Beyond energy – monetising biomethane's whole-system benefits

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Guidehouse

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Abbreviations

AHDB	(UK) Agriculture and Horticulture Development Board
BAT	Best available techniques
bcm	Billion cubic metres
BDR™	Biogasdoneright
C	Carbon
CAP	Common agricultural policy
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EBA	European Biogas Association
e_{sca}	Emission savings from soil carbon accumulation
EU	European Union
EU ETS	EU Emissions Trading Scheme
EU RED	EU Renewable Energy Directive
FAO	Food and Agriculture Organization of the United Nations
GGR	Greenhouse Gas Removals
GWh	Gigawatt hour
ha	Hectare
IEA	International Energy Agency

JRC	Joint Research Centre (of the European Commission)
K	Potassium
kt	Kilo tonne
LNG	Liquified natural gas
Mt	Million tonne
MWh	Megawatt hour
N	Nitrogen
OECD	Organisation for Economic Co-operation and Development
P	Phosphorus
RAN	Readily available nitrogen
RTFO	(UK) Renewable Fuel Transport Obligation
SOC	Soil organic carbon
SOM	Soil organic matter
t	Tonne
TWh	Terawatt hour
UK	United Kingdom

Executive Summary

The future energy mix will be dominated by renewable energy sources. Together with wind and solar, renewable gases such as biomethane and renewable hydrogen will play a pivotal role in delivering Europe's long-term energy security and climate mitigation objectives.

Biomethane is the cheapest and most scalable form of renewable gas available today. It can directly substitute natural gas and is flexible as it can be readily stored and deployed across the whole energy system, using existing gas infrastructure and end-use technologies. Moreover, biomethane is a dispatchable energy carrier and as such can be deployed to balance intermittent renewable energy generation. It is well placed to deliver significant, long-term economy-wide benefits beyond renewable energy provision, thereby supporting the European Green Deal and the transition to a more sustainable and circular economy.

As well as renewable energy provision, biomethane production can deliver numerous additional **environmental, economic and social externalities**[1] (or benefits), a selection of which are summarised below[2]. Importantly, many of these benefits are unique compared to other renewable energy sources.

» **Soil health:** Biogas production from anaerobic digestion produces a nutrient rich digestate. Application of digestate to agricultural soils has been shown to improve a range of soil health indicators and to sequester organic carbon in the soil. Its organic rich composition can support the recovery of degraded soils, necessary for long-term agricultural sustainability. Applying digestate to the soil also recycles a large fraction of the nutrients contained in the feedstock, reducing the need for fossil-derived synthetic fertiliser and contributing to a circular economy. Deployment of sequential crops can also reduce soil erosion as the land is covered year-round.

» **Greenhouse gas emissions impact:** Biomethane is a versatile renewable energy vector. It can be used in multiple end-use sectors, including transport (road, shipping), heating (for use in industry and buildings) and power production. Biomethane can directly replace the use of fossil fuels in these sectors, with the potential to deliver significant greenhouse gas emissions reduction. Furthermore, fugitive emissions in the agricultural sector can largely be avoided by using manure as a feedstock for biomethane production, thereby providing a valuable solution to support efforts to reduce global methane emissions (for example, as part of the Global Methane Pledge which aims to reduce global methane emissions by at least 30% from 2020 levels by 2030[3]). Similar benefits will be realised when organic waste streams in other sectors, such as biowaste, are treated via anaerobic digestion. Finally, replacing synthetic fertiliser use with digestate also reduces greenhouse gas emissions, since the production of synthetic fertilisers is very energy intensive (in particular nitrogen-based fertilisers, as natural gas is used as both feedstock and process fuel).

1 The OECD Glossary of Statistical Terms defines externalities as: "Externalities refers to situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided". https://stats.oecd.org/glossary/detail.asp?ID=3215

2 Chapter 1 of the main report provides additional externalities relevant to biomethane production, while Chapters 3 to 5 provide a detailed assessment of a selection of the externalities summarised above.

3 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/en/statement_21_5766

- **Energy security:** Europe is heavily reliant on energy imports, including natural gas. Domestically produced biomethane can reduce the need to import gas and directly improve Europe's energy independence and security. This can help cushion against exposure to volatile natural gas prices, protecting the competitiveness of Europe's industries and reducing the risk of energy poverty for households. The role that biomethane can play in strengthening Europe's energy independence and security has been duly recognised by the European Commission in the REPowerEU[4] plan, which sets a target of 35 billion cubic metres (bcm) of biomethane production per year by 2030 in the European Union (EU27).
- **Provision of biogenic carbon dioxide:** Biomethane production through both anaerobic digestion and thermal gasification can produce a pure biogenic carbon dioxide (CO_2) stream. Biogenic CO_2 can be used as a feedstock in multiple industrial applications, largely displacing fossil CO_2 sources, or in emerging applications such as renewable fuels, chemicals and algae production. Alternatively, it can be permanently stored within geological features (e.g. closed saline aquifers below the sea) to deliver Greenhouse Gas removals (GGR; also known as Carbon Dioxide Removals, CDR). Such removals are essential to the delivery of Net Zero targets, due to their ability to offset unavoidable emissions in other sectors.
- **Organic waste processing:** Biomethane production from organic waste feedstocks provides waste processing services, as well as energy generation services, which can improve the overall economics of the operation. Importantly, this also plays a valuable role in contributing to the circular economy by recycling organic wastes and turning them into useful products, including renewable energy and nutrient rich digestate that can be returned to the soil.
- **Job creation:** Biomethane production can contribute to the creation of between 1.1 and 1.8 million jobs across the value chain in Europe by 2050. As biomethane production through anaerobic digestion will involve a more decentralised production model based on agricultural wastes, residues and sustainable crops, its deployment is expected to bring new employment benefits especially to rural regions across Europe. In contrast, it is expected that biomethane production from thermal gasification will lead to employment benefits in more centralised production facilities and largely located near to sustainable forest-based industries or urban areas from which the feedstock will be collected.

