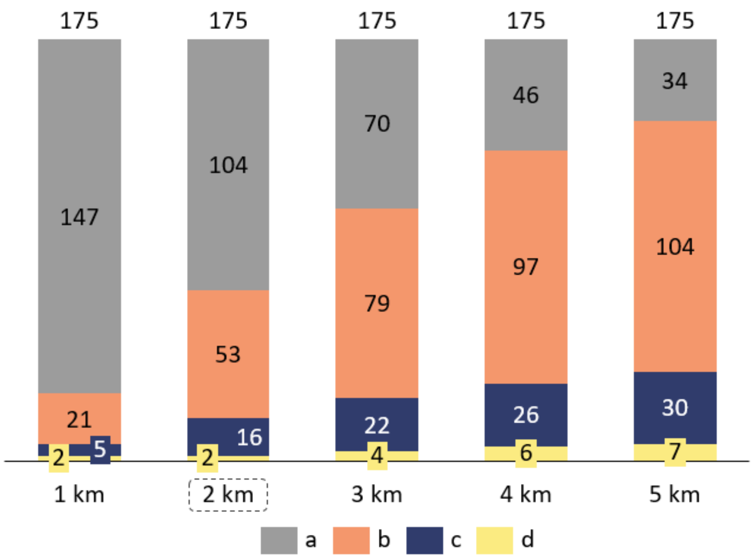



*Figure 12: Number of plants in relation to the distance to electricity and gas network (2 km is the base scenario).*

The second sensitivity analysis (Figure 13), shows the distance to existing wind turbines, where the base buffer distance was a 3 km radius around each biogas producer. As this sensitivity does not influence the number of plants in category [a], this is not shown in the figure, which will be the same in the rest of the sensitivity analyses. The sensitivity shows the buffer distance changed from 1-10 km. Reducing the buffer distance, naturally reduces the number of plants in category [c], where most ends up in category [b]. However, an interesting point is that, reducing the distance to 1 km adds a plant to category [d] from [c], which is due to the requirement that if existing wind is large enough, new wind will not be examined. So, in this sensitivity, when existing wind is reduced, the model finds a potential for new wind in one of the plants. Increasing the buffer distance also has an influence on the potential, where going to 5 km doubles the number of plants and 10 km almost triples the number of plants in category [c]. This result is interesting, as category [c] is a more attractive scenario, so if it is possible to use local wind from these distances, the biogas methanation potential is significantly larger.

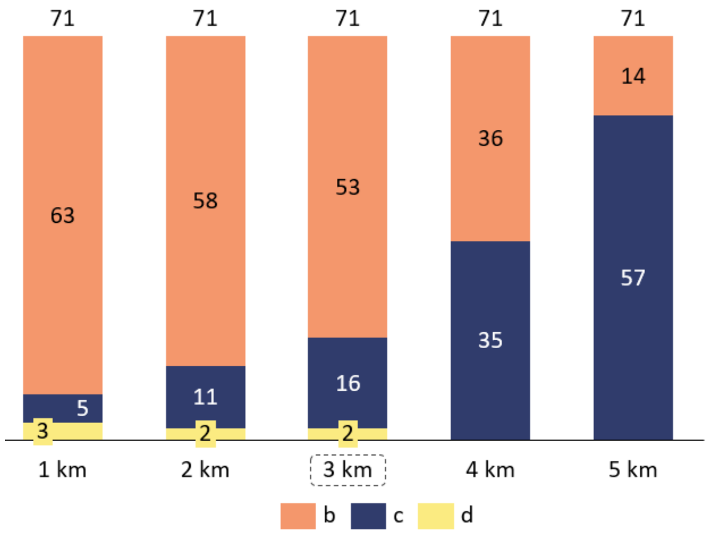



*Figure 13: Number of plants in relation to distance to existing wind turbines (3 km is the base scenario).*

When examining the existing wind potential, it is not only the radius where wind is applicable, but also the ratio used between electrolysis and wind capacity. A base value of 3 is used, as this is what is close to the assumptions in the power-to-x report [5]. However, having a lower requirement could still be a possible option. The sensitivity of this ratio is shown in Figure 14, and indicates that the influence is there, but it is not as significant as the search radius. Reducing the ratio requirement to 2, increases the plants in category [c] to 21 and reducing the ratio to 1 increases the plants in [c] to 25. Increasing the requirement to a 4 ratio, reduces the number of plants in category [c] to 14. As the base scenario has 16 plants in category [c], these changed cannot be deemed significant.

