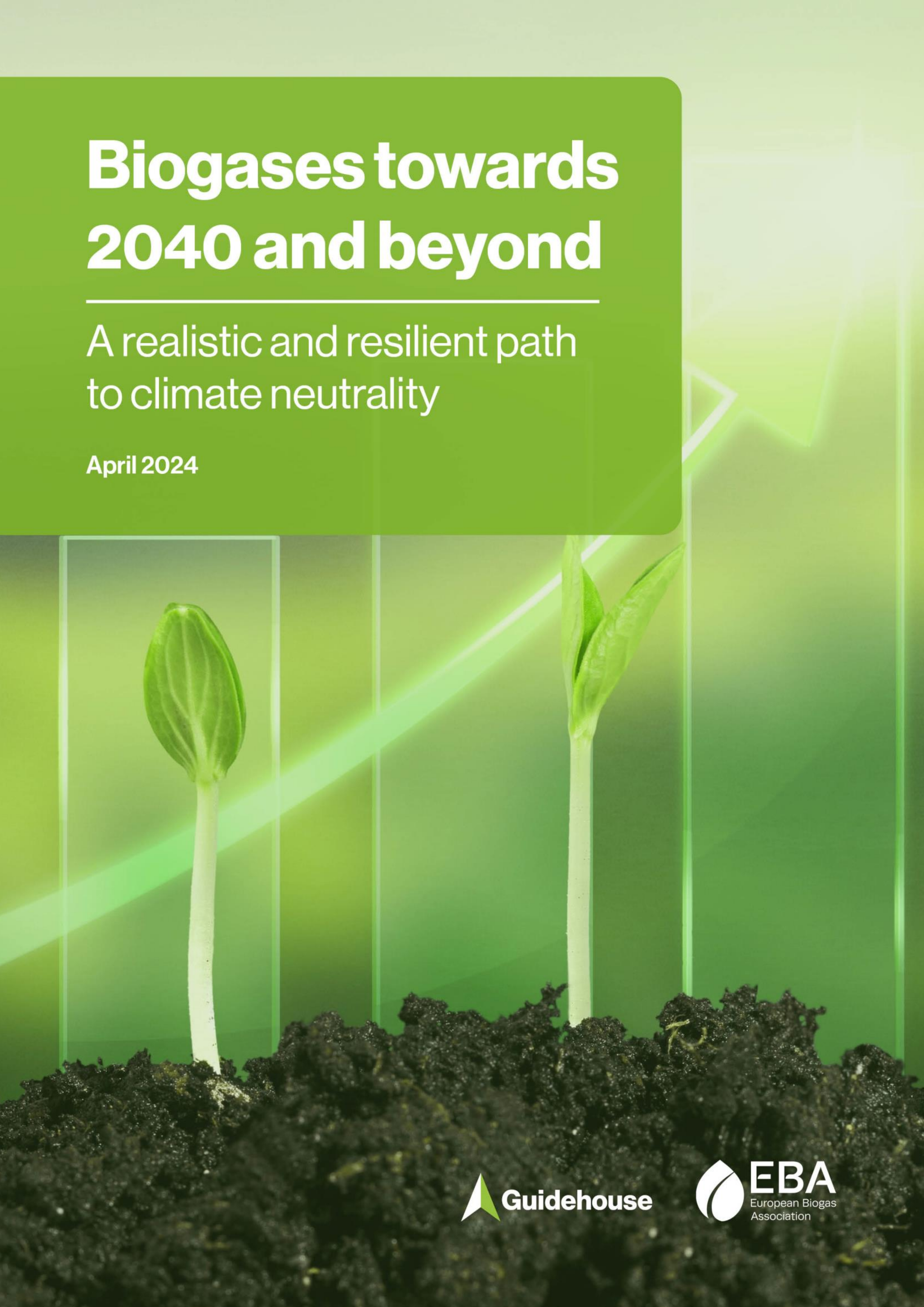
Biogases towards 2040 and beyond

A realistic and resilient path to climate neutrality

April 2024



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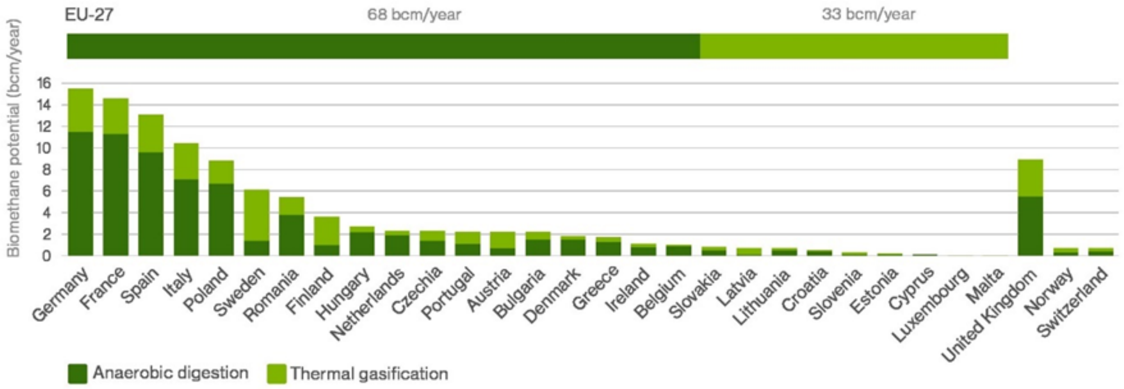
Executive Summary

Biogases will play an important role in the decarbonisation of Europe's energy sector. In 2022, Gas for Climate published a study[1] estimating the potential for biomethane production in the EU-27 (plus Norway, Switzerland and the UK) in 2030 and 2050. Via the REPowerEU Plan, the European Commission has set a target to produce 35 billion cubic meters (bcm) of biomethane annually in the EU by 2030, representing a ten-fold increase of biomethane production today.

This paper provides a refresh of the 2022 Gas for Climate study, incorporating latest data and insights to update the potential estimates for 2030 and 2050, and turns the focus to 2040 to provide a realistic estimate of how the potential for biomethane production in Europe can continue to develop.

The updated estimate shows that up to 44 bcm of biomethane could be produced in Europe in 2030 and 165 bcm in 2050 (of which 40 bcm in 2030 and 150 bcm in 2050 are for the EU-27). The estimated biomethane production potentials in this study are broadly consistent with the 2022 Gas for Climate study, given that the underlying methodology and key assumptions have not fundamentally changed.

In 2040, Europe could produce 111 bcm biomethane, of which 101 bcm relates to the EU-27. This potential is made up of 74 bcm **anaerobic digestion** (67% of the total) and 37 bcm **thermal gasification** (33% of the total).



Anaerobic digestion: A potential of 74 bcm is estimated for anaerobic digestion in 2040, of which 68 bcm relates to the EU-27. The top 5 countries include France, Germany, Spain, Italy and Poland. Key feedstocks in 2040 are sequential crops (42%), as well as animal manure (19%) and agricultural residues (19%). Collectively these feedstocks represent 81% of the total. Industrial wastewater also contributes 12% of the potential in 2040.

Thermal gasification: A potential of 37 bcm is estimated for thermal gasification in 2040, of which 33 bcm relates to the EU-27. The top 5 countries include Sweden, Germany, France, Spain, United Kingdom and France. Key feedstocks in 2040 are wood waste (32%), the organic fraction of municipal solid waste (27%) and forestry residues (26%). Collectively these feedstocks represent 85% of the total.

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[1] Gas for Climate, Biomethane production potentials in the EU, 2022. https://gasforclimate2050.eu/wp-content/uploads/2023/12/Guidehouse_GfC_report_design_final_v3.pdf

On top of this, **additional potential** could be unlocked from **novel feedstocks** such as crops grown on marginal or contaminated lands, seaweed and digestate, as well as through the application of **novel technologies** such as hydrothermal gasification and renewable methane. In addition, landfill gas can further increase the potential in the short to medium term. This paper provides qualitative insights on how each of these can play an important role in further contributing towards a sustainable biomethane production in 2040 and beyond.

This paper provides a scenario of what is possible when action is taken across Europe to mobilise available feedstock streams towards producing biomethane towards 2040 and beyond.

1. Introduction

Biogases will play an important role in the European Union's (EU) ambition to achieve a net-zero future by 2050. Via the REPowerEU Plan, the European Commission has set a target to produce 35 billion cubic metres (bcm) of biomethane annually in the EU by 2030, providing a renewable and domestically-produced source of gas that can act as a direct substitute to fossil natural gas across many sectors of the economy. The target is ambitious, but momentum is building and the industry is fast mobilising. The Biomethane Industrial Partnership (BIP)[2] has been launched, enabling different parts of the biomethane value chain to work together with the European Commission and Member States to set the foundation upon which biomethane production can scale up to achieve the 35 bcm target, and to create the preconditions for a further ramp-up of potential towards 2050.

Today, 4 bcm of biomethane and 17 bcm of biogas for combined heat and power production are produced in Europe[3]. In 2022, Gas for Climate published a study[4] estimating the potential for biomethane production in the EU-27 (plus Norway, Switzerland and the United Kingdom). The EU-27 potential in 2030 was estimated to be 41 bcm, increasing to 151 bcm in 2050 if the full sustainable biomethane potential can be realised[5].

The EU's focus is now turning to 2040. The aim is to put in place measures to ensure the EU reaches climate neutrality by 2050. The European Commission is recommending that the EU's 55% greenhouse gas (GHG) emission savings target for 2030 is increased to 90% saving by 2040,[6] relative to 1990 levels. This will require action to decarbonise all sectors of the economy. The accompanying Impact Assessment shows that even in a scenario with accelerated electrification across the economy, there will still be a significant residual demand for gas.

In this light, this paper aims to refresh and update the 2022 Gas for Climate study with latest data and insights and to provide an estimate for the **potential biomethane production in the EU in 2040**. The estimate is provided for the EU as a whole and also broken down to what this could mean at the Member State level. Although the focus of this study is to develop potential estimates for biomethane production, it is acknowledged that part of this potential could be produced and used as biogas for combined electricity and heat where needed.

This paper is not a prediction of what will happen in 2040. Rather, it provides a scenario of what is possible when concerted action is taken across Europe to mobilise available and sustainable feedstock streams towards producing biomethane.

The 2030 and 2050 potential estimates in this paper are an update of, and therefore directly comparable to, the 2022 Gas for Climate paper. The core potential estimate focuses on feedstocks that are well suited for anaerobic digestion. Many of the feedstocks are wastes and residues. The waste and residue streams already exist and the main challenges are to collect them and channel them for biomethane production, and to build sufficient biomethane production capacity to process them.

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[2] Biomethane Industrial Partnership: https://bip-europe.eu/

[3] EBA Statistical Report 2023, Tracking biogas and biomethane deployment across Europe, 2023.

[4] Gas for Climate, Biomethane production potentials in the EU, 2022. https://gasforclimate2050.eu/wp-content/uploads/2023/12/Guidehouse_GfC_report_design_final_v3.pdf

[5] The estimated potentials for the EU-27 plus Norway, Switzerland and the United Kingdom are 45 bcm in 2030 and 165 bcm in 2050.

[6] European Commission, Climate Action, 2040 climate target. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en

In addition to the feedstocks quantified in the previous study, this paper provides qualitative insights into additional and novel sources of feedstock and technologies, as well as landfill gas, that can further boost the potential for biomethane production. Realising those potentials will require a favourable and stable policy environment that gives certainty to stakeholders across the biomethane value chain, but with the right conditions, Europe holds a significant sustainable potential waiting to be unlocked.

2. Biomethane production potentials in Europe

This chapter sets out the feedstock and technology scope, and the overall calculation methodology applied to estimate the biomethane potentials. Although the focus of this study is 2040, updated estimates for 2030 and 2050 are also provided.