Today, producers of biomethane are primarily rewarded for contributing to renewable energy targets via support or market-based mechanisms. The additional positive externalities that biomethane production delivers, as described above, are currently not fully rewarded by policy makers or recognised by society at large. This study therefore aims to quantify the value of these externalities for a selection of sustainable feedstocks[5] relevant for **anaerobic digestion** and **thermal gasification** biomethane production technologies, both in terms of €/MWh biomethane produced and in total annual value in 2030 and 2050 for the EU27 and UK.

Benefits quantification

The total externality benefits per unit of biomethane produced for anaerobic digestion are broadly similar, and of the same order of magnitude, as the total externality benefits estimated for thermal gasification (see Figure I).

Anaerobic digestion delivers an additional benefit of **84-175 €/MWh** of biomethane produced, while **thermal gasification** delivers an additional benefit of **80-162 €/MWh**. Importantly, these benefits outweigh the current cost of producing biomethane through these technologies (55-100 €/MWh and 85-110 €/MWh for anaerobic digestion and thermal gasification respectively).

The higher externality value for anaerobic digestion largely results from the higher greenhouse impact due to reducing fugitive emissions in agriculture, benefits from the application of digestate (replacing synthetic fertiliser) and organic waste processing, as well as a lower cost of production which increases the overall value of energy security. Fugitive emissions from biomethane production and digestate storage do not make a significant impact to the overall results.

4 European Commission, *REPowerEU: A plan to rapidly reduce dependency on Russian fossil fuels and fast forward the green transition*, 2022. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

5 Anaerobic digestion: Agricultural residues, Animal manure, Biowaste, Industrial wastewater, Sequential crops, Sewage sludge
Thermal gasification: Forestry residues, Landscape care wood, Municipal solid waste (organic fraction only), Prunings, Wood waste. See Chapter 2 for further details.

However, the relative share of each externality varies between the low and high scenarios, and also between the technologies. For **anaerobic digestion**, the shares in the low scenario are relatively evenly spread. Job creation (33%), greenhouse impact (28%), provision of biogenic CO_2 (15%) and energy security (14%) make up over 80% of the total. In the high scenario, energy security (43%) and job creation (28%) dominate. For **thermal gasification**, job creation (40%) and the provision of biogenic CO_2 (37%) make up the highest share of the low scenario, with the balance largely made up of green-house gas impact (20%). In the high scenario, the shares are more evenly spread with energy security providing a greater contribution (28%).

