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ESTIMATING THE EU BIOGAS POTENTIAL FROM MANURE AND CROP RESIDUES – A SPATIAL ANALYSIS

Report from a project within the collaborative research program *Renewable transportation fuels and systems*

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THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This project is financed and carried out within the f3 and Swedish Energy Agency collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system).

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities
- Carries through system oriented research related to the entire renewable fuels value chain
- Acts as national platform stimulating interaction nationally and internationally.

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SUMMARY

Anaerobic fermentation of agricultural wastes such as crop residues and animal manure, producing biogas, is an example of an advanced biofuel that can contribute to the EU target of a minimum 10% of transport fuels from renewable sources in 2020. Producing biogas from residues has received increasing attention following the debate on the impact conventional biofuel production has on food prices, poverty and land-use change. The EU, as well as major producers of biogas such as Germany and Italy, are currently revising their policy framework to incentivize the sourcing of biogas substrates from waste streams.

Given these developments it is important to improve our understanding of how large the potential is for producing biogas and biomethane from agricultural wastes in the EU, how that potential is distributed across member states, and what the main limitations to this potential are. Previous studies on the potential for producing biogas from agricultural wastes in the EU, however, have either been local cases studies that account for a host of detailed economic and technical constraints, an approach that is almost impossible to scale up to the EU level, or top-down assessments of gross substrate potentials that do not account for any of the technical and economic limitations specific to biogas production.

In this report we present a spatially explicit approach for estimating the availability of agricultural wastes — crop residues and animal manure — across the EU, which also allows for an analysis of how key economic and technical constraints such as minimum viable plant size, maximum collection distances for substrates, and substrate composition affects the total potential for biogas production.

Our main results from this analysis can be summarized as follows:

- Total annually available biogas substrates from agricultural wastes in the EU28 amounts to roughly 80 million tonnes of crop residues (dry matter) and 110 million tonnes (dry matter) of animal manure.
- In our base case scenario, three quarters of the manure and a fifth of the crop residues are technically and economically exploitable for biogas production, yielding a total biogas potential from agricultural wastes of almost 700 PJ (HHV) per year.
- Animal production and arable farming are spatially highly segregated in some parts of the EU28. This leads to some areas having considerable surpluses of either dry, carbon-rich crop residues or nitrogen-rich manures which cannot be fully utilized due to technical constraints on dry matter content and carbon-to-nitrogen ratios. There are, however, potential ways to relax these constraints, for example using dry fermentation technology or adding wet, carbon-rich co-substrates, such as energy crops.
- If we assume a larger minimum viable biogas plant size of 8 MW, typical if the biogas is to be upgraded to vehicle fuel quality, the potential decreases by about a quarter. However, the base case potential can still be reached or even surpassed under this constraint if one allows for a somewhat increased collection radius for substrates or if the constraint on maximum dry matter content is relaxed.

SAMMANFATTNING

Biogas producerad från lantbrukets restflöden, i form av stallgödsel och skörderester, är ett exempel på ett biobränsle som kan bidra till att möta EU:s mål om minst 10% förnybara drivmedel i transportsektorn till år 2020. Möjligheten att producera biogas från restflöden har aktualiserats ytterligare i kölvattnet av diskussionen kring de negativa effekter konventionella biodrivmedel kan ha på livsmedelspriser, fattigdom och markanvändning. I såväl EU som enskilda medlemsstater med stor biogasproduktion, som Tyskland och Italien, pågår idag processer för att se över regelverk och stödsystem för att ge starkare incitament för att utnyttja restflöden för biogasproduktion.

Givet denna utveckling är det viktigt att öka vår kunskap kring hur stor potentialen är för att producera biogas från lantbrukets restflöden i EU, hur denna potential är fördelad geografiskt, samt vilka de huvudsakliga begränsade faktorerna för denna potential är. Tidigare analyser av potentialen för biogasproduktion från restflöden är dock antingen lokala studier som tar hänsyn till en rad detaljerade tekniska och ekonomiska begränsningar, men som är omöjliga att skala upp till EU-nivå, eller grova uppskattningar av tillgängliga substratmängder på EU-nivå som inte tar hänsyn till några tekniska och ekonomiska begränsningar av biogaspotentialen.

I denna rapport presenterar vi en geografiskt explicit metod för att uppskatta tillgängliga restflöden från jordbruket (stallgödsel och skörderester) över hela EU som också gör det möjligt att analysera hur centrala tekniska och ekonomiska faktorer som minsta anläggningsstorlek, maximalt hämtningsavstånd och substratens sammansättning, påverkar den totala biogaspotentialen.

Våra huvudsakliga resultat kan summeras som följer:

- Den totala årliga tillgängliga mängden biogas-substrat från restflöden i jordbruket är ca 80 miljoner ton skörderester (torrsubstans) och 110 miljoner ton stallgödsel (torrsubstans).
- I vårt basfall kan tre fjärdedelar av stallgödseln och en femtedel av skörderesterna nyttjas för produktion av biogas, givet de tekniska och ekonomiska begränsningar vi antagit. Detta resulterar i en total biogaspotential på knappt 700 PJ (högre värmevärde) per år.
- Djurhållningen och växtodlingen är i delar av EU mycket segregerade. Detta medför att vissa områden har stora överskott antingen på torra, kolrika skörderester eller på kväverik stallgödsel som inte fullt ut kan användas i biogasproduktion på grund av de tekniska begränsningarna för torrhalt och kol-kväve-kvoter. Det finns dock potentiella sätt att släppa på dessa begränsningar, till exempel att använda torrötningsteknik eller att tillsätta andra vatten- och kolrika substrat, t ex energigrödor.
- Om vi begränsar modellen till anläggningar på minst 8 MW, vilket är en typisk storlek på uppraderingsanläggningar till fordonsgas, så minskar denna potential med en fjärdedel. Dock kan potentialen i basfallet fortfarande uppnås, eller till och med överstigas, om man samtidigt lättar något på begränsningen för maximalt hämtningsavstånd eller substratens maximala torrhalt.

CONTENTS

1 INTRODUCTION

In order to reduce emissions of greenhouse gases and limiting its contribution to global climate change, the EU's Renewable Energy Directive[1] (RED) requires member states to source a minimum of 10% of transport fuels from renewable sources in 2020. This push for renewable transportation fuels has primarily led to an increased demand and production of so-called conventional biofuels, produced from food crops (e.g., wheat ethanol and rapeseed biodiesel). Production and consumption of bioethanol in the EU more than tripled between 2006–2014, from just over 1,500 million liters to around 5,500 million liters, and biodiesel production and consumption roughly doubled in the same period, from just under 6 billion liters to around 12 billion liters (USDA 2014).

However, this rapid increase in conventional biofuel consumption has caused concerns over the impact increased demand for biofuel feedstocks may have on agricultural commodity markets, raising food prices, which hurts the world's poor (Persson 2015), and causing indirect land-use changes (ILUC) that weakens (or reverses) the climate gains from biofuel use. The EU Commission has responded to these concerns by proposing amendments to the RED[2], mandating a minimum 60% greenhouse gas savings achieved by biofuels counted towards the RED target, limiting the share of conventional biofuels (produced from food crops) to 7%, and incentivizing the production of advanced biofuels produced from feedstocks that do not compete for land with food and feed production.

One example of such advanced biofuels is biogas produced from municipal and industrial wastes or agricultural residues through anaerobic fermentation and upgraded to biomethane[3] (vehicle fuel quality biogas). In 2013 it is estimated that there were nearly 14 000 anaerobic digesters in the EU, producing a total of 156 TWh of biogas (corresponding to roughly one quarter of Swedish total annual energy use) (EurObserv'ER 2014). Over two thirds of the EU biogas is currently produced from dedicated energy crops, agricultural residues or municipal solid waste (the rest coming from landfills and sewage plants) and used mainly to produce electricity.

Roughly, 10% of the total biogas production in the EU is upgraded to biomethane, half of which is produced in one country, Germany. Two thirds of German upgraded gas is produced from dedicated energy crops (mainly maize silage), which — given the concerns of land competition, food price increases and ILUC — has caused the German government to remove subsidies for biogas produced from energy crops and instead encourage the use of agricultural waste (EurObserv'ER 2014). A similar development is taking place in the second largest biogas producer country in the EU, Italy. The EU Commission has also highlighted the need for improving the greenhouse gas performance of biogas and biomethane production by raising the share of agricultural waste, manure and slurry as substrate sources (European Commission 2014).

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[1] https://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive

[2] http://ec.europa.eu/energy/sites/ener/files/com_2012_0595_en.pdf

[3] Biogas produced through anaerobic fermentation commonly consists of 50–75% methane (CH4) and 25–50% carbon dioxide (CO2). To be used as a transportation fuel, or be injected in the natural gas grid, the biogas needs to be dried, desulfurized and removed of CO2, raising the CH4-content above approximately 96%.

Given these policy developments, both in the EU and in individual member states, pertinent questions are what the potential is for producing biogas and biomethane from agricultural waste stream such as straw and manure in the EU, how that potential is distributed across member states, and what the main limiting factors for this potential are. These are the questions we set out to answer in this report.

Estimating a potential for biogas production for a region the size of the EU is fraught with difficulties, given the array of biophysical, technical and economic factors affecting biogas production feasibility and that vary across the landscape and across institutional environments (Bidart et al. 2014). Consequently, most prior analyses of biogas potentials have taken a local approach, making detailed analyses using geographic information systems (GIS) for regions such as East Anglia, UK (Dagnall et al. 2000), Lecce province, Italy (Zubaryeva et al. 2012), Utiel-Requena region, Spain (Perpiña et al. 2013), southern Finland (Höhn et al. 2014). There have also been a couple of national level studies, e.g., for Greece (Batzias et al. 2005) and Chile (Bidart et al. 2014).

In a biogas potential analysis for the EU as a whole, it would be almost impossible to account for all of the local factors affecting optimal biogas plant locations and economic potentials, but a less detailed EU-wide study can complement the local case studies with a broad picture on where development of biogas production from agricultural wastes seems most promising (and hence where detailed, finer resolution studies might be beneficial) and, most importantly, which factors are key in limiting the biogas potential in different regions of the EU.

