Biomethane production potentials in the EU

Feasibility of REPowerEU 2030 targets, production potentials in the Member States and outlook to 2050

A Gas for Climate report

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GAS FOR CLIMATE
A path to 2050

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Authors
Sacha Alberici, Wouter Grimme and Gemma Toop

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Contact
Guidehouse
Stadsplateau 15, 3521 AZ Utrecht
The Netherlands
+31 30 662 3300
guidehouse.com

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Design
Annemiek Schellenbach | byannem.nl

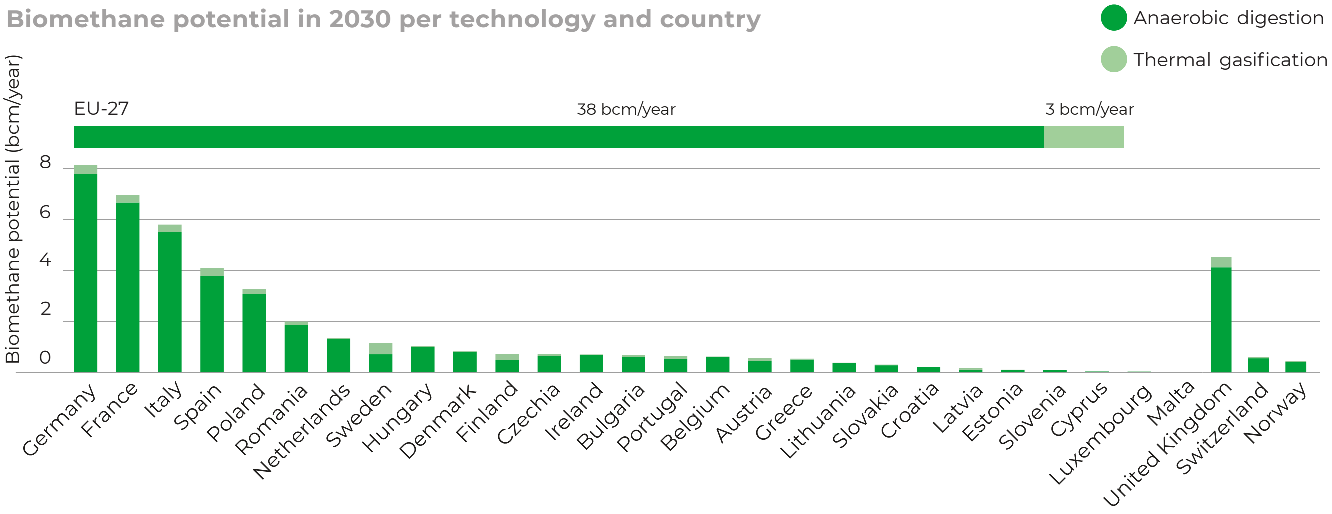
Executive summary

Biomethane can play an important role in meeting the European Union (EU) 2030 GHG reduction target and achieving net-zero emissions by 2050. Additionally, biomethane increases European energy security by reducing the dependency on Russian natural gas and can alleviate part of the energy cost pressure on households and companies. The European Commission fully recognises these benefits and thus set a target of 35 billion cubic meters (bcm) of annual biomethane production by 2030 in its recent REPowerEU plan. Today, 3 bcm of biomethane and 15 bcm of biogas are produced in the EU-27.

Gas for Climate[1] previously estimated the sustainable supply potential of biomethane in the EU-27 and UK at 35 bcm in 2030 and 95 bcm by 2050. Building on the renewed ambition by the EU to accelerate biomethane production and the advancements in technology, we updated our production potentials to reflect these recent developments. In this paper, we apply a unified methodology to identify both the short- and long-term potential of biomethane production in each EU Member State (plus Norway, Switzerland and the UK), based on sustainable feedstocks.[2] Our key findings include:[3]

→ **Enough sustainable feedstocks are available in the EU-27 to meet the REPowerEU 2030 target (35 bcm). Our estimation shows that up to 41 bcm of biomethane in 2030 (Figure 1) and 151 bcm in 2050 (Figure 2) could be available.** This is significant as the current (2020) EU natural gas consumption is 400 bcm (of which 155 bcm was imported from Russia).[4]

Figure 1.
Biomethane potential in 2030 per technology and country



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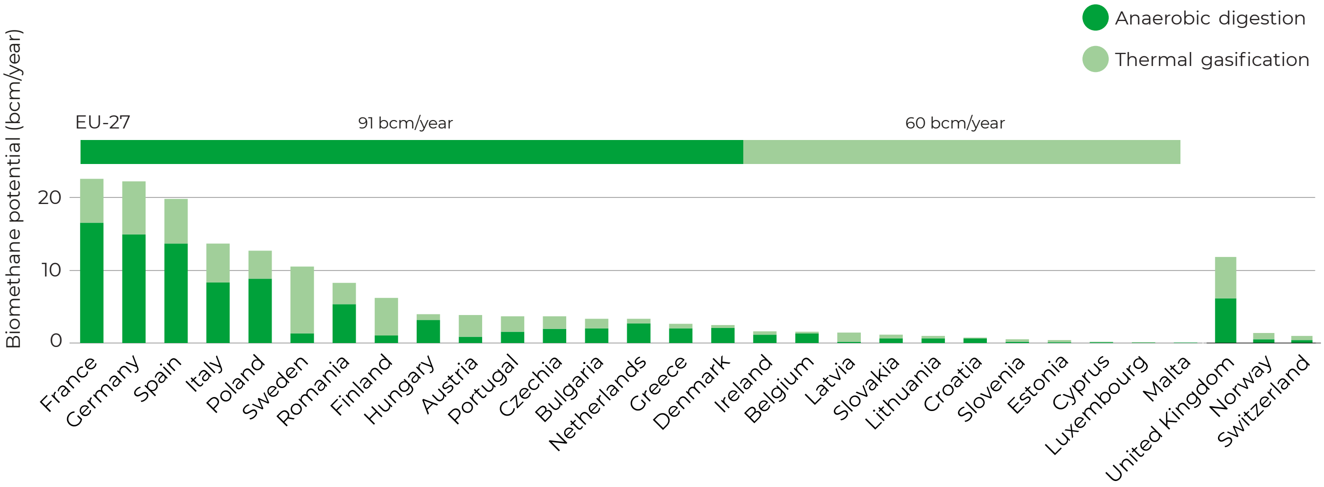
[1] Gas for Climate (2019), The optimal role for gas in a net-zero emissions energy system. Navigant. https://gasforclimate2050.eu/sdm_downloads/2019-gas-for-climate-study/

[2] In the context of this study, strict sustainability criteria are applied in the selection of the feedstocks. As such, wastes and residues are prioritised with consideration of sustainable removal rates and existing uses (as applicable). Energy crops (e.g. mono-cropping of maize) and stemwood are not considered. Sequential crops are considered as they do not impact existing food or feed markets (see section 2.3.7).

[3] Note that our estimates might deviate from nationally specific studies investigating feedstock availability for sustainable biomethane production. This is due to varied methodologies and assumptions being applied across national studies. Our approach applies a common methodology to all countries. Comparisons with selected national studies are included in the Annex of this paper.

[4] European Commission (2021), Energy. https://ec.europa.eu/energy/sites/default/files/quarterly_report_on_european_gas_markets_q4_2020_final.pdf

Figure 2.
Biomethane potential in 2050 per technology and country



→ **Anaerobic digestion:**[5] A potential of **38 bcm is estimated for anaerobic digestion in 2030 for EU-27** increasing to **91 bcm in 2050**. The top 5 countries in both 2030 and 2050 consistently include France, Germany, Italy, Poland and Spain. Key feedstocks in 2030 are manure (33%), agricultural residues (25%) and sequential cropping (21%). This contrasts with 2050 in which sequential cropping dominates (47%), with again a significant contribution from manure (19%), and agricultural residues (17%). Industrial wastewater contributes over 10% of the potential in both 2030 and 2050.

→ **Thermal gasification:**[6] A potential of **2.9 bcm is estimated for thermal gasification in 2030 for EU-27** increasing to **60 bcm in 2050**. The top 5 countries in 2030 and 2050 consistently include France, Germany, Spain, Sweden and Italy.[7] Key feedstocks in both 2030 and 2050 are forestry residues and wood waste, which collectively represent over 60% of the potential.

→ Even **more biomethane potential can be unlocked** by looking at additional feedstocks (e.g. biomass from marginal or contaminated land and seaweed, as noted in the REPowerEU plan[8]), and technologies (e.g. hydrothermal gasification of wet feedstocks, including organic wastes and residues). Renewable methane (or power to methane), produced from renewable electricity and biogenic CO$_2$ captured in biogas upgrading can furthermore contribute additional potential, as can landfill gas.

Following the renewed biomethane ambition by the EU, the 35 bcm target needs to be translated by the Member States into national targets, incorporated into their National Climate and Energy Plans and appropriate measures (e.g. permitting, financing, certification, etc) enacted to scale up their domestic biomethane industries.

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[5] Anaerobic digestion is a commercially deployed technology and is able to readily process a wide variety of biogenic feedstocks, including wastes such as animal manure, biowaste and industrial wastewater.

[6] Thermal gasification with biomethane synthesis is not yet commercially available, but the potential to scale up is large in the mid to long term (2030 and beyond). Importantly this technology can process feedstocks with low anaerobic biodegradability, such as sustainable woody biomass and solid wastes.

[7] The UK is another country with significant gasification potential, however, is excluded in this overview as a non-EU country.

[8] European Commission (2022), Commission Staff Working Document, SWD(2022) 230 final, Implementing the REPowerEU Action Plan: Investment needs, hydrogen accelerator, and achieving the bio-methane targets. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230&from=EN

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1.

Results

In this chapter, we provide an overview of the biomethane potential estimates per country in 2030 and 2050. The potentials are presented by technology and by feedstock for each technology type. Renewable methane (or power to methane), produced from renewable electricity and biogenic CO_2 captured in biogas upgrading can contribute further to future supply but is not the focus of this report. Landfill gas is also not included.

1.1 Total biomethane potentials in 2030 and 2050

A biomethane potential of 45.1 bcm is estimated for 2030 (of which 41.1 bcm relates to the EU-27), increasing to 165 bcm in 2050 (of which 151 bcm relates to the EU-27). The 2030 estimate is almost entirely based on anaerobic digestion (93% of the total). Thermal gasification makes a meaningful contribution to the potential in 2050, with a 41% share of the total (67 bcm).

