The current Nordic biogas and biofertilizer potential:

An inventory of established feedstock and current technology

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Summary

Biogas solutions in the Nordics is undergoing rapid developments and the demand for biogas is ever increasing because of the Russian war on Ukraine and the transition to fossil free industry and transportation. Furthermore, with the introduction of several multi-national companies into the biogas sector in the Nordics and with more and more biomethane being traded across national borders, it becomes increasingly important to view biogas solutions in the Nordics as a whole and to go beyond the confines of each individual nation. Since the transition and the current energy crisis require a quick response, understanding what could be done with current technologies and established substrates is important to guide decision-making in the short-term. This study aims to do just that by presenting the current biogas potential for the Nordics, including Denmark, Finland, Iceland, Norway, and Sweden. The potential was estimated for eight categories: food waste, manure, food industry waste, sludge from wastewater treatment, landscaping waste, straw, agricultural residues, and crops with negligible indirect land use effects (such as ley crops and intermediary crops). Two categories were excluded due to a lack of appropriate estimation procedures and time to develop such procedures, and these were marine substrates and forest industry waste. Furthermore, several categories are somewhat incomplete due to lack of data on the availability of substrates and their biogas characteristics. These include, for example, crops grown on Ecological focus areas, excess ley silage, damaged crops, and certain types of food industries. The specifics of each category is further detailed in Section 2 of the report.

In the report, the biogas potential includes the biomethane potential, the nutrient potential, and the carbon dioxide production potential, capturing all outputs of a biogas plant. The results of the potential study show that the current biomethane potential for the Nordics is about 39 TWh (140 PJ) per year when considering the included biomass categories in the short-term perspective. In relation to current production, realizing this potential would mean a roughly fourfold increase in

yearly production, meaning that a significant unexploited potential remains. On the nutrient side, the biogas system in the Nordics would, given the realization of the estimated potential, be of roughly the same size as current mineral fertilizer use (about 75 percent for nitrogen and 160 percent for phosphorous). While this represents the management of a significant portion of nutrients used in agriculture, the potential to replace or reduce mineral fertilizer use through biogas expansion remains unexplored in this study since a significant portion of nutrients come from biomass that is already used as fertilizer (e.g., manure). Finally, on the carbon dioxide side, about 4.2 million tonnes of carbon dioxide would be produced, which could be either captured and stored or captured and utilized, thereby further increasing the positive environmental effects associated with biogas solutions. In conclusion, there remains a large unexploited biogas potential in the Nordics, even when only considering current technologies and established feedstock that could be realized in the short-term (the theoretical potential is much larger since many substrate categories are excluded and the potential is limited to established technologies). Such a realization would bring large increases to biomethane production but would also mean that a significant amount of nutrients would be recirculated through the biogas system. This means that the biogas system has a key role to play in increasing both the food and energy security in the Nordic countries, in addition to its many positive environmental effects.

Acknowledgements

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1 Introduction

1.1 Background

In recent years, the Nordic countries[1] have seen a large increase in biogas production, spearheaded by developments in Denmark [1,2]. Additionally, it is not only the biogas production increase that heralds an expansion, innovations in the realization of new substrates give further indications of an expansive development of the biogas system in the Nordic countries. This is emphasized by the significant growth in acquisitions of biogas-related businesses in the Nordic market, with several large multinational energy-related businesses entering the market. Furthermore, innovations in logistics and trade, such as advancements in LBG (liquid biogas) production and "guarantees of origin" certificates have led to a more interconnected system in the Nordics with more and more biomethane being traded across national borders.

Because of the entry of multinational businesses and investors the increasing cross-border trade of biomethane, it becomes increasingly important to view the Nordic countries as a whole—rather than five separate markets—in regards to the potential for development and expansion of biogas. While many national potential studies exist, which review biomass and biogas potential in individual Nordic countries [see, e.g., 3–5], there is no unified study for the entire Nordics. Because the national potential studies that exist differ a lot in their methodology, for example in relation to what substrates are included, what timeframes are used, and what biomethane conversion factors are applied, these potential studies are not commensurable nor comparable. In order to enable both an overview of the Nordic biogas potential and comparison between individual Nordic countries, a harmonized approach is needed where the same methodology is used to assess the potential in all countries. Furthermore, previous biogas potential studies have focused solely on the biogas production part (energy) of biogas systems and the other major outputs of biogas plants (biofertilizer and carbon dioxide) have not been included.

[1] The Nordic countries include the countries of Denmark, Finland, Iceland, Norway, and Sweden.

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1.2 Aim

Therefore, this study aims to estimate the biogas potential in the Nordic countries using a harmonized approach that is applied in the same manner to all Nordic countries (while taking into consideration national differences in relation to, for example, agriculture and food industry). The study focuses only on biogas from anaerobic digestion and does not include biogas produced through pyrolysis, gasification, or methanation. Because of the current energy and climate crisis in Europe, expedience in the development of biogas systems is crucial, which is furthermore reflected in the REPowerEU plan [6]. Thus, this potential study focuses on established biomass substrate categories and currently available technologies for biogas production, which means that the study assesses the short-term potential for biomethane, biofertilizer, and carbon dioxide production from biogas systems in the Nordic countries. In doing this, the objective is to give an overview of what could be achieved today, within current technological and political regimes. As such, the potential would be expected to be higher when considering a longer time horizon and more feedstock categories.

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2 Method

2.1 Methodology

There are many ways to perform a potential study. In this report, a "potential study" refers to a study focusing on understanding the potential to produce a certain product (or process a certain substrate) within a defined geographical area (considering, e.g., cultural, meteorological, and legislative context). This means that we are concerned with absolute potentials, not relative ones (such as biogas yield per kilo of substrate). When performing these types of potential studies, many assumptions and simplifications are typically necessary because of the size and breadth of the investigated biomass. For example, while one may perform a lab batch test to establish what the relative potential is from the biomass, this is typically impossible for absolute potentials since performing batch tests for every substrate type within a geographical region (even if it is a relatively small region) is not feasible. Thus, substrates need to be aggregated and their, for example, biomethane potentials must be estimated using generic data. Furthermore, the absolute potentials are often dependent on the availability of data within the studied area. Common data that are needed are, for example, how much biomass is available of different types within the chosen geographical area. Because of this, how data is reported (geographical scope or aggregation level) often decide what categories and what resolution levels are chosen in potential studies.

Absolute potential studies do not have a standardized approach nor even a unified understanding of its ontology, epistemology, or methodology[2]. Ontologically, potential studies may be seen as prognoses or projections to some, while others may be seen as visions or goals. Considering their epistemology, potentials studies provide (at best) estimations of what the potential of a certain type of technology may be within a given area but the knowledge they provide is set by their aim and therefore, limited by the aim. For example, a study that seeks to explore future technological advancement and aim to drive innovation by showing the theoretical limits of the potential will make assumptions and use data governed by this aim. A potential study aiming for a potential in

[2] Ontology refers to the identity and being of things, that is, identifying what a certain phenomenon is, in this case, what are potential studies? Epistemology refers to how knowledge can be created, used and verified, in this case, what knowledge potential studies create and how this can be used and verified. Methodology refers to how research methods are performed, in this case, how potential methods are performed and why certain assumptions are used.

the long-term perspective like this may, for example, include substrates that are currently not used but could be, it may increase the effectiveness of current technologies to estimate the future technological developments when calculating yields, and it may investigate substrates that are currently not usable due to laws and regulations. On the other hand, a study focusing on the short-term potential and what can be achieved today (such as this study), will make its own assumptions in relation to this aim. For example, such a study would only include established substrates that are already in use and would exclude substrates that are not usable within the current political context. Therefore, these ontological and epistemological questions have impact on the methodology of potential studies. Moreover, knowledge from a potential study cannot be used for other purposes than its aim and scope, for example, knowledge from long-term potential studies should not be used to state something about the short-term potential, and vice versa. For this specific study, it means that this study's results is not meant to be used to understand what the long-term potential of biogas solutions in the Nordics is, since that is beyond its aim.

2.2 Categorization and aggregation

Potential studies that seek to present results on a large geographical area (such as the Nordics) always have to balance between providing details and overloading the results with said details. For biogas potentials, many different substrates can be used, which can be grouped at different levels of aggregation. For example, at the highest level one could find the categories of organic waste or crops. At the lowest level of aggregation, we could find categories such as specific crops, manure from specific animals, or waste flows from individual industries. Very high-level categories enable results that are easy to grasp and overview but such results do not allow readers to understand what substrates are important for the estimated potential since the aggregation level may be too high. Very low-level categories, on the other hand, mean that results become impossible to overview because it would be composed of potentially hundreds of categories. In this study, eight categories were chosen, which were based on the idea of ensuring that the result can provide readers with knowledge about what substrates are important for the total biogas potential while allowing readers to survey results at a glance. These eight categories are: food waste, manure, food industry waste, sewage sludge, landscaping waste, straw, agricultural residues, and crops with low indirect land use change (ILUC) and descriptions of each of these categories and what sub-categories each is made up of can be seen in Sections 2.3 to 2.10.