Here we develop a new methodology to analyze the biogas potential from crop residues and manure in combination. The first step is inspired by the methodology used by Monforti, Bódis, et al. (2013) and Monforti, Lugato, et al. (2015) for analyzing the spatial distribution of agricultural crop residues available for energy purposes in the EU. We use a similar approach and extend it by adding a spatial analysis of the availability of animal manure. By overlaying the availability of these two waste sources of biogas substrates, and accounting for key technical and economic factors limiting biogas potentials (e.g., biogas plant scale and maximum transportation distance for substrates, dry matter (DM) content and carbon-to-nitrogen (C:N) ratios of substrates), we are able to make an estimate of the total potential for biogas and biomethane production from agricultural wastes in the EU, as well as to explore the key factors limiting this potential and how these vary across member states and may be addressed or overcome.

1.1 MAIN FINDINGS

The available crop residues from cereals, rapeseed, maize, sugar beets, and sunflowers, after accounting for other uses, amount to roughly 80 million metric tonnes (Tg) dry matter (DM) per year in EU28. Manures from cattle, pigs, and chickens, including bedding materials such as straw, amount to roughly 110 Tg DM year^{-1}. These numbers are rather uncertain, primarily because detailed data on the production and management of these resources are not available.

The production of manure and crop residues is in some areas spatially highly segregated: some areas have very large quantities of manure and little crop residues, and vice versa. This segregation, in combination with technical and economic constraints, contributes to limiting the biogas potential.

Our analysis of technical and economic constraints (biogas plant scale and maximum transportation distance for substrates, DM content and C:N ratios of substrates) indicates that around half of all the available substrates (DM basis) are possible to utilize for biogas production (around three fourths of the manure and one fifth of the crop residues). In energy units, this corresponds to a CH_4 production of around 700 PJ $year^{-1}$ higher heating value (HHV) in EU28. This conclusion is based on the assumptions that only continuous wet digestion (the most common and mature technology) is possible, and that no other substrates are added.

The single most important constraint is the upper limit on DM concentration in wet digestion substrates (maximum 12% DM assumed). Many of the considered crop residues are very dry and cannot be added in large quantities to manure without making the whole mixture too dry for wet digestion. Therefore, our estimate of biogas production potential is substantially higher if other technologies (e.g. dry digestion) or other wet co-substrates (e.g. some energy crops) are allowed.

Another important limitation is the minimum C:N ratio of the substrate mixture. The simulated biogas production increases by 20–50% if we reduce our default value of the minimum C:N ratio limit from 10 to 7, i.e. allow a higher N concentration. This indicates that some areas have a surplus of N-rich manure substrates which need additional C-rich co-substrates to be successfully digested. Conversely, if the minimum C:N ratio is increased compared to the base scenario, the biogas production quickly falls to zero because the nitrogen-rich manure substrates cannot be supplemented with carbon-rich crop residues in any large amounts without raising dry matter content above the 12% DM allowed in the base scenario. In other words, there is a non-linear relationship between constraints on the DM content and C:N ratio, meaning that these constraints should not be studied in isolation.

In some areas, low substrate density is also an important limitation, especially if we require the relatively large production scale typically used when upgrading biogas to vehicle fuel quality. About one quarter of the total potential in EU28 is lost if we increase the minimum plant size from 1 MW HHV, a typical size for biogas-fueled electricity production, to 8 MW HHV, a typical size for upgrading units.

In conclusion, the constraints on maximum DM content, minimum C:N ratio, and minimum production scale all play a large role in determining the biogas potential from crop residues and manure. These limitations can be tackled either by loosening the constraints on the substrate supply (e.g. using dry digestion technology, or small-scale biogas plants) or by changing the substrate supply itself (adding energy crops or other suitable co-substrates to improve the chemical composition and support a larger production scale).

2 METHODS AND MATERIAL

In the following sections, we present a detailed description of the method and the data sets used. Before going into detail, we briefly summarize the analysis in three steps (also illustrated in Figure 1): First, we estimate the amounts of manure and crop residues available for biogas production, based on subnational agricultural statistics and several other data sources, which are further, discussed below. The result of this is an estimate of substrate production on the same statistical aggregation level as the agricultural statistics used.

Second, we disaggregate the regional substrate amounts to a much finer spatial resolution using a land cover map (Corine Land Cover) and a livestock population density map (Gridded Livestock of the World 2). Disaggregating the substrate densities allows us to estimate the mix of substrates that can be collected to any given point in EU28.

Third and last, the economic and technical limitations are analyzed using a stylized model of a biogas plant. A local estimation of biogas potential is obtained by maximizing the use of locally available substrates taking into account technical and economic constraints such as the minimum viable plant size, reasonable collection distances for different substrates, and the water content and C:N ratio of substrates. Finally, this local potential measure is up-scaled to the EU level to obtain an overall potential estimate.

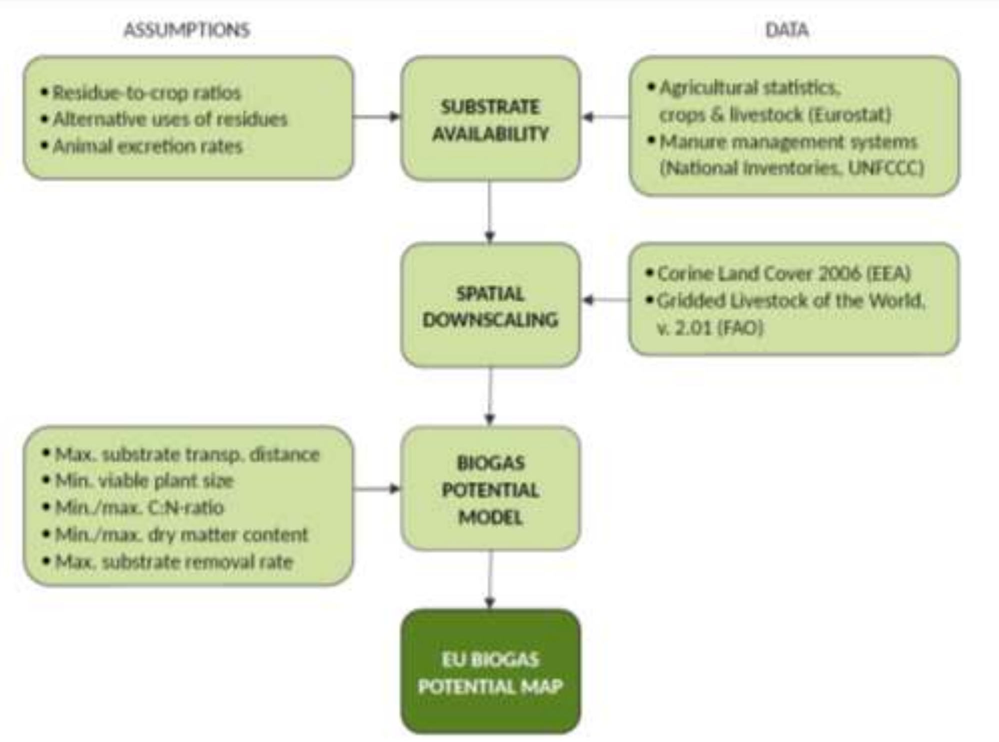

Figure 1. Illustration of the main computation steps and data sources used.

2.1 REGIONAL ESTIMATION OF SUBSTRATES

2.1.1 Crop production

The management of crop residues is highly variable, depending on competing uses, soil properties, crop rotations, weather and climate conditions, and many other factors. Some residues, primarily straw, are directly used elsewhere, e.g. as animal bedding material, in mushroom production, or incinerated for energy production, but a large fraction of crop residues is also left in the fields. In general there is little data available on the produced quantities of crop residues and how they are managed, but there have been some efforts to estimate how much could be used for energy purposes using national statistics (Scarlat et al. 2010) and subnational statistics (Monforti, Bódis, et al. 2013). Our method for estimating crop residues is in many parts similar to their methods.

Here, we estimate the production of collectable residues from wheat, barley, rye, rapeseed and turnip rape, grain maize, sugar beets, and sunflower. For each crop, the crop harvest is multiplied by a residue production ratio indicating how much residues could technically be collected. However, all the technically collectable residues cannot be sustainably removed from the fields if soil organic matter is to be preserved. This constraint is further discussed in a separate section below.

Subnational agricultural production statistics are collected and published by Eurostat according to the NUTS classification (Nomenclature of territorial units for statistics). The 28 member countries of EU constitute the NUTS0 level, which is further subdivided in 98 regions on NUTS1 level and 276 regions on NUTS2 level. For many crops in most countries, harvested amounts are published by Eurostat on NUTS2 level each year. Where harvest data is missing, we estimate harvests on NUTS2 level using national yield data and NUTS2 data on planted areas from the detailed triannual Eurostat farm structure survey. Production data used are averages of the years 2009–2011 where available (see Appendix A for details).

For each crop, the harvest is multiplied by a residue-to-crop ratio indicating how much residues are produced per unit of harvest (see Table 1). Data used is taken from Swedish measurements (Nilsson and Bernesson 2009; Kreuger et al. 2014) and from the review by Scarlat et al. (2010). Although the Swedish residue-to-crop ratios are generally in line with the values collected by Scarlat et al. (2010), it should be noted that sources often disagree by 50% or more, likely depending both on differences in measurement methods and on actual variation across countries, crop varieties, and years. Also, all the technically collectable residues cannot be sustainably removed from the fields if soil organic matter is to be preserved. This constraint is accounted for in the third step of the analysis, when biogas potentials are calculated (for details, see section 2.3.5 below).

Table 1.Residue-to-crop production ratios. The values are based on data from Nilsson and Bernesson (2009), Kreuger et al. (2014), and Scarlat et al. (2010). See Appendix A for details.