Figure 3.
Biomethane potential in 2030 per technology and country

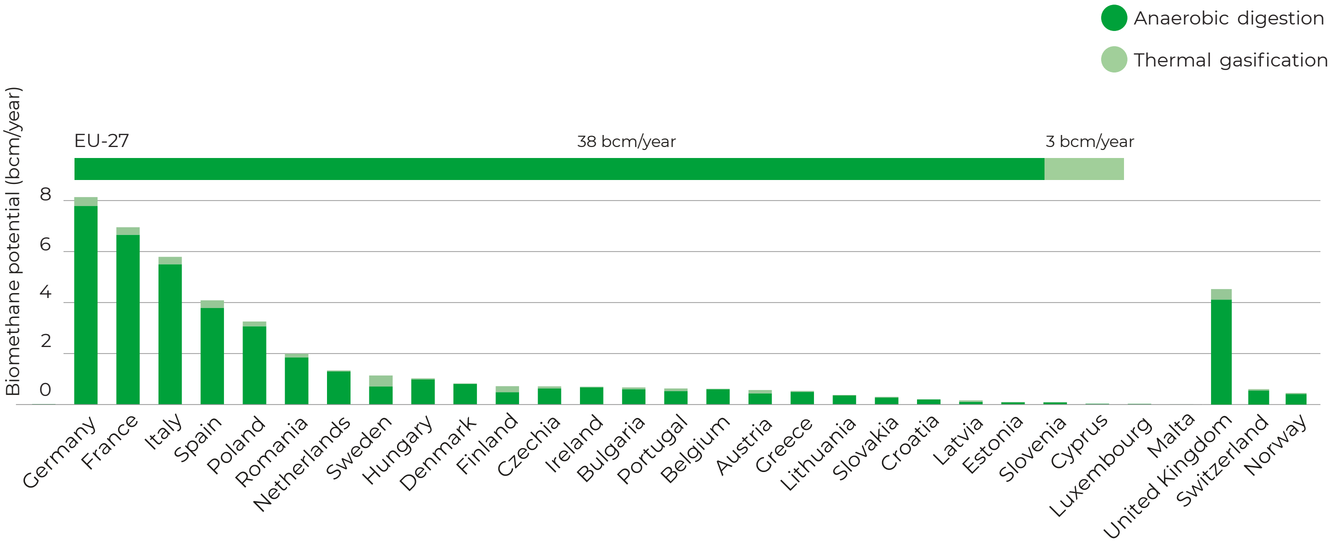
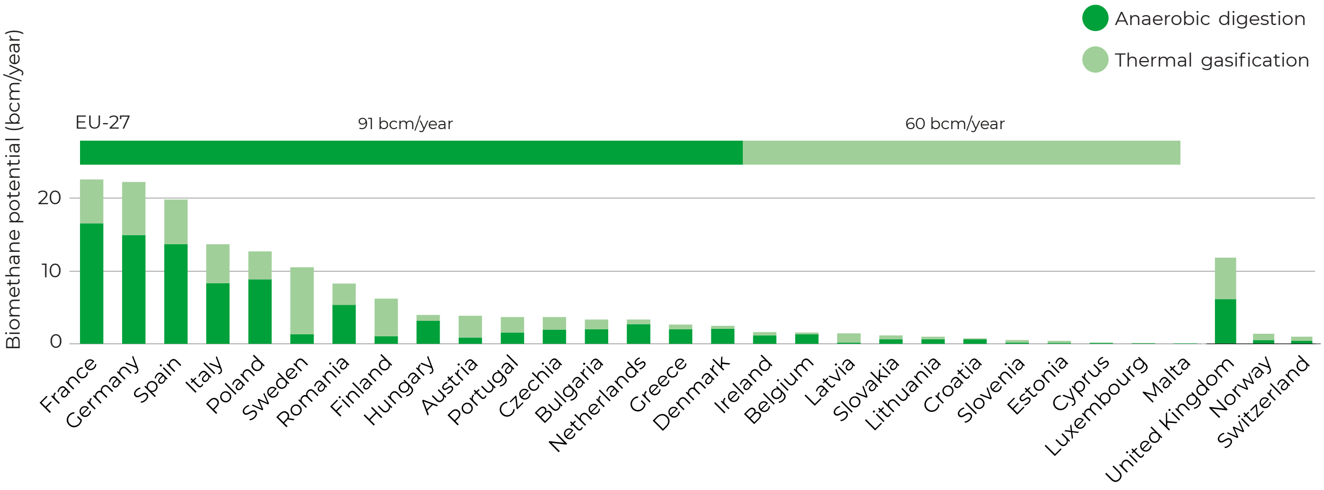


Figure 4.
Biomethane potential in 2050 per technology and country



The EU-27 countries with the highest potentials in both 2030 and 2050 are broadly similar and include France, Germany, Italy, Spain and Poland. Collectively these countries represent over 50% of the total biomethane potential. High potentials are also seen in the UK in both 2030 and 2050. The distribution between 2030 and 2050 differs slightly, with Germany having the highest potential in 2030 and France in 2050. Of note, is that Sweden, and Finland to a lesser extent, contribute significant potentials in 2050, largely driven by the significant gasification potential.

1.2 Biomethane potentials – Anaerobic digestion in 2030 and 2050

A potential of 41.8 bcm is estimated for anaerobic digestion in 2030, of which 38.1 bcm relates to the EU-27 (Figure 5). The potential increases to 98 bcm in 2050, an increase of 56 bcm (Figure 6). The top 5 countries in both 2030 and 2050 consistently include France, Germany, Italy, Spain and Poland. Key feedstocks in 2030 are animal manure (32%), agricultural residues (24%) and sequential cropping (21%). This contrasts with 2050 in which sequential cropping dominates (47%), with again a significant contribution from manure (19%), and agricultural residues (17%). Industrial wastewater contributes over 10% of the potential in both 2030 and 2050.

Figure 5.
Anaerobic digestion potential in 2030 per feedstock and country

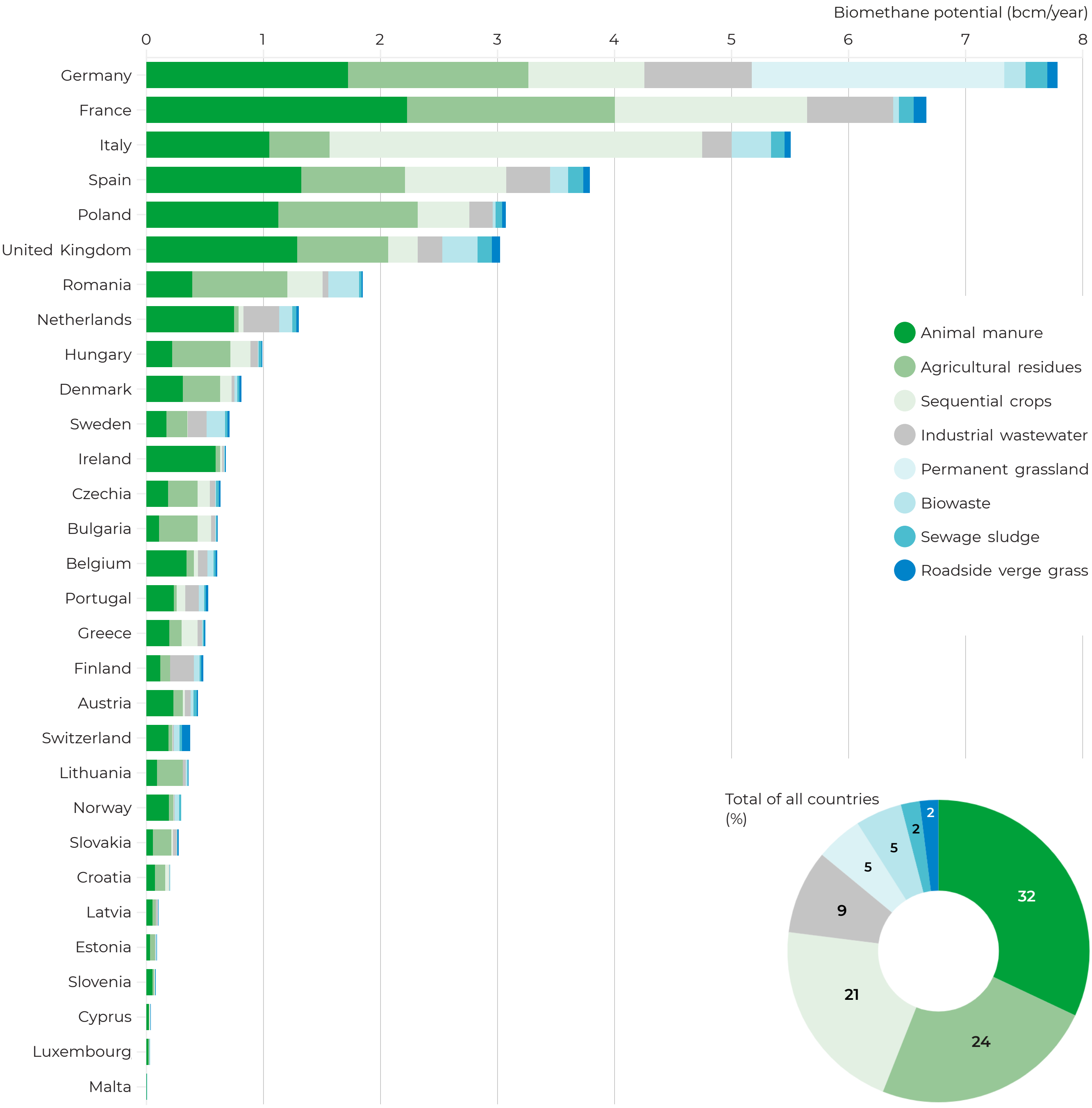
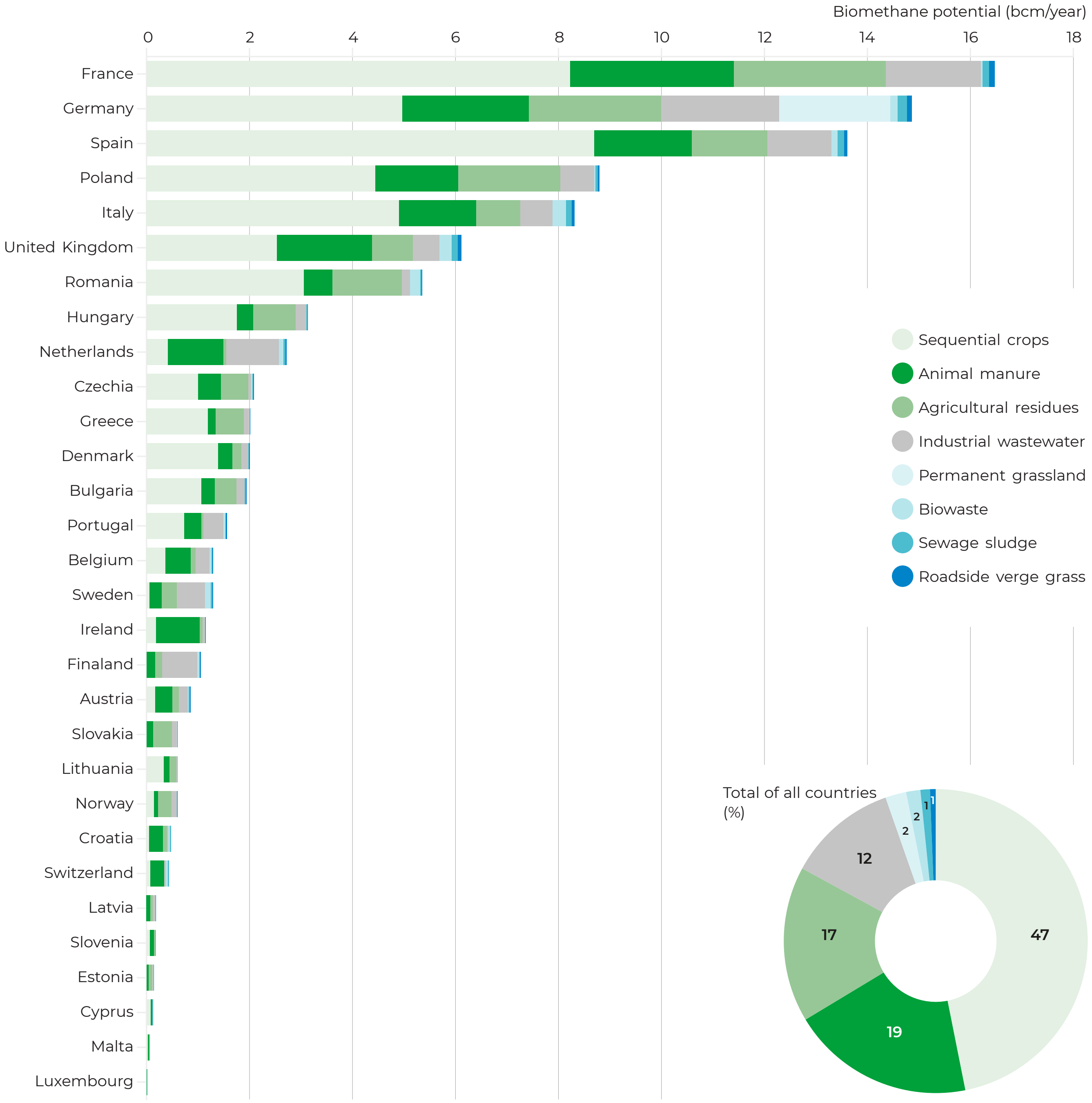