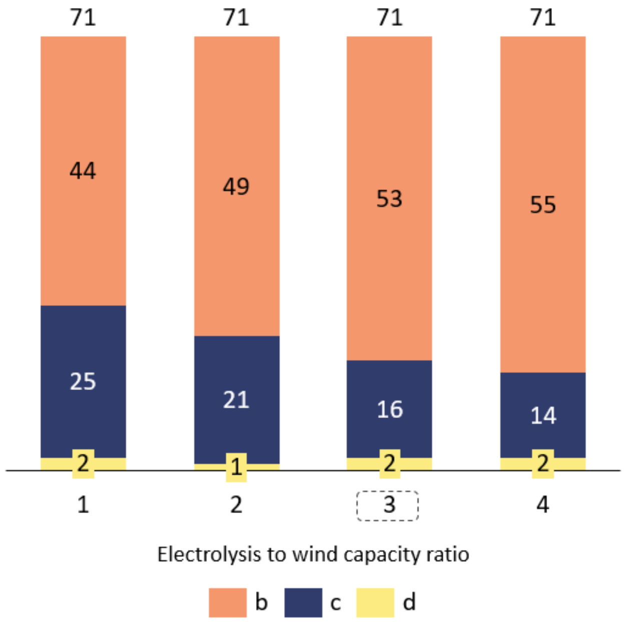



*Figure 14: Number of plants in relation to the ratio requirement between electrolysis capacity and existing wind capacity (a ratio of 3 is the base scenario).*

The last two sensitivities relate to the requirements for new wind potential, and like the sensitivity of the existing wind turbines, the search radius for new wind turbines is changed from 1 to 10 km. The output of this sensitivity is shown in Figure 15 and indicates that reducing the distance to 1 and 2 km, has no influence on the result, while increasing the distance to 5 and 10 km, respectively adds 2 and 11 plants to category [d]. Thus, the potential could be larger for category [d], than initially indicated in the base scenario.

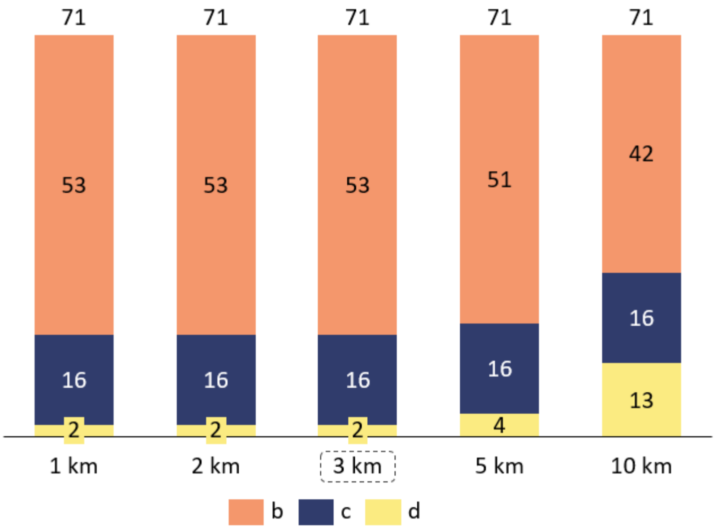



*Figure 15: Number of plants in relation to distance for new wind potential (3 km is the distance in the base scenario).*

Another aspect of the potential for new wind turbines, is the wind resource requirement, which in the base scenario was set to be 4 MWh/year. In Figure 16 this requirement is reduced to 3 MWh/year and increased to 5 MWh/year, similarly. Decreasing the requirement adds 4 plants to category [d], which is significant in relation to the 2 plants in the base scenario; however, increasing the requirement to 5 MWh/year removes all plants from category [d]. This indicates that the plants in category [d] are very sensitivity towards the realisation of new wind turbines in the vicinity.