Crop	Value
Wheat	0.9
Rye	1.1
Barley	0.7
Oats	0.8
Rapeseed and turnip rape	1.2
Maize	1
Sugar beets	0.6
Sunflower	2

2.1.2 Alternative uses of crop residues

The most important alternative use for crop residues is straw as bedding for animals. The amount of straw used for bedding is estimated in the section on manure below. We compute the straw balance separately in each NUTS2 region by subtracting the bedding straw from the available resource, based on the assumption that straw for bedding is not moved between regions. In some regions where the demand for bedding exceeds the amount of collectable straw, we limit the bedding use to equal the collectable amount. As previously mentioned, some straw is used for mushroom cultivation. However, we choose to omit this term since it is typically quite small (less than 1% of the total production according to Scarlat et al. (2010)) and because reliable data is lacking. Other energy uses (primarily incineration of straw) are assumed to be zero since we are studying an alternative way of producing energy from crop residues and manure. All other uses of residues, e.g. in industrial applications, are approximated to zero since they are likely very marginal (around 1% of straw production) (Scarlat et al. 2010).

2.1.3 Manure substrates

Manure production is estimated for dairy cows and other cattle, breeding and fattening pigs, broilers and laying hens, divided into different manure management systems. The calculation is based on animal population statistics from Eurostat on the finest level publicly available (NUTS1 for Germany, NUTS2 for all other countries in EU28). See Appendix B for details on data sources.

In principle, it is straightforward to estimate the available manure resources by multiplying each animal population by its average excretion rate and the shares excreted in different manure management systems. However, neither of the latter two parameters are systematically and comparably measured across the European Union. Therefore, we have to rely on incomplete survey data and expert judgement for these parameters.

We have chosen to use a single excretion rate for each animal class across the EU, see Table 2. However, in reality the excretion rates vary depending on animal weight, feed characteristics, growth rate, milk yield of cows, etc. Since there is substantial variation in these parameters between EU countries, there are likely also differences in average excretion rates.

One way to account for the variation between countries would be to use the excretion rates reported in the National Inventory Reports (NIRs) to the UNFCCC. In some cases, these numbers may be more accurate, especially where country-specific models incorporating detailed data are used.

However, it is hard to judge how the overall accuracy of the calculation would be affected given the large variations in methods used by different countries.

Another method for predicting excretion rates is to use feed digestion models for the different animals (see e.g. Vu et al. (2009) and NRC (2001)), but such models typically require detailed data on both animals and feed characteristics which are also not systematically collected across the EU. Despite these difficulties, this approach has been taken e.g. by Leip et al. (2010) to calculate manure-related greenhouse gas emissions using the CAPRI model with estimated animal feed data.

In summary, we choose to use a simple representation of excretion because the real values are highly uncertain. Compared to highly complex model systems such as CAPRI, we gain improved model transparency and ease of sensitivity analysis at the expense of potentially reduced accuracy.

2.1.4 Manure management

Manure management systems are included in the model for two distinct reasons: (1) because some of the excretions fall on pastures and we assume that this portion cannot be collected; (2) because manure is often mixed with significant amounts of cereal straw or other bedding materials. This addition of dry materials into solid manure is important to consider because it changes the characteristics of the manure as a biogas substrate by increasing its dry matter content and C:N ratio, and affects the techniques and costs associated with transportation. Furthermore, straw use for bedding of course reduces the amount of straw available elsewhere.

Information sources on manure management practices in the EU are scarce, typically based on expert judgement rather than measurements, and either qualitative or highly uncertain. It is widely recognized that manure management practices differ significantly both between and within countries. Furthermore, comparison of different information sources is complicated since no standardized terminology is agreed upon. Some recent surveys covering all or most of the EU are found in Menzi et al. (1998), Menzi (2002), and Leip et al. (2010) and references therein.

In face of this data scarcity, we choose to make a very simple quantitative description of manure management systems, which we hope catches the most important variations across the EU. Three management systems are included and assumed to be identical for our purposes wherever they are used: liquid manure, solid manure, and pasture. The shares in each category is based on country-specific data reported by EU countries in the NIRs. Average values for the years 2009–2011 are used where available. See Appendix B for details on our manure management model and the data sources used.

For liquid manure, we assume that no bedding material is used. For solid manure, we assume a single bedding material (straw for cattle and pigs, wood shavings for poultry) added in fixed proportions. In a few NUTS2/NUTS1 regions, this derived demand for bedding straw exceeds the collectable resource, which indicates an error in the model: we have either underestimated the straw supply or overestimated the straw use. In these cases, we assume that no straw is transported across region boundaries and instead change shares of straw-based solid manure into liquid manure until the straw use is sufficiently small. Manure management is adjusted only in the NUTS1/NUTS2 regions where needed.

The resulting production of manure-based biogas substrates per animal head in different manure management systems is listed in Table 2. For each animal species and manure management system, we have assumed a composition (concentrations of volatile solids (VS), DM, C, and N), listed in Table 3, but it must be noted that different sources sometimes disagree considerably regarding the chemical composition of manure. This variation is to large extent a reflection of variations in animal feed composition and in manure management systems, e.g. in the rate of straw and water addition, or presence of urine separation in animal houses.

Table 2. Assumed excretion and total manure production per animal head for different animals and manure management systems. Excretion values for cattle and pigs from IPCC (2006). Excretion for poultry based on Litorell (2005). See Appendix B for details on manure management and bedding.

Animal	Excretion (kg VS head^{-1} d^{-1})	System	Manure incl. bedding (kg VS head^{-1} d^{-1})
Dairy cows	5.1	liquid solid	5.1 10.2
Other cattle	2.6	liquid solid	2.6 5.2
Breeding pigs	0.5	liquid solid	0.5 1.0
Fattening pigs	0.3	liquid solid	0.3 0.6
Laying hens	$8 \cdot 10^{-3}$	liquid solid	$8 \cdot 10^{-3}$ $8 \cdot 10^{-3}$
Broilers	$5 \cdot 10^{-3}$	liquid solid	$5 \cdot 10^{-3}$ $5 \cdot 10^{-3}$

Table 3. Properties of substrates. Dry matter (DM) expressed as fraction of total weight. Volatile solids (VS) expressed as fraction of DM, and carbon (C) and nitrogen (N) expressed as fractions of VS. For conversion of methane volume to higher heating value (HHV) we use the factor 40 MJ m^{-3}. Compositions are based on data reported by Sommer and Hutchings (2001), Menzi (2002), De Vries et al. (2012), Hamelin, Naroznova, et al. (2014), Koch and Salou (2015), Møller et al. (2004), Nahm (2003), and Kreuger et al. (2014).

		DM %	VS/DM %	C/VS %	N/VS %	Methane yield (m^3 CH_4/Mg VS)
Cattle manure	liquid solid	8 20	80 85	55 ″	7 3.5	200 ″
Pig manure	liquid solid	6 20	80 85	″ ″	10 5	″ ″
Chicken manure	liquid solid	30 70	70 70	″ ″	9 9	250 250
Crop residues	straw maize sunflower sugar beet	85 ″ ″ 13	90 ″ ″ ″	″ ″ ″ ″	0.5 ″ ″ 3	200 ″ ″ 300

2.2 SPATIAL DISAGGREGATION OF SUBSTRATES

2.2.1 Crop residues

To estimate the spatial distribution of crop residue production in resolution fine enough to allow us to model the production potential of stylized biogas plants across the landscape, we use the Corine

Land Cover 2006 (CLC2006) dataset, version 17 (EEA 2007), a land cover map classifying land and water bodies in 44 different classes based on computer-aided interpretation of satellite images. CLC2006 version 17 includes all EU28 countries except Greece. We use a raster version of CLC2006 with 250 m resolution.

The spatial distribution of crop production is obtained assuming that the above-mentioned crops are allocated to five land cover classes, weighted by the share of each land cover class likely to be cropland (see Bossard et al. (2000) for details). The classes and their assigned weights are as follows. Non-irrigated arable land: 100%; permanently irrigated land: 100%; annual crops associated with permanent crops: 50%; complex cultivation patterns: 50%; and land principally occupied by agriculture with significant areas of natural vegetation: 50%.

2.2.2 Manure

The disaggregation of manure production is done in a similar manner as for crop production, but using the FAO Gridded Livestock of the World dataset, version 2.01 (GLW2) (Robinson et al. 2014). The GLW2 dataset is an estimation of animal population densities in a resolution of roughly 1 km, based on a subnational animal population statistics and a statistical model with predictor variables describing vegetation and climate, topography and demography.

Manure amounts in each region are distributed proportionally to the corresponding animal population in GLW2. Note that the GLW2 animal classes (e.g. cattle and chickens) are more aggregated than the excretion categories (e.g. dairy cows and other cattle; broilers and laying hens). In other words the difference in spatial distribution, e.g. between dairy cows and other cattle, is only accounted for down to the resolution of Eurostat animal statistics. Beyond this resolution, we only have the GLW2 dataset, which does not distinguish between dairy cows and other cattle.

2.3 ESTIMATION OF LIMITATIONS TO BIOGAS POTENTIAL

The steps described above produce an estimation of manure and crop residues which could theoretically be used as substrates in biogas production at a spatial scale of 250 m (by interpolating the GLW2 dataset to the same spatial reference system as CLC2006). The next step is to estimate the potential for producing biogas from these substrates if we would place a hypothetical biogas plant somewhere in the EU. In doing so, we also consider the following economic and technical constraints which impose further limits on the biogas production potential:

- Maximum transportation distances for substrates
- Minimum viable plant size
- Minimum and maximum dry matter content
- Minimum and maximum carbon-to-nitrogen (C:N) ratio
- Maximum sustainable removal rate of residues

In the following sections, these constraints are first introduced in general terms and then described in terms of a quantitative model. The parameter values used in our base scenario are summarized in Table 4.

Table 4. Parameters for the constraint parameters, as assumed in the base scenario. Alternative scenarios (results in Section 3.2) are defined by varying two of the constraint parameters at a time, while keeping the others equal to the base scenario values.

Parameter	Symbol	Min	Max
DM Concentration	D	0	12%
C:N Ratio	CN	10	35
Plant size	P	1 MW (HHV)	-
Collection radius	r	-	20 km
Residual removal rate	R	-	40%

2.3.1 Transportation distances

In areas where substrate density is low, the collection of substrates and spreading of digestate may require uneconomically long transportation distances. An absolute upper limit for transport should be when the net energy balance of the operations turns negative, i.e. when more energy is used by than produced. For manure and straw this maximal transportation distance can be some 200 km (Berglund and Börjesson 2006), but the economically feasible distance is much less.