In addition, two categories were identified as relevant for the study but they had to be excluded from the study (marine substrates and forestry waste) because of difficulties with estimating their biogas potential. Descriptions of these categories and the reasons for their exclusion can be found in Sections 2.11 and 2.12.

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From the geographical perspective, aggregation is also necessary to enable overview of the results. While most data is reported on farm, industry, or city level and found in databases on the municipality level (in the Nordic countries), the aim of the study was to provide results on national and Nordic levels and therefore, results are calculated for each country and the Nordics as a whole.

2.3 Calculations and estimations

Three different potentials are calculated and estimated in this study. These are the outputs of a biogas plant (biomethane, biofertilizer, and carbon dioxide). These are all based on the categories of biomass and the amount of each biomass category. In general, each category is made up of sub-categories and the potentials are weighted averages of these sub-categories, where the weights are based on how much of the main category said sub-category makes up. To clarify, the biogas characteristics (e.g., nutrient content and biomethane yield) of the main categories used in the study are based on the biogas characteristics of the sub-categories, where the influence of a sub-category on the main category is proportional to the biomass amount. The biogas characteristics used for both main and sub-categories can be seen in Appendix B.

Regarding biomethane potentials, this is calculated based on biomethane yields reported by studies focusing on commercial scale or pilot scale biogas plants. When no yields could be found for these scales, biomethane yields from batch test results were used. The biomethane potential calculations followed the equation in Equation 1.

$$BMP = BA_{dm} \cdot VS_{\%\,of\,TS} \cdot BY \cdot EC \qquad \text{Equation 1}$$

Where BMP is the biomethane potential
BA is the biomass in tonnes dry matter
VS is the volatile solid content as percentage of total solid content
BY is the biomethane yield per tonne volatile solids
EC[3] is an efficiency coefficient that reflects what the BMP could be in commercial scale plants

Biofertilizer potentials are calculated based on the total nutrient and carbon content in the biofertilizer. Three nutrients were selected based on data availability and that these nutrients are often used as yardsticks for fertilizer products, which were nitrogen, phosphorous, and potassium. In addition to the nutrients, the carbon content in the biofertilizer was also estimated as the carbon in the biofertilizer provides further value to the biofertilizer product and is important to consider for both climate change impact and agricultural systems. The biofertilizer potential was calculated according to Equation 2.

$$BFP = BA_{dm} \cdot \frac{TN\ or\ TC}{t\ BA_{dm}} \qquad \text{Equation 2}$$

Where BFP is the biofertilizer potential
BA_{dn} is the biomass amount in tonnes of dry matter
TN is the total nutrient content in the biomass per tonne of biomass
TC is the total carbon content in the biomass per tonne of biomass

Finally, carbon dioxide potential was calculated based on a simplified assumption that 35 percent (volumetric) of the rawgas produced in biogas plants is carbon dioxide. Based on this assumption, carbon dioxide potential was calculated based on the volume of methane estimated according to Equation 1. Based on the methane volume, rawgas volumes were calculated, which was then used to estimate the carbon dioxide potential.

For all of these calculations, the data used in the calculations along with references to the data sources can be found in Appendices A and B. In Appendix A, the reader will find data on biomass amounts for the studied geographical area while Appendix B lists the parameters used to perform potential calculations, such as biomethane yield, dry matter contents, and nutrient contents.

[3] In this study, this efficiency coefficient was set to 0.9 because many of the biomethane yields that are used are lab scale or pilot scale studies, which are performed for longer retention times or with better operating conditions.

2.4 Food waste

The category of food waste is made up of four different sub-categories each divided based on their point of origin: households, restaurants, large kitchens, and grocery stores. While household food waste is, by far, the largest sub-category the waste from large kitchens and grocery stores has a larger biomethane yield due to them having lower amounts of inert or partially decomposed material. Because household food waste is the dominant sub-category, the size of this category is very closely tied to the population size of the geographical area that is studied; therefore, countries with higher populations often have higher potentials in this category.

The estimations of biomass amounts for food waste were based on reported annual amounts of food waste from households, restaurants, large kitchens, and grocery stores for the different countries that were studied. This means that the estimations are sensitive to the accuracy of the reporting of waste management organisations and sampling studies that are often the basis for waste generation statistics. Basing estimations on reported statistics further means that such estimations should be seen as representing a theoretical potential, since the maximum realistic collection rate of this food waste would be less than 100 percent.

2.5 Manure

The manure category includes five sub-categories: horse manure, pig manure, poultry manure, and liquid and solid cattle manure. This means that several livestock types were excluded from the study. This choice was made because of the difficulty in finding accurate data on certain livestock types and because many of the excluded livestock categories represent a small number of animals that are seldom stabled. It is believed that the five included substrate categories include the majority of the manure potential, although there can certainly be other livestock types that are relevant on a local scale.

Manure amounts were calculated based on data on average manure yields per animal and year as well as factors for how much of the animals yearly time is spent stabled (it is currently not feasible to collect manure from grazing animals as this manure is too dispersed). This means that manure produced by animals while grazing are not included in the study. The manure yields were estimated based on different types and sizes of livestock, for example, cattle were divided into cows, heifers, steers, bulls, and calves while pigs were divided into sows, boars, piglets, and slaughter pigs.

2.6 Food industry waste

Food industry waste is the most diverse category that was included in the study. It was diverse because there are many different types of food industries that each produce waste with their own characteristics. Dairy waste, for example, is of vastly different characteristics from slaughterhouse waste. Trying to estimate the food industry waste potential for all types of food industries proved too demanding for this study, instead a generic food waste category was created based on the characteristics of slaughterhouse waste, dairy waste, spent grain from breweries, and waste from juicing industries. This was also done because data on amounts of food industry waste was only available on a highly aggregated level, which meant that generic characteristics that could approximate the "average" food industry waste was needed to estimate the potential for this category. Food industry waste is, however, not a substrate without competition. In many cases, the food industry waste may be used as feed for animals, which lowers the potential for its use in biogas. Therefore, the realizable or practically feasible potential in this category is most likely lower than what is estimated in this study.

This category also includes fish industry waste, which was handled separately to the generic food industry waste due to the relatively large fish industries that exist in two of the Nordic countries (Iceland and Norway) and the distinct characteristics of fish waste compared to other types of food industry waste. For fish industry waste, this was calculated based on two types of fish waste, sludge from hatcheries [7] and ensiled waste from fish processing industries [8]. Waste from open-sea fish farming where not included because it is currently not captured but dispersed into the ocean. Moreover, possible substrates from fishing and trawling were also not included, such as unwanted catch or fish guts from vessels that clean the fish on-board, because of the difficulty with finding logistical solutions for how to transport this waste to biogas plants in a cost-efficient manner.

2.7 Wastewater and sewage sludge

Within this category, one finds sludge from municipal wastewater. This is divided into two sub-categories, biosludge and primary sludge. Sludge from industries were treated within the "food industry waste" category or excluded (as was the case for sludge from forest industries). Because of this, this category is closely tied to population size and population density (since private sewage wells were not included in the potential). Therefore, countries with large urban populations and advanced sewage systems tend to have high potentials, while countries with small populations or poor sewage infrastructure often have small potentials for producing biogas in this category.

2.8 Landscaping waste

Landscaping waste is made up of two sub-categories, gardening waste (from, for example, private gardens or public parks) and roadside grass. Much of the organic matter in this category was, at the point of this report's writing, treated through composting, thus enabling recycling of nutrients. Anaerobic digestion, however, would enable the extraction of energy along with nutrient recycling. While it is a relatively poor substrate for biogas production (with low biomethane yield and it may require pre-treatment or long retention times), the fact that it is (in part) already collected does speak for the fact that it could be possible to realize this potential with the correct economic or administrative incentives.