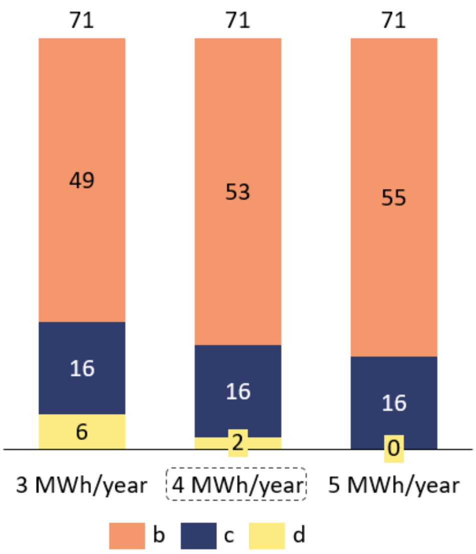



*Figure 16: Wind resource requirement for the new wind site (4 MWh/year is used in the base scenario).*

## 3.3 ARCGIS WEB APPLICATION TOOL

The data used for the methodology described in 2.1 responding to geospatial characteristics has been used as basis for the creation of an online mapping application – see Figure 17. Taking open access as the publication mechanism, the application is freely available on the following website: http://energymaps.eu. As deemed, the user interface is tailored in order to facilitate a self-scenario development as to analyse the Biogas Methanation Sources included in this research. It is worth mentioning however, that the results of the modelling included in 3.1 correspond to a single outcome of the modelling for the given parameters described in the selection criteria, section 2.4. The following lines include a brief description of the application's functions and layers so to guide the user through its enabling, usage and disabling.

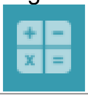
1. The *Biogas Methanation Sources* application comprises the listed functions:

- **Filter:** Filtering performs geospatial data refining for the plants according to data attribute selection with the possibility of varying parameters to perform specific scenarios. The filters build on each other, meaning that they follow an automation as the user process the different filters. The parameters go in the order as follows:

    - Electrolyser capacity: Minimum capacity of the plants in megawatts [MW]
    - Electricity network distance: Maximum distance from plants to electricity network in meters [m]
    - Natural gas network distance: Maximum distance from plants to natural gas network in meters [m]
    - District heating distance: Maximum distance from plants to district heating network in meters [m]
    - Gas injection: Display plants allowing plan injection
    - Plant type: Facility plan type
    - Region: Limits the display to facilities within geo-political regional boundaries
    - Municipality: Limits the display to facilities within geo-political municipality boundaries

| Function [location on display] | Enabling | Usage | Disabling |
|---|---|---|---|
| **Filter [Left panel]** Filter Biogas Methanation Sources |  | Parameters input |  |

- **Summary:** This tool performs accumulative records mechanically, according to the map extend the user chooses. The summary includes the total yearly E-Methane production potential and their respective electricity demand for the number of facilities shown in the display. This tool requires no user interaction but the desired zoom level.

| Function [location on display] | Enabling | Usage | Disabling |
|---|---|---|---|
| Summary [Right top header]  | Click on icon | Automatic display | Click on icon |

- **Wind capacity analysis:** By means of a buffer, the tool summarizes attributes given a specific geographic boundary set by the user. The tool identifies potential wind capacities laying within a specific distance range. This tool requires a facility selection by means of either point, line or area, and a buffer distance. The output from this tool is presented in the self-opening tab which shows the summary of the wind turbines counts and the total wind capacity set by the buffer range.

| Function [location on display] | Enabling | Usage | Disabling |
|---|---|---|---|
| Wind capacity [Right top header]  | Click on icon | Facility selection and buffer input | Click on icon |

2. The *Biogas Methanation Sources* application has built in geospatial information layers. The application enables/disables the layers automatically according the zoom level operated by the user, however layers can be manually modified using the menu located next to the left panel - see image below. The set of icons incorporates 3 functions, a measuring tool, symbology legend, and layers menu; the user clicks on the specific icon in order to enable them.

The layers included in the map are listed as follows, according to the format in brackets [layer name, layer type, visibility range].