2.1 Feedstock and technology selection

Biogas and biomethane are produced from a diverse range of 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 is particularly well suited to the treatment of water-based organic wastes and effluents.

Almost all biomethane in Europe today is produced via anaerobic digestion. Thermal gasification with biomethane synthesis is currently at a demonstration scale, for example, ENGIE's Salamander project in France. Hydrothermal gasification is at an industrial demonstration stage, with initiatives underway in several European countries, for example, SCW Systems' 20 MW_{th} plant in the Netherlands[7]. The potential to scale up both technologies is large in the medium to long term (2030 and beyond).

The feedstock and technology selection applied in this study is set out in Table 1 below.

Table 1. Feedstock and technology scope

Anaerobic digestion	Thermal gasification
Agricultural residues Materials that are left over in the field, following the harvesting of the main crop (e.g. cereal straw).	**Forestry residues** Primary residues from thinnings and final fellings, pre-commercial thinnings and logging residues.
Animal manure Liquid and solid animal waste arising from livestock housed in stables or barns.	**Landscape care wood** Includes, for example, tree management operations performed along roadsides, railways and in private gardens.
Biowaste Food and vegetal waste produced by households or commercial enterprises.	**Municipal solid waste (organic fraction only)** Mixed municipal waste represents the waste material that has not been separately collected for recycling, composting or anaerobic digestion, and originates mainly from households but can also be generated by industries.
Industrial wastewater Wastewaters arising from industry sectors in which anaerobic digestion technology could be implemented as a pre-treatment method.	**Prunings** Woody residues produced after cutting, mulching and chipping activities of fruit trees, vineyards, olives and nut trees.
Sequential crops 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.	**Wood waste** Secondary woody biomass, including wood processing, wood from paper and pulp production, construction and demolition waste, waste collected from households and industries.
Permanent grassland [Germany only] Grass cut from grassland which does not compromise use of animal husbandry purposes.	
Roadside verge grass Roadside verge grass is collected during maintenance operations in urban areas.	
Sewage sludge Residual, semi-solid or liquid material that is produced as a by-product during sewage treatment of municipal wastewater.	

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[7] SCW Systems: https://scwsystems.com/en/

As can be seen in Table 1 above, with the exception of sequential crops, all of the feedstocks included in the main potential estimate for 2040 are either wastes or residues. Energy crops (e.g. mono-cropping of maize) and stemwood[8] (roundwood) are not considered in the potential estimate.

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, such as animal manure, industrial wastewater and sewage sludge, could be converted to biomethane through hydrothermal gasification. However, in the context of this study, the feedstocks have been assigned to one technology type only, as a simplification step 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 at scale. However, in the future, hydrothermal gasification can further extend the scope of feedstocks suitable for biomethane production. An overview of this technology is covered in section 3.2.1.

2.2 Calculation methodology

The calculation methodology used in the 2022 Gas for Climate study has largely been replicated to facilitate comparison of the two studies. A short summary is provided below.

The total biomethane potential per country was calculated considering an assessment of the availability of each feedstock and its conversion yield to biomethane through the assigned biomethane conversion technology. For some feedstocks[9], the feedstock potential was estimated using a 'bottom-up' method, based on current statistical data (European/national level) and projections up to 2050 (for example considering trends in population, land area/crop production or livestock numbers). For other feedstocks[10], estimates from credible third party reports were utilised, notably a study conducted by Imperial College London[11].

The feedstock potentials reflect **technical constraints** (e.g. share of the theoretical feedstock potential that can be realistically mobilised) and where relevant **environmental constraints** (e.g. soil preservation), to derive a **sustainable** potential. The sustainable potential was further reduced to take into account **existing non-energy uses**, to ensure that the use of the feedstock for biomethane production does not impact these existing uses and lead to indirect impacts. Finally, for thermal gasification, as a further constraint, it was assumed that only 5% of the feedstock potential could be utilised by 2030 given this technology is currently at a demonstration scale.

This assumption increases to 55% in 2040 and 100% in 2050. The potential estimates were **not** adjusted for the use of feedstocks in **other energy sectors** (e.g. production of advanced biofuels, including sustainable aviation fuels, or heat and power generation). As such, the estimates derived in this study aim to provide a perspective on the total potential that could be realised if all of the available sustainable feedstock was utilised for biomethane production.

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[8] Stemwood is suitable for the production of sawn logs, panel products or pulp logs.

[9] Namely: agricultural residues, animal manure, industrial wastewater, sequential crops and sewage sludge.

[10] Namely: biowaste, forestry residues, landscape care wood, municipal solid waste, permanent grassland, prunings, roadside verge grass and wood waste.

[11] Imperial College London, Sustainable biomass availability in the EU to 2050, 2021. https://www.concawe.eu/publication/sustainable-biomass-availability-in-the-eu-to-2050/

Some feedstocks, such as animal waste and biowaste, present societal challenges with respect to fugitive emissions. Their use for biomethane production can play an important role in helping to reduce these emissions, while also producing valuable renewable energy. The key consideration is how much of the feedstock can realistically be mobilised and processed into biomethane towards 2040. For animal manure, the Global Methane Pledge[12] provides a specific driver to do this. The pledge aims to reduce global methane emissions by at least 30% from 2020 levels by 2030. Similarly, as landfilling of biowaste is no longer permitted in the EU from 2024, this will result in a significant increase in the biowaste material that is collected and that could be available for biomethane production.

Estimating the potential for biomethane from sequential crops is more challenging as these innovative crops are not yet widely cultivated in Europe. Farmers need to make a conscious decision to plant these crops in this way. The European Commission's intention to include 'intermediate crops' in Annex IX of the RED[13] is likely to serve as a catalyst to enable a scale-up of these feedstocks. The text box below contains a comparison between the 2022 Gas for Climate methodology to estimate the potential from sequential crops and the methodology recently developed by Task Force (TF) 3.1[14] of the BIP, to determine whether our approach was in-line with the latest thinking by industry, academia and policy makers.

Box 1. Comparison of 2022 Gas for Climate and Biomethane Industrial Partnership estimates of sequential crop potential in Europe

The term **sequential crop** is used here (as it was used in the previous 2022 study) and refers to crops that are grown before or after the main crop on the same agricultural land in the same harvest year. The Commission has proposed to include **intermediate crops** in Annex IX of the RED. The BIP notes that the term intermediate crop can be used more broadly to refer to different multi-cropping practices, but it appears to be used by the Commission to mean the same as the term sequential crop used in this and the previous study, to refer to a crop grown in sequence that is not the main crop.

In 2022, the Gas for Climate study estimated a biomethane potential from sequential crops of 8.8 bcm/year for 2030 and 46 bcm/year for 2050. At a Member State workshop in March 2024, the BIP announced that in their upcoming study they estimate a total potential for sequential crops of over 50 bcm/year in 2050. The magnitude of the total biomethane potential from sequential crops estimated in the two studies is therefore very similar.

The two studies both divide countries into different climatic regions, allocate appropriate crop types to the different regions, and assess the feasibility to grow sequential crops in the rotation in different regions. In both studies, the boreal region is assumed to have zero potential due to the short growing cycles available. The two studies differ slightly in the granularity of the climatic regions and the exact growing cycles.

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[12] European Commission, Launch by United States, the European Union, and Partners of the Global Methane Pledge to Keep 1.5C Within Reach, 2 November 2021. https://ec.europa.eu/commission/presscorner/detail/%20en/statement_21_5766

[13] The Commission has included intermediate crops in the new feedstocks proposed to be added to Annex IX of the REDII (Delegated Directive C(2024) 1585, adopted by the Commission on 14 March 2024 and currently under scrutiny of the co-legislators). The intention is to include intermediate crops defined as "catch crops and cover crops, […] that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land and provided the soil organic matter content is maintained […]."

[14] TF 3.1 aims to assess the EU-wide potential for sustainable rotational/sequential cropping to produce biomethane feedstock by improving sustainable farming practices and reducing food and biogas carbon intensity.

The 2022 Gas for Climate study categorised countries into four main climate regions, and assumed that only 20% of the available arable land would be used for sequential cropping. The study then attributes specific crops to these climatic regions with appropriate and realistic yields. The technical potential per country was then calculated to come up with the final estimate. The BIP study used the same four main climate regions, but the approach differs slightly as they outline five different cropping systems per climate region, based on conditions including climate and landscape. The study assumes 100% of the arable land would be suitable to change to one of these cropping systems (except the boreal region). However, the BIP study then applies a correction factor, tailored to the criteria applicable in the respective regions. This correction factor includes, but is not limited to, changes in the length of the cropping period rotation, competition from other bioenergy technologies, arable land readiness, and climate risk. With this correction factor, the total estimated potential decreased by 44% of the maximum biomethane potential.

Although the overall calculation methodologies applied for all feedstocks were largely the same as the 2022 Gas for Climate study, newly available data are included. For example, the most recent EUROSTAT/FAOSTAT country level statistics are included, as well as the updated European Commission Agricultural Outlook[15] which provides projections on how crop production and livestock numbers may develop to 2035. Also importantly, unlike in the 2022 study, for agricultural residues and animal manure updated projections to 2035 as well as extrapolations up to 2050 were applied to derive a more realistic view of the future potential of these two feedstock categories. In the 2022 Gas for Climate study, the projections were only available to 2030 and the 2050 production volumes for agricultural residues and animal manure were assumed to be the same as in 2030.

The feedstock potential estimates for forestry residues and wood waste were reviewed in light of the strengthened sustainability criteria for woody biomass under the Directive 2023/2413 (amended RED II)[16]. The updates to the RED II include additional criteria to protect old growth forests, highly biodiverse forests and heathlands, the introduction of the ‘cascading principle’ to ensure that Member States incentivise woody biomass to be ‘used according to its highest economic and environmental added value’, and not allowing financial support for energy from logs, industrial grade roundwood, roots and stumps. The 2022 study was judged to already satisfactorily address all of these aspects through requirements relating to the protection of land with significant biodiversity, deducting a representative share (50%-60%) of the feedstock potential for non-energy uses and importantly excluding stemwood, roots and stumps. Nonetheless, a further deduction of 15% was applied in this study in order to take a conservative approach.

Finally, the assumed biomethane ramp up from 2030 to 2040 reflects the European Commission’s intention to set an ambitious target to accelerate decarbonisation in the EU and to reduce the EU’s net greenhouse gas emissions by 90% by 2040 relative to 1990. This implies that significant effort will be required well in advance of 2040 to meet this target.

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[15] European Commission, EU Agricultural Outlook 2023-2035, 2024. https://agriculture.ec.europa.eu/data-and-analysis/markets/outlook/medium-term_en

[16] The feedstock potentials applied in 2022 were based on the Imperial College London (2021) study.

2.3 Biomethane potentials in 2040

A biomethane potential of **111 bcm** is estimated for 2040, of which 101 bcm relates to the EU-27 (see Figure 1). This potential is made up of 74 bcm **anaerobic digestion** (67% of the total) and 37 bcm **thermal gasification** (33% of the total). The EU-27 countries with the highest potential in 2040 are Germany, France, Spain, Italy and the United Kingdom. Collectively, these countries represent over 50% of the total biomethane potential. A high potential is also seen in Poland.