Figure 6.
Anaerobic digestion potential in 2050 per feedstock and country



1.3 Biomethane potentials – Thermal gasification in 2030 and 2050

A potential of 3.3 bcm is estimated for thermal gasification in 2030, of which 2.9 bcm relates to the EU-27 (Figure 7). The potential increases to 67.1 bcm in 2050, an increase of 63.8 bcm (Figure 8). The top 5 countries in 2030 and 2050 consistently include France, Germany, Spain, Sweden and the UK. Key feedstocks in both 2030 and 2050 are forestry residues and wood waste, which collectively represent over 60% of the potential. Finland and Poland also contribute significant potential in both 2030 and 2050.

Additional potential could be available from hydrothermal gasification, which as indicated in section 2 was not considered in this study.

Figure 7.
Thermal gasification potential in 2030 per feedstock and country

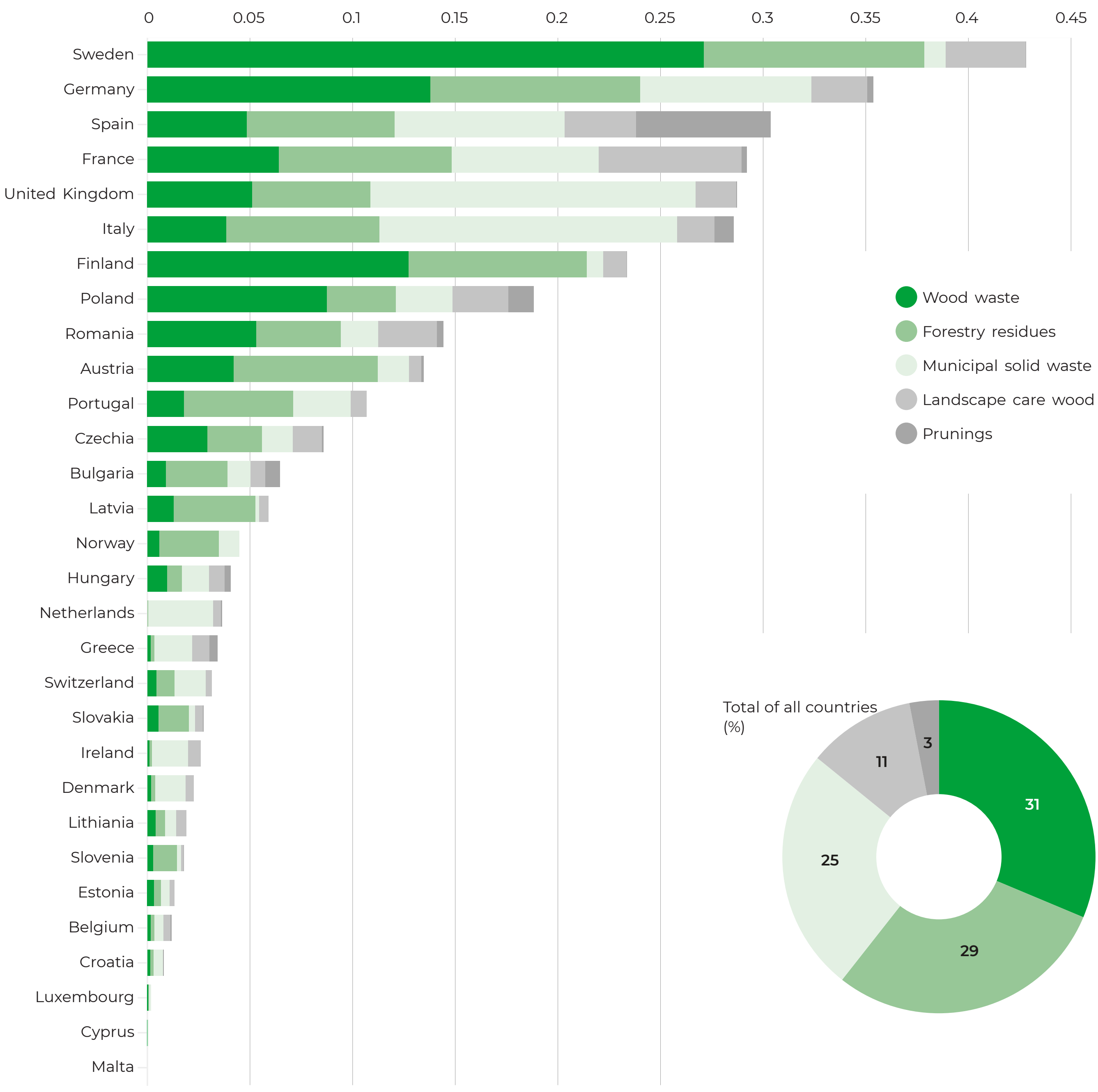
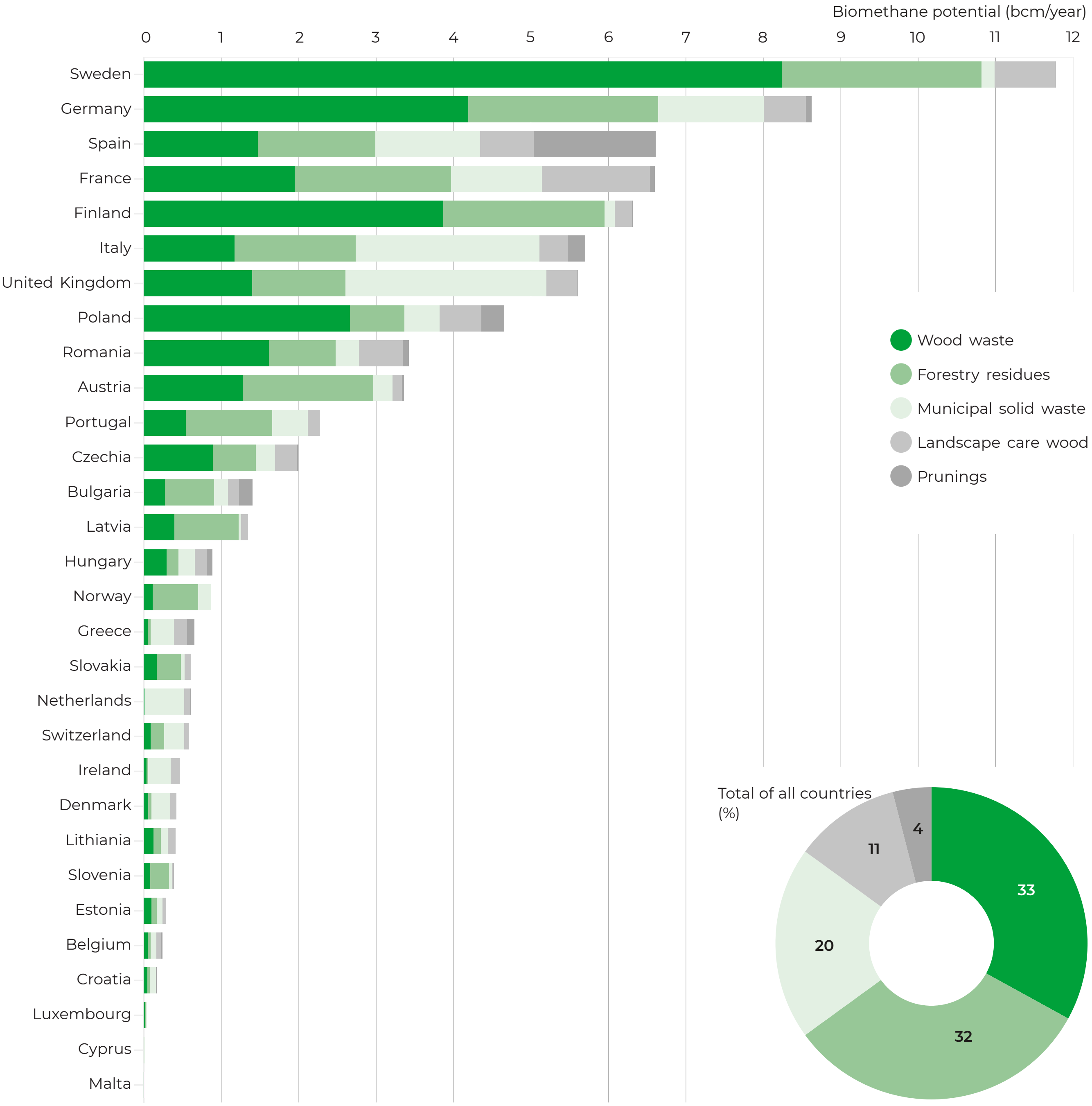