- Biogas Methanation Source, vector point layer, visible at all scales
- Electricity Transmission, vector line layer, visible from neighbourhood visibility scale
- Natural Gas Grids, vector polygon layer, visible from neighbourhood visibility scale
- District Heating Areas, vector polygon layer, visible from neighbourhood visibility scale
- Wind capacity, vector point layer, visible from neighbourhood visibility scale

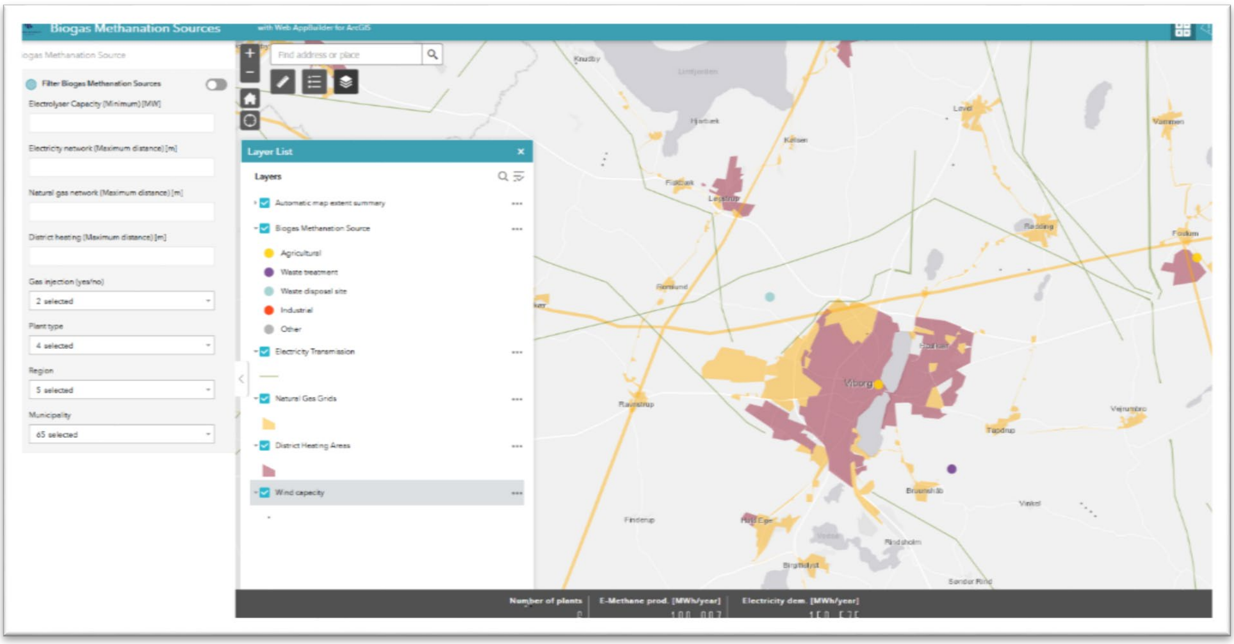



*Figure 17: Screenshot of the ArcGIS web application*
*(available at http://energymaps.eu)*

# 4 DISCUSSION

This chapter discusses various aspects of the report, and is split into three main topics, the model, the data and potential further investigations.

## 4.1 THE MODEL

The model in this report both quantifies production potential, and evaluates 175 different biogas producers in relation to four categories of biogas methanation plants on a national level. Biogas plants of all sizes have been evaluated. Thus, the model is simplified in many aspects compared to the details that a local case study approach would have applied. Please, note that the discussion is not to undermine the result of the report, but merely to inform about the simplifications in the model.

One of the simplifications is how the distance to existing energy infrastructure is estimated, where the geospatial model uses Euclidean distances – simplified ordinary straight line between two points. The reality for each plant would be more intricate as local restrictions and obstacles would influence the routing. Thus, in a planning situation with more knowledge of these restrictions and obstacles, the result could be fairly different. In general, the model can be though as the most optimistic situation as it considers the shortest route between biogas methanation plant and other infrastructure. Another aspect that is neglected in the model, is the capacities of the existing energy infrastructure, as only the distance is used for the evaluation.

In relation to the existing wind turbines, the model only considers the capacity and not the electricity production of the wind turbines. Here an underlying assumption is that existing wind turbines are assumed to be placed in areas with good wind conditions. Also, the model assumes that the wind turbines can be used as a local production, however the ownership of the turbines is not considered, which can be a deciding factor in relation to the economic feasibility of the biogas methanation plants. Another factor that is not included in the assessment of existing wind turbines, is how actually to connect the turbines to the biogas methanation plant, as the turbines can be spread all over the approximately 28 $km^2$ of land that is assessed in the base scenario.