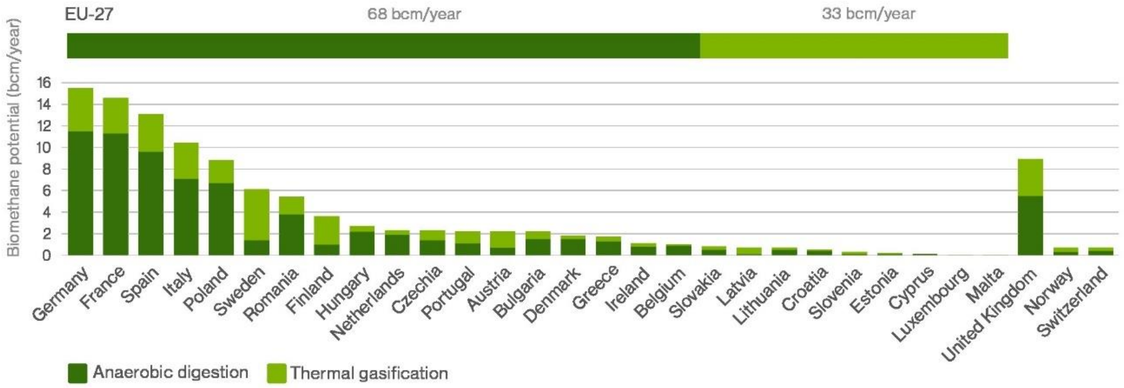

Figure 1. Biomethane potential (bcm/year) in 2040 per country and technology

The biomethane potential estimates derived in the context of this study are intended to provide a sense of the overall scale at a European level, 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).

For some of the assessed feedstocks, competition can emerge. For example, **agricultural residues and the thermal gasification** feedstocks could be used directly to generate heat and/or power[17]. Alternatively, these feedstocks could be processed into advanced biofuels, such as cellulosic ethanol, renewable diesel, methanol or sustainable aviation fuels (particularly beyond 2030).

A potential of **74 bcm** is estimated for **anaerobic digestion** in 2040, of which 68 bcm relates to the EU-27 (Figure 2 overleaf). The top 5 countries include Germany, France, Spain, Italy and Poland. Key feedstocks in 2040 are sequential crops (43%), as well as agricultural residues (20%) and animal manure (19%). Collectively these feedstocks represent 82% of the total. Industrial wastewater also contributes 11% of the potential in 2040.

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[17] Note that this study applies a deduction of 24 million tonnes to the waste wood potential to reflect the estimated existing use of wood waste in sawmills for heat and power.

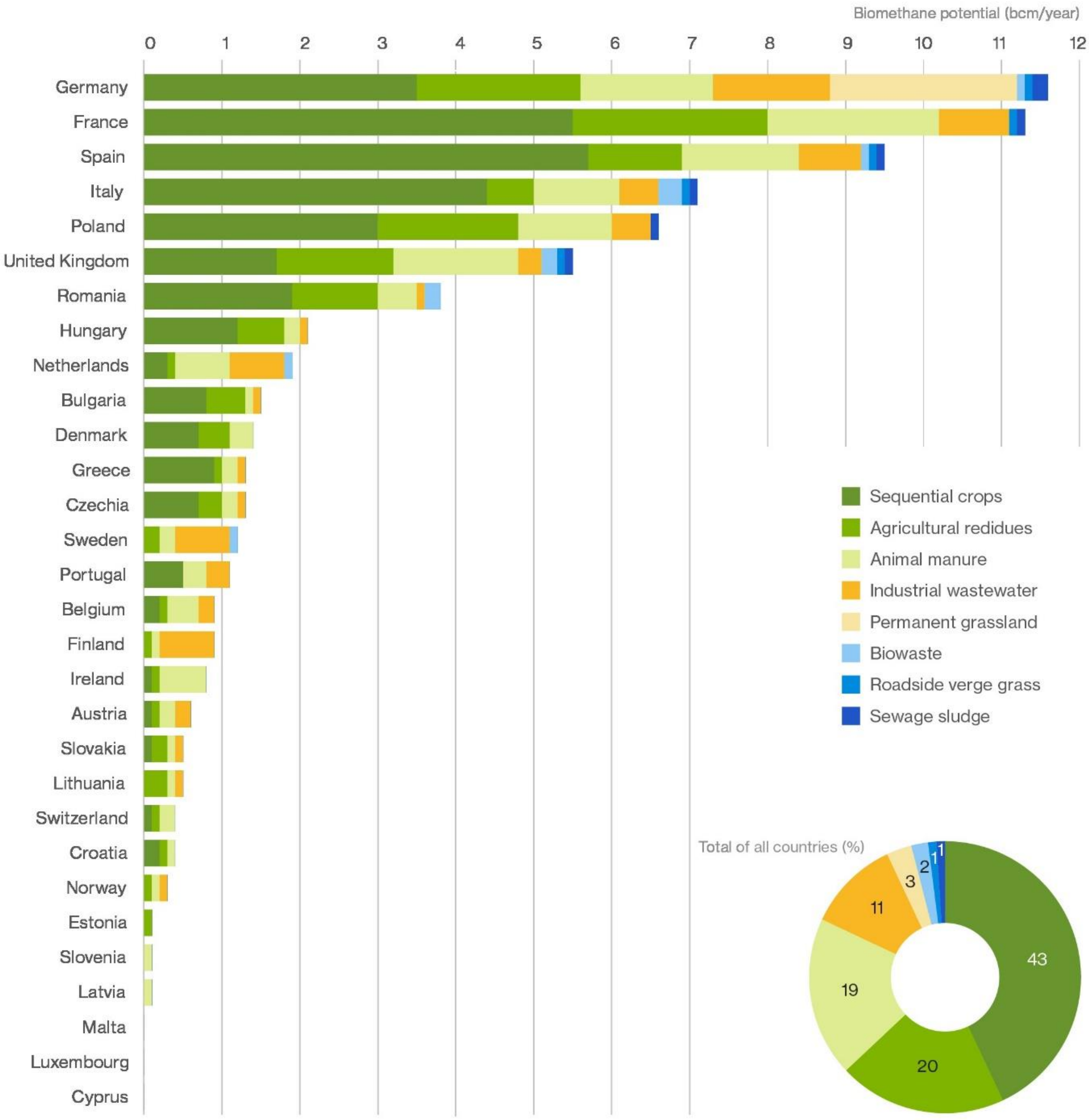

Figure 2. Biomethane potential (bcm/year) per country in 2040 for anaerobic digestion

A potential of **37 bcm** is estimated for **thermal gasification** in 2040, of which 33 bcm relates to the EU-27 (Figure 3 overleaf). The top 5 countries include Sweden, Germany, Spain, United Kingdom and France. Key feedstocks in 2040 are wood waste (32%), the organic fraction of municipal solid waste (27%) and forestry residues (26%). Collectively these feedstocks represent 85% of the total.

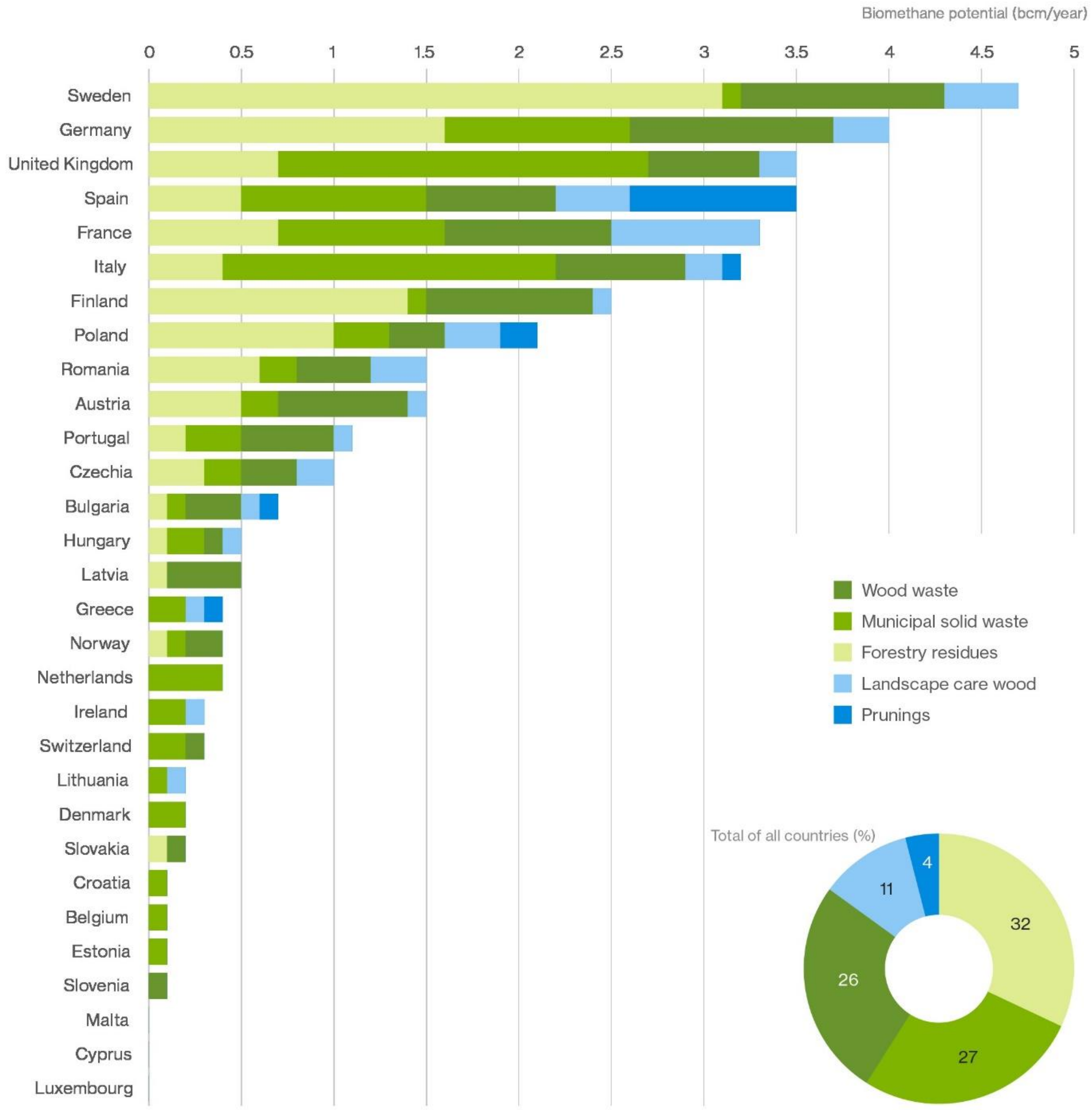

Figure 3. Biomethane potential (bcm/year) per country in 2040 for thermal gasification

Figure 4 overleaf illustrates the projected evolution of biomethane production from 2022 (actual data), through to 2050. Today, around 4 bcm of biomethane and 17 bcm of biogas are produced in Europe. This is almost exclusively based on anaerobic digestion. The potential of biogases is projected to steeply increase by 2030 (to around 44 bcm), and still be dominated by anaerobic digestion. A further steep increase is seen towards 2040 and 2050, with both production technologies playing an important role. The increase in anaerobic digestion is largely driven by greater deployment of sequential crops, and increased mobilisation of wastes and residues. Thermal gasification is set to become significantly more relevant in the 2040 timeframe as the technology further commercialises (representing over 30% of the total), and further still in 2050 (with a 40% share).