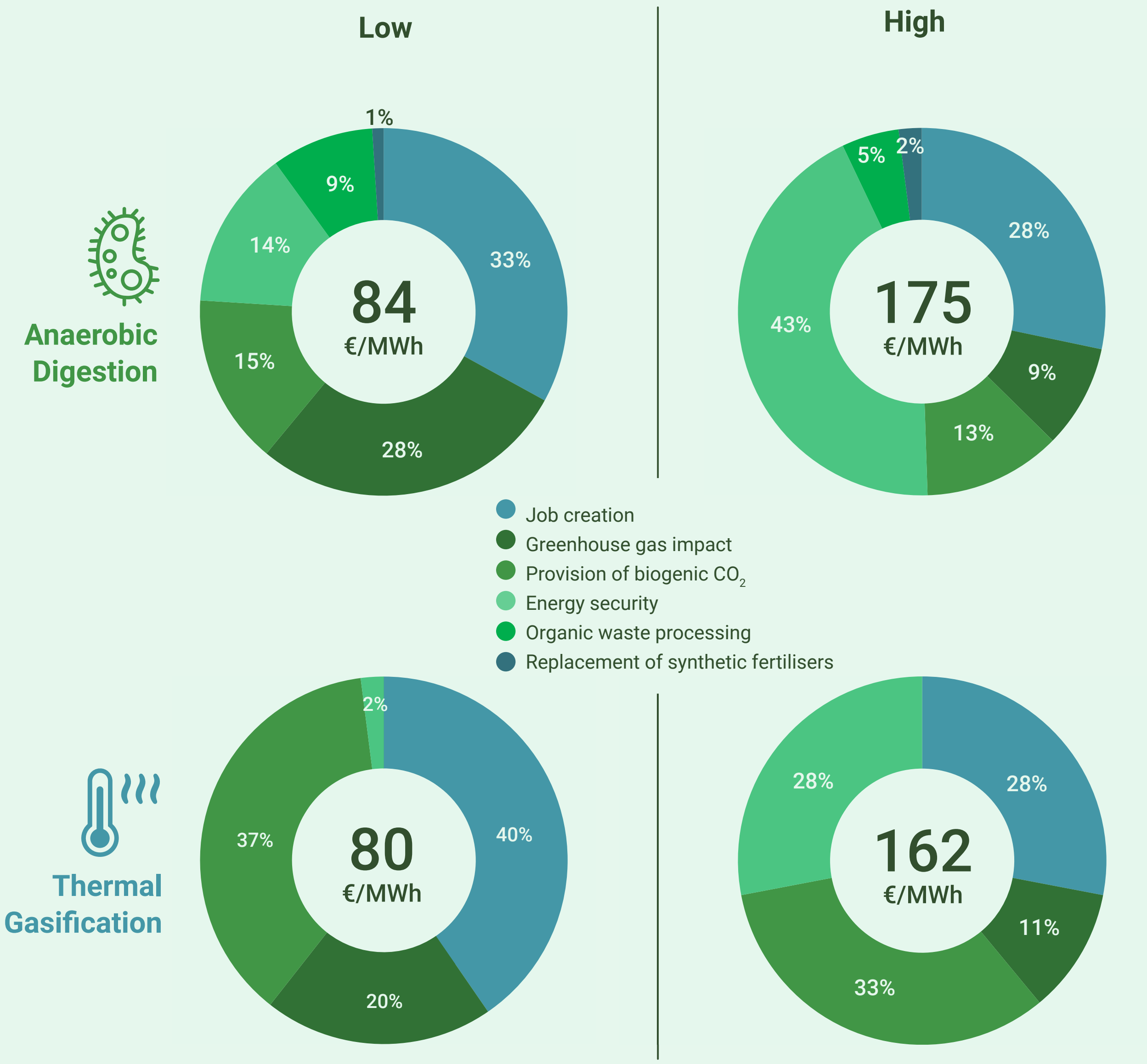


Figure I | Low and high estimate of biomethane externalities categorised per externality and technology type (€/MWh)

The total estimated annual benefits are significant and demonstrate the value that biomethane production can deliver to the European economy (see Figures II and III below)[6].

In **2030**, the additional economy-wide benefits of biomethane production to the EU27 and UK range from **€38-78 billion per annum** and almost entirely relate to **anaerobic digestion** (€35-73 billion). This technology is already widely deployed across Europe today and will further scale-up to 2030. In contrast, biomethane production from **thermal gasification** is expected to be fully commercially available from 2030 onwards. As such, biomethane production **from gasification** in 2030 will likely be available in significantly lower volumes compared to anaerobic digestion.

In **2050**, the additional economy-wide benefits of biomethane production to the EU27 and UK range from **€133-283 billion per annum**. The share between the two technologies is more balanced as thermal gasification is expected to make a significantly larger contribution in this timeframe. **Anaerobic digestion** represents around 60% of the total (€77-168 billion) and **thermal gasification** 40% (€57-115 billion).

As a frame of reference, the values in the high scenarios in 2030 and 2050 approximately correspond to the gross domestic products (GDPs) of Luxembourg and Finland in 2021, respectively[7].

These benefits are considered to be an underestimate since the scope of this study specifically focussed on a selection of the externalities identified. The selection made ensured that a varied and representative range of aspects were covered and included those externalities likely to have greatest overall impact. Furthermore, the benefits of biomethane production to soil health were not quantified due to the lack of well-established methodologies available today that can robustly assign monetary values to these benefits. This study has instead focused on a qualitative description of these benefits.

6 The total externality values (€ billion) were quantified by multiplying the value per MWh of biomethane produced (€/MWh) by the biomethane potential (MWh) per technology in 2030 and 2050 as published by Gas for Climate, *Biomethane production potentials in the EU*, 2022. https://gasforclimate2050.eu/wp-content/uploads/2022/10/Guidehouse_GfC_report_design_final_v3.pdf.