2.9 Straw

The potential from straw was calculated for both oilseed straw and cereal straw. In the Nordics, cereal crop production is much larger than oilseed crops, which means that the category is dominated by cereal straw. The straw potential was based on estimates of how much straw can be extracted from harvesting with current technology and without damaging the fertility of the soil; using different salvage coefficients for different cereal crops (see Appendix A). Furthermore, straw-to-kernel factors were used to estimate the amounts of straw produced per amount of crop produced. Therefore, this category is strongly related to the acreage grown with cereal and oilseed crop within each nation studied. The following cereal crops were included in the potential: winter and spring wheat, rye, triticale, winter and spring barley, and oats. The oilseed crops included were winter and spring rapeseed. A large portion of straw is currently used as, for example, bedding material. This was not included in the potential estimations and therefore, there is a portion of the straw included in these estimates that is currently in a competing use (however, this amount could also reach the biogas plant after it has been used as bedding materials).

2.10 Agricultural residues

While it is possible to combine straw within this category, because straw is such a large amount of organic matter, it was given its own category in order to enable the potential of other non-straw agricultural residues. In this category potato tops and sugar beet tops make up the sub-categories. Several other categories of agricultural residues, such as carrot tops, excess ley silage, damaged crops and pea stocks had to be excluded due to the difficulty of finding reliable data on both the biogas-related characteristics and on the amounts of residues available in each of the studied countries. Because of this, it is expected that the potential from agricultural residues is in reality larger than the one estimated in this study.

2.11 Low ILUC crops

Low ILUC crops is a category that encompasses such crops that do not contribute to direct or indirect land use change (ILUC) from competing with food crops. This includes crops grown on fallow land for the purpose of biogas production, increasing the current production of ley crops on through intensification (not by increasing the land acreage used to grow ley crops), and the introduction of intermediary crops that are used in biogas production. All of these changes to the agricultural system can be done with little negative impact (and sometimes even positive impact) on agricultural system's ability to produce food and feed [9]. One sub-category was excluded from this category due to lack of data, this was crops grown on ecological focus areas, that is, areas that are specifically set aside to grow crops that enhance biodiversity. These crops could be used to produce biogas if they are harvested and processed at the end of the growing season when their biodiversity service has been done. Unfortunately, data could not be found on the biogas-related characteristics of these crops nor on the amount of land set aside for ecological focus areas in the studied countries.

2.12 Marine substrates (excluded)

Marine substrates, such as seaweed, mussels, and ascidians can be harvest and used in biogas production. Often this is done as an environmental remediation to remove nutrients from eutrophied water bodies. Other potential substrates that could be included in this category are beach cast seaweed and reed, which are often removed for aesthetic purposes from beaches and beach meadows. This category was excluded as it is not currently used for biogas production and it was (at the writing of the report) still unclear to what extent it may be used in the future. Because a large part of the potential is grown, the potential will vary a lot depending on how much is assumed to be grown. Therefore, plausible scenarios would have had to been explored to estimate the potential of this category, which was not possible within this study. The theoretical potential from this category is, however, believed to be large as the Nordic countries all have long coastlines and many water bodies in the Nordics suffer from eutrophication, which could be remediated through harvesting marine organic matter to produce biogas.

” In addition, two categories were identified as relevant for the study but they had to be excluded from the study (marine substrates and forestry waste) because of difficulties with estimating their biogas potential.

2.13 Forestry waste (excluded)

Forestry waste includes both excess material from forestry and waste from sawmills, which have large potentials to produce methane through gasification; however, since the study only focused on anaerobic digestion this category is primarily based on waste streams from pulp and paper industries. The biogas potential from such industries varies a lot from mill to mill because different technologies and different waste treatment setups have large impacts on the biogas yield. Because of lack of data on these aspects in the pulp and paper mills of the Nordic countries and because of the difficulty of creating average or generic estimations for this category it had to be excluded from the study. As many of the Nordic countries are large producers of pulp and paper, this category is believed to represent a large uncaptured potential, which should be estimated in the future to compliment other potentials estimated in this study.

3 Results

3.1 The Nordic

The potential for outputs from biogas systems in the Nordics can be seen in Table 1. In total, the biomethane output is estimated to be approximately 39 TWh (140 PJ) per year. In relation to the current production of around 10 TWh (36 PJ) per year, this represents an unexploited potential of almost 75 percent. This means that with current established technologies and substrates it is possible to increase production of biomethane roughly fourfold.

Table 1. The estimated Nordic potential for different outputs of a biogas system.

Outputs	*Per year*	*Per capita and year*
Energy (biomethane)	38,817 GWh (140 PJ)	1.4 MWh (5.1 GJ)
Nitrogen	534,094 tonnes	19.4 kg
Phosphorous	89,202 tonnes	3.2 kg
Potassium	437,872 tonnes	15.9 kg
Carbon in digestate	7,943,810 tonnes	288.8 kg
Carbon dioxide	4,179,773 tonnes	152.0 kg

Regarding the biofertilizer output, the potential represents a significant volume of nutrient throughput. For example, the total nitrogen amount in biofertilizer products from biogas plants (if the potential is realized) would be about 76 percent of current mineral nitrogen fertilizer use. For phosphorous, this is even larger at about 160 percent of current mineral phosphorous use. Here, it is important to recognize that a large part of this nutrient potential is already used and recycled in the current system through, for example, application of undigested manure (which represents about 70 to 80 percent of the nutrient potential). Utilizing biogas systems to digest manure can, however, enable a more optimal way of spreading the nutrients in the manure [10] and may make nutrients more readily available for plant uptake. This could also provide tools to manage nutrient emissions to waterways. Combined with the fact that there are additional nutrients that represent added nutrient recycling through biogas plants (e.g., food waste and sludge), there is a significant potential to reduce mineral fertilizer use through realizing the biogas potential in the Nordic countries, although further studies are needed to say how large this potential may be.

Finally, the carbon flowing through the biogas system in the Nordics (if the estimated potential is realized) would be very significant and should not be ignored. The potential carbon dioxide output from the biogas system is approximately equal to 4.1 million tonnes per year, which could be compared to the Nordic fossil carbon dioxide emissions in 2020 of about 148 million tonnes [11]. Being able to store or utilize this carbon dioxide could, therefore, represent an opportunity for withdrawing carbon dioxide from the atmosphere or replacing fossil carbon dioxide in food and chemical industry. Similarly, the carbon in the digestate represents a large amount of carbon, in this case roughly 5 percent of the Nordics fossil carbon dioxide emissions. Since application of biofertilizer may increase the soil organic carbon content [12], thereby storing carbon in the soil, the effective application of biofertilizer products represent a further opportunity for climate change mitigation.

Taking a look at how the potential is distributed across the eight categories it is clear that agricultural substrates dominate (although to a lesser degree than in other European settings [13]) with about 35 percent of the biomethane potential consisting of manure (see Figure 1). On the nutrient side this is even more evident with manure representing about 70 to 80 percent (depending on nutrient type) of the nutrient potential (see Figures 2-4). Since the low-ILUC crops change the nutrient need, in addition to containing nutrients, these were excluded from the biofertilizer potential results since it was not possible to assess the net effect within this study.

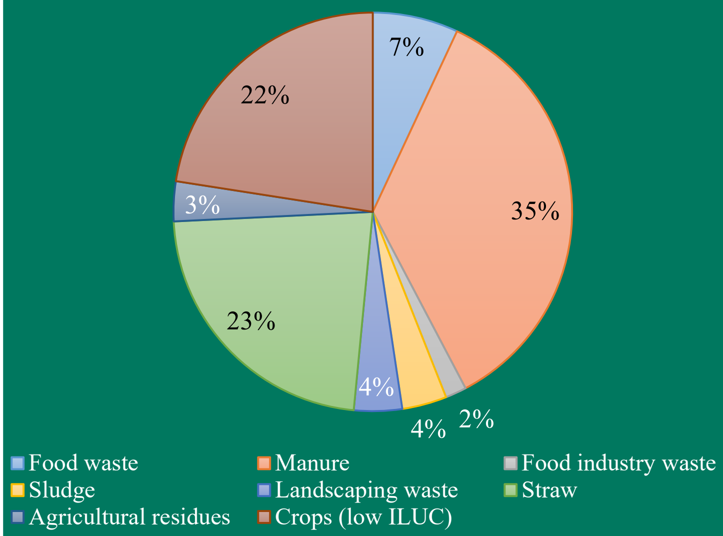

Figure 1. The proportional contribution of each studied substrate category to the Nordic biomethane potential.