The assessment of new wind turbine potential is also simplified, as it only considers wind resources and a fixed land area use of 5000 $m^2$ per wind turbine. In reality, this is much more complex as these factors depend on the sizes of wind turbines used and the layout of the wind park. Furthermore, the restrictions in relation to the distance to inhabited buildings and nature protection area are conservative, as both exemptions and expropriation are not evaluated in any way. Therefore, the potential for the new wind turbines is most likely larger than this report indicates. In addition, the wind resource potential could be combined with areas with existing wind potential that was too small for [c], where in the analysis these two categories are evaluated separately. It is however, deemed reasonable to keep this conservative estimate as both public opposition and nature protection are essential parts of wind planning that should not be ignored. Another aspect left out of the model is that photovoltaics is an alternative option for local renewable energy that could be used to supplement biogas methanation plants.

## 4.2 THE DATA

Various data sources have been used to make the analysis in this report. In general, data quality can be evaluated based on completeness, consistency, accuracy and timeliness. In this report, the aim has been to use data of the highest quality available, however some important shortcomings have still been identified.

In terms of quality, most of the data is up to date, with data from 2018 or even 2019. However, it was not possible to retrieve updated datasets for electricity transmission and natural gas transmission networks, as these were from 2017-2018. This could have a significant influence on the results in this report. In relation to the electricity networks the 50kV grid was used in the study, however, in many cases the 10kV grid could be enough for a biogas methanation plant. If the 10kV grid had been available to the study, the results would most likely have shown more feasible locations. The natural gas networks were crosschecked with a PDF version of the networks, where a manual update of the dataset was carried out. However, this approach lacks accuracy when compared to using a map produced by the gas system operators.

Another lacking data in terms of completeness is related to the district heating networks, where only the distribution areas are used. In many larger cities, district heating transmission lines are placed between the dispersed distribution areas in small town around the larger cites. Potentially, the biogas producers could be closer to some of these transmission lines than to the district heating distribution areas.

## 4.3 FURTHER INVESTIGATIONS

Deliberately, and described in Section 1.1, some important aspects of planning for biogas methanation plants has not been included in this report. These aspects are very important and should be analysed in further investigations. Two of the aspects are related, which is the operation of the plants as well as the economic assessment of the plants. The expected operation of the biogas methanation plants has a significant influence on the technical design, which further influences both capacities and efficiencies of the plants. In relation to this, an economic assessment could contribute with information in relation to the feasibility of the plants, where in this report only an indication of where theoretically good locations would be. The economic assessment could both be in terms of plant operation, but also related to investment in both the plant but also the infrastructure needed.

Another aspect, is that this report only assesses the potential from existing biogas producers, this could be expanded both to potential new biogas producers as well as other carbon sources for biogas methanation plants, such as energy producers and large industries. Finally, how the plants fit into the rest of the energy system, and a future 100% renewable energy system, has not been assessed in this report.

Confidently, this report can contribute with the needed information for such analyses.

# 5 CONCLUSION

This aim of this report is to quantify and assess the overall potential for biogas methanation plants in Denmark. The general methodology of the report is a spatial analysis of the existing biogas producers in the country, assessing various geographically dependent parameters for each biogas plant. The report, uses four categories to evaluate each type of plant: [a] Far from electricity and gas infrastructure, [b] Near electricity and gas infrastructure, [c] Near electricity and gas infrastructure and existing wind turbines and [d] Near electricity and gas infrastructure and good locations for new wind turbines. The reason for choosing these four categories as the main evaluation parameters, is that these are deemed important in terms of evaluating good locations for biogas methanation. In short, locations with both good connections to infrastructure and local wind production are best, while locations close to infrastructure also could be suitable.

To make the evaluation, a spatial model is developed, which uses data inputs on biogas producers, electricity, gas and heat infrastructures, CNG stations, existing wind turbines, wind resources for potential, building distance and nature protected and other restricted areas. Initially, a base scenario is established for the selection criteria associated with the four categories of biogas methanation. The base scenario uses a distance of 2 km to electricity and gas networks, for evaluating existing wind a 3 km distance with a ratio of 3 between electrolyser capacity and required new wind capacity, and finally for new wind potential a distance of 3 km and a theoretical wind potential more than 4 $MWh/m^2$.