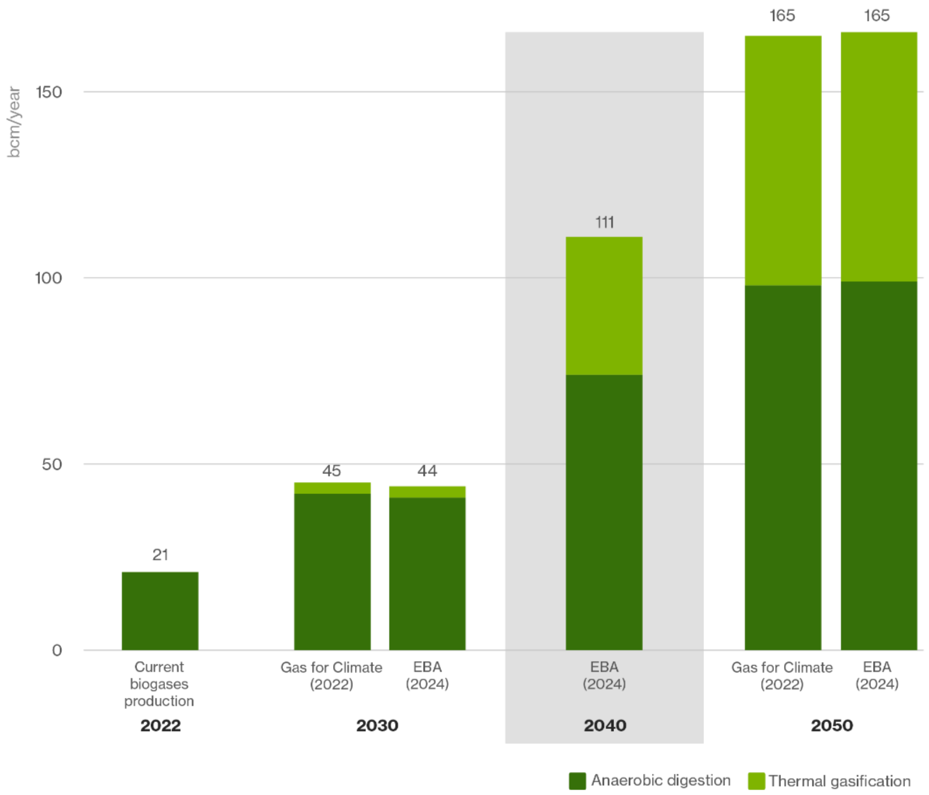

Figure 4. Biogases production in Europe in 2022 and estimated biomethane production potentials between 2030 and 2050 per conversion technology

2.4 Comparison with Gas for Climate study

The estimated biomethane production potentials in this study are broadly consistent with the 2022 Gas for Climate study, given that the underlying methodology and key assumptions have not fundamentally changed. The European production potentials for 2030 and 2050 in the Gas for Climate study were **45 bcm** and **165 bcm** respectively, which compares to **44** and **165 bcm** in this study. However, although the total potential estimates are similar, there are some differences observed in the potential estimates for some feedstocks.

For **anaerobic digestion**, notable differences exist for agricultural residues (+8%/18% vs previous study in 2030/2050) and animal manure (-7%/-11% vs previous study in 2030/2050). These differences largely arise from applying the amended projections for crops and livestock numbers published by the European Commission, and also importantly extrapolating these assumptions to 2050 (which was not the case in the previous Gas for Climate study). Differences for industrial wastewater also exist (-15%/-1% vs previous study in 2030/2050). This results from using the latest available statistical data (e.g. EUROSTAT) for the twenty one industry sectors covered, and also from applying a three year average rather than the most recent reported year.

For **thermal gasification**, notable differences exist for forestry residues (-15% vs previous study in both 2030 and 2050) and municipal solid waste (+30%/+22% vs previous study in 2030/2050). The reduction for forestry residues can be explained by the additional deduction applied to the feedstock potential estimates as explained in section 2.2. The increase in the potential for municipal solid waste results from using a different dataset published by Imperial College London. In the previous Gas for Climate study, we inadvertently applied the ‘Scenario 2’ dataset, rather than the ‘Scenario 3’ dataset (as outlined in the study report). This oversight has been corrected in this study.

3. Novel feedstocks and technologies

This chapter showcases several novel feedstocks and technologies that are not currently widely deployed today, as well as landfill gas. Each have the potential to contribute to increasing the production of sustainable biomethane supply towards 2040 and beyond, in addition to the quantitative estimates derived in chapter 2.

3.1 Feedstocks

3.1.1 Marginal and contaminated land

There is a significant potential for currently underutilised lands to produce crops for bioenergy. So-called **marginal** and **contaminated land** could provide a new source of feedstock for biomethane production without contributing to an increase in land use change, or compromising existing food or feed production. Marginal and contaminated land may have lower yields per hectare compared to good quality agricultural land because of biophysical and climatic challenges, but can nonetheless still offer a significant feedstock potential. Bringing these types of land into productive use can also bring benefits to the soil and biodiversity by halting further degradation and erosion, or restoring the soil through phytoremediation in cases of contamination.

There is no specific definition of marginal or contaminated land in the context of EU energy legislation, however biomethane potential from marginal and contaminated land was mentioned in the Biomethane Action Plan[18] which accompanied the REPowerEU Plan.

In this study, we include **unused, abandoned and severely degraded** types in the broader category of marginal land. The RED II[19] and Low ILUC Delegated Regulation 2019/807 promote the use of unused, abandoned and severely degraded lands (see definitions textbox below) to certify the production of “additional biomass” with low indirect land use change (ILUC) for bioenergy purposes. Furthermore, in the newly adopted amendments of RED II Annex IX, the European Commission proposes to include crops grown on severely degraded land[20]. Crops produced on such lands could be used to produce biomethane.

Box 2. EC definitions of unused, abandoned and severely degraded lands

From Delegated Regulation 2019/807 (Low ILUC Regulation):

- ‘Unused land’ means areas which, for a consecutive period of at least 5 years before the start of cultivation of the feedstock used for the production of biofuels, bioliquids and biomass fuels, were neither used for the cultivation of food and feed crops, other energy crops nor any substantial amount of fodder for grazing animals.
- ‘Abandoned land’ means unused land, which was used in the past for the cultivation of food and feed crops but where the cultivation of food and feed crops was stopped due to biophysical or socioeconomic constraints.

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[18] European Commission, Implementing the RePowerEU Action Plan: Investment needs, Hydrogen Accelerator and achieving the Biomethane targets. SWD(2022) 230 final, 2022. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230&from=EN

[19] Biomass grown on severely degraded land may be eligible for a greenhouse gas bonus of 29 g CO_2eq/MJ. See Annex V Part C point 8(b) and Annex VI Part B point 8(b).

[20] Delegated Directive C(2024) 1585, adopted by the Commission on 14 March 2024 and currently under scrutiny of the co-legislators, proposes to include in Annex IX “Crops grown on severely degraded land excluding food and feed crops […]”. The Commission proposes to include these crops in Part A of Annex IX if the final fuel is used for aviation and in Part B if used for other transport purposes.

From Directive 2018/2001 (RED II):

- ‘Severely degraded land’ means land that, for a significant period of time, has either been significantly salinated or presented significantly low organic matter content and has been severely eroded.

In this study we use the definition of marginal land from the HORIZON-2020 MAGIC project[21], which considers contaminated land as a subset of marginal land[22]. Land that is left fallow in between the growing season of the main crop(s) is not considered ‘marginal’ in the context of this study; biomass grown in these fallow periods is covered in sequential crops in section 2.2.

Marginal land

Mapping efforts to estimate marginal land availability and achievable yields

In December 2023, TF3.2[23] of the BIP published a comprehensive literature overview of the feedstock production potential on marginal (and contaminated) land and recent mapping efforts[24]. The overview includes several HORIZON-2020 projects which have attempted to estimate and classify the marginal land available in Europe, however these derive widely different results.

The MAGIC project mapped just under 70 million hectares (Mha) of *agricultural*[25] marginal land available across Europe, which is equivalent to around 30% of the total agricultural area (see Figure 5). This land is currently either not being used or otherwise underutilised due to biophysical constraints, such as excessive soil moisture, low soil fertility, or adverse conditions regarding the climate, chemical composition of the soil, rooting conditions or terrain.

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[21] Elbersen, B. et al., Deliverable 2.6 Methodological approaches to identify and map marginal land suitable for industrial crops in Europe. EU Horizon 2020; MAGIC; GA-No.: 727698, 2020. https://magic-h2020.eu/wp-content/uploads/2022/04/MAGIC_D2.6-Methodological-approaches.pdf

[22] Definition of marginal land used in the MAGIC project: “lands having limitations which in aggregate are severe for sustained application of a given use and/or are sensitive to land degradation, as a result of inappropriate human intervention, and/or have lost already part or all of their productive capacity as a result of inappropriate human intervention and also include contaminated and potentially contaminated sites that form a potential risk to humans, water, ecosystems, or other receptors”.

[23] TF 3.2 focuses on evaluating the potential for feedstock production on marginal and contaminated land across the European Union.

[24] Buffi, M. and Motola, V., Feedstock production on marginal and contaminated land – An EU wide potential assessment, Biomethane Industrial Partnership, 2023. https://bip-europe.eu/downloads/?filter%5B%5D=19

[25] Agricultural land includes arable land and pastureland.

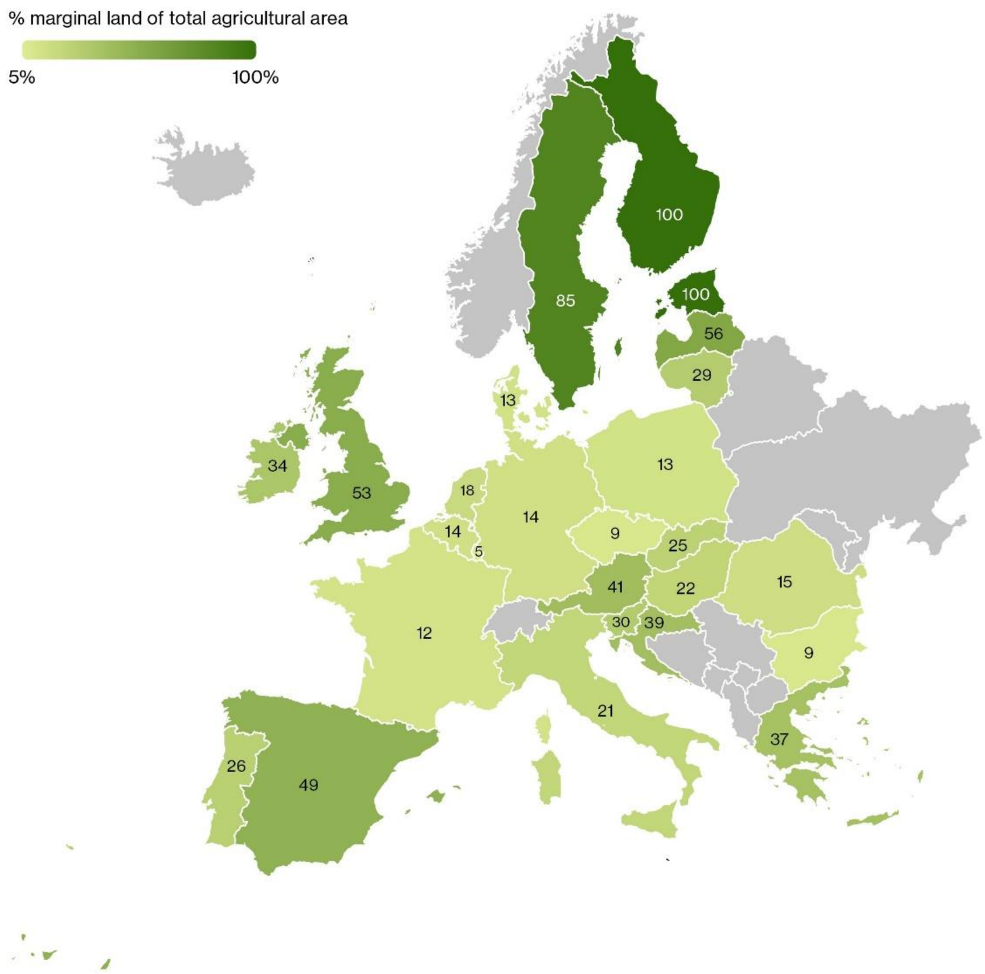

Figure 5. Total marginal land in Europe as a percentage of the total agricultural area[26]

The largest marginal land area is seen in Spain with an estimated 16.8 Mha (49% of the total agricultural area in Spain). The main reasons for the marginal land classification were due to adverse rooting conditions and adverse climate conditions. The United Kingdom has the second highest marginal land area at 10.7 Mha. In the case of the United Kingdom, the lands were deemed marginal mainly due to excessive soil moisture (7.9 Mha), adverse rooting conditions (3.2 Mha hectares) and adverse climate conditions (3.2 Mha).The Nordic countries have very with high proportions (>50%) of their agricultural land classified as marginal land (with exclusion of land improved by management), notably Estonia and Finland (both at 100%) and Sweden (81%). In these countries, the most influential limitation is adverse climate, and particularly the short vegetation cycles.