As a rough example, consider transportation of straw. Its marginal transportation cost is at least 0.2 €$Mg^{-1}km^{-1}$ (1 Mg = 1 metric tonne), and the fixed costs associated with collection might be at least 20 €Mg^{-1}(Archer and Johnson 2012). Assume (quite generously) that the biogas can be used to generate electricity with the efficiency 1 MWh Mg^{-1} straw (Berglund and Börjesson 2006) and that all other fixed costs sum to 10 €MWh^{-1} (Walla and Schneeberger 2008). If the electricity can be sold for 35 €MWh^{-1}, break-even for the whole operation occurs at 25 km average collection distance, an order of magnitude lower than the distance where net energy production turns negative. Note the sensitivity to assumptions: Changing the electricity price from 35 €MWh^{-1} to 30 or 40 €MWh^{-1} reduces the break-even average transportation distance to zero, or increases it to 50 km.

For the base scenario we assume a collection distance of 20 km for all substrates.

2.3.2 Minimal plant size

When the biogas is used to produce electricity, calculations indicate considerable returns to scale, perhaps a 30% cost reduction going from 150 to 1000 kW methane production (higher heating value, HHV) (Walla and Schneeberger 2008; Lantz 2012). If the gas is to be upgraded to vehicle fuel quality, the production scale increases almost by an order of magnitude: 1 MW HHV is a relatively small upgrading unit and many commercial units handle 5 MW HHV or more (Bauer et al. 2013; Petersson and Wellinger 2009).

Again, as an order of magnitude estimation, consider the production of 1 MW HHV from cereal straw. Assuming a methane yield of 2 MWh HHV Mg^{-1} straw and operation 8000 h $year^{-1}$, the straw needed is 4000 Mg $year^{-1}$. If the straw removal rate is 2 Mg ha^{-1} $year^{-1}$, 2000 ha of cereal production is needed to support the biogas production.

In summary, construction and operation of biogas plants have considerable returns to scale, but the transportation needs for large plants may outweigh some or all of those advantages if the local substrate concentration is too low.

For the base scenario we choose a minimum plant size of 1 MW HHV, which is a typical size for power production. In alternative scenarios (see section. 3.2), we also present results for both smaller and larger production units.

2.3.3 Dry matter content

Biogas processes can be divided into two main categories: wet and dry fermentation. The dry matter concentrations in reactors are typically below 10% for wet fermentation and in the range 15–35% for dry fermentation (Weiland 2010) (note that the DM concentration can be somewhat higher for the substrate mixture feeding the process since dry matter is continuously decomposed and removed). A number of chemical and physical substrate characteristics can influence which reactor type, mixing equipment, etc., are most suitable. For an introduction to this rather complicated topic, see e.g. Weiland (2010) and references therein. Here it will suffice to say that dry matter content of the substrate mixture is one possible predictor of technical feasibility.

There is also an economic aspect to the DM concentration, or rather the C concentration. In biogas plants using very dilute substrates such as pig slurry, co-substrates increasing the average C content can improve economic viability by increasing production per unit reactor volume (Hamelin, Wesnæs, et al. 2011) and decreasing costs for transportation of substrates and digestate. Therefore, a minimum DM concentration could be used as a rough proxy of the economic limits to using very water-rich substrate mixtures.

In the base scenario, we assume a maximum dry matter concentration possible to use is 12%, in line with the limitations for wet fermentation. We assume wet fermentation in the base case since this is the most commonly used technology, and considerably more mature than dry fermentation. For the lower DM limit, we choose to leave it at 0% in the base scenario, and to analyze its influence in alternative scenarios.

2.3.4 C:N ratio

Anaerobic digestion requires a balance between C and N content. The C:N ratio is an often-mentioned parameter since ammonia inhibition (see Rajagopal et al. 2013) is a potential obstacle to digestion of manure slurries with low C:N ratios. Very high C:N ratios should also be avoided since reactor stability and biogas yield may decrease if N available for microbial growth is lacking.

Recent experiments on mixtures of dairy manure, chicken manure and rice straw reported by Wang et al. (2014) indicate optimal C:N ratios in the range 25-35. In contrast, Hamelin, Naroznova, et al. (2014) mentions C:N ratios below 20 as state-of-the-art in Danish biogas plants, and Shanmugam and Horan (2009) found optimal digestion results of leather fleshing waste and municipal solid waste mixtures at C:N ratio of 15. We find this variation in reported optimal C:N ratios unsurprising, considering the complexity of digestion processes and the many possible confounding variables such as pH, temperature, other nutrient composition, etc.

In the base scenario, we therefore adopt a relatively wide range for possible C:N ratios for substrates, requiring it to be in the range 10-35.

2.3.5 Sustainable removal rate of residues

Out of the technically collectable residues, only a certain share can be sustainably removed from fields without creating unacceptable impacts on soil quality. The weather conditions after harvest also affect the potential: very wet conditions can both degrade the quality of the residues and lead to severe soil compaction if heavy machinery is used for removal of residues. A number of sources reviewed by Scarlat et al. (2010) report sustainable removal rates mostly in the range 30–60% for the crops considered here, but it should be noted that these values could be both above and below this span in some locations, depending on soil type, climate, topography, other sources of organic matter, etc. It is also likely that higher removal rates are sustainable in a biogas production system, if the digestate is returned to the same fields. However, even if all the digestate is returned, the biogas production unavoidably entails a considerable amount of carbon removal.

Following Scarlat et al. (2010), we choose a residue removal rate of 40% throughout Europe for all crop residues in the base scenario.

2.3.6 Mathematical formulation of constraints

After estimating the regional substrate amounts and disaggregating them to a fine spatial resolution, two more steps are taken in order to assess the limitations to biogas production from manure and crop residues. First, we introduce a stylized model of a biogas plant to derive a location-specific measure of the biogas potential, given the constraints discussed in the previous sections. Then we use a weighted average of this measure over the whole EU as an estimate of the overall limitations.

The biogas plant is placed in a point **p**. The available quantity $\boldsymbol{S_i}$ of each substrate is computed as the integral of the substrate density over an area with ***radius***[4] $\boldsymbol{r_i}$ centered at **p**.

The radius $\boldsymbol{r_i}$ associated with each substrate is a simplified representation of its economically feasible collection distance, which may depend e.g. on its energy density and the technology used for transportation. Since roads and topography are not included in the model, no adjustment is made for the very variable density, layout and quality of road networks.

As explained above, some of the available substrate quantities $\boldsymbol{S_i}$ may be impossible to utilize because the overall mixture is too dry or too wet, or has too high or too low C:N ratio, or if the substrates within the collection area are not enough to support the minimal plant size. The production potential is therefore obtained by maximizing production from all the available substrates, subject to these constraints.

We assume that each substrate has a methane yield, which is not affected by co-substrates, in other words that there are no synergy effects of substrate mixtures. Then the biogas production becomes a linear function of the used substrate quantities, allowing us to formulate the production maximization as a linear optimization problem, as follows. The available substrate quantities at the point $\boldsymbol{p}$, after accounting for other uses and the maximum crop residue removal rate, are denoted $\boldsymbol{S_i}$, and the utilized quantities are denoted $\boldsymbol{s_i}$. The quantities are measured as DM mass. The energy yield of each substrate is $\boldsymbol{Y_i}$ (energy/DM) so that the total energy output is $\boldsymbol{P} = \sum_i \boldsymbol{s_i Y_i}$. The DM fraction (of

[4] The disk shape is defined in the area-preserving projection recommended by EEA for spatial analysis in the EU (EPSG:3035).

the total weight) of each substrate is D_i and the corresponding limits on average DM concentration in the reactor infeed are $D_{\min}$ and $D_{\max}$. The C and N fractions are C_i and N_i, and the limits on C:N ratios are denoted $CN_{\min}$ and $CN_{\max}$. Finally, $P_{\min}$ is the minimum output effect of a plant.

The problem can now be written as

$$\begin{aligned}
&\text{maximize} \quad \sum_i Y_i s_i \\
&\text{subject to} \\
&\qquad 0 \le s_i \le S_i \qquad \forall i, \\
&\qquad D_{\min} \le \frac{\sum_i s_i}{\sum_i s_i / D_i} \le D_{\max}, \\
&\qquad \mathrm{CN}_{\min} \le \frac{\sum_i C_i s_i}{\sum_i N_i s_i} \le \mathrm{CN}_{\max}, \\
&\qquad P_{\min} \le \sum_i Y_i s_i.
\end{aligned}$$

There are two possible outcomes: (1) the problem can be solved and the substrate flows s_i can be used to produce the effect $P = \sum_i Y_i s_i$, or (2) the problem is infeasible (has no solutions), indicating that the available substrates cannot satisfy all the constraints. We interpret infeasibility as $P = 0$.

As a benchmark for the production potential, we take the theoretical biogas production obtained if all the available substrates could be digested, i.e. $P_{\max} = \sum_i Y_i S_i$. The quantity $P(\mathbf{p})/P_{max}(\mathbf{p})$ is therefore a number between 0 and 1, equal to the utilized share of the theoretical potential at a point $\mathbf{p}$.

Assumed values for the constraint parameters are listed in Table 4.

2.3.7 Biogas potential in a larger area

Finally, as a measure of the overall potential P_{tot} in some area A, we take

$$P_{tot}(A) = P_{theoretical}(A)\alpha(A),$$

where $P_{theoretical}$ is the theoretically maximal biogas production obtained by assuming that all available substrates in the whole area can be digested. It is multiplied by a number $\alpha\,(A)$ (between zero and one), defined as the area's average of the utilizable share in each point, $P(\mathbf{p})$=$P_{\max}(\mathbf{p})$, weighted by the maximum potential, i.e.

$$\propto (A) = \frac{\int_A \frac{P\,(\mathbf{p})}{P_{max}\,(\mathbf{p})e} P_{max}(\mathbf{p})\mathrm{d}A}{\int_A P_{\max}(\mathbf{p})\mathrm{d}A} = \frac{\int_A P(\mathbf{p})\mathrm{d}A}{\int_A P_{max}(\mathbf{p})\mathrm{d}A}$$

We approximate this quantity by sampling n = 32;785 points[5] $\{\mathbf{p}_j\}_1^n$, uniformly distributed in the whole analysis area, and replacing the integral by a sum:

$$\propto (A)\frac{\sum_{j=1}^{n} P(p_j)}{\sum_{j=1}^{n} P_{max}(p_j)}.$$

The overall relative potential *α(A)* comes with a caveat. The model does not consider competition for substrates between adjacent biogas plants, so a strict interpretation of *α(A)* should be that it measures the relative substrate utilization for only one randomly located biogas plant in absence of competitors. To utilize all substrates, some plants would have to face additional costs not described in this model because the disk-shaped collection areas of this model cannot be combined to cover the whole map without overlaps.