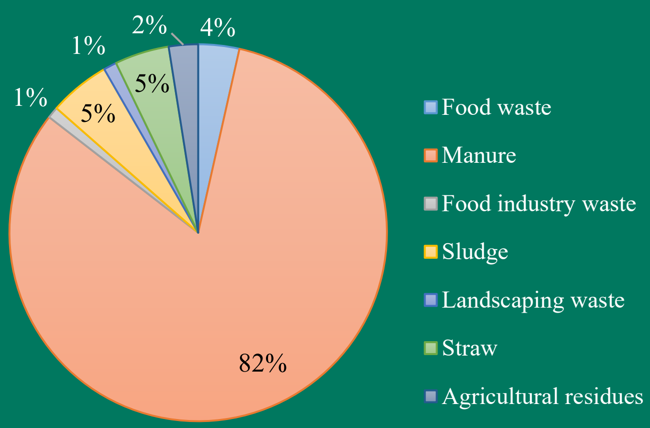

Figure 2. The proportional contribution of each studied substrate category to the Nordic nitrogen potential from biogas systems.

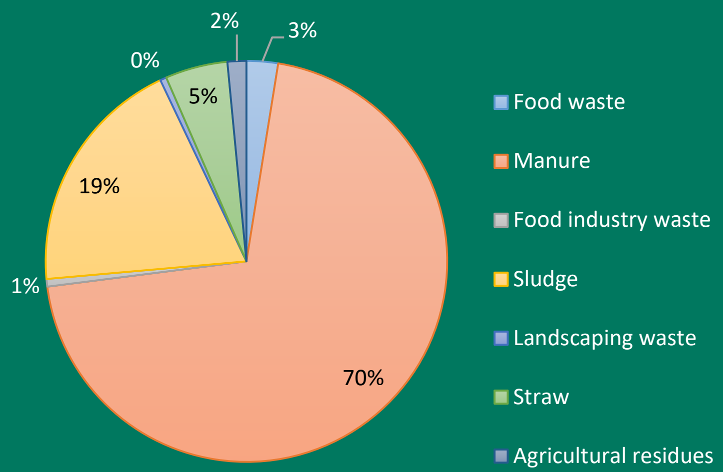

Figure 3. The proportional contribution of each studied substrate category to the Nordic phosphorous potential from biogas systems.

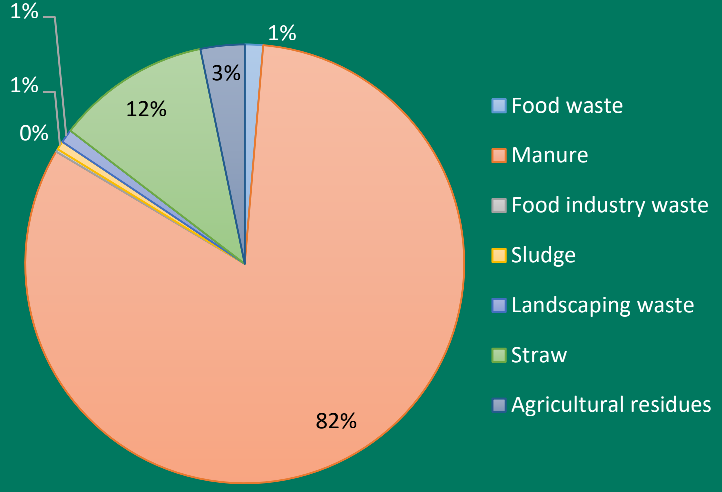

Figure 4. The proportional contribution of each studied substrate category to the Nordic potassium potential from biogas systems.

3.2 Country comparison

When zooming in and looking at the biomethane potential of each of the studied countries (see Figure 5), certain national differences appear. First, Denmark has the highest potential, both per capita (Figure 6) and in absolute terms (Figure 5). This is due to their extensive agricultural sector, where many substrates originate (mainly straw, agricultural residues, and manure) and which creates opportunities for large potentials from low-ILUC crops. As in the case for the entire Nordics, agricultural substrates represent the largest potentials in each individual country but for the more northern countries (Finland, Iceland, and Norway), low-ILUC crops have significantly lower potentials than for Sweden (Figure 7) and Denmark (Figure 8). This is because intermediary crops are assumed impossible to implement in large scale due to the short growing season in those countries. Because of this reason, intermediary crops are also only assumed to be possible to implement in the south of Sweden. Instead, in the northern parts of the Nordics, manure is the most dominant category (see Figures 9, 10, and 11), making up around 50 percent of the current biomethane potential in these countries. When it comes to realising the current biomethane potential, it is clear that Denmark has gotten the furthest with approximately 40 percent of the current potential already realized; for the other countries studied, the realized potential varies between 10 and 20 percent. This indicates that Denmark is quite a lot further than other Nordic countries when it comes to volume of biogas developments.

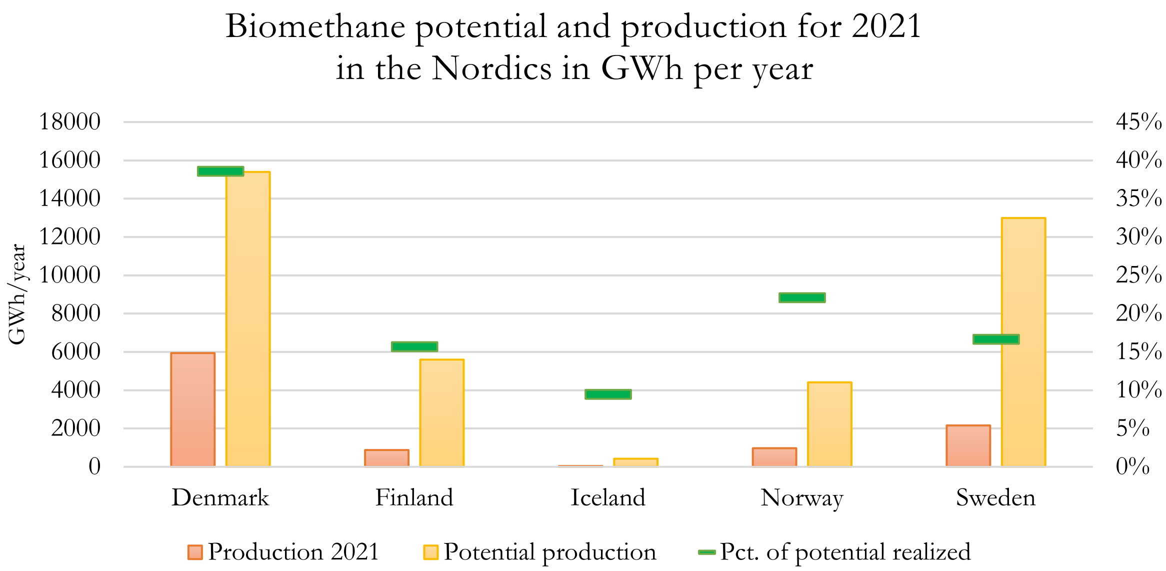

Figure 5. The biomethane production in 2021 (orange bars and left axis), the estimated current biomethane potential (yellow bars and left axis), and the percent of the potential that is realized as of 2021 (green line and right axis).

Regarding biofertilizer potentials, the picture is much the same as for the entire Nordics with manure representing between 75 to 90 percent of nutrient throughput for all three assessed nutrients. Looking beyond manure, food waste and sludge represents important categories of nutrients for all countries as they hold fairly large potentials of nutrient, which would not be recycled if treated through, for example, incineration.

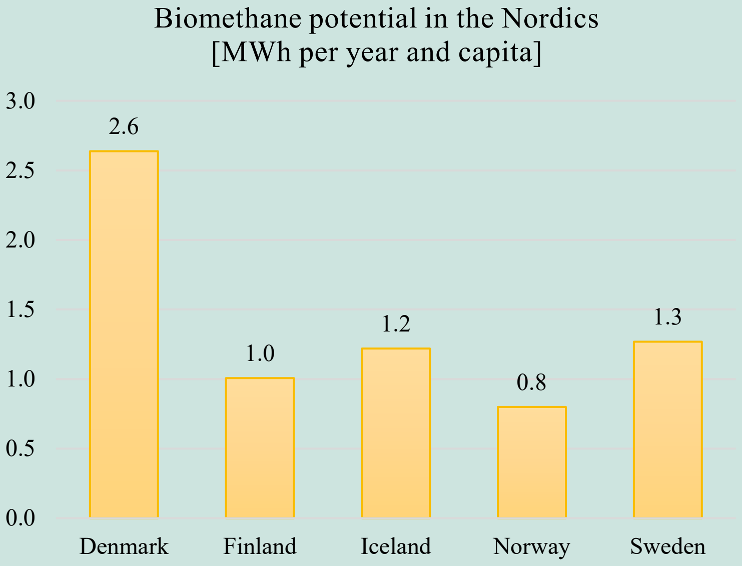

Figure 6. The estimated biomethane potential in MWh per year and capita for each assessed country.