Other studies have estimated the marginal land area in Europe through mapping, while also considering land that is suitable for the cultivation of bioenergy feedstocks or land that is compliant with the RED II sustainability criteria. Hirschmugl et al. (2021) included abandoned farmland and severely degraded land when mapping marginal and underutilised land, which resulted in an estimate of 5.3 Mha of underutilised land in Europe potentially available for

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[26] Design: Annemiek Schellenbach. Data taken from: Definition of marginal land used by the MAGIC project: “lands having limitations which in aggregate are severe for sustained application of a given use and/or are sensitive to land degradation, as a result of inappropriate human intervention, and/or have lost already part or all of their productive capacity as a result of inappropriate human intervention and also include contaminated and potentially contaminated sites that form a potential risk to humans, water, ecosystems, or other receptors”.

bioenergy production.[27] Vera et al. (2021) evaluated the marginal land availability, in line with the RED II sustainability criteria, which estimated approximately 21 Mha of marginal land available from 2020-2050. Most of the 2040 estimate relates to shrubland (15.2 Mha), followed by open space (4.3 Mha).[28] Both of these studies did not include contaminated land in their estimates for marginal land.

The yields achievable on marginal land are lower than on utilised agricultural land. This can be due to degradation, abandonment or contamination which negatively affects plant growth. In this study we mostly consider lignocellulosic feedstocks, as these feedstock types are most commonly tested in the studies focusing on marginal (and contaminated) land. These include poplar, sorghum, miscanthus, switchgrass, cardoon, giant reed and reed canary grass for marginal lands and miscanthus and sorghum for contaminated land. Yield estimates per climatic region were published in the HORIZON-2020 BIKE project for marginal land (see Table 2 below)[29]. Anaerobic digestion is the most appropriate conversion technology for the majority of the feedstocks below when estimating biomethane potential.

Table 2. Average yields per climatic region on marginal land with natural constraints (dry matter t/ha)

	Atlantic	Continental & Boreal	Mediterranean
Sorghum	9	9	12
Tall wheat grass	-	-	7
Miscanthus	8	9	9
Switchgrass	10	10	12
Cardoon	8		10
Giant reed	9	9	11
Reed canary grass	7	7	7
AVERAGE	8.4	8.5	9.8

Biomethane potential from marginal lands

There is a high land availability for marginal land in Europe, of nearly 70 Mha. However, due to the broad categorisation of marginal land (including climatic constraints, excessive soil moisture, adverse chemical composition, low soil fertility, adverse rooting condition, and adverse terrain) not all land will be unused, suitable for biomass production or necessarily compliant with the sustainability provisions of European renewable energy regulations. Therefore, attempting to quantify the total biomethane potential is challenging. For **illustrative purposes**, if a marginal land area of 10 Mha is assumed to be used for the cultivation of bioenergy feedstocks, then this could realise a biomethane potential of up to bcm/yr based on the average yields per crop and climate region in Table 2.

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[27] Hirschmugl, M. et al., Pan-European Mapping of Underutilized Land for Bioenergy Production. Land 2021, 10, 102, 2021. https://www.mdpi.com/2073-445X/10/2/102

[28] Vera, I. et al., Supply potential of lignocellulosic energy crops grown on marginal land and greenhouse gas footprint of advanced biofuels—A spatially explicit assessment under the sustainability criteria of the Renewable Energy Directive Recast, 2021. https://onlinelibrary.wiley.com/doi/10.1111/gcbb.12867

[29] Elbersen B., Verzandvoort S., Panoutsou C., Alexopoulou E., Horizon 2020 BIKE (Grant Agreement No. 952872) - Deliverable 2.2 - Options to grow crops on unused, abandoned and/or severely degraded land, Wageningen University & Research, 2022.

Contaminated land

The right biomass grown on contaminated land can remove contaminants, such as metals, pesticides, explosives, and oil from the soil through phytoremediation. Some of these metals could be recovered and re-used in a process called phyto-mining. An additional benefit of using phytoremediation to recover contaminants, is that under the right conditions, the biomass could be used to produce biomethane.

The Biomethane Action Plan published by the European Commission in 2022, and accompanying the REPowerEU Plan, identifies a need to support innovative technologies for biomethane potential including feedstocks grown on contaminated soils through phytoremediation. Developing such innovative approaches has environmental co-benefits in cleaning the land and can boost the regional bioeconomy.

The recent BIP report further outlines mapping efforts to estimate the amount of contaminated land suitable for phytoremediation. One of the HORIZON-2020 projects, GOLD, estimates that there is 2 Mha of contaminated land available in Europe that is suitable for phytoremediation[30]. France, Germany, Spain and the United Kingdom have the largest total areas of all types of potentially contaminated sites (>150,000 ha each). These sites include military sites, landfill, quarries, industrial sites and mining sites that are less than 40% impermeable. Agriculture covers between 7% and 20% of the total area for military sites and landfills respectively, and around half of the mines that were deemed suitable for phytoremediation were located on agricultural land. In the HORIZON-2020 project MAGIC estimated 2.7 Mha of marginal land with adverse chemical conditions, which included salinity, sodicity and contamination of soils. The average yields achieved on contaminated land are lower than those reported for marginal land. For example, the average yields for miscanthus was 5.4 t/ha/yr[31] (compared to 8-9 t/ha/yr). Sorghum tends to grow normally in contaminated soils, specifically in cadmium polluted soils where sorghum performed quite well to absorb the cadmium from the soil without it affecting the biomass.[32] The HORIZON-2020 project GOLD sets the threshold at 1.0 mg/kg for critical concentrations of cadmium in the soil, at this level sorghum yields of 5.8 t/ha/yr are still achievable. Sorghum yields tend to be significantly impacted at levels above 50 mg/kg of cadmium in the soil.[33]

Although lower yields are achievable on contaminated soils, there is a vast land area suitable for phytoremediation in Europe which can be used to unlock significant additional sustainable biomethane potential.

3.1.2 Digestate

Anaerobic digestion of organic feedstocks produces biogas and digestate (also termed biofertiliser) as a co-product. Digestate is a nutrient rich organic material. It contains the three key macronutrients required for plant growth, nitrogen (N), phosphorous (P) and potassium (K). Also present are secondary nutrients such as magnesium (Mg), calcium (Ca) and sulphur (S) and micronutrients copper (Cu) and zinc (Zn). Digestate can therefore be used as an agricultural fertiliser, replacing synthetic fertiliser.

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[30] GOLD. Growing energy crops on contaminated land for biofuels and soil remediation. Issue 3 / July 2023.

[31] Sestak I. et al., Assessment of the Impact of Soil Contamination with Cadmium and Mercury on Leaf Nitrogen Content and Miscanthus Yield Applying Proximal Spectroscopy. Agronomy 2022 12(2), 2022. https://doi.org/10.3390/agronomy12020255

[32] Xioa M-Z. et al., A sustainable agricultural strategy integrating Cd-contaminated soils remediation and bioethanol production using sorghum cultivars, 2021. https://www.sciencedirect.com/science/article/abs/pii/S0926669021000637

[33] Tian Y.L. et al., Morphological Responses, Biomass Yield, and Bioenergy Potential of Sweet Sorghum Cultivated in Cadmium-Contaminated Soil for Biofuel. International Journal of Green Energy V. 12(6), 2014 https://doi.org/10.1080/15435075.2013.871722

Importantly, this plays a valuable role in contributing to the circular economy by recycling organic wastes and turning them into useful products, including both renewable energy and the nutrient rich digestate that can be returned to the soil.

According to the European Biogas Association, 31 Mt of digestate were produced in Europe in 2022, of which 28 Mt (90%) was derived from agricultural feedstocks (manure, agricultural residues, energy crops) and 3 Mt (10%) from biowaste[34]. The volume of digestate is set to grow significantly in the coming years in-line with the expected scale-up of the biomethane sector.

Digestate is available in three forms. **Whole digestate** is the direct output from digesters and can be used without processing[35]. For the purposes of volume reduction and nutrient management (to reduce transport costs, ease spreading and increase nutrient value) digestate can, however, be separated into solid (fibres) and liquid fractions using separation techniques. The **liquid fraction** of digestate typically contains high levels of nitrogen and can be applied to the fields of nearby farms or be further processed for upgrading. The **solid fraction** is stable and rich in carbon and phosphorus. The reduced volume facilitates transport to a wider region. It can also be used as a soil conditioner.

The application of digestate to land should be prioritised where feasible and environmentally safe. However, in some specific cases this may be challenging due to digestate spreading limits (for zones which have a nitrogen surplus)[36] in the surroundings of the plant, or a lack of demand for digestate if the plant is located in an urban area. Additionally, there may potentially be restrictions in the spreading digestate from wastewater treatment plants due to the presence of heavy metals or microplastics. In these situations, technology options are available to utilise the digestate as a feedstock to produce additional biomethane. These include **hydrothermal gasification** and **pyrolysis**.

Hydrothermal gasification

Hydrothermal gasification is a thermo-chemical process that is particularly well suited to the treatment of water-based organic wastes, including digestate. The process also has the benefit of being able to recover mineral salts (phosphorus in particular) upstream of the reactor, which provides an additional revenue stream for the process. The process can also remove the need for the hygienisation or other specific upstream treatments of certain waste streams that are processed prior to anaerobic digestion due to the presence of pollutants, pathogens or insufficient methanogenic capacity. A 2023 study published by the French National Hydrothermal Gasification Working Group estimated a biomethane potential of around 21 TWh (~ 2 bcm) from digestate in France in 2050 based on agriculture waste and sewage sludge origin (~60 Mt/year which is equivalent to around 15% of the estimated digestate capacity in France in 2050).[37]

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[34] European Commission, Digestate and compost as fertilisers: Risk assessment and risk management options, 2019.

[35] In some countries, such as France and regions in Spain there are regulations for the pasteurisation of the digestate for larger scale biogas plants where manure from several farms is used.

[36] The Nitrates Directive places a limit of 170 kg N/ha for livestock manure, including in “processed form” such as manure based digestate.

[37] GRTgaz, Hydro-thermal Gasification White Paper, French National Hydrothermal Gasification Working Group, 2023. https://www.grtgaz.com/en/medias/press-releases/white-paper-hydrothermal-gasification

Pyrolysis

Pyrolysis is an alternative solution to treating digestate. This technology is being actively explored in Denmark, in particular with a focus on treating the undigested fraction of straw and other fibres that remains in digestate[38]. Here, the solid fraction of the digestate is heated to a temperature of around 650 ^{O}C in the absence of air. The process produces pyrolysis gas (a gas containing carbon dioxide, methane, carbon monoxide and hydrogen), bio oil and biochar[39]. The pyrolysis gas can either be injected back into the digester to produce additional biogas, or otherwise used on-site for energy generation instead of using natural gas (thereby indirectly increasing the greenhouse gas emission balance). Biochar has significant value as a soil improver, improving soil health and providing improved water and nutrient retention. It also importantly serves as an effective means of storing carbon in soils, thereby delivering significant greenhouse gas emission savings. This is one of the main drivers to choose to pyrolyse digestate. The pyrolysis technology can also provide the additional benefit of breaking down Perfluoroalkoxy alkanes (PFAS) and other impurities that may be present in the digestate. A number of companies[40] are pursuing this technology in Denmark, with several commercial scale and demonstration plants already in operation, or otherwise under construction[41].