7 Statista, *Gross domestic product at current market prices of selected European countries in 2021, 2022*. https://www.statista.com/statistics/685925/gdp-of-european-countries/

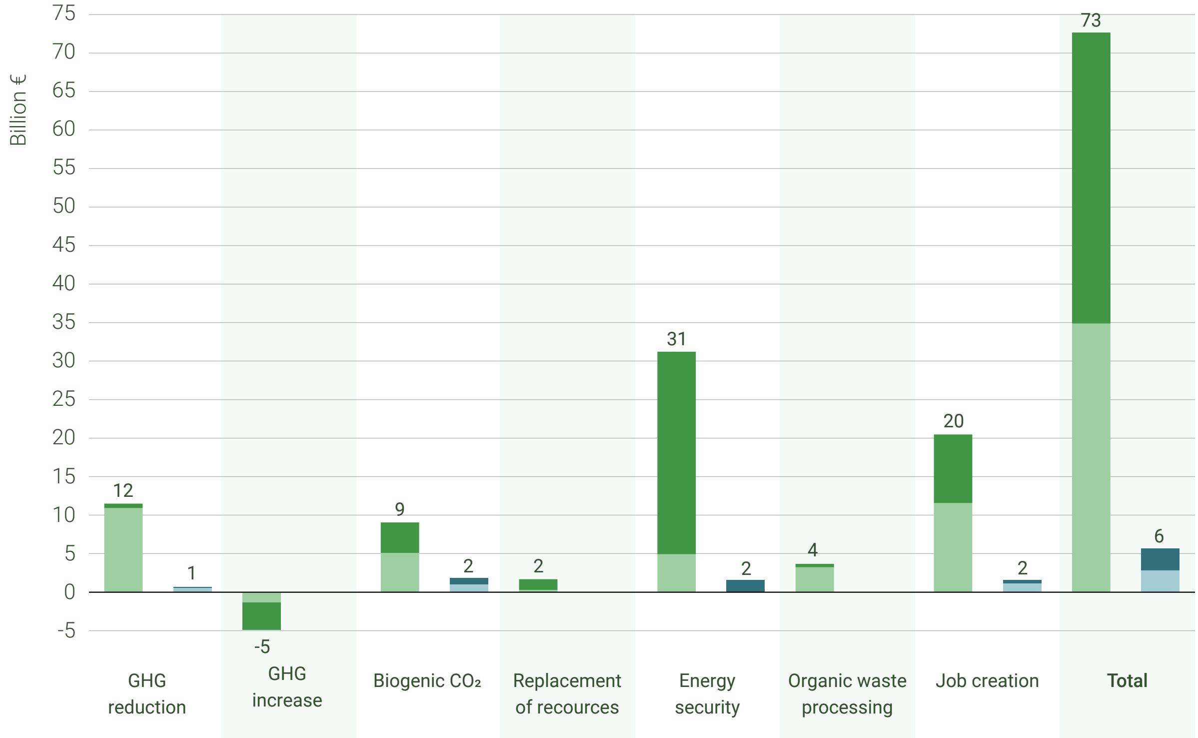
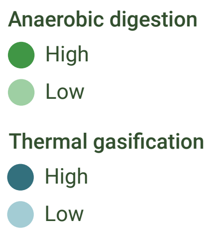


Figure II | Total externality values per category in 2030 per annum (billion €)



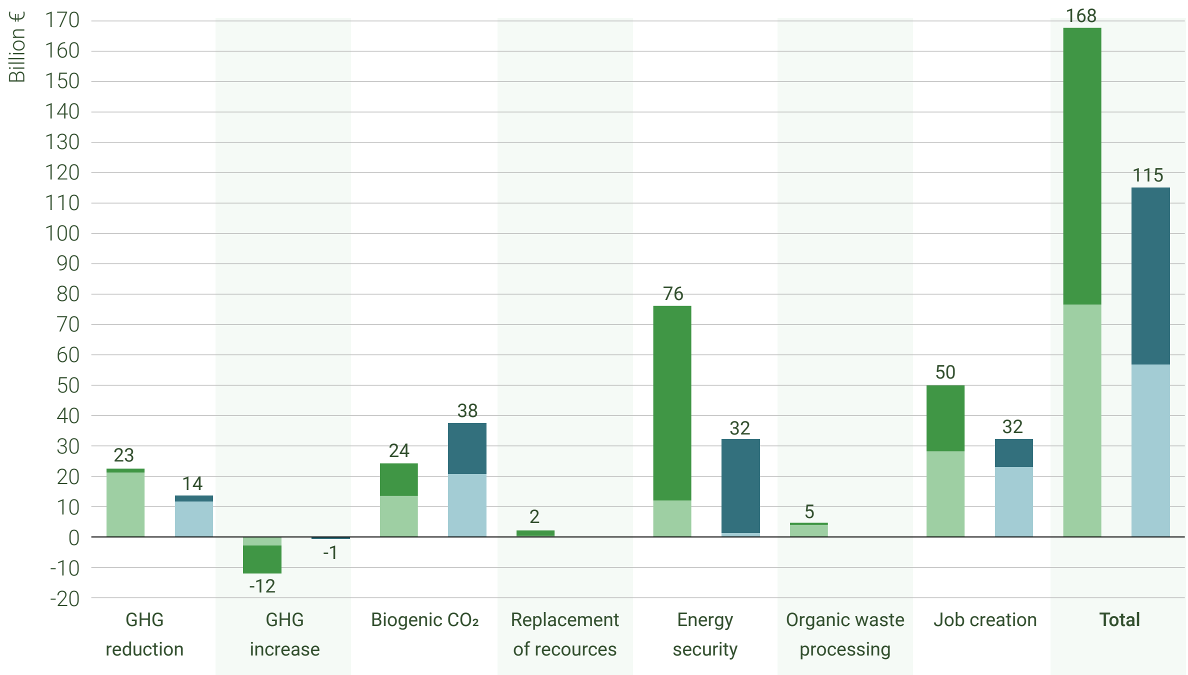


Figure III | Total externality values per category in 2050 per annum (billion €)