Figure 8.
Thermal gasification potential in 2050 per feedstock and country



1.4 Comparison of 2022 estimates with the 2019 Gas for Climate estimates

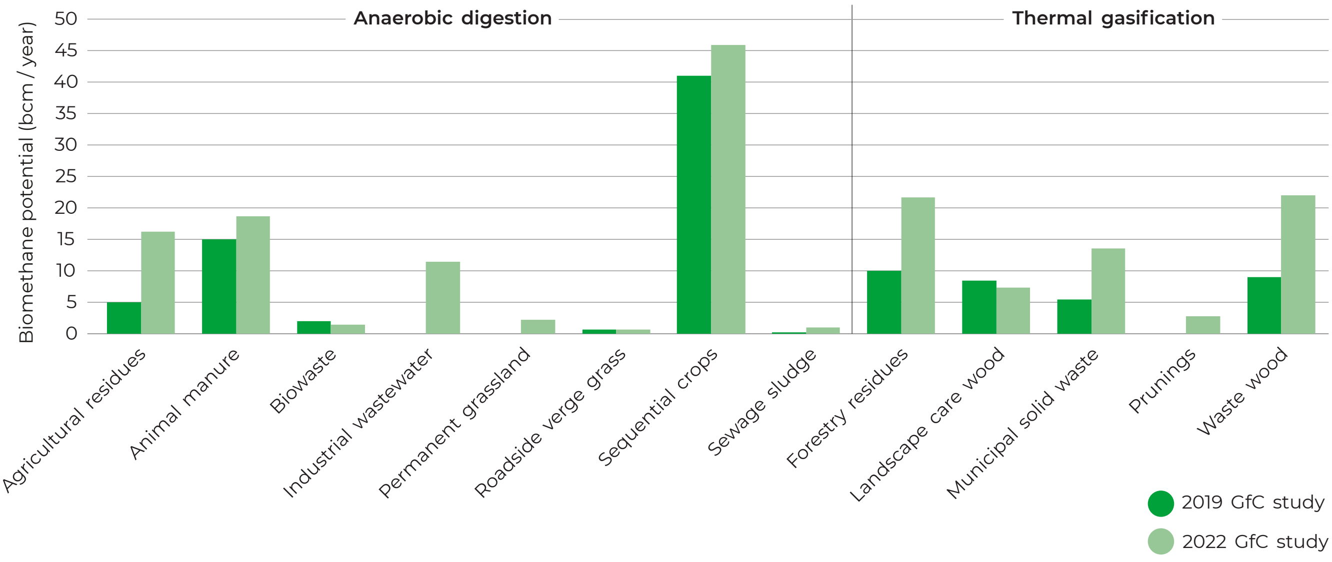
Figure 9 below provides a side-by-side comparison of the estimates in this study with the 2019 Gas for Climate[9] estimates. Several key differences are identified.

For the **anaerobic digestion feedstocks**, differences are observed in the potential for agricultural residues (+11 bcm), which can be largely explained by the slightly higher sustainable removal rates per country that were applied in this study as well as a lower assumed share of agricultural residues deducted for existing uses (both of which were informed by peer-reviewed literature). This study also includes two additional anaerobic digestion feedstocks, industrial wastewaters (+11 bcm) and permanent grassland (+2 bcm –for Germany only). In the case of industrial wastewater, a methodology to calculate the potential from the most relevant industrial sectors in which anaerobic digestion technology could be implemented was recently published by the EBA and applied in this study. Permanent grassland was included for Germany specifically as there is already a significant amount utilised for biogas production, which is not needed for feeding animals. Data at a European level was not readily identified and so a potential estimate for this feedstock was not included for other countries. Overall, the additional potential for anaerobic digestion in 2050 is +33 bcm compared to the 2019 Gas for Climate study.

For the thermal **gasification feedstocks**, differences are observed with forestry residues (+11 bcm) and wood waste (+13 bcm). These differences result from using the feedstock potential estimates published by Imperial College London (2021) in this study, as in the 2019 Gas for Climate study a bottom-up estimate was undertaken with different underlying assumptions applied. A large part of the difference for wood waste can likely be explained by the more complete coverage of the feedstock potential estimate for wood processing residues which are included in the Imperial College London study. Overall, the additional potential for gasification in 2050 is +33 bcm compared to the 2019 Gas for Climate study.

The estimates for the other feedstocks are broadly similar for both technologies.

Figure 9.
Biomethane potential in 2050 per technology and feedstock



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[9] Gas for Climate (2019). The optimal role for gas in a net-zero emissions energy system. Navigant. https://gasforclimate2050.eu/sdm_downloads/2019-gas-for-climate-study/

1.5 Comparison with national level biomethane estimates

The biomethane potential estimates derived in the context of this study are intended to provide a credible sense of the overall scale at a European level in 2030 and 2050, as well as an indication of the likely distribution per country, feedstock and technology. It is acknowledged that biomethane potential estimates that have been developed at the national level will invariably derive different outcomes, as the data and assumptions that are applied are likely to be available at a more granular level, more refined and better fit the national context (including a more comprehensive understanding of the feedstocks available, current deployment levels per feedstock and the policy framework for biomethane).

Tables 2 to 7 in the Annex compare the potentials estimated in this study to national-level estimates in a selection of key biomethane-producing countries (where such estimates were readily identified). These studies either relate to the 2030 or 2050 time period[10].

Overall, the pattern that emerges is that the national-level estimates are higher than those estimated in this study, in part because additional feedstocks are included in these estimates. These include feedstocks suitable for anaerobic digestion (such as algae, discarded crops, deep litter from animal husbandry and permanent grassland which was only included for Germany in this study) and various feedstocks suitable for hydrothermal gasification (such as digestate from anaerobic digestion that cannot be utilised and dredging muds).

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[10] Note that the studies present the potential estimates in a variety of units (namely bcm, TWh and PJ), and either on a lower heating value or higher heating value basis. We have included the potentials in the original units in the report Annex to aid reconciliation with the national level studies, but have expressed all units on a lower heating value basis for consistency with this study.

2. Methodology

In this chapter, we set out the feedstock and technology scope, and describe both the overall calculation methodology applied and the methodology per feedstock to estimate the biomethane potential in 2030 and 2050.

2.1 Feedstock and technology scope

Biogas and biomethane are produced from a diverse range of organic feedstocks. Two main biomethane production technologies exist: **anaerobic digestion** combined with upgrading the biogas and **gasification**. Gasification includes **thermal gasification** (or pyro gasification), which converts dry woody or lignocellulosic biomass and solid waste, and **hydrothermal gasification**, also known as supercritical water gasification, which converts raw liquid and wet biomass by upgrading syngas. Almost all biomethane in Europe today is produced via anaerobic digestion. Thermal gasification with biomethane synthesis is not yet commercially available and only exists at a demonstration-scale, for example, the Gaya[11] project in France. Hydrothermal gasification is at an industrial demonstration stage, with initiatives underway in several European countries, for example, those by SCW Systems[12] in the Netherlands. The potential to scale up both technologies is large in the mid to long term (2030 and beyond).

The feedstock and technology selection applied in this study are set out in Table 1 and are largely consistent with the 2019 Gas for Climate study, however, a few differences exist. Firstly, two new feedstocks have been included, namely, industrial wastewater (all countries) and permanent grassland (in Germany only). Both of these feedstocks are suitable for conversion to biomethane through anaerobic digestion. In addition, roadside verge grass is now included in the potential estimate for anaerobic digestion, as this technology is seen as a more likely conversion route than gasification for this feedstock. Similarly, prunings are now included in the gasification potential since they are a woody biomass feedstock and so less well suited for anaerobic digestion.

It should be noted that some of the feedstocks listed in Table 1 could be converted to biomethane through either technology. For example, agricultural residues are suitable for either anaerobic digestion or thermal gasification. Likewise, several of the anaerobic digestion feedstocks could instead be converted through hydrothermal gasification, such as animal manure, industrial wastewater and sewage sludge. However, in the context of this study, the feedstocks have been assigned to one technology type to avoid double counting towards the potential estimate. Biomethane production from hydrothermal gasification was not explicitly included in this study given the potential overlap with anaerobic digestion, which is already commercially deployed.

Additional feedstocks not included in this study include biomass from marginal or contaminated land and seaweed, which are suitable for anaerobic digestion. Importantly, these feedstocks are both mentioned in the European Commission's Biomethane Action Plan[13]. These feedstocks were not included in this study as limited data is available, or otherwise not yet consolidated at a European level, but would further add to the potential.