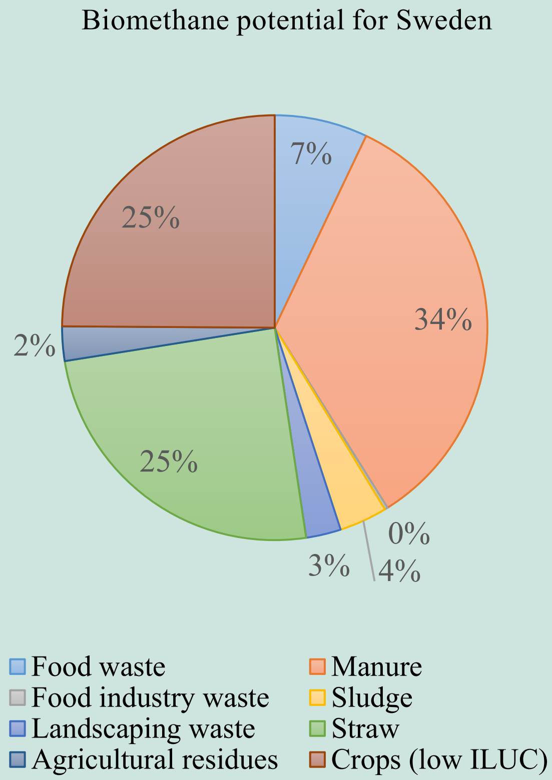

Figure 7. The biomethane potential for Sweden divided across the assessed categories.

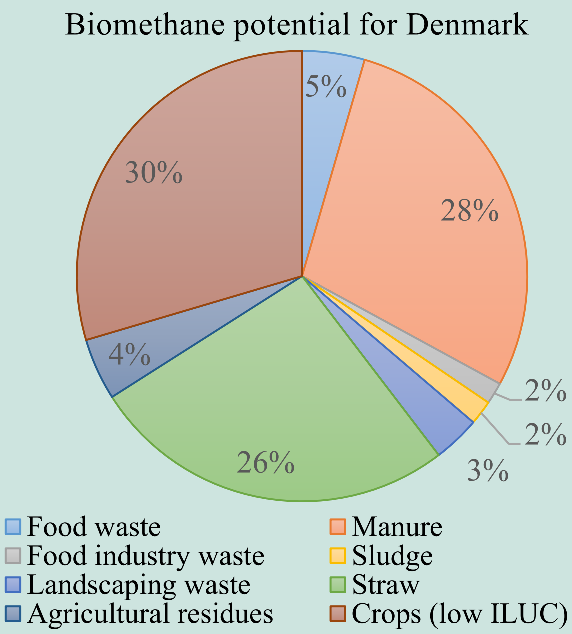

Figure 8. The biomethane potential for Denmark divided across the assessed categories.

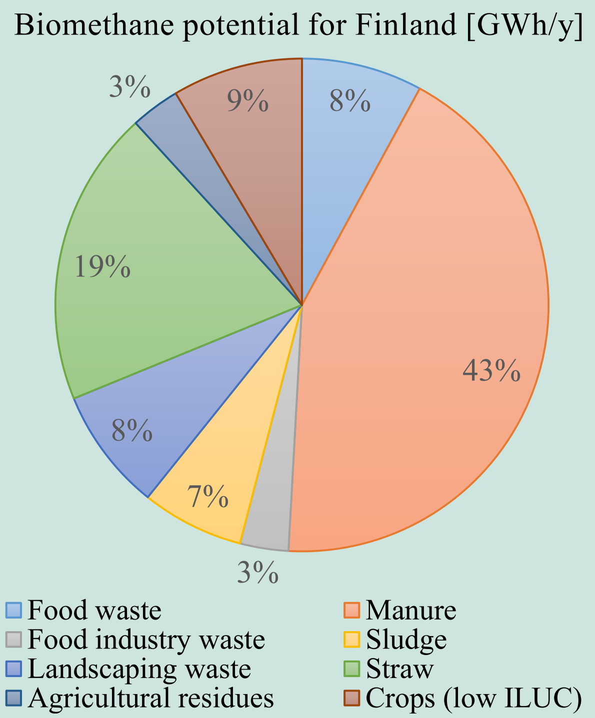

Figure 9. The biomethane potential for Finland divided across the assessed categories.

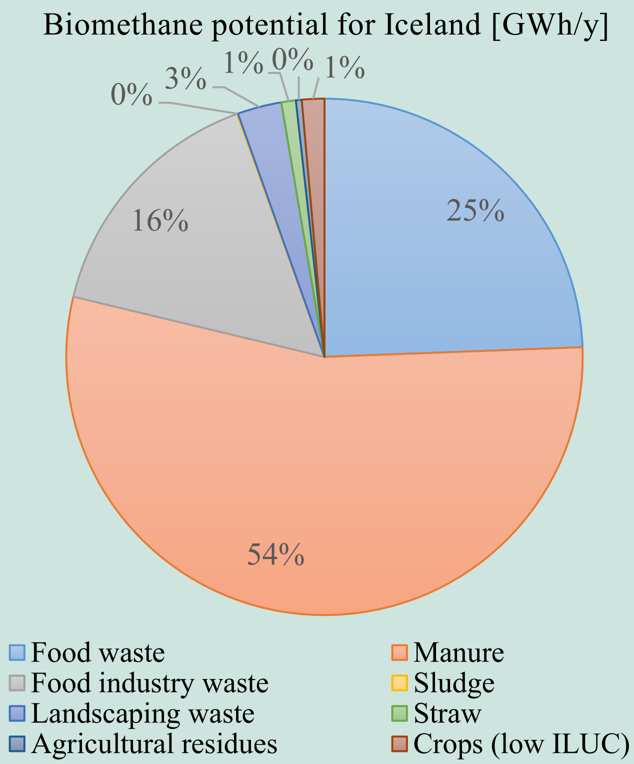

Figure 10. The biomethane potential for Iceland divided across the assessed categories.

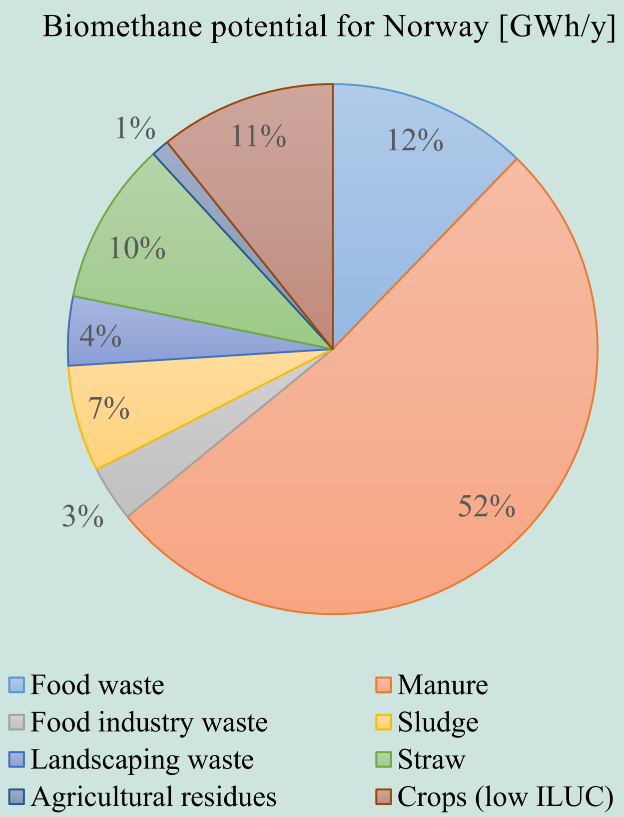

Figure 11. The biomethane potential for Norway divided across the assessed categories.

4 Discussion

The results of this study is, because it aims to estimate the short-term (or current) potential, on the conservative end of the breadth of other national potentials studies that have been done, for example, [3,5,14–23]. A comparison between this study's results (considering biomethane potential) and the estimated potential of other nationally focused studies can be seen in Figure 12. Since the aim of many other national potential studies have been to show the long-term or theoretical potential for biogas, their estimations are typically higher than this study. Therefore, it is important to reiterate that the theoretical potential to produce biogas is much higher than the results of this study if you consider the full breadth of biomass (for example, food and feed crops are excluded) or include the increase in potentials due to future technological development (for example, biomethanation or optimizations of digestion techniques).

Regarding this type of studies (absolute potentials that focus on large geographical areas), while the results can show an estimation of the potential that could be realized, they do not give much advice on realizing said potential. This is one of the weaknesses of this type of studies and they often need to be complimented by more focused implementability studies or potential studies focusing on smaller geographical areas [24]. Because of the high level of aggregation and generalization needed for potential studies of large geographical areas, the details and specific flows of substrate is lost to the viewer. This is typically one piece of information needed to initiate the implementation of a biogas plant. Despite this weakness, some guidance on the implementation of actual biogas plants can be given from the results of this study.