Action is needed to realise these benefits

To fully realise these benefits will require a concerted effort from the biomethane industry, policy makers and regulators alike. We recommend that focus should be directed at the following areas:

1. **Ensure benefits are recognised by policy makers:** Policy makers at both the European and national level should recognise the benefits that biomethane can deliver (additional to renewable energy provision) and ensure that agriculture, climate, energy and waste policy enables these benefits to be fully realised by biomethane producers.

   European level: The European Commission could consider developing an EU strategy for energy transition in rural areas to support biomethane production, as recommended in the REPowerEU Biomethane Action Plan[8]. Anchoring the 35 bcm biomethane production target proposed in the REPowerEU plan in the revision of the EU Renewable Energy Directive recast would also serve to strengthen this target, supporting Europe's energy security. The environmental benefits of sustainable sequential cropping cultivation for biomethane should also be recognised, for example, by including this agronomic practice as an 'eco-scheme' under the common agricultural policy (CAP)[9].

   National level: Countries should develop an overall vision for the long-term role of biomethane in their energy system and economy, as recommended in the Biomethane Action Plan. The strategy should recognise the rural and circular economy benefits that biomethane can bring in the national context and put in place a supportive regulatory framework to enable this. Financial incentives (including loans or tax credits), support or market mechanisms and targets should be implemented accordingly to provide greater market security for biomethane producers, thereby improving the bankability of projects. Furthermore, actions should be taken to remove any barriers that may prevent, or hinder, the scale-up of biomethane production (such as reducing the time for permitting and granting access to inject in to the gas grid). The Gas for Climate manual to develop and implement national biomethane strategies may serve as a useful reference source in this respect[10].

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

9 https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/new-cap-2023-27_en; https://agriculture.ec.europa.eu/news/commission-publishes-list-potential-eco-schemes-2021-01-14_en

10 Gas for Climate, *Manual for National Biomethane Strategies*, 2022. https://gasforclimate2050.eu/wp-content/uploads/2022/09/2022-Manual-for-National-Biomethane-Strategies_Gas-for-Climate.pdf

2. **Mobilise waste and residue feedstocks:** The mobilisation of waste and residue feedstocks, such as animal manure and biowaste, should be prioritised as these feedstocks offer the highest greenhouse gas saving benefit, as well as supporting job creation. Support should be provided at the national level to facilitate the collection and aggregation of these feedstocks, with a particular focus on animal manure given the significant benefit of reducing fugitive emissions in agriculture when this feedstock is used for biomethane production. The banning of landfilling or incineration of biowaste from 2024 provides an immediate opportunity to unlock additional sustainable feedstock for biomethane production, where the greatest societal benefit can be realised. Finally, municipal and industrial wastewater sludges should be fully utilised for biomethane production.

3. **Incentivise sustainable agricultural production:** Sustainable sequential crops can play an important role in the scale-up of biomethane production to 2050, and similarly realise significant economy wide benefits. To date, sequential crops for biomethane production have been deployed commercially in Italy and successfully tested in France. A further scale-up requires research to test to what extent this can be implemented in more temperate parts of Europe, and in particular in key European agricultural regions such as Germany, Romania and Poland. Large-scale training and awareness-raising programmes would need to be implemented for farmers in all countries in which sequential cropping is targeted. In conjunction with this, the benefits of sustainable agricultural methods such as no or low-till, and application of digestate should also be promoted. Funding to invest in specialist machinery should be allocated from the rural development measures under the CAP[11].

4. **Support further commercialisation of thermal gasification:** Biomass gasification with biomethane synthesis exists at demonstration scale. However, the potential to scale up is large in the mid-term (2030 and beyond). This technology could realise benefits of €115 billion annually in 2050 if production is scaled-up. Setting out a long-term policy framework that supports biomethane from gasification and provides investors with the confidence to support this technology is needed. Such a framework should also target continuous cost reductions to minimise societal costs.

5. **Maximise valorisation of biomethane co-products:** The valorisation of biogenic CO_2 and digestate co-products provides producers with an opportunity to generate additional revenue streams and improve the overall business case of biomethane production. The benefit for biogenic CO_2 could be worth at least 12 €/MWh for anaerobic digestion and up to 52 €/MWh for thermal gasification alone. Similarly, the value of digestate as an alternative product to synthetic fertilisers could be worth an additional 4 €/MWh. Maximising these benefits will place the industry on a sustainable path to subsidy independence in the long-term.