3.1.3 Seaweed

Seaweed is the common name for multicellular (macro) algae that grow in water bodies, including seas and coastal waters in Europe. There are numerous seaweed species globally; these can be classified into three broad groups based on their pigmentation[42]: brown, red and green. Biogas production rates for selected species of brown and red seaweeds can be comparable to land-based energy crops, such as sugarcane or sorghum[43]. Although seaweed can potentially be cultivated as a feedstock for biogas production, there is currently greater market interest in using so-called **‘cast seaweed’** (seaweed that is naturally deposited on the beach and therefore a waste that can be collected). Cast seaweed represents a more sustainable and economically attractive option to using cultivated seaweed.

The COASTAL Biogas project (2018-2021) explored the potential of using ‘cast’ seaweed harvested in the Baltic Sea within the boundaries of the Interreg South Baltic Programme[44], which includes Denmark, Germany, Poland, Lithuania and Sweden. The annual potential of cast seaweed in the South Baltic Sea area is estimated to be ~2 Mt, of which ~1.3 Mt is in non-protected areas. The COASTAL Biogas project showcases two examples of biomethane production from seaweed.

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[38] Straw represents an increasing share of the feedstock used for biomethane production in Denmark resulting in a higher dry matter content in the digestate calling for a post treatment of the digestate to improve the quality of the digestate as a fertiliser and reduce the risk of emission of ammonia. In addition to the direct use of straw as a feedstock, so-called “deep litter” (livestock manure from stables using a lot of straw as bedding material) plays an important role in Danish biogas plants.

[39] According to Danish company Stiesdal SkyClean, biogas digestate produces a biochar with 63% C (carbon), 31.6% ash, 2.1% P, 1.6% N and 1.5% K, and also with high water retention.

[40] Including Aquagreen, Frichs and Stiesdal.

[41] https://agrienergy.dk/pyrolyse/; https://aquagreen.dk/; https://frichs-pyrolysis.com/projekter/; https://www.greenlab.dk/knowledge/stiesdal-is-building-an-ambitious-skyclean-plant-at-greenlab/; https://www.odsherredforsyning.dk/nyheder/biokoks-fra-odsherred-paa-jysk-vinmark/

[42] Brown (Phaeophyceae), red (Rhodophyceae) and green (Chlorophyceae).

[43] Brown Macrocystis seaweed: 0.39–0.41 m^3 CH_4/kg Volatile Solids. Green Gracilaria seaweed: 0.28–0.40 m^3 CH_4/kg volatile solids (VS). Zhao Y. et al., Biofuel Production from Seaweeds: A Comprehensive Review, Energies 2022, 15(24) 9395. https://doi.org/10.3390/en15249395

[44] COASTAL Biogas. Report on potential of cast seaweed and policy frameworks in South Baltic Sea area, Deliverable 3.3, 2022. https://www.coastal-biogas.eu/resources/D33_Report_on_potential_of_cast_seaweed_and_policy_frameworks.pdf

These include the **Solrød industrial scale** biogas plant in Denmark[45], where around 1,500-2,000 tonnes of cast seaweed per year have been successfully co-digested since 2015[46] (this represents less than 10% of the available cast seaweed in the area of the plant), and the **Smyge pilot scale** biogas plant in Sweden. Testing at Smyge indicated that the seaweed co-digested with easily degradable organic material resulted in a stable process with a high methane content (around 70%) and a high biogas production[47].

The COASTAL Biogas project also explored how cultivation of seaweed can serve to mitigate eutrophication impacts and reduce nutrient discharges, offering important co-benefits. Furthermore, the harvesting of cast seaweed also delivers socio-economic benefits in coastal areas, including eliminating the odour of rotting seaweed on the beaches (thereby also reducing the associated fugitive greenhouse gas emissions), reducing the prevalence of flies and improving the water quality for the benefit of recreation and tourism.

The rate of methane production from seaweed is heavily influenced by the seaweed's biochemical composition and is dependent on the presence of components that are resistant to microbial breakdown (Jard et al., 2013[48]). To increase the biogas yield, the seaweed first needs to be pretreated. Pretreatment methods are: physical, chemical and biological routes. The choice of pretreatment method is generally based on the algae species. According to the COASTAL Biogas project, hydrothermal pretreatment is the most effective, resulting in an increase of 50-83% in biomethane yield compared to untreated seaweed and cattle slurry, while mechanical pre-treatment results in the lowest increase in yield of 4-24%. Acid pretreatment resulted in a yield increase of 25-33%[49].

In the case of cast seaweed, the methane yield is dependent on the distance from the coast and the transport speed to reach the coast. Once the seaweed has washed up on the beach it already starts to decompose. To illustrate, seaweed near to the coast can have a methane yield of 0.12 to 0.15 m^3/kg volatile solids (VS), whereas the methane yield of seaweed collected from the beach is considerably lower at 0.036 to 0.056 m^3/kg VS. Contamination with sand is another contributing factor in reducing the methane yield and this needs to be removed in a pretreatment step at the biogas plant.

Seaweed can also be produced as a feedstock. According to the United Nations Food and Agriculture Organisation (FAO), the global production of brown, green and red seaweed reached 35.5 million tonnes in 2019[50], of which Europe produced around 1% (287 kt wet). In Europe, seaweed production is developed through both wild harvesting (68%) and cultivation (32%), across 13 countries. China is the global leader with around 56% of the market (20 Mt wet), and almost exclusively based on seaweed cultivation. Today, most of the seaweed harvested globally is for high-value non-energy markets, including commercial alternative protein sources, food additives, dietary supplements and cosmetics.

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[45] According to COASTAL Biogas, the Solrød biogas plant is the only known industrial scale plant where cast seaweed is used as a feedstock material for biogas production.

[46] The total capacity of the plant is 226 kt of substrate per year (Coastal Biogas project).

[47] COASTAL Biogas. A report on operating biogas facilities utilising anaerobic digestion of cast seaweed, Deliverable 3.2, 2020. https://www.coastal-biogas.eu/resources/D32_Report_on_operating_biogas_facilities_utilising_anaerobic_digestion_of_cast_seaweed.pdf

[48] Jard G. et al., French Brittany macroalgae screening: composition and methane potential for potential alternative sources of energy and product, Bioresource Technology, Volume 144, September 2013, Pages 492-498. https://www.sciencedirect.com/science/article/abs/pii/S0960852413010432?via%3Dihub

[49] COASTAL Biogas, Pre-treatment and Biogas Yield, FINAL COASTAL Biogas Conference, 2021. https://www.coastal-biogas.eu/resources/Pre-treatment_and_biogas_yield.pdf

[50] United Nations Food and Agriculture Organisation, Seaweeds and microalgae: an overview for unlocking their potential in global aquaculture development, FAO Fisheries and Aquaculture Circular No. 1229, 2021. https://www.fao.org/documents/card/en?details=cb5670en

Seaweed cultivation is expected to increase in Europe, in-line with projected growth in the demand for seaweed products[51].

Several research initiatives have tested the potential of using cultivated seaweed for biogas production. For example, the SeaGas[52] project in the UK (2015-2018) assessed the technical and financial viability of farming sugar kelp for biogas production. The project successfully tested the operation of two 800 litre reactor vessels over a twelve-month period. However, today no commercial scale projects exist in Europe.

Technical challenges of seaweed cultivation relate to potential interference with natural and anthropogenic processes, including sustainability considerations[53]. Careful site selection and on-going management is necessary to ensure that ecosystem impacts are minimised. There are also economic challenges for the current market readiness of seaweed cultivation in Europe. The costs of producing seaweed are an important determinant for successful upscaling of production. Van den Burg (2019)[54] estimated that costs for large-scale seaweed cultivation in the North Sea could be reduced from €5,200 to €1,200 per ton dry matter if yield increases combined with a lower cost of plant material are realised. In comparison, the use of cast seaweed is a far more attractive option as it only requires collection and aggregation of the material.

Several plants have successfully demonstrated that cast seaweed can be a suitable feedstock for biomethane production in Europe. Significant future potential exists given that only a very small share of the available cast seaweed is currently being collected. Next steps should be focused on improving collection methods and targeting cast seaweed off the coast, as well as continued research to optimise conversion processes, thereby reducing costs and improving operational performance. Policy makers can play an important role in helping the industry scale-up by providing funding for research and in establishing a supportive regulatory environment that facilitates a sustainable scale-up.

3.2 Technologies

3.2.1 Hydrothermal gasification

Hydrothermal gasification (also known as supercritical water gasification), is a thermo-chemical conversion process that takes place at high pressure (210-350 bar) and high temperature (360-700 ^{O}C)[55] in the presence of water. The technology is particularly suitable for the treatment of organic waste that contains or can easily be mixed with water, which acts as a reagent. Two variants of the technology are available, each with specific operational conditions: **catalytic hydrothermal gasification**[56] (360-450 ^{O}C and 210-300 bar) and **high temperature hydrothermal gasification** (550-700 ^{O}C and 221-350 bar). Catalytic hydrothermal gasification typically yields syngas with up to 60-70% methane, 0-10% hydrogen and 20-35% carbon dioxide.

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[51] CBI, The European market potential for seaweed, Last updated 14 February 2022. The European market potential for seaweed | CBI

[52] Seagas Project: https://seagas.co.uk/

[53] Declining germplasm diversity, degradation of agronomic traits, the presence of polluted environments, changing ocean conditions, increasing anthropological interference, genetic cross-contamination between wild and farmed kelp populations, and the impacts of ocean warming and ocean acidification.

[54] Van den Burg S, Economic prospects for large-scale seaweed cultivation in the North Sea, Wageningen Economic Research, 2019. https://edepot.wur.nl/470257

[55] Hydrothermal gasification takes places at either above or below the critical point of water (374 ^{O}C, 221 bar).

[56] The catalyst is typically ruthenium based.

In contrast, high temperature hydrothermal gasification produces a syngas with a lower share of methane of around 20-40% and a higher share of hydrogen of 20-50%, and up to 12% hydrocarbons.[57]

Hydrothermal gasification offers several reported benefits. These include a very high carbon conversion rate of up to 99%, reduced reaction temperature and heat input, thereby resulting in an overall energy efficiency of up to 85% and a simplified syngas processing stage (due to the higher share of methane). For **high temperature hydrothermal gasification**, the reported benefits include a (potentially) lower capex cost (but higher costs for the syngas treatment) and the flexibility to adapt production to preferentially target either the methane or hydrogen market[58].

Hydrothermal gasification is a very versatile technology as it can process a wide variety of (wet or moist) biogenic and fossil wastes and effluents. A pre-condition is that the feedstock is pumpable. Biogenic feedstocks include agricultural waste and effluent (e.g. animal manure and slurry), digestate from anaerobic digestion (as discussed in section 3.1.2), dredging and cleaning sludge, organic urban waste (often treated in incineration plants), sludge from wastewater treatment plants, as well as a wide range of waste and effluent from processing industries (e.g. biofuel production, black liquor, industrial sludge) and food processing waste (e.g. beet pulp, vinasse). Fossil wastes include solvents, plastics and waste from the chemical and petrochemical industries.