The error in the measure *α(A)* is obviously worse if substrates have very different collection distances r_i, because it leads to a sort of double counting. For example, if straw can be collected from within a 30 km radius and manure only within 10 km, several different biogas plants could be on safe distance from each other's manure sources while all counting the same straw on some field as an available co-substrate. To account for the effect of such competition it would be necessary to describe the substrate redistribution in a more detailed manner, e.g. explicitly model the location of plants and their substrate collection areas. However, we feel that the added complexity of such a treatment is not warranted considering the limited completeness and spatial resolution otherwise used in this work. To minimize the inherent problems of the proposed measure *α(A)*, we instead choose to present results with all collection radii equal, i.e. $r_i = r$.

[5] The 32,785 points are obtained by sampling each point in a 15 km grid.

3 RESULTS

3.1 BASE SCENARIO

The estimated total available substrate amounts in EU28 in the base scenario, after accounting for maximal removal rate and other uses of crop residues, are shown in Figure 2. Straw and cattle manure together make up roughly two thirds of all the available dry matter. Maize stover, liquid pig manure and solid chicken manure together contain another quarter of the substrates, while all the other substrates account only for roughly 5% of the total.

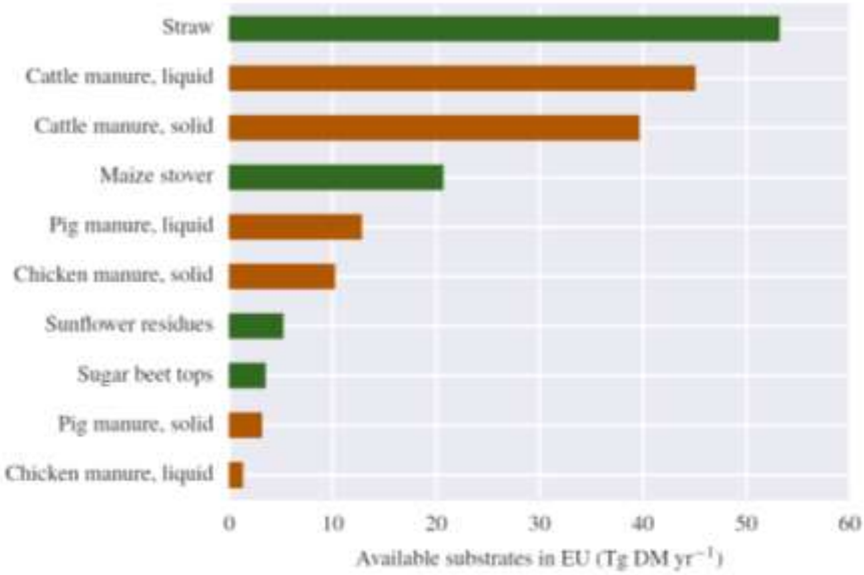

Figure 2. Estimated substrate quantities available in EU28, excluding Greece, after accounting for other uses for crop residues (bedding) and the maximum removal rate (40%, see Table 4).

However, the substrate composition varies widely across the EU, as seen in Figure 3. Some general trends are easily identified. First, crop residues are less common in mountainous areas. Second, manure and crop residue concentrations are rather segregated in some areas, for example in Ireland and the UK, Portugal and Spain, parts of France, Poland and Romania. Third, liquid manure management is less common in Eastern Europe, being almost nonexistent in some countries. Fourth, the C:N ratio of the available substrate mixture varies widely between regions (see Figure 4), as expected considering the spatial segregation of animal production and arable farming.

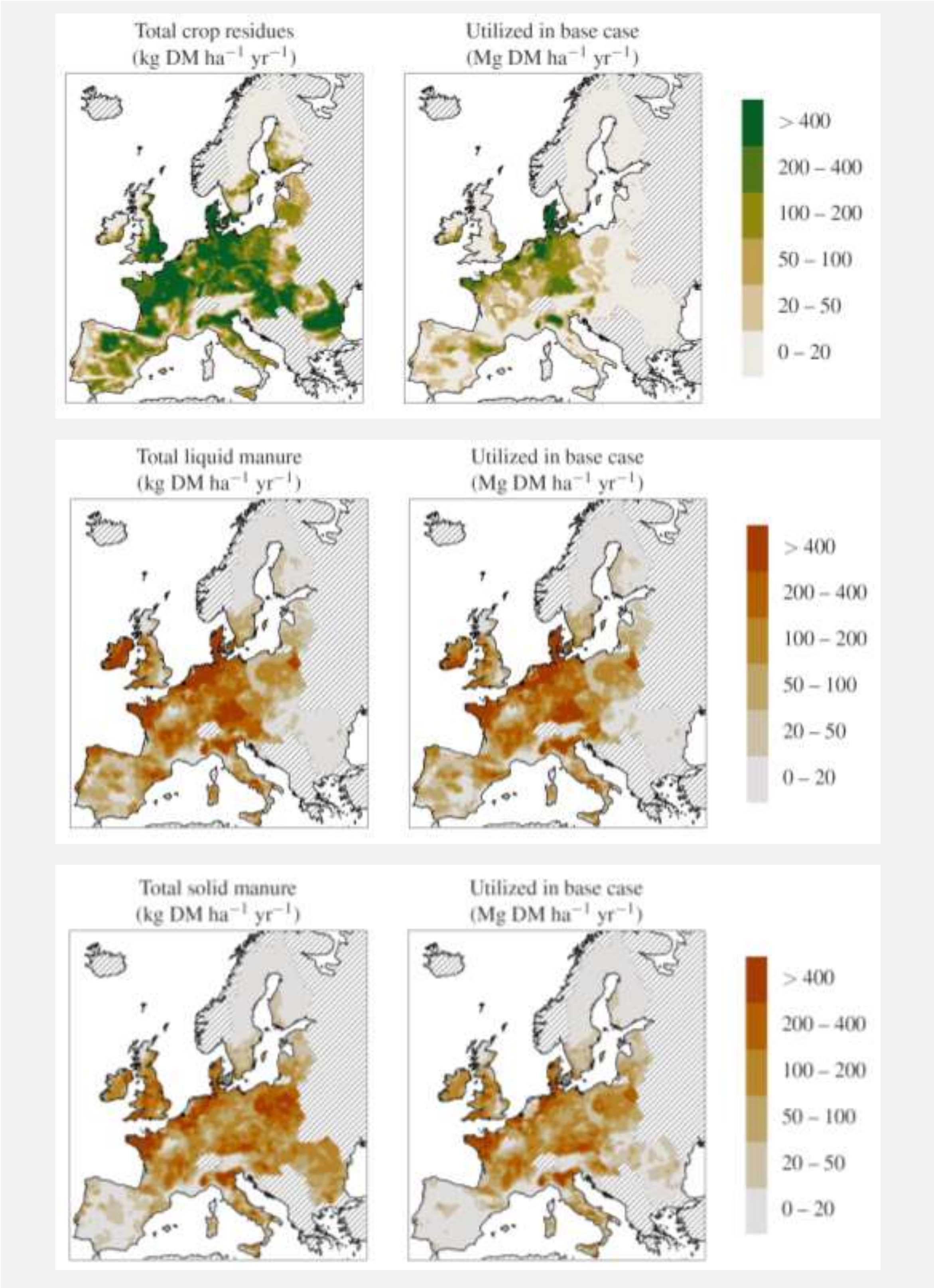

Figure 3. Total available substrates (left) and optimized use of substrates under technical and economic constraints (right) in the base scenario (see Table 4). Striped areas indicate missing data. See Section 2.3 for details on the optimization.

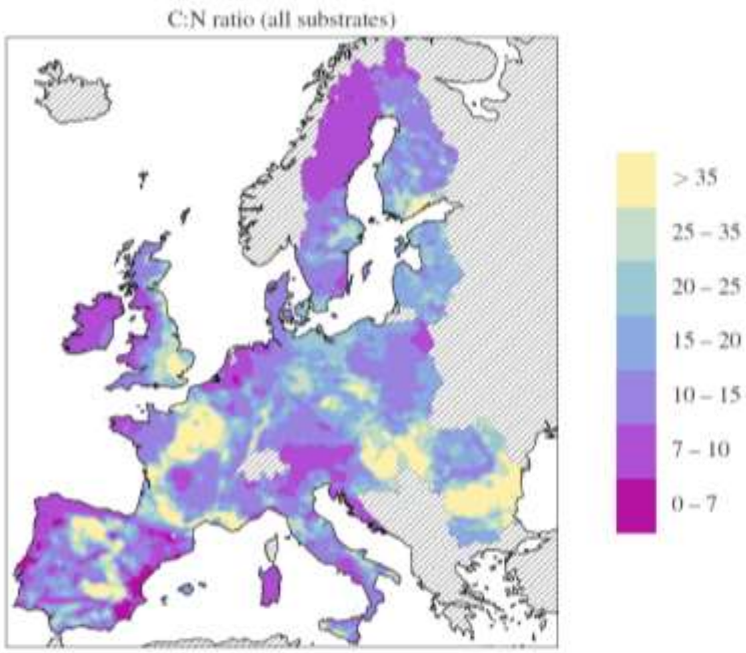

Figure 4. C:N ratio of the available substrates in the base scenario (see Table 4). Carbon and nitrogen contents of substrates are given in Table 3. Striped areas indicate missing data.