11 European Commission, *Agriculture and rural development*. https://agriculture.ec.europa.eu/common-agricultural-policy/rural-development/measures_en

Biogenic carbon dioxide: To ensure that the benefits for biogenic CO_2 can be realised it is critical that biogas is first upgraded to biomethane in the case of anaerobic digestion. Efforts to create greater awareness of the commercial opportunities of biogenic CO_2 provision within the biomethane sector are also necessary. Policy makers can support the market development by putting in place a policy framework that values biogenic CO_2 as a commodity above that of CO_2 arising from fossil origin. The European Commission's proposal for the certification of carbon removals[12] is a helpful first step in this regard. Further action is required, however, to establish a policy mechanism that values the certificates, for example, through linkage to the EU Emissions Trading Scheme (ETS). Additionally, a range of CEN/ISO quality standards should be made available in order to optimise the market potential for biogenic CO_2 across all applications.

Digestate: Internal market barriers must be removed to ensure that digestate can be recognised as a product (i.e. organic fertiliser), and not a waste, in order to realise greatest value. Industry quality standards, such as those in Sweden and the UK, should be established in all markets to allow users to be confident that the digestate is of consistent and sufficiently high quality. Further efforts should also be targeted on the processing of digestate to create more customised nutrient mixes. Synergies of combining digestate production with composting should also be explored as a future circular economy strategy for organic municipal solid waste management.

12 European Commission, *European Green Deal: Commission proposes certification of carbon removals to help reach net zero emissions*, 30 November 2022. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7156

Table of Contents

1. Introduction

1. Introduction

The future energy mix will be dominated by renewable energy sources. Together with wind and solar, renewable gases such as biomethane and renewable hydrogen will play a pivotal role in delivering Europe's long-term energy security and climate mitigation objectives.

Biomethane is the cheapest and most scalable form of renewable gas available today. It can directly substitute natural gas and is flexible as it can be readily stored and deployed across the whole energy system, using existing gas infrastructure and end-use technologies. Moreover, biomethane is a dispatchable energy carrier and as such can be deployed to balance intermittent renewable energy generation. It is well placed to deliver significant, long-term economy-wide benefits beyond renewable energy provision, thereby supporting the European Green Deal and the transition to a more sustainable and circular economy.

As well as renewable energy provision, biomethane production can deliver numerous additional **environmental, economic and social externalities**[13] (or benefits), a selection of which are summarised below. Importantly, many of these benefits are unique compared to other renewable energy sources.

- **Environmental externalities** reflect the role that biomethane can play in delivering benefits to the environment and climate. These include reducing greenhouse gas emissions in agriculture (through improved management of livestock manure and replacement of synthetic fertiliser), and in transport, heat and electricity production (by replacing fossil fuels). On the other hand, fugitive methane emissions from biomethane production can have a negative environmental impact, offsetting some of the reduction. Biomethane production can furthermore provide benefits to soil through the application of digestate (a co-product arising from biogas production), and through the application of regenerative agricultural practices in the cultivation of sequential crops.
- **Economic externalities** are those that support, add value or reduce costs to the overall European economy. These include the role that biomethane can play in supporting Europe's energy independence and security (as recognised by the European Commission in the REPowerEU[14] plan), diversifying the energy system and lowering adaptation needs in hard-to-electrify industry sectors, reducing the processing costs of treating organic wastes, and the provision of biogenic carbon dioxide (which if permanently stored results in negative greenhouse gas emissions).
- **Social externalities** include aspects affecting people's livelihoods and wellbeing in Europe. In this respect, a future large-scale biomethane industry has the potential to support the creation of stable jobs across the value chain, and in particular in the rural economy. For example, in the construction and operation of biomethane production facilities, in the development of sequential cropping schemes or in establishing supply chains for the collection of agricultural residues and livestock wastes. Furthermore, the development of renewable gas production technologies in Europe enables the export of knowledge and technologies, boosting employment opportunities even further.

13 The OECD Glossary of Statistical Terms defines externalities as: "Externalities refers to situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided". https://stats.oecd.org/glossary/detail.asp?ID=3215

14 European Commission, *REPowerEU: A plan to rapidly reduce dependency on Russian fossil fuels and fast forward the green transition*, 2022. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

The tables below provide an overview of selected externalities that biomethane can provide, based on a literature review[15]. These are presented per externality category, although in some cases, individual externalities address multiple categories. The overview also indicates whether the externality has a positive (+) or negative (-) impact.