Hydrothermal gasification can deliver significant benefits over traditional waste treatment technologies, in particular incineration. A key benefit of the technology is that **metals** (e.g. aluminum, copper, iron) and **mineral compounds** (e.g. potassium and phosphorus[59]) contained in the feedstock precipitate out as salts and concentrate at the bottom of the reactor, where they can be removed. Nitrogen can also be recovered separately in the “liquid residue” stream (the surplus of water that is not recycled for the hydrothermal gasification process). These provide potential additional revenue streams, for example to be sold as alternatives to inorganic fertilisers. The liquid residue after the nitrogen separation has an industrial quality level and can also be recovered, for reuse. Importantly, the technology safely eliminates pathogens and micropollutants and convert microplastics in the syngas. Finally, since hydrothermal gasification specifically treats wet or moist (between 20% and 90% moisture content) feedstocks there is no requirement to dewater the feedstock prior to processing as is the case with incineration, thereby greatly reducing the energy demand and overall energy efficiency of the system.

Hydrothermal gasification initiatives are underway in several European countries, including France, Germany, Spain, the Netherlands and Switzerland. Most projects are currently at the pilot scale (the Hydro-thermal Gasification White Paper provides a comprehensive overview). The most advanced project is the industrial scale plant developed by SCW Systems[60] in the Netherlands, which was commissioned in 2023[61]. The plant has a total processing capacity of 10-16 tonnes/hour (based on four modules of 4 tonnes/hour), equivalent to 20 MW_{th} gas output depending on the energy content and type of feedstock. In 2023, SCW Systems became the first company globally to inject renewable gas into the Dutch high-pressure gas network (at ~70 bar). Since then, the company has successfully injected 60,000 m^3 high calorific on-spec gas and produced over 750,000 m^3 of syngas.

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[57] GRTgaz, Hydro-thermal Gasification White Paper, French National Hydrothermal Gasification Working Group, 2023. https://www.grtgaz.com/en/medias/press-releases/white-paper-hydrothermal-gasification

[58] This will also be possible in the future for catalytic hydrothermal gasification with a dedicated hydrogen catalyser.

[59] Wastewater treatment plants and dredging sludge typically have high contents of phosphorus.

[60] SCW Systems: https://scwsystems.com/en/

[61] Invest-NL and Gasunie New Energy are supporting partners.

The project has benefited from support provided by the Dutch government through the SDE subsidy scheme, which provides a fixed gas price guarantee for up to 12 years. SCW Systems and its partners are developing two additional projects in the Netherlands, in Delfzijl and nearby Rotterdam, as part of the Dutch 2 bcm national target for green gas production by 2030[62].

In 2023, the French National Hydrothermal Working Group estimated the potential for produce renewable and low carbon gas in France in 2050 based on 18 organic waste streams. The group estimated a potential of at least 63 TWh (~6 bcm), with the highest shares arising from digestate (21 TWh), agricultural livestock effluent (16 TWh) and urban wastewater treatment sludge and industrial sludge (8 TWh)[63]. A separate study published by Roland Berger[64] published in 2023 estimated a potential for hydrothermal gasification in Europe of 110 bcm (assuming 80% conversion efficiency), of which around 25% corresponds to biogenic feedstocks. This potential excludes all streams that are currently being recycled and the 'non-released' streams which are processed on-site (like manure and industrial sludges). Of this potential, 5.7 bcm corresponds to the Netherlands of which 1.5 bcm is based on biogenic waste streams (excluding feedstock such as manure, food and agriculture waste).

3.2.2 Landfill gas

Landfilling in Europe is targeted to decrease to 10% in every Member State by 2035, with a biowaste ban in the landfilled waste by 2024, as set out under the EU Landfill Directive[65][66]. Despite this, existing landfill sites will represent an important feedstock source for biomethane production well into the future, particularly if the typical methane production curve of a landfill plant of 25-30 years is considered. The greatest long-term potential is likely to be seen in countries with high landfill rates (such as in Eastern and Southern Europe). As landfill gas is one of the lowest cost sources of biomethane, it presents an ideal candidate for increasing biomethane potential in Europe.

Landfill gas arises from the decomposition of biodegradable waste within a landfill site. In a modern landfill site, the gas is captured using extraction wells connected to a central collection point by creating a vacuum in the network. The captured landfill gas is sometimes flared, but more commonly used to produce renewable electricity on-site and exported to the grid. The gas can also potentially be upgraded to biomethane. According to the European Biogas Association[67], landfill is the second largest source of biogas production in Europe, with a production of 23 TWh in 2022, equivalent to 13% of the total biogas production. The production of biomethane from landfill gas is lower at around 4 TWh in 2022, equivalent to 1% of the total biomethane production. France is currently the frontrunner in upgrading landfill gas to biomethane with 18 operational sites today, and 9 more planned for operation in 2024. An estimated 65 sites could potentially be in operation by 2030.

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[62] Personal communication with Wout de Groot, Director at SCW Gas.

[63] Note that the potentials are on a Higher Heating Value (HHV) basis.

[64] Roland Berger, Sustainable Gas Generation Potential in the Netherlands, 2023.

[65] European Commission, Environment, Landfill Waste. https://environment.ec.europa.eu/topics/waste-and-recycling/landfill-waste_en

[66] According to the European Environment Agency the overall landfill share of total MSW in Europe decreased from 23% to 16% between 2010 and 2020. https://www.eea.europa.eu/en/analysis/indicators/diversion-of-waste-from-landfill

[67] EBA Statistical Report 2023, Tracking biogas and biomethane deployment across Europe, 2023.

Other countries, such as Spain, Italy and Iceland are also producing biomethane from landfill gas, while additional projects are in development in these countries as well as in UK and Portugal. Other countries such as Greece, Poland, Slovenia are looking at this opportunity[68].

Increased interest in upgrading landfill gas to biomethane is fast growing in Europe, particularly as incentives that have previously supported electricity production are starting to be phased out. Importantly, upgrading landfill gas to biomethane can also yield up to three times the energy content as conversion to electricity. Landfill biomethane is currently one of the most competitive biomethane production solutions available.

While upgrading landfill gas to grid specification biomethane is a promising option, it poses several technical challenges. One key challenge is that landfill gas quality varies across different sites (due to the variability in the quality of waste managed) and furthermore varies significantly during the day and season (as gas production is linked to temperature, atmospheric pressure and humidity). A variation in the landfill gas composition and volume is also present along the lifetime of the landfill, with the greatest share of gas being produced in the earliest years of operation. A second challenge is due to the air co-presence into the landfill gas, which is due to the vacuum created to avoid fugitive emissions. This results in a high and variable share of nitrogen and oxygen in the landfill gas (average 18%, but potentially as low as 2% and as high as 48%). Landfill gas also includes small shares of trace gases, such as hydrogen sulfide and volatile organic compounds (VOCs).[69]

These challenges, can however, be overcome by the deployment of a combination of different gas upgrading technologies that enable the effective removal of all impurities in the landfill gas. These include absorption (water/chemical), adsorption (PSA), permeation (membrane separation) and cryogenic separation. While adsorption, absorption and permeation have dominated the landfill gas upgrading market, cryogenic technologies are taking off in Europe and North America. The benefit of cryogenic upgrading is that it is the only technology able to treat landfill gas with a high and volatile air content (up to 30%) compared to the other technologies (which are limited to up to 10%). Several companies are deploying commercially available technology solutions to upgrade landfill gas to biomethane[70].

A study undertaken in 2023 by the waste management companies Suez and Veolia, along with WAGA Energy estimated that the biomethane production from landfill gas in France could increase from around 600 GWh/year in 2024 to between 2.1 and 2.6 TWh/year in 2030 (reflecting ‘current French practices’ and ‘Good practices’). This would represent ~10% of the 2030 biomethane injection target in France. Extrapolated at the EU level, a biomethane potential of ~15-20 TWh could be realised, which is equivalent to around 5% of the 2030 target.[71] Importantly, the report authors also consider that landfills producing greater than 1,000 Nm^3/hour would be able to operate unsubsidised when considering the overall cost of energy recovery, which is the case with the PreZero (Can Mata site) in Spain.[72]

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[68] Personal communication with Marco Venturini, Corporate Strategic Advisor at WAGA Energy.

[69] ENEA, What are the best landfill gas upgrading technologies for grid injection?, Executive summary - Assessment of landfill gas upgrading technologies’ relevance for grid injection, 2019.

[70] These include, Air Liquide, Guild Associate, Sysadvance and WAGA Energy. Of these, WAGA Energy is currently the market leader in Europe, with 21 landfill sites deploying its WAGA Box technology and a further 10 projects in development. This technology is the most commercialised technology using cryogenic separation.

[71] The extrapolation was made assessing the volume of waste that would be landfilled at the European level from 2024 and 2035 if all countries would decrease the volume of waste landfilled from now to 2035 in order to respect the target of 10% of MSW landfilled by 2035. No assumption was made on waste characterisation at a European level. The methane potential generated by a tonne of waste in France over this period has been extrapolated at a European level.

[72] The site started operation in June 2023 and has a biomethane production of ~70 GWh/year. The biomethane is commercialised through a long-term unsubsidised Biomethane Purchase Agreement contract.

A separate study by SEDIGAS estimated that the potential for biomethane production in Spain to be around 9 TWh[73].

3.2.3 Renewable methane

Renewable methane (also known as e-methane) is a renewable gas that is produced by combining renewable hydrogen with a source of CO_2. It has the potential to be carbon neutral if the electricity is additional and emission-free and CO_2 source is biogenic. The produced gas is identical to fossil natural gas on a molecular level and can therefore serve as a replacement to conventional fuels and utilise current natural gas infrastructure.

The process to produce renewable methane is typically referred to as Power-to-Methane (PtM) and consists of two steps. First, renewable hydrogen is produced by water electrolysis using renewable electricity. Within the EU, the hydrogen production needs to comply with the rules set out in two Delegated Regulations, both published in 2023. Delegated Regulation (EU) 2023/1184[74] sets out the technical rules for the production of RFNBOs, and Delegated Regulation (EU) 2023/1185[75] specifies the methodology to calculate the GHG savings from RFNBOs, such as renewable methane, (and recycled carbon fuels – RCFs).

The second step is the methanation reaction, also known as the Sabatier-reaction. In this process, the hydrogen exothermically reacts with CO_2, often over a catalyst to improve the conversion rate. An overview of the PtM process is shown in Figure 6 below.