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[11] https://www.engie.com/en/news/gaya-energy-waste-gas-renewable

[12] https://scwsystems.com/en/the-supercritical-water-gasification-process/

[13] European Commission (2022), Commission Staff Working Document, SWD(2022) 230 final, Implementing the REPowerEU Action Plan: Investment needs, hydrogen accelerator, and achieving the bio-methane targets. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230&from=EN

Table 1.
Feedstock and technology selection for the assessment of biomethane potentials

Anaerobic digestion	Thermal gasification
Agricultural residues	Forestry residues (primary residues from thinnings and final fellings, stem and crown biomass from early thinnings and logging residues)
Animal manure	Landscape care wood
Biowaste (mixed food waste and vegetal waste)	Municipal solid waste (organic fraction only)
Industrial wastewater [new]	Prunings (from agriculture)
Permanent grassland [new – Germany only]	
Roadside verge grass	
Sequential cropping	

As in the 2019 Gas for Climate study, strict sustainability criteria are applied in the selection of the feedstocks. As such, energy crops (e.g. mono-cropping of maize) and stemwood[14] (roundwood) are not considered.

2.2 Overall assessment approach

The total potential per country was calculated considering an assessment of the availability of each feedstock and its conversion yield to biomethane, either through anaerobic digestion or gasification. The assessment essentially consisted of two main steps.

1. Estimate sustainable potential per feedstock per country in 2030 / 2050;
2. Convert feedstock potentials to biomethane potentials in 2030 / 2050.

The collection of feedstock potential data per country in 2030 and 2050 was a key task in this study. We used a variety of approaches. We first undertook a literature review to identify any relevant studies that we could use to provide feedstock potential data for 2030 and/or 2050 (ideally with no modification to the data). In the absence of such data sources, we estimated the potential using a bottom-up method, based on current statistical data (European/ national level) and projections for 2030 and 2050 (for example considering trends in population, land area/crop production or livestock numbers). The potentials were adjusted downwards (where relevant) to take into account both **technical constraints** (e.g. share of the total feedstock potential that can be mobilised in 2030 and 2050) and where relevant **environmental constraints** (e.g. soil preservation), to derive a sustainable potential. A further deduction for existing (non-energy) uses was also applied to ensure that the use of the feedstock for biomethane production does not impact these existing uses and result in indirect impacts. Finally, for gasification, as a further constraint, it was assumed that only 5% of the feedstock potential could be utilised by 2030 given this technology is not yet commercially available and only exists at a demonstration-scale. Through these assumptions, this study should therefore give realistic estimates of biomethane potential in 2030 and 2050.

The feedstock potentials are then converted to biomethane potentials using specific biomethane conversion factors per feedstock and technology.

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[14] Stemwood is suitable for the production of sawn-logs or pulp-logs.

2.3 Assessment approach – Anaerobic digestion feedstocks

Sections 2.3.1 to 2.3.8 describe the approaches applied to determine the biomethane potential for the feedstocks relevant for anaerobic digestion.

2.3.1 Agricultural residues

Agricultural residues (such as cereal straw) are defined as the materials that arise *in the field*, following the harvesting of the main crop (i.e. grain or seed). In practice, this is predominantly the stem of the plant but may also include some small amounts of leaf material and chaff. The crop roots are not classified as residue. In scope were the following commonly cultivated primary crops: cereal crops (barley, maize, oat, rye, triticale, wheat), rapeseed, rice, sugar beet and sunflower.

As a first step, current production volumes (wet tonnes) for the selected crops were extracted from FAOSTAT[15] per country. A five-year average (over 2016 to 2020) was taken to ensure that the production volumes were representative, given likely crop rotations and the potential impacts of one-off events. The 2030 production volumes were estimated based on the EU-level growth forecasts per crop included in the European Commission's EU Agricultural Outlook 2021-2031.[16] In the absence of available data, the 2050 production volumes were assumed to be the same as 2030.

The *theoretical potential* of agricultural residues was then estimated using a 'crop to residue index', specific to each crop and country (based on Scarlat et al., 2019).[17] [18] This index determines the volume of residue that is produced per dry volume of the primary crop. The theoretical potential represents an upper bound on the potential and needs to be adjusted downwards to derive the sustainable potential.

The *sustainable potential* refers to the share of agricultural residue that can be removed from the field considering (crop-specific) technical constraints for harvesting and collecting, and environmental constraints related to the preservation of soil quality. Scarlat et al. (2019) was used as the basis to determine country-level sustainable removal rates. This paper determined that the sustainable removal rate across Europe is around 42% (with Denmark having the highest removal rate at 50%).[19] In addition to the sustainable removal rate, existing uses of agricultural residues (primarily animal bedding and feed) must be considered when deriving the potential available for biomethane production. An estimated 25% of the sustainable potential was assumed to be required for existing uses, based on Thorenz et al. (2018).[20] Finally, it was assumed that on average 60% of the available potential could be accessed for biomethane production by 2030 since it will be necessary to mobilise supply chains to collect and aggregate this material. By 2050, 100% of the available potential (i.e. sustainable potential minus existing uses) was assumed.

As a last step, residue volumes per crop were converted to biomethane volumes using production yields specific to each crop type, ranging between 0.18 to 0.25 m^3 methane per kg of dry feedstock (based on ADEME, 2018[21]).

An overview of the key assumptions applied to agricultural residues is provided in the Annex (Table 10 and Table 11).

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[15] FAOSTAT. Food and agriculture data. https://www.fao.org/faostat/en/#home

[16] European Commission (2021), EU Agricultural Outlook for markets, income and environment, 2021-2031. DG Agricultural and Rural Development. https://ec.europa.eu/info/food-farming-fisheries/farming/facts-and-figures/markets/outlook/medium-term_en

[17] Scarlat et al. (2019), Integrated and spatially explicit assessment of sustainable crop residues potential in Europe. https://doi.org/10.1016/j.biombioe.2019.01.021

[18] This paper provides estimates of available agricultural residues at the European level. The methodology incorporates temporal variability of the theoretical potential resources and consideration of technical and environmental constraints.

[19] The feedstock data estimates were checked with those derived by Scarlat et al. (2019) at a country level for overall consistency.

[20] The estimate applied in this study is more conservative than the implied 22% estimate in the Thorenz et al. (2018) study (based on an assumed straw use of around 30 million tonnes per year in Europe).

[21] ADEME (2018), Un mix de gaz 100 % renouvelable en 2050?. https://librairie.ademe.fr/energies-renouvelables-reseaux-et-stockage/1548-mix-de-gaz-100-renouvelable-en-2050--9791029710476.html

2.3.2 Animal manure

Animal types considered were cows (dairy and meat production), pigs, goats, sheep and chickens. As a first step, livestock numbers per country and animal type were identified (Eurostat was used for the EU-27 and UK). An estimate of the livestock numbers in 2030 was made by applying the EU-level growth forecasts included in the European Commission's EU Agricultural Outlook 2021-2031. This resulted in reductions to 2030 of around 7% and 8% respectively for cows and pigs and *increases* of 3% and 4% for sheep/goats and chickens. In the absence of available data, the 2050 livestock numbers were assumed to be the same as in 2030.

Next, an estimate of the *theoretical potential* of animal manure was made by applying typical manure production volumes per animal type per day, as set out in Scarlat et al. (2018).[22] [23] Of this total, only the manure produced in stables or barns can be collected. The *technical potential* was assumed to be 70% of the theoretical potential for all animal types in all countries, except for chickens and sheep/goats for which 85% and 40% respectively were assumed. This was based on the interpretation of the modelled outputs in the Scarlat et al. paper.[24] In reality, the factor will vary between countries and depend on the type of livestock system applied (indoors vs outdoors) and the size of the farm. However, this data was not readily identified.

Finally, it was assumed that on average 70% of the available potential could be accessed for biomethane production by 2030 since it will be necessary to mobilise supply chains to collect and aggregate this material. By 2050, 100% of the available potential was assumed. The biomethane potential was then calculated by applying biogas production yields per animal type, again based on Scarlat et al. (2018), and an assumed methane content of biogas of 57%.

It should be noted that animal manure is often mixed with cereal straw (an agricultural residue). Which is used as bedding for livestock, rather than collected as a separate feedstock. In Denmark, the so-called 'deep bedding/litter' method is widely implemented, which results in significant volumes of straw being mixed with the manure. The additional potential arising from the straw has not been included in this study.

An overview of the key assumptions applied to agricultural residues is provided in the Annex (Table 12).

2.3.3 Biowaste

The potential for biowaste in 2030 and 2050 was derived from Imperial College London (2021).[25] Feedstocks included in the biowaste category are paper and cardboard, wood waste, animal and mixed food waste, vegetal waste, municipal solid waste (MSW) and common sludges from households and economic sectors included in the Statistical Classification of Economic Activities in the European Community[26] (NACE). Data is reported separately for each biowaste type for the EU-27 and UK.

In this study, we based the biowaste feedstock potential on mixed food waste and vegetal waste, both of which are suitable for treatment via anaerobic digestion. MSW and wood waste are both suitable for thermal gasification and are considered separately in the gasification section (see sections 2.4.3 and 2.4.5. Paper and cardboard were excluded, as it is considered better for these to go for recycling.

The Imperial College London study applies the approach set out in Elberson et al. (2016a).[27] First, the waste production and waste treatment volumes

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[22] Scarlat et al. (2018), A spatial analysis of biogas potential from manure in Europe. https://doi.org/10.1016/j.rser.2018.06.035

[23] This study provides an assessment of the spatial distribution of the biogas potential of farm manure from livestock and poultry in Europe, at 1 km spatial resolution.

[24] The feedstock data estimates were checked with those derived by Scarlat et al. (2018) at a country level for overall consistency.

[25] Imperial College London (2021), Sustainable biomass availability in the EU, to 2050. https://www.fuelseurope.eu/publication/sustainable-biomass-availability-in-the-eu-to-2050/#:~:text=%E2%80%9CSustainable%20biomass%20availability%20in%20the,more%20than%20sufficient%20to%20supply

[26] Eurostat (2008), Statistical classification of economic activities in the European Community. https://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF

per waste category are identified for each country using Eurostat, or national level data. For each waste type, 'waste treatment factors' were calculated to identify the share of waste that is already going to alternative uses and which part of the waste is available for further conversion into energy or other bioeconomy uses.

Potentials for 2030 and 2050 were calculated based on extrapolations of waste potentials into the future and estimated based on population growth trends and the waste per head ratios (total waste generation by the number of inhabitants). Population development projections were taken from data sources, such as Eurostat. The study also applied assumptions on how waste treatment and recycling rates would develop in the future. In the 'high' potential scenario[28] (Scenario 3 – Bioenergy), 60% of biowaste is separately collected and available for anaerobic digestion in 2030, and 55% in 2050 (the balance is recycled). This (more optimistic) scenario was considered most representative of mixed food waste and vegetal waste given the suitability of these feedstocks for anaerobic digestion over other end uses.