Environmental externalities

Table 1.1 | Environmental externalities

Externality description		Impact (+ / –)
Change in biodiversity	Coverage of land with sequential crops can create positive effects for biodiversity as animals, such as ground-dwelling insects, are more able to take refuge on covered land compared to fallow land.	+ / –
Change in soil heath	The application of digestate, and of conservation agricultural practices, such as precision farming and minimum tillage, in combination with sequential cropping, or the Biogasdoneright (BDR™) system, can lead to an improvement in soil health, including organic carbon and organic matter content, water retention and a reduction in soil erosion.	+
Change in water use	Sequential crop cultivation may create additional water demand. This impact could, however, be mitigated through water efficient irrigation using drip-feeding systems, as practiced in the BDR™ system.	+ / –
Change in water quality	When organic waste streams, such as animal waste or biowaste, are treated in biogas plants instead of land spreading or disposal to landfill, local water contamination and risk of eutrophication of local water courses is avoided.	+
Depletion of raw materials	Biomethane production largely relies on the use of sustainable wastes and residues as feedstocks. In contrast to other renewable energy technologies, it does not involve mining raw materials, such as metals (e.g. lithium, nickel, silicon which are used in electric batteries, solar PV and wind turbines) or rare earths (e.g. neodymium, praseodymium and terbium used in wind turbines).	+
Diverting material from existing uses	Diverting materials (such as agricultural or forestry residues and wastes) from other existing uses could lead to negative impacts. For example, impacts to soil quality, soil carbon and biodiversity if residues are over-extracted. These impacts could, however, be mitigated through the effective implementation of monitoring or management plans[16]. Additional (economic) impacts may be an increase in the price paid for the material in existing markets (e.g. for straw used as animal feed or animal bedding in the livestock sector).	–

15 Key literature sources include: ENEA, *Boosting the competitiveness of the French biomethane sector*, 2018. https://www.enea-consulting.com/en/publication/boosting-the-competitiveness-of-the-french-biomethane-sector/; Swedish Gas Association, *Proposal for National Biogas Strategy 2.0*, 2018. https://www.energigas.se/library/2303/national-biogas-strategy-2_0.pdf; World Biogas Association, Biogas: Pathways to 2030, 2019. https://www.worldbiogasassociation.org/pathwaysto2030/

16 Note that Article 29(2) of the EU Renewable Energy Directive recast sets out specific sustainability requirements for the use of agricultural wastes and residues in bioenergy.

Externality description		Impact (+ / –)
Greenhouse gas reduction	Biomethane can replace fossil fuels, reducing production and consumption emissions. Digestate can replace synthetic fertiliser and reduce synthetic fertiliser production emissions by recycling nutrients from feedstock back to the soil, contributing to the development of a circular economy. Fugitive emissions from manure management and organic municipal solid waste management can be avoided by using these feedstocks for biomethane production.	+
Greenhouse gas increase	Methane can leak from biomethane plants during the digestion/gasification and upgrading/methanation processes. Digestate storage can also lead to fugitive emissions, depending on the storage method.	–
Reduction of non-greenhouse gas pollutants	Biomethane and digestate deployment reduces emissions of non-greenhouse gas pollutants, including SOx, NOx and phosphates. In addition, a fuel switch to biomethane in transport would reduce traffic related NOx emissions.	+

Economic externalities

Table 1.2 | Economic externalities

Externality description		Impact (+ / −)
Balance energy system	Biomethane is a non-variable form of energy that can be readily stored and transported using existing gas infrastructure, providing renewable energy when and where it is needed across the European economy (including the generation of dispatchable power). Biomethane deployment reduces the overall requirement, and associated costs, of widespread electrification in a future climate-neutral European energy system[17].	+
Change in main crop yield	Introducing a sequential crop to produce biomethane may affect the yield of the main crop positively or negatively.	+ / −
Diversification of agricultural revenues	Increased farm resilience through the creation of diverse revenue streams (biogas, biomethane, digestate) provides a buffer against crop commodity prices.	+
Gas transmission and distribution costs	Biomethane will be transported via the gas grid and therefore help to maintain a certain level of gas throughput, reducing the specific grid costs.	+
Improved energy security	Domestically produced biomethane can directly displace natural gas and therefore reduce the dependency of Europe on imports and exposure to volatile prices.	+
Organic waste processing	Anaerobic digestion provides an efficient waste treatment option for organic waste streams, such as industrial wastewater or sewage sludge. It enables the creation of value from waste by converting it to a useful energy form and nutrient rich digestate, contributing to the development of a circular economy.	+
Provision of biogenic carbon dioxide	Biogenic carbon dioxide from the biogas upgrading or syngas methanation process can be captured and either utilised or permanently stored, leading to economic benefits for the biomethane producer and environmental benefits to society.	+

17 According to Gas for Climate, compared to a ‘Minimal Gas’ scenario, the ‘Optimised Gas’ scenario (with a balanced deployment of renewable gases) leads to societal cost savings of over €200 billion annually by 2050. https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf

Social externalities

Table 1.3 | Social externalities

Externality description		Impact (+ / −)
Exportable sector	The biomethane sector is developing quickly globally. A leading European biomethane industry will serve as a centre of knowledge and expertise, providing opportunities to export technologies to other countries.	+
Job creation	Biomethane production creates jobs, especially in rural areas, for the planning, construction and operation of biomethane plants and their feedstock supply chains.	+
Local energy transition	Biomethane can catalyse a local energy and agricultural transition.	+
Reduced noise pollution	A fuel switch to biomethane in transport would reduce traffic related noise pollution, as gas fired vehicles are significantly quieter compared to conventionally fuelled vehicles.	+
Reduced odour pollution	Using digestate generated from the treatment of manure and slurries with anaerobic digestion, instead of using these feedstocks directly on field, reduces odour pollution.	+

Today, producers of biomethane are primarily rewarded for contributing to renewable energy targets via support or market-based mechanisms. The additional positive externalities that biomethane production delivers, as described above, are currently not fully rewarded by policy makers or recognised by society at large. This study therefore aims to quantify the value of these externalities for a selection of sustainable feedstocks relevant for anaerobic digestion and thermal gasification biomethane production technologies, both in terms of €/MWh biomethane produced and in total annual value in 2030 and 2050 for the EU27 and UK. The outputs of this study will serve as a solid basis for European policy makers to recognise these externalities in future climate, energy and waste policy, and for society as a whole to understand the benefits biomethane can bring to the future European energy system.