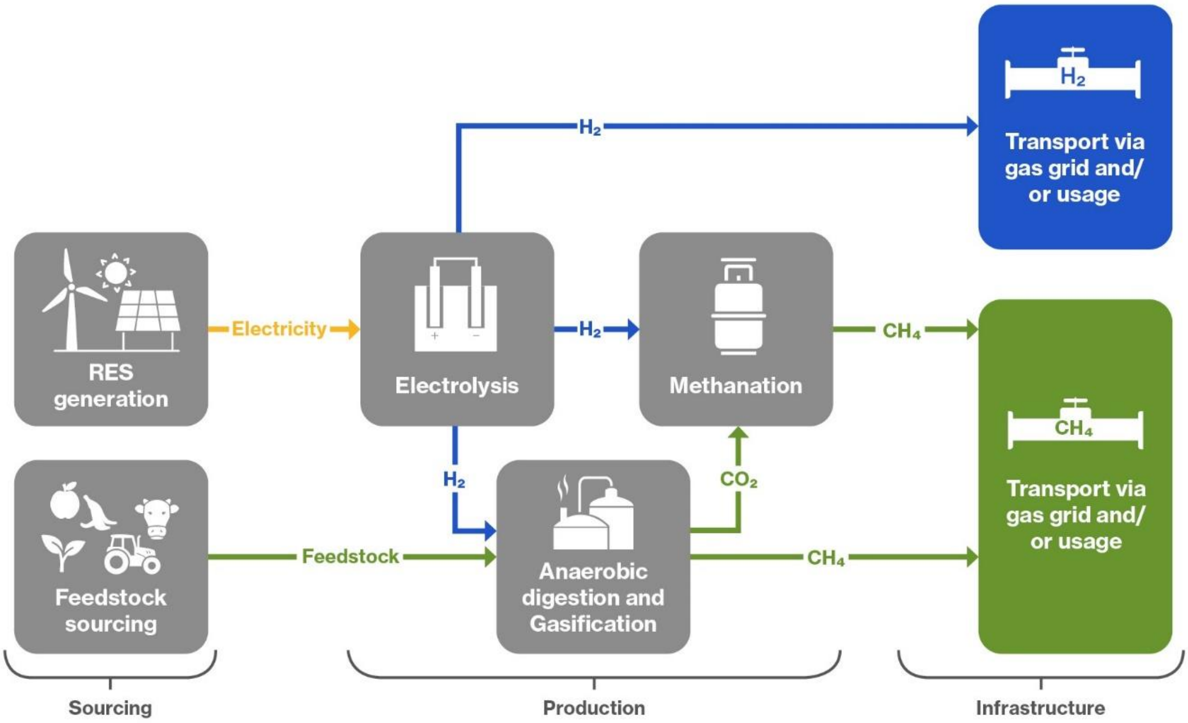

Figure 6. Schematic showing renewable methane production pathway[76]

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[73] SEDIGAS, A study of the capacity for biomethane production in Spain, 2023. https://estudio-biometano.sedigas.es/wp-content/uploads/2023/03/sedigas-report-potential-biomethane-2023.pdf

[74] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1184&qid=1704969010792

[75] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1185&qid=1704969410796

[76] Design: Annemiek Schellenbach and Guidehouse.

Various carbon sources can potentially be used to produce renewable methane. In the EU, CO_2 sources currently include from **natural processes, biogenic processes and fossil fuel sources**, so long as it is demonstrated that the fuels comply with RED II sustainability and greenhouse gas criteria, and that any CO_2 captured did not receive credits for emissions savings. Non-biogenic carbon, such as from process emissions, is only permitted to be used until 2040 and only if it is covered by an effective carbon pricing scheme. Non-biogenic carbon from electricity generation is only permitted until 2035, and again only if it is covered by an effective carbon pricing scheme. In the EU, renewable fuels, such as renewable methane, need to meet a minimum 70% greenhouse gas savings over the full life cycle. Biogenic CO_2, biogas and syngas from sustainable biomethane production, are considered carbon neutral and can therefore serve as an attractive source of CO_2 to produce renewable methane (or other renewable fuels or chemicals). According to the European Biogas Association, the theoretical potential of CO_2 arising from biomethane production of 35 bcm (as targeted in the REPowerEU Plan) would be 46 Mt.[77] A further scale-up of the sector will significantly increase the amount available.

The production of renewable methane can be beneficial in certain circumstances. However, as both the production of hydrogen (~65% efficiency) and the methanation reaction (~75% efficiency) come with significant losses, it is key to prioritise electricity and hydrogen use first and in that order. An example could be when hydrogen is produced in grid-congested areas, but there is no (existing) hydrogen infrastructure available. This hydrogen can then be produced using low-priced electricity and combined with CO_2 from a nearby source, for instance from biomethane plants. Alternatively, the hydrogen could be directly fed into the anaerobic digestion reactor, which is an effective way to increase the yield of the facility. These options help to provide further flexibility to the energy system.

The technology readiness level of methanation is currently at 6-9, with several different demonstration projects executed across Europe in the past decade.[78] The number and size of methanation plants have increased in recent years, with notable large-scale plants announced for instance in France and the Netherlands. Examples of two frontrunning methanation projects in Europe are:

- **BIOMETHAVERSE:** The BIOMETHAVERSE project aims to diversify the technological basis for biomethane production in Europe[79]. Five innovative biomethane production pathways, are being demonstrated in France, Greece, Italy, Sweden and Ukraine[80]. In the BIOMETHAVERSE's demonstrators, captured CO_2 from anaerobic digestion or gasification production (in the case of the Swedish demonstrator) combined with green hydrogen or renewable power to increase the overall biomethane yield. The project production routes cover one, or a combination, of the following production pathways: thermochemical, biochemical, electrochemical and biological. Four of the demonstration plants use anaerobic digestion, and one uses thermal gasification. According to the BIOMETHAVERSE project partners, the application of these technologies has the potential to increase biomethane production by 66% and furthermore reduce biomethane production costs by up to 44%.

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[77] European Biogas Association, Biogenic CO_2 from the biogas industry, 2022. https://www.europeanbiogas.eu/wp-content/uploads/2022/10/Biogenic-CO2-from-the-biogas-industry_Sept2022-1.pdf

[78] Gasunie, GasTerra and DNV GL (2019). Methanation. https://www.gasterra.nl/en/news/methanation-technology-enables-gas-system-decarbonization

[79] The project involves 22 partners across 9 countries and will run for 54 months. Total funding is around €10 million, of which the European Commission is contributing 70%.

[80] BIOMETHAVERSE Demo sites: https://www.biomethaverse.eu/demo-sites/

- **Nature Energy:** In November 2023, Nature Energy and Andel commissioned the world's first commercial scale biological methanation plant. The plant, located at Glansager on Als in Denmark, was constructed in just one year. Andel's electrolysis plant converts excess renewable electricity into hydrogen that is fed into Nature Energy's methanation plan, where it combines with CO_2. Here it forms renewable methane, thereby increasing biogas production from the existing biogas plant. Once fully operational, the hydrogen produced is expected to increase Nature Energy's biogas production by 12,000 m^3 per day.[81]

To further scale up renewable methane and increase the yield of biomethane facilities, several actions are required. First, smart integration between power and gas grids is vital. Renewable hydrogen is needed at the right locations and at significant volumes, and electricity and gas infrastructure need to be available. To enable this integration, research and development on the optimisation of production sites in relation to nearby infrastructure will be needed. These projects will need proper due diligence, including business model analysis. Where methanation projects benefit the local energy system context, for instance by reducing curtailment of renewables, policy support and funding mechanisms should be put in place.

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[81] Nature Energy, Power-to-X plant put into operation, 2023. https://nature-energy.com/news/power-to-x-plant-put-into-operation

Appendix A. Biomethane production potentials in 2030 and 2050

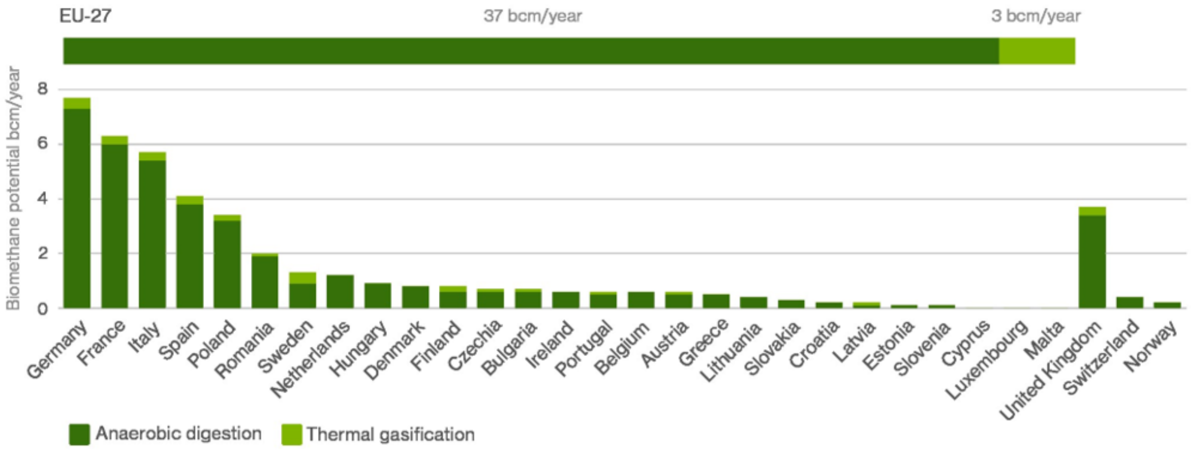

Figure A1. Biomethane potential (bcm/year) in 2030 per country and technology

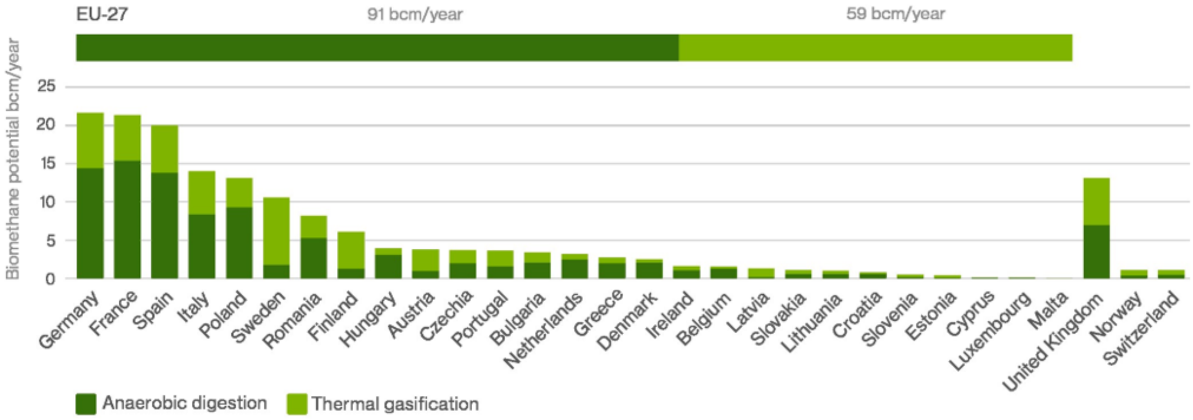

Figure A2. Biomethane potential (bcm/year) in 2050 per country and technology

Appendix B. Comparison with Gas for Climate study

Table B1. Anaerobic digestion in Europe in 2030 (bcm/year)

Feedstock	Gas for Climate study (2022)	European Biogas Association study (2024)
Agricultural residues	10.1	10.9
Animal manure	13.4	12.4
Biowaste	1.9	1.9
Industrial wastewater	4.0	3.4
Permanent grassland	2.2	2.2
Roadside verge grass	0.6	0.6
Sequential crops	8.6	8.5
Sewage sludge	1.0	1.0

Table B2. Anaerobic digestion in Europe in 2050 (bcm/year)

Feedstock	Gas for Climate study (2022)	European Biogas Association study (2024)
Agricultural residues	16.3	18.1
Animal manure	19.1	17.0
Biowaste	1.5	1.5
Industrial wastewater	11.5	11.3
Permanent grassland	2.2	2.2
Roadside verge grass	0.6	0.6
Sequential crops	46.0	47.0
Sewage sludge	1.0	1.0

Table B3. Thermal gasification in Europe in 2030 (bcm/year)

Feedstock	Gas for Climate study (2022)	European Biogas Association study (2024)
Forestry residues	1.0	0.8
Landscape care wood	0.4	0.4
Municipal solid waste	0.8	1.1
Prunings	0.1	0.1
Wood waste	1.0	1.0

Table B4. Thermal gasification in Europe in 2050 (bcm/year)

Feedstock	Gas for Climate study (2022)	European Biogas Association study (2024)
Forestry residues	21.6	18.3
Landscape care wood	7.3	7.3
Municipal solid waste	13.5	16.4
Prunings	2.7	2.7
Wood waste	22.0	22.0

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