The biomethane production was calculated by applying a biogas yield of 0.575 m^3 per dry kg, and an assumed methane content in the biogas of 57%.

2.3.4 Industrial wastewaters

Many industrial sectors produce wastewaters which are heavily loaded with organic matter, which must be purified before discharging. The currently widely applied treatment method is the activated sludge process through aeration. This method has a high energy consumption and greenhouse gas footprint and produces large amounts of sludge. Pre-treatment of the wastewater in an anaerobic digestion plant provides an effective means of reducing the organic matter content before aerobic treatment, resulting in reduced energy consumption and sludge production.

The biomethane potential from industrial wastewaters is considered the most relevant industrial sector in which anaerobic digestion technology could be implemented as a pre-treatment method. Twenty-one diverse industrial sectors were covered, ranging from ice cream production to biofuel production.

The approach set out in EBA (2021)[29] was followed. As a first step, the annual production volume for each sector per country[30] was identified, primarily using Eurostat data.[31] Next, the volume of wastewater in each country was estimated using specific production ratios per industrial sector (m^3 wastewater per tonne production). Finally, the biogas yield per sector was calculated by multiplying the chemical oxygen demand (COD) in kg COD per m^3 of wastewater by the biogas yield in m^3 of biogas. Methane content of 57% in the biogas was assumed to estimate the biomethane production.

It was assumed that on average 30% of the technical potential could be accessed for biomethane production by 2030, with a higher share of 40% assumed in Denmark, France, Germany, Italy and the UK reflecting that these countries are understood to already be utilising this feedstock for biomethane production or otherwise have set out plans to do so. It was assumed that 100% of the technical potential could be accessed by 2050 in all countries.

An overview of the key assumptions applied to industrial wastewaters is provided in the Annex (Table 13).

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[27] Elbersen et al. (2016a), Guidelines for data collection to estimate and monitor technical and sustainable biomass supply. Deliverable 2.2 of the Biomass Policies project. https://spiral.imperial.ac.uk/bitstream/10044/1/76345/2/IEE%2012%20835%20D2%202%20Guidelines%20for%20data%20collection%20to%20estimate%20and%20monitor%20biomass%20supply.pdf

[28] Scenario 3 – Enhanced availability through research and innovation and improved mobilisation. This scenario refers to all EU-27 Member States and the UK and applies the highest rates for assumptions on increased mobilisation as well as increased improvements in management practices which can maximise the sustainable biomass availability across all feedstocks.

[29] European Biogas Association (2021), The role of biogas production from industrial wastewaters in reaching climate neutrality by 2050. https://www.europeanbiogas.eu/the-role-of-biogas-production-from-industrial-wastewaters-in-reaching-climate%20neutrality-by-2050/

[30] Note that production data in some countries/industrial sectors was not readily identified, although this was mostly relevant to Norway and Switzerland.

[31] The data was converted to a per tonne basis if the reported production was in alternative unit (such as litres or ktoe).

2.3.5 Permanent grassland

In general, grass cut from permanent grassland was not considered a key feedstock in this study as there could be competing uses for the land in some countries. However, in Germany, there is already a significant amount that is not needed for feeding animals and that is used for biogas (around 2 bcm), so it was included in the potential estimate for Germany specifically.[32] In the future, if there are lower levels of animal husbandry in Europe, more grassland areas could become available for biogas use.

2.3.6 Roadside verge grass

Roadside verge grass is collected during maintenance operations in urban areas and treated as waste. Feedstock potentials for the EU-27 and UK in 2030 were taken from Elberson et al. (2016b).[33] The feedstock potentials in Elberson et al. are based on Biomass Futures[34] potential data, which in turn derived these data from the EUwood project.[35] No significant changes in potentials are expected towards 2050 since the potentials are essentially linked to land area which in the case of roadside verge grass is expected to remain broadly at current levels.

The roadside verge grass potentials were converted to a dry basis assuming a moisture content of 25%. 90% of the total assumed collectable quantity in 2030 and 2050 is considered to be used for biomethane production (Ecofys, 2018). No feedstock potential estimates could be identified for either Norway or Switzerland, so these countries do not have a biomethane potential for roadside verge grass included in this study.

A biomethane yield of 0.419 m^3 methane per kg of dry feedstock was used to calculate biomethane production.

2.3.7 Sequential cropping

Sequential cropping (also referred to as multi-cropping, double cropping or growing a “harvestable cover crop”) is the cultivation of a second crop before or after the harvest of the main food or feed crop on the same agricultural land during an otherwise fallow period. Sequential cropping does not impact existing food or feed markets as no existing food or feed is used for biogas production. As the sequential crop is put the whole into the anaerobic digestion plant, it does not necessarily require a fully matured crop to be grown. Therefore, given the right climatic conditions, it can be implemented in a way which does not impact the yield of the main crop.

This study largely followed the approach to estimate the potential of sequential cropping as set out in the University of Ghent (2021) study. First, countries were categorised into four biogeographical regions: Atlantic, Continental, Mediterranean and Other (including Boreal and Mountain). Some countries, such as France, Italy and Spain, were split into multiple regions. Next, the arable land area (hectares) for each country was extracted from Eurostat (the three-year average between 2018 to 2020 was taken). The arable land areas in 2030 were estimated based on projections published by the European Commission.[36] This led to a decrease of around 1% by 2030 compared to the current arable land areas. The 2050 arable land area was assumed to be the same as in 2030. The area of arable land dedicated to sequential cropping was assumed to be 20% in all regions, consistent with the ‘conservative’ scenario in the University of Ghent study.[37]

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[32] Personal communication with Stefan Rauh (Facherverband Biogas).

[33] Elberson et al. (2016b), Outlook of spatial biomass value chains in EU28. Deliverable 2.3 of the Biomass Policies project. https://iinas.org/app/downloads_from_old_page/bio/biomasspolicies/Elbersen_et_al_2016_Outlook_of_spatial_biomass_value_chains_in_EU28_(D2.3_Biomass_Policies).pdf

[34] Panoutsou et al. (2013), An integrated approach for estimating the future contribution of biomass value chains to the European energy system and inform future policy formation. Funded by the European Union’s Intelligent Energy Programme.

[35] Mantau et al. (2010), EUwood: Real potential for changes in growth and use of EU forest.

[36] European Commission (2021), EU Agricultural Outlook for markets, income and environment, 2021-2031. DG Agricultural and Rural Development. https://ec.europa.eu/info/food-farming-fisheries/farming/facts-and-figures/markets/outlook/medium-term_en

[37] Note that the in the University of Ghent study the land area devoted to primary crop production was taken as the area for potential sequential cropping deployment. This represents over 80% of the arable land area in the EU-27 and UK.

The suitability of deploying different sequential crops per region was specified, along with the respective shares of each crop. For example, green rye (67%) and ryegrass (33%) were selected for the Continental region. The average yield for sequential cropping for each region was then estimated by applying the region and crop-specific yields published in the University of Ghent (2021) study. The derived yields are 7.1 dry t/ha in the Atlantic region, 7.3 dry t/ha in the Continental region and 13.5 dry t/ha in the Mediterranean region. No potential was assumed for the Other region. As a final step, the theoretical sequential cropping production was calculated based on the available land area (20% of arable land) per country and the average regional yields.

To date, sequential cropping has been widely implemented in Italy (the so-called 'Biogasdoneright' concept). Successful pilot tests have also been undertaken in France funded by ADEME. However, the deployment of sequential cropping in the rest of Europe, in particular in key European agricultural regions such as Germany, Spain, Romania and Poland, remains largely untested. A key assumption is how frequently a harvestable sequential crop could be implemented on a piece of land (e.g. every year or only every 2 to 3 years to give some years when the land is still fallow or to allow for an assumption that some years the second crop would not reach a yield that was worthwhile to harvest and it instead might be ploughed into the land as a cover crop). It was therefore assumed that on average 10% of the theoretical potential could be realised by 2030. A higher share of 65% was applied for Italy to reflect the advanced deployment already achieved to date and dedicated focus to continue to develop this concept. Similarly, a higher share of 20% was applied to France for the same reason although deployment is not yet as advanced as in Italy. A share of 20% was also applied for Germany, although this was done to recognise that the existing biogas sector in Germany has developed with high use of main crops and there is likely to be a strong driver for the biogas sector to diversify away from such mono-crop use to 2030. The theoretical potential for sequential cropping was assumed to be fully realised in all countries by 2050.

Finally, the biomethane production was calculated assuming a biogas yield of 0.57 m^3 per kg of dry feedstock and a 57% methane content in the biogas.

An overview of the key assumptions applied for sequential cropping is in the Annex (Table 14).

2.3.8 Sewage sludge

As a first step, current production volumes (dry tonnes) of sewage sludge per country were taken from Eurostat. Estimates for the theoretical production of sewage sludge in 2030 and 2050 were calculated by applying population growth forecasts per country (Eurostat, except for the UK which was based on the UK Office of National Statistics projections).

The sustainable potential was assumed to be the same as the theoretical potential as there are limited alternative uses for sewage sludge. 100% of the sewage potential was assumed to be realised for anaerobic digestion in both 2030 and 2050.

A biomethane yield of 0.2 m^3 methane per kg of dry feedstock was used to calculate biomethane production.

2.4 Assessment approach – Thermal gasification feedstocks

Sections 2.4.1 to 2.4.5 describe the approaches applied to determine the biomethane potential for the feedstocks relevant for thermal gasification.

2.4.1 Forestry residues

Forestry residues include primary residues from thinnings and final fellings, stem and crown biomass from early thinnings and logging residues. The potentials for forestry residues in the EU-27 and UK in 2030 and 2050 published by Imperial College London (2021) were applied. The methodology applied by Imperial College London largely follows that set out in the Biomass Energy Europe best practices handbook.[38]

Biodiversity protection is included in the estimated potentials accounting for: i) conservation of land with significant biodiversity values (direct and indirect), and ii) land management without negative effects on biodiversity. A sustainable removal rate of between 25% and 40% was applied, depending on soil quality, tree species and climate.

Potentials from the 'medium' scenario[39] (Scenario 2 – Bioenergy) were taken. This assumes that 50% of the feedstock potential is available for bioenergy.

The potentials for Norway[40] and Switzerland[41] are based on feedstock estimates provided in separate studies, but again take into account technical and environmental constraints, as well as existing uses.