The technical and economic constraints described in Section 2.3 lead to very significant limitations on the biogas production potential. In the base scenario, we find that about three quarters of the manure substrates and one fifth of the crop residues can be used. The utilized share of each substrate is shown in Figure 5. In terms of biogas production, the potential in the base scenario is almost 700 PJ year^{-1} (HHV), or around half of the theoretical total obtained by assuming all substrates in Figure 2 could be digested.

The difference between available and utilized substrates is illustrated in Figure 6, showing a comparison between the theoretical biogas potential assuming all available substrates can be utilized and the technical potential in the base case. Note that many regions deviate significantly from the EU-wide utilization rates (Figure 5). In some regions (e.g. Denmark, the Netherlands, Belgium, and some parts of Germany, France and Italy), it seems possible to utilize almost all substrates, while in others (e.g. Poland, Hungary, Romania, Finland, parts of UK and France) only a small fraction could be used. The maps showing substrate densities and C:N ratios (Figures 3 and 4) provide more detail on the causes of this variation.

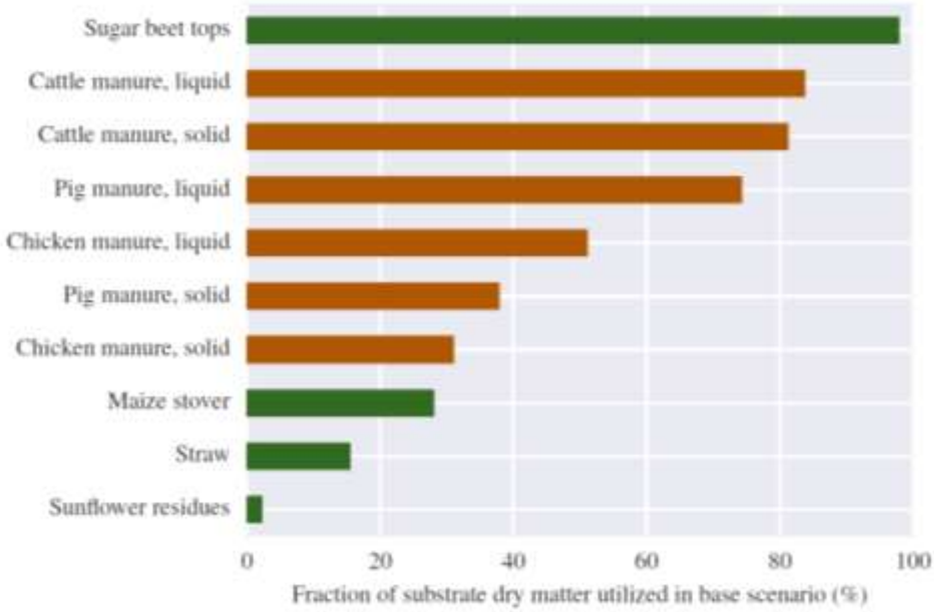

Figure 5. Estimated utilization of manure and crop residues, expressed as percent of the total available substrate quantities in the base scenario (see also Figure 2 for total amounts).

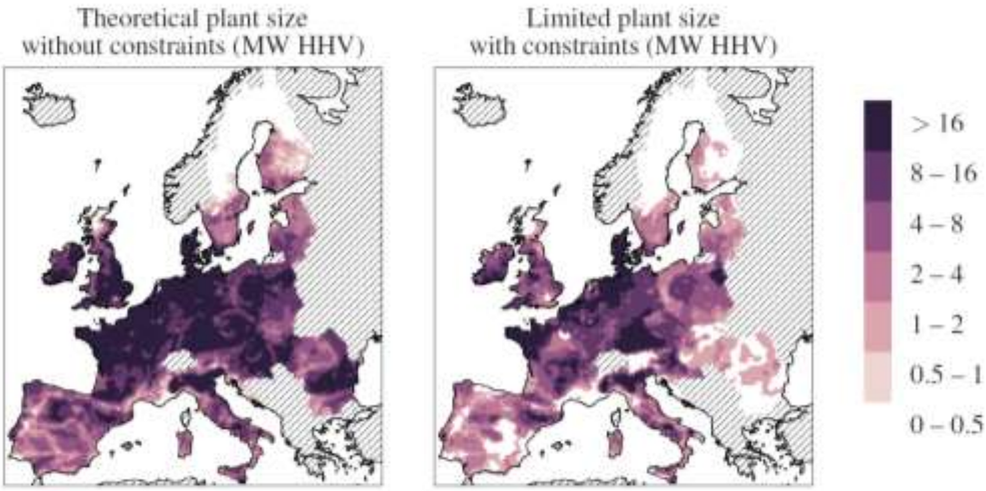

Figure 6. Left side: Theoretical biogas plant size supported by substrates available within a 20 km radius, without technical and economic constraints. Right side: Limited biogas plant size supported by the same substrates under the technical and economic constraints in the base scenario (produce ≥ 1 MW HHV, substrate mixtures with ≤ 12% DM and 10 ≤ C:N ≤ 35). Areas that are white on the right but not on the left support less than 1 MW HHV biogas production under technical constraints. Striped areas indicate missing data.

3.2 ANALYSIS OF SENSITIVITY TO MAJOR PARAMETER CHANGES

To learn how the biogas potential depends on the economic and technical constraints discussed above, we formulate a number of alternative scenarios starting from the base scenario and varying different combinations of two parameters at a time, in a wide range of values. We express the results of these scenarios as the total biogas potential relative to the biogas potential in the base scenario, thereby focusing attention on the relative response to changes in parameters. In this section we present illustrations and briefly describe results of some alternative scenarios. Interpretations of these results are further discussed in Section 4 below.

We first turn to the spatial density of substrates. Figure 7 shows that the potential is not much increased by allowing smaller production units or longer collection distances than in the base scenario, which means that low substrate density alone is not a primary limitation in the base scenario. Even with a minimum plant size typically used in vehicle fuel production (e.g 8 MW HHV), much of the total base case potential can be achieved by just extending the maximum collection radius to 30 km.

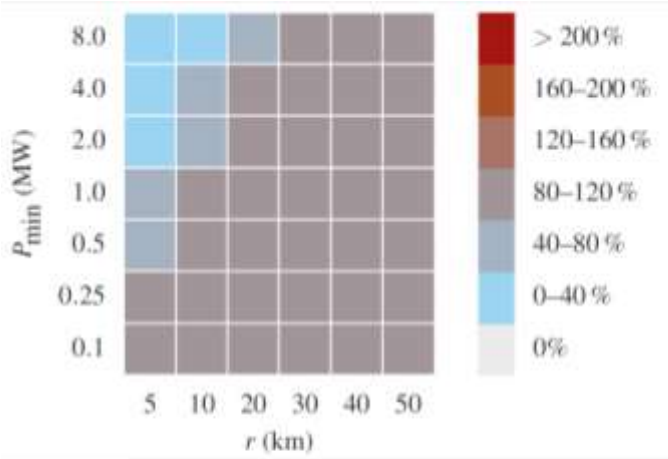

Figure 7. Total biogas potential expressed as percent of the base scenario potential. Each cell in the grid represents a different scenario, with all parameters as in the base scenario except for the collection radius (horizontal axis) and minimal plant size (vertical axis). Results show that total potential is not much increased by only increasing collection radius and/or decreasing the minimum plant size.

However, we noted above that only around one quarter of the crop residues and three quarters of the manure are used in the base scenario. Two of the constraint parameters are especially important to explain this. One is the maximal dry matter content of substrate mixtures, shown against minimal plant size in Figure 8. The figure shows that total biogas production increases by 60–100% in the model if substrate mixtures with up to 30% DM content can be digested. In these cases, the increased biogas production is due to increased use of the dry crop residues (straw, stover, sunflower residues). Allowing for drier substrate mixtures, a substantial amount of gas can be produced even if we require relatively large (4–8MW) plants.

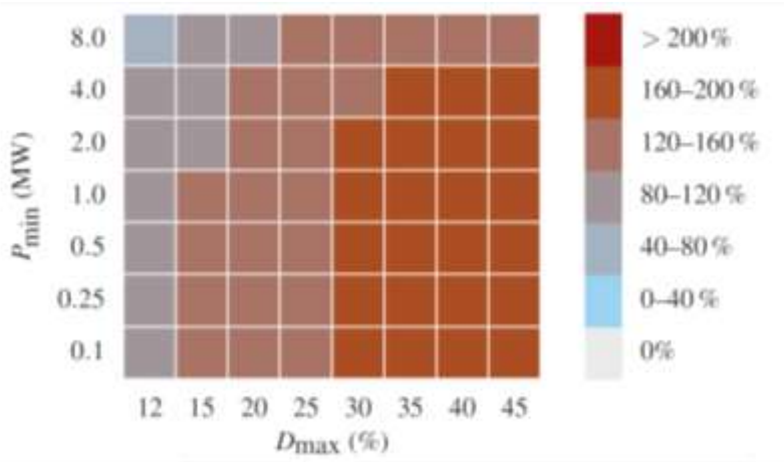

Figure 8. Total biogas potential expressed as percent of the base scenario potential. Each cell in the grid represents a different scenario, with all parameters as in the base scenario except for the maximum DM content (horizontal axis) and minimal plant size (vertical axis). The total potential can be increased by 60-100% compared to the base scenario by only allowing DM content up to around 30%.

Another notable limitation is the minimum C:N ratio of the substrate mixture. Figure 9 shows that simulated biogas production increases by 20–50% if the minimal C:N ratio is reduced from 10 (base scenario) to 7. Conversely, if the C:N ratio is increased compared to the base scenario, all other things equal, the biogas production quickly falls to zero because the nitrogen-rich manure substrates cannot be supplemented with carbon-rich crop residues in any large amounts without raising dry matter content above the 12% allowed in the base scenario.

Therefore it makes sense to consider modifications to the minimum C:N ratio and the maximum dry matter content in combination, as in Figure 10. The figure shows that allowing higher dry matter content has a strong positive effect on the simulated biogas production. It also shows that an increased minimal C:N ratio requires a higher maximal dry matter content in order to maintain a certain biogas production potential.