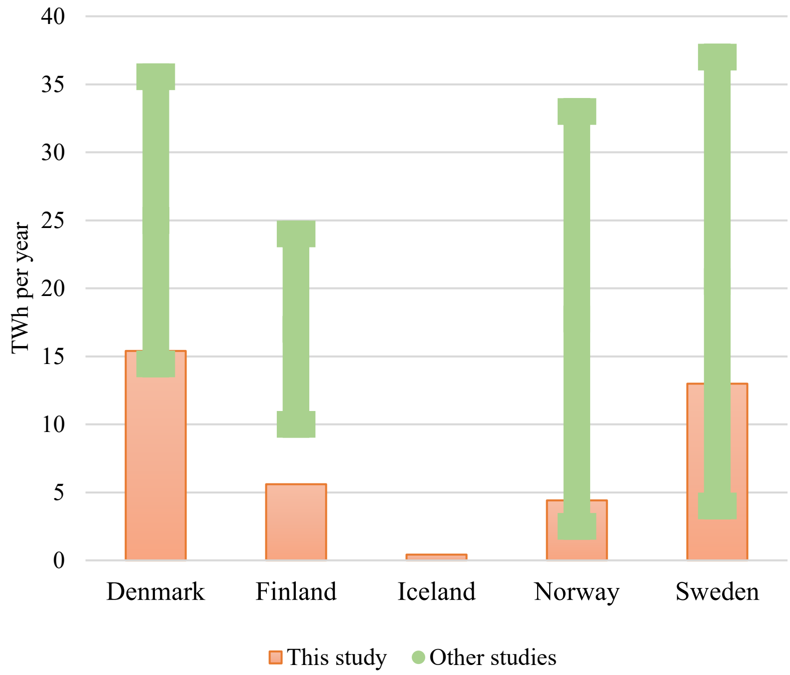

Figure 12. A comparison between the biomethane potential of this study (orange bar) and other national potential studies (green intervals), the studies used to form the green bars can be found in [3,5,14–23].

The large unexploited potential in the Nordics remain mostly within the agricultural sector and while many new plants have been, or are being, built based on large amount of manure in the substrate base, other agricultural substrates, such as ley crops and intermediary crops, provide promising avenues for further expansion of biogas production. However, there are some limitations here since intermediary crops are difficult to grow in the north of the Nordics, due to the short growing season [9], which means that developments in those regions should possibly focus on ley crops and manure (in addition to food waste, food industry waste, sludge, and potential agricultural residues). Furthermore, the northern parts of the Nordics include large amounts of substrates not included in this study, such as forestry waste and marine substrates, which should be included in future studies and which is something especially important to consider when studying biogas potentials or developments in the northern part of the Nordics.

If the potential were to be realized, it would mean that biogas represents a significant portion of the methane production and the nutrient use in the Nordic countries. This emphasizes the key role that biogas systems can fulfil in ensuring food and energy security in these countries. This, in combination with the many positive environmental effects associated with biogas systems [25,26], means that biogas systems should be promoted and their development facilitated in the Nordic countries to maximize their desirable societal effects.

5 Conclusions

This study aimed to estimate the potential for biogas within the Nordic countries as a whole and within each country. This potential was estimated based on the inclusion of only established substrates (mainly substrates that are in use) and current technologies (conventional anaerobic digestion techniques). Within this scope, the biomethane potential in the Nordics was estimated to about 39 TWh (140 PJ) per year. Since the current production is about 10 TWh per year, a large unexploited potential remains. On the nutrient side, the realization of the estimated potential would mean that the Nordic biogas system would produce about the same amount of nutrients as current mineral fertilizer use. However, this is not to say that it can replace this amount of mineral fertilizer since much of this is already recycled through the application of undigested manure or the ploughing down of straw. Nutrient recirculation through biogas systems may, however, present opportunities for additional nutrient recirculation as well as optimization of nutrient management. It may therefore contribute to a reduced need for mineral fertilizer but the size of this reduction remains to be investigated. The results of the study show that the highest potential can be found in the agricultural sector, from substrates such as manure, straw, intermediary crops, and agricultural residues. While the agricultural substrates are larger in size, there are also several important substrates from cities and industrial activities, such as food waste, food industry waste, and sludge, which will be needed in order to achieve higher efficiencies through co-digestion with the agricultural substrates.

Finally, several unexplored potentials are still left to investigate. First, two significant categories of substrates could not be estimated in this study (marine substrates and forestry waste) due to lack of available data and issues with generalizing biomethane yields. These categories should be further explored and ways of estimating their potentials should be proposed. Second, the potential in this study was performed by utilizing biomethane yields for each substrate in a mono-digestion setting. In addition to this, there may be co-digestion benefits by digesting several substrates together at the same time. Such co-digestion could equate to a higher biomethane yield than mono-digestion. This represents another potential type that remains to be captured where there are uncertainties around methods for how to do so. Third, and last, there are many potentially unused and unexplored substrates that may be utilized in the future, which were not included in the study. Moreover, new technological developments may bring higher yields from the substrates that were included in the study. Because of this, studies are needed that explore how radical changes may increase the potential in the long-term future in order to understand what the role of biogas systems may be in, for example, 2050 and beyond.

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Appendix A – Biomass inventory

In this appendix, the reader will find the references and data used for the biomass amounts used in the study.

Table A 1. Biomass amounts and references used in the study to calculate biogas, biofertilizer and carbon dioxide potentials.

Country	Biomass type	Amount [tonnes]	Reference
Denmark	Food waste	626,000	[27]
	Manure	26,396,312	Table A2
	Food industry waste	588,000	[27]
	Sludge	3,401,377	[28][a]
	Landscaping waste	646,667	[14]
	Straw	3,051,262	Table A3
	Agricultural residues	2,047,244	Table A4
	Crops (low ILUC)	8,570,007	Table A5
Finland	Food waste	402,075	[5,29]
	Manure	14,510,400	Table A2
	Food industry waste	435,000	[29]
	Sludge	4,725,00	[5]
	Landscaping waste	561,877	[5]
	Straw	816,801	Table A3
	Agricultural residues	541,732	Table A4
	Crops (low ILUC)	648,723	Table A5
Iceland	Food waste	93,356	[30][b]
	Manure	1,224,763	Table A2
	Food industry waste	92,332	[30,31]
	Sludge	3,220	[30]
	Landscaping waste	14,538	[32][a]
	Straw	2,869	Table A3
	Agricultural residues	4,606	Table A4
	Crops (low ILUC)	11,154	Table A5
Norway	Food waste	489,462	[4]
	Manure	13,471,293	Table A2
	Food industry waste	209,481	[4]
	Sludge	3,613,773	[4]
	Landscaping waste	231,645	[32][a]
	Straw	330,040	Table A3
	Agricultural residues	144,042	Table A4
	Crops (low ILUC)	891,539	Table A5
Sweden	Food waste	833,000	[33]
	Manure	25,676,627	Table A2
	Food industry waste	75,000	[33]
	Sludge	5,966,710	[28]
	Landscaping waste	430,000	[32]
	Straw	2,183,308	Table A3
	Agricultural residues	1,019,843	Table A4
	Crops (low ILUC)	6,085,064	Table A5

[a]Scaled based on population

[b]Assumed 70 percent of organic waste to be household food waste according to [34]

Table A 2. Data and data sources used to calculate manure amounts for the included countries. In brackets are the references for the data.