The results of the base scenario show a total maximum theoretical production potential of 6,666 GWh/year of e-methane from all biogas sources. These can be split into 104 biogas sources in category [a] and are thus too far from gas and electricity infrastructure. 53 sources are in category [b], only fulfilling the distance to gas and electricity infrastructure requirement, while 16 are in category [c] (existing wind turbines available) and only 2 in category [d] (potential new wind locations available). Furthermore, the results show that 99% of the capacity is in category [a] and [b], out of which 48% is in category [b]. This indicates that, in the base scenario, around half of the biogas sources are relevant for biogas methanation. Furthermore, most of the potential comes from agricultural biogas plants. Also, more than half of the total capacity for biogas methanation plants already has gas injection to the natural gas grid, even though it is only 36 of the 175 biogas producers. Around 114 plants are located within 2 km of district heating, while only one plant is within 2 km distance of an existing CNG station.

The sensitivity analyses show that these conclusions are highly sensitive to changes in the criteria. If the distance to existing gas and electricity infrastructure is increased to 4 instead of 2 km, around 129 (from 41% to 74%) of the plants are in category [b], [c] and [d]. Increasing the distance to existing wind to 5 instead of 3 km, increases number of plants in category [c] to 35 (from 9% to 20%). A similar tendency can be seen in relation to the potential for new wind turbines, however not to the same extent.

# 6 BIBLIOGRAPHY


[1] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA ' s Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark. 2015. doi:10.1016/j.energy.2012.11.030.

[2] Energinet. System Perspective 2035 Long-term perspectives for efficient use of renewable energy in the Danish energy system. 2018.

[3] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. doi:10.1016/j.apenergy.2015.01.075.

[4] Skov IR, Nielsen S, Nørholm MS, Vestergaard JP. Screening of biogas methanation in Denmark – Resources, technologies and renewable energy integration. 2019.

[5] Energinet.dk. PtX i Danmark før 2030 - Potentiale for PtX i Danmark på kortere sigt i et systemperspektiv. Fredericia, Denmark: 2019.

[6] ESRI. ArcGIS Desktop 10.6.1 2018.

[7] Danish Energy Agency. Biogas plants in Denmark 2018.

[8] Energinet.dk. Liste over biogasanlæg og handlere der får gascertifikater 2019. https://energinet.dk/Gas/Biogas/Liste-over-kontoindehavere (accessed July 9, 2019).

[9] FOTDanmark. Common Public Geodata (extract march 31th 2017) 2017.

[10] Dansk Gasteknisk Center A/S. Gasselskabernes oversigtskort 2018. https://www.dgc.dk/sites/default/files/filer/dokumenter/Gasledninger_Danmark_juni2018.pdf (accessed July 9, 2019).

[11] The Danish Ministry of the Environment. PlansystemDK 2017.

[12] The Danish Energy Agency. Stamdataregister for vindkraftanlæg 2019. https://ens.dk/service/statistik-data-noegletal-og-kort/data-oversigt-over-energisektoren.

[13] CNG Europe. Natural Gas Vehicle (NVG) Compressed natural gas (CNG) filling stations for Denmark 2019. http://cngeurope.com/countries/denmark/ (accessed July 8, 2019).

[14] Energi- og Miljødata. Vindressourcekort for Danmark. Aalborg, Denmark: 2001.

[15] The Danish Wind Industry Association. Hvor mange kilowatt producerer sol og vind pr. hektar? (In Danish) 2018. http://www.videnomvind.dk/svar-paa-rede-haand/hvor-mange-kilowatt-producerer-sol-ift-vind-pr-hektar.aspx (accessed July 8, 2019).

[16] The Danish Business Authority. Afstandskort 2018. http://kort.erst.dk/spatialmap?profile=vindmoeller (accessed July 8, 2019).

[17] Danmarks Arealinformation. Download data 2019. http://www.miljoeportal.dk/myndighed/arealinformation/sider/download-data.aspx (accessed July 8, 2019).

[18] The Danish Environmental Protection Agency. Natura 2000 planer 2016 2016. http://miljoegis.mim.dk/spatialmap?&&profile=natura2000planer2-2016 (accessed July 8, 2019).

[19] Danish Energy Agency; Technology data for renewable fuels. June 2017. Last update March 2018. Copenhagen K, Denmark: 2018.