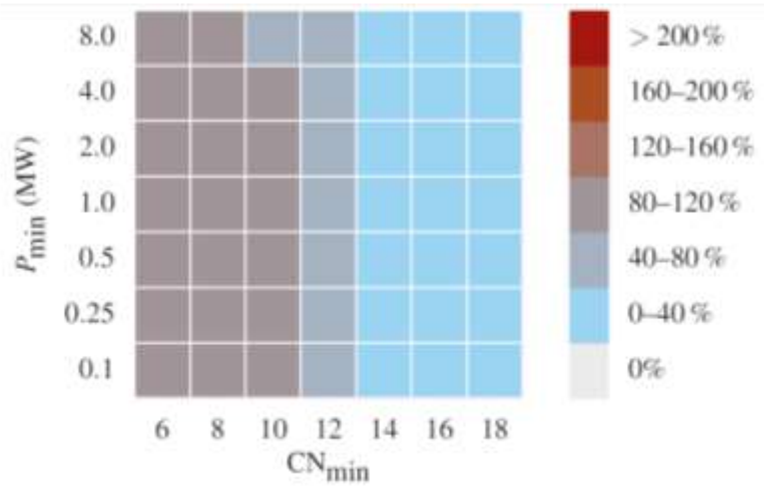

Figure 9. Total biogas potential expressed as percent of the base scenario potential. Each cell in the grid represents a different scenario, with all parameters as in the base scenario except for the minimum C:N ratio (horizontal axis) and minimal plant size (vertical axis). Increasing the minimum C:N ratio quickly erodes the biogas potential.

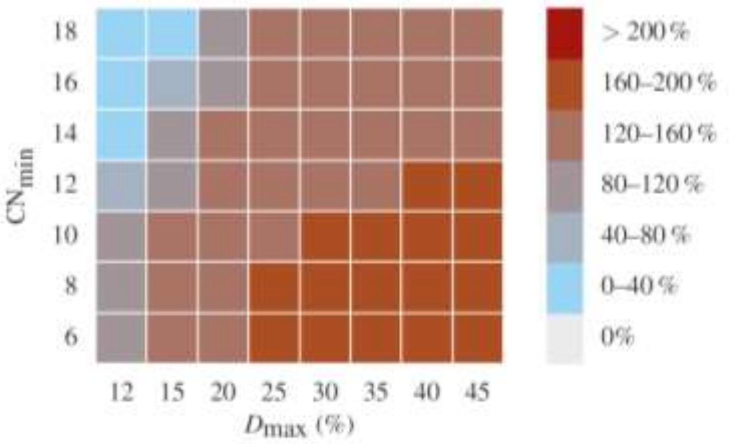

Figure 10. Total biogas potential expressed as percent of the base scenario potential. Each cell in the grid represents a different scenario, with all parameters as in the base scenario except for the maximum DM content (horizontal axis) and the minimum C:N ratio (vertical axis). Increasing the minimum C:N ratio quickly reduces the potential unless the maximum DM content is increased. The results show that carbon-rich crop residues are often available in sufficiently large quantities to adjust the C:N ratio upwards, but they cannot be used in any large proportion without increasing the DM concentration above the 12% allowed in the base scenario.

As shown in Figure 11, it makes almost no difference to reduce the maximum removal rate of crop residues in the base scenario. This further illustrates that the base scenario is not primarily limited by access to crop residues. However, if a higher maximum dry matter content is allowed in substrate mixtures, the maximum removal rate has a large effect on the maximum biogas production. With a low (20%) crop residue removal rate it does not help much to allow dry matter contents above 20%, but with very high (70–80%) residue removal the biogas production potential still increases fordry matter contents above 45%.

Another indication that crop residues are often available in relatively large quantities is found in results with a lower limit on dry matter concentration (not shown). In the base scenario, requiring dry matter > 10% makes almost no difference, and still larger DM contents could be arranged in many areas.

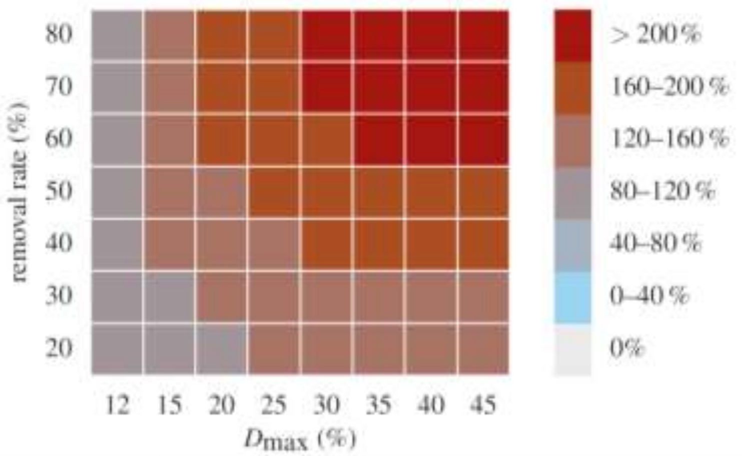

Figure 11. Total biogas potential expressed as percent of the base scenario potential. Each cell in the grid represents a different scenario, with all parameters as in the base scenario except for the maximum DM content (horizontal axis) and the removal rate of crop residues (vertical axis). Only changing the supply of crop residues up or down makes almost no difference, but if the upper limit on DM content is increased, additional crop residues can increase the potential very substantially.

4 DISCUSSION

The main purpose of this section is to summarize and discuss our contributions to the understanding of what limits biogas production from crop residues and manure in the EU. We discuss a number of technical and economic aspects and show, where possible, how the presented model can be used to analyze the problem. Along the way, we also point out the main uncertainties in the analysis, and suggest some possible directions for further work.

Before beginning this discussion we make a general point which is very important to keep in mind when interpreting the model results. In addition to the constraints explicitly included in the model, i.e. the constraints on physical and chemical properties of substrates, collection distances, and so forth, there are some important constraints implicitly enforced simply by not including them in the model. For example, since our model only covers manure and crop residues, it is implicitly assumed that no addition of other co-substrates, such as energy crops or industrial waste, is possible. Another notable omission in the model is the possibility to affect the production of manure and crop residue substrates, e.g. by changing manure management systems or crop production. Given economic incentives to do so, there is considerable room for changes in the production of these streams.

These examples demonstrate that there are good reasons to vary the model's constraint parameters (minimal/maximal dry matter content and C:N ratios, residue removal rate, collection distance, minimal plant size) in one direction or the other, beyond what is motivated from the literal model interpretation of biogas production based only on manure and crop residues. For example, the changes in dry matter content and C:N ratios modelled in the alternative scenarios above can be interpreted as the possibility to add wet and carbon-rich substrates (e.g. some energy crops) to avoid the constraint limiting the potential in the base case. Admittedly, such an approach is crude, and hard to apply in a quantitatively precise manner, but it may nevertheless provide important insights on how the maximal utilization of crop residues and manure would be affected by various aspects not explicitly included in the model.

4.1 CARBON SOURCES AND DRY MATTER CONCENTRATION

We find the constraints on maximum dry matter content and minimum C:N ratio of substrate mixtures to be among the most interesting, both because they strongly influence the model results and because there is considerable room to argue for different parameter values. Recall that only about one quarter of the available crop residues is utilized for biogas production in the base scenario. In many locations, their full utilization would lead to dry matter concentrations far too high to be compatible with wet digestion, which is the technology assumed in the base scenario. Therefore, we consider ways to ease the limitations caused by high dry matter content, i.e., either to allow digestion of drier substrate mixtures (increase D_{max} in the model), or to lower the dry matter concentrations by adding water or other wet substrates. Only the first of these two is explicitly covered by our model, but increasing the D_{max} value could also be taken as a crude proxy for the effect of adding wet co-substrates, at least giving a useful indication of how that would affect the potential for utilization of crop residues.

To some extent, it might also be possible to increase DM concentrations in existing CSTR technology depending on degradation rate in the reactor as well as mixing technology and the acceptance for increasing electricity use for mixing, etc. It is also possible to implement other reactor configurations designed for dry feedstock. However, such designs are today less common and probably require additional development. Regarding the C:N ratio it should be noted that this is a rough indicator of how suitable different substrates are for biogas production. Still, it does indicate something about the characteristics, which need to be considered. We have noted (results not shown) that excess C is rarely a limitation, even if high DM concentrations are allowed. Excess N is likely a bigger limitation in some areas, but nowhere near as important as the dry matter content: as seen in Figure 10, the estimated potential does not change much if one reduces CN_{min} from 10 to 5. However, increasing the CN_{min} much above 10, as can be argued according to some investigations (see Section 2.3.4), quickly erodes a large part of the biogas production potential. This is also related to the dry matter concentration: Plenty of carbon-rich crop residues are available to increase the C:N ratio, but doing so would often lead to dry matter concentrations unsuitable for wet digestion.

4.2 PRODUCTION AND REMOVAL OF CROP RESIDUES

In the base scenario, it makes little or no difference to increase or decrease the allowed removal rate of crop residues, because the base scenario is primarily limited by too high dry matter content, not by lack of crop residues. However, relaxing the constraint on maximum dry matter concentrations (see Figure 11) it turns out that the removal rate of crop residues has a strong effect on the biogas potential. Therefore, it is important to look closer at some arguments for what the maximum removal rate should be.

Most often mentioned in the literature is an agricultural sustainability argument: excessive removal of straw and other crop residues may result in decreased soil quality and fertility (for example due to lower microbial activity in soil, weaker erosion protection and water retention capacity). What is to be considered excessive depends both on local conditions (e.g. soil type and climate) and on management-related conditions (crop rotations, the quality and application rate of other soil amendments such as manure and/or biogas digestate). Clearly, this is a point where our analysis is limited. The model can trivially be modified with a location-dependent removal rate, but the determination of that rate is a hard task.

Another important consideration is the annual variability in residue supply. Kretschmer et al. (2012) have discussed this in some detail and point out two reasons for why annual variability might be high. First, the weather conditions affects both the crop yield and the residue yield considerably. Second, and perhaps more importantly, the weather conditions after harvest may make it impossible or inappropriate to collect some residues because doing so would lead to large damages on soils, or because residues are degraded by rain. In years with low supply of crop residues, there can be strong competition for other uses, leading to higher prices. We conclude that there is an economic risk associated with investing in energy production capacity which is dependent on a locally high residue removal rate.