Country	Animal type	Manure per animal and year [t DM]	Collection rate/stabled time	Animals	Manure [t DM]
Denmark	Cows	37,00 [17]	75% [17,35]	646,731 [36]	17,946,785
	Heifers, bulls and steers	16,20 [17]	45% [17,35]	856,569 [36]	6,244,388
	Calves	8,70 [17]	65% [17,35]	332,214 [36]	1,878,670
	Sows and boars	10,05 [17]	50% [17,35]	2,313 [36]	11,622
	Slaughter pigs and piglets	3,40 [17]	80% [17,35]	11,872 [36]	32,292
	Horses	5,00 [17]	50% [17,35]	42,782 [36]	106,955
	Laying hens	0,03 [17]	50% [17,35]	5,794,673 [36]	79,677
	Pullets	>0,01 [17]	45% [17,35]	1,497,936 [36]	5,561
	Chickens	>0,01 [17]	90% [17,35]	14,056,101 [36]	90,361
Finland	Cows	37,00 [17]	75% [17,35]	248,530 [37]	6,896,708
	Heifers, bulls and steers	16,20 [17]	45% [17,35]	232,561 [37]	1,695,370
	Calves	8,70 [17]	65% [17,35]	286,882 [37]	1,622,318
	Sows and boars	10,05 [17]	50% [17,35]	83,404 [37]	419,105
	Slaughter pigs and piglets	3,40 [17]	80% [17,35]	1,024,418 [37]	278,647
	Horses	5,00 [17]	50% [17,35]	15,286 [37]	38,215
	Laying hens	0,03 [17]	50% [17,35]	4,180,930 [37]	57,488
	Pullets	>0,01 [17]	45% [17,35]	81,637 [37]	303
	Chickens	>0,01 [17]	90% [17,35]	758,575 [37]	4,877
Iceland	Cows	37,00 [17]	75% [17,35]	25,772 [38]	715,173
	Heifers, bulls and steers	16,20 [17]	45% [17,35]	32,568 [38]	237,421
	Calves	8,70 [17]	65% [17,35]	22,223 [38]	125,671
	Sows and boars	10,05 [17]	50% [17,35]	261 [38]	1,314
	Slaughter pigs and piglets	3,40 [17]	80% [17,35]	2,732 [38]	7,433
	Horses	5,00 [17]	50% [17,35]	54,069 [38]	135,173
	Laying hens	0,03 [17]	50% [17,35]	187,565 [38]	2,579
	Pullets	>0,01 [17]	45% [17,35]	N/A	N/A
	Chickens	>0,01 [17]	90% [17,35]	N/A	N/A
Norway	Cows	37,00 [17]	75% [17,35]	317,073 [39]	8,798,776
	Heifers, bulls and steers	16,20 [17]	45% [17,35]	282,947 [39]	2,062,687
	Calves	8,70 [17]	65% [17,35]	282,948 [39]	1,600,068
	Sows and boars	10,05 [17]	50% [17,35]	6,566 [39]	32,994
	Slaughter pigs and piglets	3,40 [17]	80% [17,35]	68,634 [39]	186,685
	Horses	5,00 [17]	50% [17,35]	125,000 [39]	312,500
	Laying hens	0,03 [17]	50% [17,35]	4,102,062 [39]	56,403
	Pullets	>0,01 [17]	45% [17,35]	N/A	N/A
	Chickens	>0,01 [17]	90% [17,35]	65,516,879 [39]	421,180
Sweden	Cows	37,00 [17]	75% [17,35]	511,595 [40]	14,196,761
	Heifers, bulls and steers	16,20 [17]	45% [17,35]	476,497 [40]	3,473,663
	Calves	8,70 [17]	65% [17,35]	465,211 [40]	2,630,768
	Sows and boars	10,05 [17]	50% [17,35]	129,239 [40]	649,426
	Slaughter pigs and piglets	3,40 [17]	80% [17,35]	1,350,947 [40]	3,674,576
	Horses	5,00 [17]	50% [17,35]	355,500 [40]	888,750
	Laying hens	0,03 [17]	50% [17,35]	6,363,416 [40]	87,497
	Pullets	>0,01 [17]	45% [17,35]	2,390,120 [40]	8,873
	Chickens	>0,01 [17]	90% [17,35]	10,315,262 [40]	66,312

Table A 3. Data and data sources used to calculate straw amounts for the included countries. In brackets are the references for the data.

Country	Crop	Amount of crop [t DM]	Straw/Kernel coeff.	Salvage coeff.	Amount of straw [t DM]
Denmark	Winter wheat	3,972,300 [36]	0.60 [41]	0.75 [41]	1,787,535
	Rye	680,400 [36]	0.78 [41]	0.75 [41]	398,034
	Triticale	49,600 [36]	0.65 [41]	0.75 [41]	24,180
	Winter barley	504,800 [36]	0.57 [41]	0.80 [41]	230,189
	Spring wheat	122,400 [36]	0.66 [41]	0.65 [41]	52,510
	Spring barley	2,998,100 [36]	0.37 [41]	0.50 [41]	554,649
	Oats	368,300 [36]	0.52 [41]	0.65 [41]	124,485
	Winter rapeseed	N/A	1.02 [41]	0.85 [41]	N/A
	Spring rapeseed	N/A	0.94 [41]	0.65 [41]	N/A
Finland	Winter wheat	259,500 [37]	0.60 [41]	0.75 [41]	116,775
	Rye	66,800 [37]	0.78 [41]	0.75 [41]	39,078
	Triticale	9,500 [37]	0.65 [41]	0.75 [41]	4,631
	Winter barley	122,466 [37]	0.57 [41]	0.80 [41]	55,845
	Spring wheat	418,200 [37]	0.66 [41]	0.65 [41]	179,408
	Spring barley	909,834 [37]	0.37 [41]	0.50 [41]	168,319
	Oats	790,200 [37]	0.52 [41]	0.65 [41]	267,088
	Winter rapeseed	6,500 [37]	1.02 [41]	0.85 [41]	5,636
	Spring rapeseed	7,100 [37]	0.94 [41]	0.65 [41]	4,338
Iceland	Winter wheat	4,364 [42]	0.60 [41]	0.75 [41]	1,964
	Rye	219 [42]	0.78 [41]	0.75 [41]	128
	Triticale	233 [42]	0.65 [41]	0.75 [41]	113
	Winter barley	191 [42]	0.57 [41]	0.80 [41]	87
	Spring wheat	228 [42]	0.66 [41]	0.65 [41]	98
	Spring barley	1,417 [42]	0.37 [41]	0.50 [41]	262
	Oats	836 [42]	0.52 [41]	0.65 [41]	283
	Winter rapeseed	N/A	1.02 [41]	0.85 [41]	N/A
	Spring rapeseed	N/A	0.94 [41]	0.65 [41]	N/A
Norway	Winter wheat	231,904 [43]	0.60 [41]	0.75 [41]	104,356
	Rye	18,439 [43]	0.78 [41]	0.75 [41]	10,787
	Triticale	19,561 [43]	0.65 [41]	0.75 [41]	9,536
	Winter barley	69,994 [43]	0.57 [41]	0.80 [41]	31,917
	Spring wheat	12,096 [43]	0.66 [41]	0.65 [41]	5,189
	Spring barley	520,006 [43]	0.37 [41]	0.50 [41]	96,201
	Oats	252,000 [43]	0.52 [41]	0.65 [41]	85,176
	Winter rapeseed	N/A	1.02 [41]	0.85 [41]	N/A
	Spring rapeseed	N/A	0.94 [41]	0.65 [41]	N/A
Sweden	Winter wheat	2,877,700 [44]	0.60 [41]	0.75 [41]	1,294,965
	Rye	144,500 [44]	0.78 [41]	0.75 [41]	84,533
	Triticale	153,300 [44]	0.65 [41]	0.75 [41]	74,734
	Winter barley	125,800 [44]	0.57 [41]	0.80 [41]	57,365
	Spring wheat	150,100 [44]	0.66 [41]	0.65 [41]	64,393
	Spring barley	934,600 [44]	0.37 [41]	0.50 [41]	172,901
	Oats	551,200 [44]	0.52 [41]	0.65 [41]	186,306
	Winter rapeseed	328,100 [44]	1.02 [41]	0.85 [41]	284,463
	Spring rapeseed	12,500 [44]	0.94 [41]	0.65 [41]	7,638

Table A 4. Data and data sources used to calculate agricultural residue amounts for the included countries. In brackets are the references for the data.

Country	Crop type	Hectare	Residue coeff. [tDM/ha]	Residue amount [tDM]
Denmark	Potatoes	56,200 [36]	4.0 [45]	112,400
	Sugar beets	36,900 [36]	2.0 [45]	147,600
Finland	Potatoes	20,400 [37]	3.2 [45]	32,640
	Sugar beets	11,300 [37]	1.6 [45]	36,160
Iceland	Potatoes	585 [42]	2.4 [45]	702
	Sugar beets	N/A	1.2 [45]	N/A
Norway	Potatoes	11,433 [43]	3.2 [45]	18,293
	Sugar beets	N/A	1.6 [45]	N/A
Sweden	Potatoes	23,750 [44]	3.2 [45]	38,000
	Sugar beets	28,600 [44]	1.6 [45]	91,520

Table A 5. Data and data sources used to low ILUC crop amounts for the included countries. In brackets are the references for the data.