The Imperial College London study also includes stumps in the potential estimate for forestry residues in Finland, Sweden and the UK. Stumps were excluded in our potential estimate due to concerns about biodiversity and carbon stock losses. A deduction of 10% of the total potential reported by Imperial College London was applied to reflect this.[42]

A biomethane yield of 0.423 m^3 methane per kg of dry feedstock was used to calculate biomethane production (via thermal gasification).

2.4.2 Landscape care wood

Landscape care wood is collected during the maintenance operations of certain urban areas and treated as waste. It includes tree cutting and pruning activities in horticulture, arboricultural activity in parks and cemeteries, and tree management operations performed along roadsides, railways, waterways, orchards, etc. to keep plantations in the desired state and wood collection from private gardens.

Feedstock potentials for EU-27 and UK in 2030 were taken from Elberson et al. (2016), as described in section 2.3.6 (Roadside verge grass) above and Steubing et al. (2010) for Switzerland. No estimate could be identified for Norway, so this country does not have a potential for landscape care wood included in this study.

The landscape care wood potentials were converted to a dry basis assuming a moisture content of 25%. 90% of the total assumed collectable quantity in 2030 and 2050 is considered to be used for biomethane production (Ecofys, 2018).

A biomethane yield of 0.419 m^3 methane per kg of dry feedstock was used to calculate biomethane production (via thermal gasification).

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[38] Biomass Energy Europe (2010), Harmonization of biomass resource assessments, Volume 1, Best practices and methods handbook. https://www.ifeu.de/fileadmin/uploads/BEE-Best-Practices-and-methods-handbook8d4c.pdf

[39] Scenario 2 – Improved mobilisation in selected countries. This scenario focuses on improved mobilisation which is the result of improvements in cropping and forest management practices. These take place in countries with high biomass availability (total estimated biomass potential ≥20 million tonnes per year) and in combination with either good institutional framework, established policies/ targets for bioenergy or advanced biofuels, strong infrastructure and strong innovation profiles (Germany, France, Sweden, Finland, Italy, United Kingdom, Austria, Spain) or in countries with low biomass supply costs (Poland, Romania, Czech Republic, Hungary, Bulgaria).

[40] Nordic Energy Research (2014). Land areas and biomass production for current and future use in the Nordic and Baltic countries. Sustainable Energy Systems 2050 Research Programme. https://www.nordicenergy.org/wordpress/wp-content/uploads/2015/02/Land-areas-and-biomass-production-for-current-and-future-use-in-the-Nordic-and-Baltic-countries.pdf

[41] Stuebling et al. (2010), Bioenergy in Switzerland: Assessing the domestic sustainable biomass potential.

[42] Note that the Imperial data was not disaggregated by forestry residue type. The deduction of 10% was an estimate of the share of stumps.

2.4.3 Municipal solid waste

The potentials for the organic fraction of MSW in 2030 and 2050 were derived from Imperial College London (2021), as discussed in section 1.1.1 (Biowaste). The potentials from the 'high' potential scenario[43] (Scenario 3 – Bioenergy) were again applied. The methodology to estimate the potential of MSW largely follows that set out in section 2.3.3, complemented by additional data sources to make a better interpretation of current and future generation levels and recycling rates across Europe.

A biomethane yield of 0.324 m^3 methane per kg of dry feedstock was used to calculate biomethane production (via thermal gasification).

2.4.4 Prunings

Prunings (also referred to as arboricultural residues) are woody residues produced after cutting, mulching and chipping activities of fruit trees, vineyards, olives and nut trees. They are the result of normal pruning management needed to maintain the orchards and improve their productivity and are available for collection on the field.

Feedstock potentials for the EU-27 and UK in 2030 and 2050 were taken from Imperial College London (2021). This study assumed a technical availability of prunings of between 65% (olives) and 85% (fruit and nut trees) and a sustainable removal rate of 85% for all prunings except for vineyards (75%). Potentials from the 'medium' scenario (Scenario 2 – Bioenergy) were taken, which assumes a collection rate of 20% in both 2030 and 2050. No feedstock potential estimates could be identified for either Norway or Switzerland, so these countries do not have a biomethane potential for prunings included in this study.

A biomethane yield of 0.419 m^3 methane per kg of dry feedstock was used to calculate biomethane production (via thermal gasification).

2.4.5 Wood waste

Wood waste is a source of secondary woody biomass that includes wood processing, wood from paper and pulp production, construction and demolition waste, as well as waste collected from households and industries.

The potentials for wood residues and wastes in 2030 and 2050 published by Imperial College London (2021) were applied. These include the feedstock categories of secondary forestry residues, post-consumer wood and waste wood (biowaste). Secondary forestry residues include sawmill by-products and sawdust from sawmills arising from the stemwood processing, and other forestry industry by-products arising from the processing of primary and further processed timber products. Potentials from the 'medium' scenario (Scenario 2 – Bioenergy) were taken. This assumes that 60% of the feedstock potential is available for bioenergy. A deduction of 24 million tonnes was applied to the potential to reflect the existing use of wood waste in sawmills for heat and power, based on Gas for Climate (2019).

The approach to estimating the potential for secondary forest residues follows the methodology set out in the EUwood[44] study (which is widely recognised as the most authoritative study undertaken to date on this topic). This essentially applies a two-step approach:

1. Analysis and categorisation of the size distribution of sawmills per country for coniferous and non-coniferous sawmills.
2. Estimation of the secondary residue potential based on recovery rates (ratios of roundwood input to sawnwood output). Recovery rates are determined by the tree species, sawmill size and technology applied per country.

A biomethane yield of 0.419 m^3 methane per kg of dry feedstock was used to calculate biomethane production (via thermal gasification).

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[43] Scenario 3 – Enhanced availability through research and innovation and improved mobilisation.

[44] Mantau et al. (2010), EUwood: Real potential for changes in growth and use of EU forest.

3. Annexes

A.1 Country level biomethane potential estimates

As discussed in section 1.5, several studies have been undertaken at the national level by other organisations to estimate the biomethane potential. Tables 2 to 7 compare the potentials estimated in this study to the national-level estimates in a selection of key biomethane-producing countries (where such estimates were readily identified). These studies either relate to the 2030 or 2050 time period.

It should be noted that the potential estimates derived in the national level studies are expressed in a variety of units (namely bcm, TWh and PJ[45]), and are either on a lower heating value or higher heating value basis. We have included the potentials in the original units in the tables below to aid reconciliation with the national level studies but have expressed all data on a lower heating value basis for consistency with this study.

Table 2.
Comparison of Gas for Climate biomethane potential estimates for Belgium in 2050 with country-level estimates (units: TWh[46])

Gas for Climate		Valbiom[47]	
Anaerobic digestion		**Anaerobic digestion**	
Agricultural residues	1.089	Straw	1.926
Animal manure	5.207	Animal manure	3.995
Biowaste	0.438	Green waste	0.540
Industrial wastewater	2.796	Industry waste and co-products	1.866
Permanent grassland		Permanent grassland	2.310
Roadside verge grass	0.121		
Sequential cropping	3.887	Sequential cropping	2.541
Sewage sludge	0.202	Sewage sludge	0.591
		Energy crops	0.341
	13.7 TWh		**14.1 TWh**

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[45] 1 bcm is equivalent to around 10.61 TWh or 38.3 PJ on a lower heating value basis.

[46] Note that the potentials were calculated on a higher heating value basis and have been converted to a lower heating value basis using a factor of 0.9 for consistency with the Gas for Climate potentials.

[47] https://greengasplatform.be/green-gas-platform-fr.html

Table 3.

Comparison of Gas for Climate biomethane potential estimates for France in 2050 with country-level estimates (units: TWh[48])

Gas for Climate		GRTgaz / Teréga / GRDF / FGR / ATEE analysis	
Anaerobic digestion		**Anaerobic digestion**	
Agricultural residues	31.4	Agricultural residues	28.2
Animal manure	33.7	Animal manure	24.5
Biowaste	0.4		
Industrial wastewater	19.5		
Permanent grassland	0.0	Permanent grassland	11.8
Roadside verge grass	1.1		
Sequential cropping	87.3	Sequential cropping	46.4
Sewage sludge	1.3		
		Industrial waste	7.3
		By-products of food industry	4.5
		Residual waste	2.3
		Seaweed	12.7
		Biogas for cogeneration	9.1
Sub-total anaerobic digestion	**174.8**	**Sub-total anaerobic digestion**	**146.8**
Pyro Gasification		**Pyro Gasification**	
Forestry residues	21.4	Forestry residues	21.8
Landscape care wood	14.8	Landscape care wood	6.4
Municipal solid waste	12.4	Municipal solid waste	81.8
Prunings	0.7	Prunings	0.0
Wood waste	20.7	Wood waste	7.3
Sub-total pyro Gasification	**70.0**	**Sub-total pyro Gasification**	**117.3**

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[48] Note that the potentials were calculated on a higher heating value basis and have been converted to a lower heating value basis using a factor of 0.9 for consistency with the Gas for Climate potentials.

Gas for Climate		GRTgaz / Teréga / GRDF / FGR / ATEE analysis	
		Hydrothermal Gasification[49]	
		Anaerobic digestion digestates, wastewater	20.9
		Dredging muds	4.5
		Animal and plant waste not suitable for anaerobic digestion	1.8
		Black liquor	4.5
		Industrial and agricultural waste	20.9
		Discount	-7.3
		Sub-total Hydrothermal Gasification	**45.5**
	244.8 TWh		**309.6 TWh**

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[49] The estimate for Hydrothermal gasification includes the potential for two feedstocks included in the Gas for Climate potentials, namely: Industrial and agricultural waste which is included under Anaerobic digestion - Industrial wastewaters and Black liquor which is included under Gasification - Wood waste. If the potentials from these feedstocks are excluded, then an additional 27 TWh is available from Hydrothermal gasification, thereby increasing the Gas for Climate estimate to 272 TWh.

Table 4.

Comparison of Gas for Climate biomethane potential estimates for Denmark in 2030 with country-level estimates (units: PJ)

Gas for Climate		Green Gas Strategy[50]	
Agricultural residues	12.1	Straw	15
Animal manure	11.9	Animal manure	12
		Deep bedding	6
Biowaste	1.1		
Industrial wastewater	0.8	Industry & other residual waste	8
Roadside verge grass	0.6		
Sequential cropping	3.8		
Sewage sludge	0.6		
		Discarded crops	1
		CODE and other green waste	6
		Green agricultural waste	7
	30.9 PJ		**55 PJ**

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[50] Danish Ministry of Climate, Energy and Utilities (2021). Green Gas Strategy. The role of gas in the green transition.