In this work we have taken the supply of crop residues as exogenously determined, essentially only dependent on the harvested amount of crops. But given a higher willingness to pay for crop residues, the supply could be increased. Nilsson and Bernesson (2009) indicate a couple of factors affecting the supply of straw, the first being that the straw-to-kernel ratio depends on which variety is cultivated. The second is that stubble height, according to Nilsson and Bernesson (2009) typically around 20 cm for cereals and 40 cm for rape and turnip rape, can easily be lowered at the expense of reduced harvester speed, meaning that straw production could be increased given a higher willingness to pay for straw removal. Similarly, Kreuger et al. (2014) have shown that the production of sugar beet residues has a rather strong dependence on the level of nitrogen fertilization, indicating that also this residue production could be increased, given economic incentives to do so.

4.3 SUBSTRATE DENSITY AND THE SCALE OF PRODUCTION

There is a number of intricacies related to substrate density, collection logistics, and the size of production units which we have not yet touched upon. In this section we discuss the difficulties in analyzing these issues and summarize our own findings.

In general, biogas production is characterized by significant positive returns to scale when comparing the investment cost and production cost for similar biogas plants based on similar feedstock. The returns to scale are, however, reduced by transportation cost for feedstock and digestate. Thus, from an economic point of view there is a tradeoff between scale of production and transportation distance.

The optimal choice of plant size and substrate collection strategy depends on many factors, for example the layout and quality of road networks, the exact spatial distribution of substrates, alternative uses for substrates, and the seasonal variation in production of some substrates such as crop residues and manure from animal housing only used during parts of the year. Furthermore, the economic viability of a biogas plant may be radically changed if it is co-located with a major source of substrates, for example the manure storage of a large farm, an industrial process with by-products suitable for biogas digestion, or a sewage treatment plant, because in such cases substrates can be automatically transported from the source to the digester using pumps or other machinery.

Taking these issues into account in a quantitative model would require a quite different approach than ours, incorporating large amounts of detailed data and preferably using an explicit model of plant locations rather than our simple weighted-average approach. As mentioned in the introduction, such analyses are possible, but have to our knowledge only been done for rather small geographical areas, probably primarily because sufficiently detailed data sources are scarce.

Despite the difficulties just mentioned, we draw a couple of general conclusions concerning substrate density, transport distances and plant sizes where the model results are strong enough to motivate it. If only small to medium-sized production plants are considered, changing the collection radius in the interval 5–50 km makes little difference for the overall potential, meaning that the majority of the biogas potential is located in areas where substrate density is quite sufficient. However, if we require a larger production scale, up to those typical when upgrading to vehicle fuel quality, a large share of the potential is lost unless the collection radius is increased. Again, note that these results assume a feedstock only consisting of manure and crop residues: if other co-substrates are added, the required production scale will be easier to reach.

4.4 VEHICLE FUEL PRODUCTION

When producing vehicle fuel, economics of scale is even more distinct and there are very few farm scale upgrading plants in operation today. For instance, IEA Bioenergy Task 37 (2015) presents a list of upgrading plants within member states in IEA Task 37 where only 10% of over 300 plants have an installed capacity of 120 $m^3 h^{-1}$ or less (roughly 0.5 MW HHV), and the average unit size is around 1000 m^3 h^{-1} (5 MW HHV). This is probably due to techno-economic reasons but also the issue of utilizing the upgraded biogas. Biogas is produced all year round and storage is expensive. Thus, the biogas produced must be utilized more or less continuously. Fuel consumption at farms is often concentrated to relatively short periods of time and are also few tractors and other machinery available that can use biogas at all. As a consequence, it is difficult to utilize upgraded biogas at farm scale even of the production cost as such would be acceptable. Thus, upgraded biogas must be transported to an external market by truck or grid. This transportation cost ads an extra parameter in the optimization of optimal scale and location of the biogas plant and the upgrading plant.

Given current techno-economic conditions it seems difficult to build profitable farmscale biogas and upgrading plants. This is also demonstrated by the fact that most biogas systems are based on production units that are large enough to support a cost-efficient upgrading plant resulting in transportation of feedstock and digestate as well as upgraded biogas.

An alternative approach, which is demonstrated in one location in Sweden (Brålanda) is to build several farm-scale biogas plants, which minimize transportation of feedstock and digestate, and connect them with a gas grid to a central upgrading plant. With this solution it is possible to build a cost efficient upgrading plant but it also requires a gas grid which adds cost to the project. The cost for the gas grid is almost only capital cost which mostly depends on the length of the grid and ground conditions. The amount of distributed biogas has a limited effect on the investment cost. Thus, the feasibility of this approach depends of the length of the gas grid, ground conditions but also the amount of biogas produced. An area with large farms with short distances between could thereby be suitable for this gas grid solution while an area with long distances or lower biogas potential might call for a more centralized approach.

The decentralized solution with several small biogas plants does however require that many farms are interested in investing in a biogas plant at the same time. Given that different farms have different conditions regarding scale, economy, time perspective on their primary production etc. this is probably an issue of great importance for the possibility to establish this kind of projects. It is also more dependent on the situation on each farm as compared to a large centralized biogas plant. How the biogas potential from agricultural residues should or could be utilized will thus vary from different areas and is not only connected to techno-economic calculations but also the interest and capacity of individual farmers.

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APPENDIX A: CROP RESIDUES

Data on harvest are collected from three different tables in Eurostat:

- agr_r_crops, listing harvested amounts of some of the investigated crops (wheat, barley, sugar beet, rapeseed and turnip rape, sunflower seed) for most NUTS2 regions (NUTS1 for Germany and the UK) in each year;
- ef_oluaareg, listing planted areas of all the investigated crops on NUTS2/NUTS1 level, as measured in the triannual farm structure survey (years 2007, 2010, 2013, etc);
- apro_cpp_crop, listing harvested amounts of all the investigated crops on NUTS0 (national) level in each year.

Where available, we use data from agr_r_crops, averaged over the years 2009–2011. When not available, we estimate the subnational harvest data by assuming a constant area yield in each country, i.e., distributing the total NUTS0 harvest (apro_cpp_crop data) proportional to the NUTS2/NUTS1 planted areas (ef_oluaareg data) for the year 2010.

The nomenclature in these table is not completely identical across tables. We connect crops to statistical codes as shown in Table 5.

Table 5. Crops and Eurostat statistical codes.

Crop	Eurostat names	Agr_r_crops, ef_oluaareg tables	Apro_cpp_crop table
Wheat	Common wheat and spelt, durum wheat	C1120, C1130	B_1_1_1_HA, B_1_1_2_HA
Rye	Rye (rye and maslin if rye not available)	C1150 (C1140)	B_1_1_3_HA
Barley	Barley	C1160	B_1_1_4_HA
Oats	Oats	C1180	B_1_1_5_HA
Grain maize	Grain maize	C1200 (C1201)	B_1_1_6_HA
Sugar beet	Sugar beet	C1370	B_1_4_HA
Rapeseed	Rape and turnip rape	C1420	B_1_6_4_HA
Sunflower seed	Sunflower seed	C1450	B_1_6_5_HA

APPENDIX B: MANURE

B.1 ANIMAL POPULATIONS

Animal populations are taken from the triannual farm structure survey, Eurostat table ef_olsaareg. We use data from 2010.

The classification of animals used for manure management systems in the National Inventory Reports is more aggregated than the Eurostat population data, so we aggregate the animal populatios from ef_olsaareg into the NIR manure management classes as follows. We use the average manure management reported during the years 2009–2011.

- **Cattle, option A**
  - Dairy cattle: C_2_6_HEADS
  - Non-dairy cattle: C_2_1_HEADS, C_2_2_HEADS, C_2_4_HEADS, C_2_3_HEADS, C_2_5_HEADS, C_2_99_HEADS
- **Cattle, option B**
  - Mature dairy cattle: C_2_6_HEADS
  - Mature non-dairy cattle: C_2_4_HEADS, C_2_99_HEADS
  - Young cattle: C_2_1_HEADS, C_2_2_HEADS, C_2_3_HEADS, C_2_5_HEADS
- Breeding pigs: C_4_2_HEADS
- Fattening pigs: C_4_99_HEADS
- Laying hens: C_5_2_1000_HEADS
- Broilers: C_5_1_1000_HEADS

The two different options for cattle classification are both included because manure management systems are reported in the National Inventory Reports according to either one of them (chosen by the reporting country).

The population data is multiplied by the excretion factors (see Table 2) to obtain a total excreted amount per animal category and manure management class. Before disaggregating the manure amounts spatially, we aggregate them to the GLW2 classes (cattle, pigs, chickens).

B.2 MANURE MANAGEMENT SYSTEMS

In the National Inventory Reports, seven manure management systems are included, which we aggregate into three classes (liquid, solid, unavailable) according to Table 6.

Countries do not seem to use the National Inventory classifications completely in the same way. For example, some countries (e.g. Sweden and Denmark) seem to use the category “Other” to indicate deep bedding (a.k.a. bedded pack) systems, while others (e.g. UK, Germany and France) include such systems in the “Solid storage” category. In face of these ambiguities, we choose to only include one type of solid manure system.

The description of solid manure systems is especially problematic since there seems to be a very wide variation within this category. The word may be used to describe everything from relatively wet (around 15% DM) mixtures of manure and straw, removed daily, to deep bedding (roughly 25-30% DM) which is stored and partially composted for several months before removal. We have only encountered anecdotal evidence on the amounts and types of bedding material used in “solid” systems. Loosely based on such evidence we have chosen to assume that in solid manure systems for cattle and pigs, bedding straw is added to excretions in the ratio 1:1 (volatile solids basis).

Table 6. Aggregation of manure management systems in National Inventory Reports to the three classes used in this report.

Management system	National Inventory Report Classification
Liquid	Anaerobic lagoon, Liquid system
Solid	Solid Storage, Dry lot, Other
Unavailable	Pasture range paddock, Daily spread

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