Country	Crop type	Hectare	Yield [tDM/ha]	ILUC yield [tWW[a]/ha]
Denmark	IC[b] on wheat	511,000 [36]	4.7 [46]	2,391,480
	IC on rye	108,300 [36]	4.7 [46]	506,844
	IC on barley	621,600 [36]	4.7 [46]	2,909,088
	IC on pea	10,300 [36]	4.7 [46]	48,204
	IC on potato	56,200 [36]	4.7 [46]	263,016
	Ley abandoned	N/A	2.6[c] [9]	N/A
	Ley fallow	77,065 [36]	3.3[c] [9]	846,158
Finland	IC on wheat	N/A	N/A	N/A
	IC on rye	N/A	N/A	N/A
	IC on barley	N/A	N/A	N/A
	IC on pea	N/A	N/A	N/A
	IC on potato	N/A	N/A	N/A
	Ley abandoned	N/A	2.1 [9]	N/A
	Ley fallow	70,900	2.7 [9]	648,723
Iceland	IC on wheat	N/A	N/A	N/A
	IC on rye	N/A	N/A	N/A
	IC on barley	N/A	N/A	N/A
	IC on pea	N/A	N/A	N/A
	IC on potato	N/A	N/A	N/A
	Ley abandoned	N/A	2.1 [9]	N/A
	Ley fallow	1,219	2.7 [9]	11,154
Norway	IC on wheat	N/A	N/A	N/A
	IC on rye	N/A	N/A	N/A
	IC on barley	N/A	N/A	N/A
	IC on pea	N/A	N/A	N/A
	IC on potato	N/A	N/A	N/A
	Ley abandoned	N/A	2.1 [9]	N/A
	Ley fallow	6,307	2.7 [9]	57,708
Sweden	IC on wheat	431,730 [44]	3,9 [46]	1,683,747
	IC on rye	25,268 [44]	3,9 [46]	98,545
	IC on barley	248,512 [44]	3,9 [46]	969,197
	IC on pea	42,373 [44]	3,9 [46]	165,255
	IC on potato	22,059 [44]	3,9 [46]	86,030
	Ley abandoned	57,500 [44]	2.1 [9]	410,282
	Ley fallow	146,016 [44]	2.7 [9]	1,336,022

[a]DM content of ley crops at 30% and intermediary crops at 20% is used
[b]Intermediary crop on the following type of field
[c]Assumed a 20% increase from yield in Swedish conditions

Appendix B – Substrate parameters

This appendix includes the substrate parameters and characteristics used to calculate the biogas, nutrient and carbon dioxide potentials in the study. Each main category is made up of several sub-categories, which apply a weighted average method according to Equation B1. The weights are based on how large the share of the main category's dry matter weight each sub-category represents.

$$P_a = \sum_{n=1}^{i} w_n \cdot P_n \qquad \text{Equation B1}$$

Where P_a is the parameter P of the main category
w_n is the weight of the n^{th} sub-category where $\sum w_n=1$, that is all weights sum up to 1
i is the number of sub-categories
P_n is the parameter P for the sub-category

Table B 1. The substrate parameters used in the study where: W is the weight of the sub-category used in Equation B1. TS is the dry matter concentration. VS is the volatile solids concentration in the dry matter. TN, TP, TK, and TC is the total amount of nitrogen, phosphorous, potassium, and carbon respectively in kg per ton dry matter. BMP is the biomethane potential in Nm^3 CH_4 per tVS. CH_4 vol.% is the assumed volumetric percentage of methane in the rawgas, which is used to calculated CO_2 output.

Class	Name	W	TS	VS	TN	TP	TK	TC	BMP	CH_4 vol.%
Main	**Manure**	**-**	**11%**	**81%**	**5.4**	**0.8**	**4.3**	**51**	**199**	**65%**
Sub	Cow manure, liquid	0.74	9% [47]	80% [47]	4.8[a]	0.6[a]	3.9[a]	41[a]	200 [47–49]	65%
Sub	Cow manure, solid	0.15	23% [47]	80% [47]	8.5[a]	1.2[a]	8.3[a]	104[a]	[47–49]	65%
Sub	Pig manure, liquid	0.10	8% [47]	85% [47]	3.3[a]	0.6[a]	1.3[a]	36[a]	[47–49]	65%
Sub	Poultry manure	0.01	42% [47]	76% [47]	23.9[a]	5.9[a]	8.4[a]	189[a]	[47–49]	65%
Main	**Horse manure**	-	**30%** [47]	**80%** [47]	**4.9** [50]	**1.5** [50]	**10.0** [50]	**135** [50]	**170** [47]	**65%**
Main	**Food waste**	**-**	**31%**	**85%**	**7.7**	**0.9**	**2.4**	**137**	**472**	**63%**
Sub	Food waste, households	0.82	33% [51]	85% [51]	8.3 [51]	1.0 [51]	2.6 [51]	149 [51]	461 [51]	65%
Sub	Food waste, restaurants	0.07	27% [51]	87% [51]	6.8 [51]	0.8 [51]	2.2 [51]	122 [51]	506 [51]	65%
Sub	Food waste, large kitchens	0.07	13% [51]	92% [51]	3.3 [51]	0.4 [51]	1 [51]	59 [51]	650 [51]	59%
Sub	Food waste, grocery stores	0.04	15% [51]	90% [51]	3.8 [51]	0.5 [51]	1.2 [51]	68 [51]	550 [51]	59%
Main	**Food industry waste**	**-**	**12%**	**86%**	**3.7**	**0.4**	**0.7**	**55**	**436**	**65%**
Sub	Slaughterhouse waste	0.61	16% [51]	83% [51]	3.8 [51]	0.4 [51]	0.7 [51]	72 [51]	434 [51]	65%
Sub	Dairy waste	0.26	6% [47]	95% [47]	3.5[a]	0.3[a]	0.6[a]	27[a]	520 [47]	65%
Sub	Brewaries spent grain	0.13	7% [47]	97% [47]	3.7[a]	0.3[a]	0.5[a]	32[a]	323 [47]	65%
Main	**Fish sludge**	**-**	**14%** [7]	**33%** [7]	**-**[b]	**-**[b]	**-**[b]	**-**[b]	**62** [7]	**65%**
Main	**Fish waste, ensiled**	**-**	**24%** [8]	**95%** [8]	**-**[b]	**-**[b]	**-**[b]	**-**[b]	**462** [8]	**65%**
Main	**Wastewater Sludge**	**-**	**4%**	**70%**	**1.6**	**1.0**	**0.2**	**17**	**343**	**65%**

Sub	Primary sludge	0.77	3% [52]	72% [52]	1.4 [52,53]	1.0 [52,53]	0.2 [52,53]	16 [52,53]	370[b]	65%
Sub	Biosludge	0.23	4% [52]	62% [52]	2.3 [52,53]	1.1 [52,53]	0.2 [52,53]	18 [52,53]	250[b]	65%
Main	**Landscaping waste**	**-**	**58%**	**61%**	**3.2**	**0.2**	**2.3**	**260**	**253**	**65%**
Sub	Gardening waste	0.93	60% [54]	60% [54]	3.0[b]	0.2[b]	2.2[b]	270[b]	250 [54]	65%
Sub	Roadside grass	0.07	30%[b]	92%[b]	5.9[b]	0.4[b]	4.3[b]	135[b]	298[b]	65%
Main	**Straw**	**-**	**78%**	**91%**	**3.9**	**0.7**	**7.8**	**352**	**209**	**65%**
Sub	Cereal straw	0.95	78% [55]	91% [55]	3.9 [55]	0.7 [55]	7.8 [55]	351 [55]	207 [55]	65%
Sub	Oilseed straw	0.05	84% [56]	86% [56]	3.9 [55]	0.7 [55]	7.8 [55]	378 [55]	242 [57]	65%
Main	**Agricultural residues**	**-**	**13%**	**87%**	**3.6**	**0.4**	**3.8**	**57**	**335**	**65%**
Sub	Potato tops	0.42	13% [45]	87% [45]	3.6 [45]	0.4 [45]	3.8 [45]	57 [45]	335 [45]	65%
Sub	Sugar beet leaves	0.58	13% [45]	87% [45]	3.6 [45]	0.4 [45]	3.8 [45]	57 [45]	335 [45]	65%
Main	**Crops, low ILUC**	**-**	**22%**	**92%**	**5.9**	**0.4**	**4.3**	**97**	**298**	**65%**
Sub	Ley crops	0.16	30% [9]	92% [58]	5.9 [55]	0.4 [55]	4.3 [55]	135 [55]	298 [57]	65%
Sub	Intermediary crops	0.84	20% [9]	92% [58]	5.9 [55]	0.4 [55]	4.3 [55]	135 [55]	298 [57]	65%

[a]Author's own data

[b]Data missing and assumed non-usable for fertilizer application.