Table 5.

Comparison of Gas for Climate biomethane potential estimates for Germany in 2030 with country-level estimates (units: TWh)

Gas for Climate		DVGW[51]	
Agricultural residues	16.3	Agricultural residues	60
Animal manure	18.3	Animal manure	21.4
Biowaste	2.0	Municipal residues	6.3
Industrial wastewater	9.7	Industrial residues	27.1
Permanent grassland	22.9	Permanent grassland	23
Roadside verge grass	0.9		
Sequential cropping	10.5		
Sewage sludge	2.0		
		Energy crops	55.3
		Extensively used grassland outcrop (optional)	0-12
		Biodiversity areas (optional)	0-30
	82.6 TWh		**193-234 TWh**

Table 6.

Comparison of Gas for Climate biomethane potential estimates for Italy in 2030 with country-level estimates (units: bcm)

Gas for Climate		Agricultural Biomethane Roadmap	
Agricultural residues	0.5	Agricultural residues	0.22
		Agro-industrial residues	0.07
Animal manure	1.0	Animal manure	2.23
		Animal by-product	0.11
Biowaste	0.3	Food residues	0.09
Industrial waste waters	0.3		
Roadside verge grass	0.1		
Sequential cropping	3.2	Sequential cropping	3.8
Sewage sludge	0.1		
	5.5 bcm		**6.52 bcm**

Note: Italian Recovery Plan implies around 4 to 5.5 bcm in 2030. CIB estimate that the total biomethane potential is around 8-8.5 bcm, of which 6-6.5 relates to agricultural and agro-industrial biomass and 1-1.5 bcm from organic waste.

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[51] DVGW (2019). Total potential of renewable gases. Determination of the total potential of renewable gases for feeding into the German natural gas network (G 201710). https://www.dvgw.de/themen/forschung-und-innovation/forschungsprojekte/g-201710-gesamtpotenzial-ee-gase-projektbeschreibung

Table 7.

Comparison of Gas for Climate biomethane potential estimates for Spain in 2050 with country-level estimates (units: TWh)

Gas for Climate		SEDIGA (Spanish gas association)	
Anaerobic digestion			
Agricultural residues	15.7	Agricultural residues	11.3
Animal manure	20.0	Animal manure	15
Biowaste	1.3	Biowaste	
Industrial wastewater	13.2	Industrial wastewater	3.4
Roadside verge grass	0.6		
Sequential cropping	92.3	Sequential cropping	59
Sewage sludge	1.4	Sewage sludge	2
		Waste materials produced in health and physiological research activities	9
Sub-total	144.4	Sub-total	100
Gasification			
Forestry residues	16.1	Forestry residues	34
Landscape care wood	7.4	Landscape care wood	
Municipal solid waste	14.3	Municipal solid waste	3.5
Prunings	16.7	Prunings	
Wood waste	10.7	Wood waste	
Sub-total	65.2	Sub-total	38
	209.6 TWh		**137 TWh**

A.2 Assumptions

Table 8.
Heating values

Gas for Climate	Unit	Heating value (LHV)
Natural gas	MJ/m^3	38.2
Biomethane	MJ/m^3	34.7

Table 9.
Biogas and biomethane yield assumptions

Gas for Climate	Feedstock type	Unit	Biogas or Biomethane yield
Anaerobic digestion	Agricultural residues	m^3 methane/kg dry	0.18 to 0.25 (see Table 11 for further details)
Anaerobic digestion	Animal manure	m^3 methane/kg fresh	0.01 to 0.05 (see Table 12 for further details)
Anaerobic digestion	Biowaste	m^3 biogas/kg dry	0.575
Anaerobic digestion	Industrial wastewater	m^3 biogas/ kg COD	0.35 to 0.5 (see Table 13 for further details)
Anaerobic digestion	Roadside grass	m^3 methane/kg dry	0.419
Anaerobic digestion	Sequential cropping	m^3 biogas/kg dry	0.57
Anaerobic digestion	Sewage sludge	m^3 biogas/kg dry	0.2
Gasification	Forestry residues	m^3 methane/kg dry	0.423
Gasification	Landscape care wood	m^3 methane/kg dry	0.419
Gasification	Municipal solid waste	m^3 methane/kg dry	0.324
Gasification	Prunings	m^3 methane/kg dry	0.414
Gasification	Wood waste	m^3 methane/kg dry	0.451

Note: A methane content of 57% in biogas was assumed for all feedstocks.

Table 10.
Assumptions for agricultural residues – crops

Primary crop	Growth to 2030 (EU, %)[52]	Dry matter content (%)[53]	Residue to methane potential (m^3/kg)[24]
Barley	-8.0	88	0.22
Maize	-1.5	63	0.24
Oats	1.0	88	0.22
Rapeseed	-1.7	88	0.25
Rice	-6.1	86	0.22
Rye	1.4	86	0.22
Sugar beet	-4.3	23	0.18
Sunflower	1.3	88	0.25
Triticale	1.0	88	0.22
Wheat	-2.0	87	0.22

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[52] European Commission (2021), EU Agricultural Outlook for markets, income and environment, 2021-2031. DG Agricultural and Rural Development. https://ec.europa.eu/info/food-farming-fisheries/farming/facts-and-figures/markets/outlook/medium-term_en

[53] ENGIE (2021), Geographical analysis of biomethane potential and costs in Europe in 2050. https://www.engie.com/sites/default/files/assets/documents/2021-07/ENGIE_20210618_Biogas_potential_and_costs_in_2050_report_1.pdf

Table 11.
Assumptions for agricultural residues – sustainable removal rates per country[54]

Country	Sustainable removal rate
Austria	23%
Belgium	38%
Bulgaria	30%
Croatia	40%
Cyprus	42%
Czechia	37%
Denmark	50%
Estonia	32%
Finland	32%
France	40%
Germany	49%
Greece	37%
Hungary	38%
Ireland	27%
Italy	44%
Latvia	11%
Lithuania	47%
Luxembourg	37%
Malta	42%
Netherlands	34%
Poland	50%
Portugal	30%
Romania	35%
Slovakia	44%
Slovenia	33%
Spain	47%
Sweden	42%
Norway	42%
Switzerland	42%
United Kingdom	49%

[54] Scarlat et al. (2019), Integrated and spatially explicit assessment of sustainable crop residues potential in Europe https://doi.org/10.1016/j.biombioe.2019.01.021

Table 12.
Assumptions for animal manure – livestock

Primary crop	Cattle	Dairy cows	Pigs	Sheep/ goats	Poultry
Growth to 2030 (%)[24]	-6.8	-6.8	-7.8	3.3	4.0
Manure (kg/head/day)[55]	25	53	5	2	0
Manure (kg/head/year)	9,125	19,345	1643	548	73
Manure solid content (SC) (%)	8.5	8.5	6.0	30.0	20.0
Volatile content (VC) of SC (5)	80	80	80	80	80
Methane yield (m^3/kg VC)	0.20	0.23	0.30	0.20	0.32
Methane yield (m^3/kg fresh)	0.01	0.02	0.01	0.05	0.05
Technical recovery rate (%)	70	70	70	40	90

Table 13.
Assumptions for industrial wastewaters[56]

Production process	Industrial wastewater produced (m^3 wastewater / ton product)	Chemical Oxygen Demand (kg COD / m^3 wastewater)	Biogas yield Nm^3 biogas / kg COD	Total amount of biogas produced (m^3 biogas / m^3 wastewater)
Cheese production (37% milk)	13	6	0.5	3
Butter production (29% milk)	13	6	0.5	3
Ice-cream production (13% milk)	13	6	0.5	3
Beer production	3	5	0.5	2.5
Wine production	4	6	0.5	3
Spirits production	15	30	0.5	15
Ethanol production	15	30	0.5	15
Pulp production	30	9	0.5	4.5

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[55] Scarlat et al. (2018), A spatial analysis of biogas potential from manure in Europe. https://doi.org/10.1016/j.rser.2018.06.035

[56] EBA (2021), The role of biogas production from wastewater in reaching climate neutrality in 2050 https://www.europeanbiogas.eu/wp-content/uploads/2021/04/Paper-The-role-of-biogas-production-from-wastewater-in-reaching-climate-neutrality-by-2050.pdf

Production process	**Industrial wastewater produced (m³ wastewater / ton product)**	**Chemical Oxygen Demand (kg COD / m³ wastewater)**	**Biogas yield Nm³ biogas / kg COD**	**Total amount of biogas produced (m³ biogas / m³ wastewater)**
Juice production	7	5	0.45	2.25
Tomato ketchup and sauces	7	6	0.45	2.7
Meat from bovine	7	7	0.5	3.5
Meat from pigs	7	7	0.5	3.5
Meat from sheep	7	7	0.5	3.5
Frozen potatoes prepared	7	4	0.5	2
Potatoes prepared or preserved (crisps)	7	5	0.5	2.5
Potato starch	7	5	0.5	2.5
Dried potatoes, flour etc	7	5	0.5	2.5
Sugar production	1	5	0.5	2.5
Yeast production	7	30	0.35	10.5
Vegetable oils production	5	50	0.4	20
Biodiesel production	30	60	0.5	30

Table 14.

Assumptions for sequential cropping (percentage crop per region, kt/year dry (2030) and total biomass yield (dry t/ha) (dry t/ha)[57]

Crop per region	Atlantic	Continental	Mediterranean	Mediterranean Mature
Maize				
Triticale	33%		67%	67%
Barley	33%			
Sorghum			33%	33%
Legume cover crops				
Maize				
Oats	33%			
Green rye		67%		
Ryegrass		33%		
Maize		14.0	16.5	16.5
Triticale	9.3		13.5	13.5
Barley	4.5		11.0	11.0
Sorghum	7.0	10.0	13.5	13.5
Legume cover crops			8.5	8.5
Maize	14.0			
Oats	7.6			
Green rye		6.5		
Ryegrass		9.0		
Biomass yield (dry t/ha)	7.1	7.3	13.5	13.5

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[57] Magnolo et al. (2021). The Role of Sequential Cropping and Biogasdoneright™ in Enhancing the Sustainability of Agricultural Systems in Europe. Agronomy 2021, 11(11), 2102. https://www.mdpi.com/2073-4395/11/11/2102

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