2. Quantification method

2. Quantification method

This chapter sets out the feedstocks and technologies in scope, the externalities that are selected for quantification and describes the overall method applied to quantify the value of each externality. The quantification aims to derive monetary values per MWh of biomethane produced (€/MWh) and in total (€ billion) annually in 2030 and 2050 for the EU27 and UK.

2.1 | Feedstock and technology scope

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 converts raw liquid and wet biomass. 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 today, while hydrothermal gasification is even less mature and is not included in this study.The feedstock and technology selection applied in this study are set out in Table 2.4, and are largely aligned with the recently published Gas for Climate analysis, which assessed the biomethane production potential in Europe in 2030 and 2050[18,19].

Table 2.4 | 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.

18 Gas for Climate, *Biomethane production potentials in the EU*, 2022. https://gasforclimate2050.eu/wp-content/uploads/2022/10/Guidehouse_GfC_report_design_final_v3.pdf
19 Multiple additional feedstocks could potentially be processed for either technology. For example, permanent grassland, biomass from marginal or contaminated land and seaweed, are all suitable for anaerobic digestion.

Anaerobic digestion	Thermal gasification
Industrial wastewater Wastewaters arising from 21 diverse industry sectors[20] 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[21].	**Wood waste** Secondary woody biomass that includes wood processing, wood from paper and pulp production, construction and demolition waste, waste collected from households and industries.
Sewage sludge Residual, semi-solid or liquid material that is produced as a by-product during sewage treatment of municipal wastewater.	

2.2 | Externality selection

The externalities selected for detailed assessment in this study are shown in Table 2.5 below. The basis for this selection was to ensure that a varied and representative range of aspects were covered, including at least one externality per category type. An initial screening was also undertaken to assess the feasibility of assessment of each externality, and also to identify the externalities likely to have greatest overall impact[22]. Importantly, both *positive* and *negative* externalities were chosen.

Table 2.5 | Externalities selected for quantification

Externality type	Externality
Environmental	Change in soil health
	Greenhouse gas impact (including both Greenhouse gas reduction[23] and Greenhouse gas increase)
Economic	Improved energy security
	Organic waste processing
	Provision of biogenic carbon dioxide
	Replacement of resources
Social	Job creation

20 Including beer production, vegetable oil production and meat processing. For further details, please refer to: EBA, *The role of biogas production from industrial wastewaters in reaching climate neutrality by 2050*, 2021. https://www.europeanbiogas.eu/the-role-of-biogas-production-from-industrial-wastewaters-in-reaching-climate%20neutrality-by-2050/
21 Also referred to as 'multi-cropping', 'double cropping', 'cover cropping' or growing a 'harvestable cover crop'.
22 The screening was in-part informed by literature review.
23 Note that reduction of fugitive emissions from improved organic waste management was not included as part of this externality as this represents a relatively small share of the overall biomethane feedstock potential and strongly depends on the counterfactual scenarios which are varied and not well documented.

2.3 | Externality quantification

This study aims to provide a quantification of the (net) benefit per unit of biomethane produced (€/MWh) and an annual total (€ billion) in 2030 and 2050 for each externality.

2.3.1 | Quantification of externality values per feedstock and technology

The quantification followed a 5-step approach:

1. **Mapping the externalities:** Although many of the externalities are universally applicable, in some cases the externalities are only relevant to anaerobic digestion or to specific feedstocks. A first step was therefore to identify the relevance of the externalities to each feedstock and technology in scope (see Annex A and B).
2. **Defining the counterfactual:** Next, the **counterfactual case** for each externality was identified. This sets out what the alternative scenario(s) is in the absence of biomethane production in Europe (EU27 and UK). For example, the counterfactual for organic waste processing is that the waste is otherwise composted, landfilled or incinerated (depending on the waste type). For energy security, the counterfactual is that in the absence of domestically produced biomethane, natural gas would otherwise need to be imported.
3. **Identifying metrics to quantify the externalities:** A bespoke approach was applied to quantify each externality (chapters 3, 4 and 5 provide a detailed overview of the specific approaches taken). Quantification was first undertaken per **feedstock** and **technology type**, using relevant **metrics** for each externality. These metrics define the basis on which biomethane production and the counterfactual case can be compared. For example, 't CO_2 saved/MWh' for greenhouse gas reduction and 't fertiliser replaced/MWh' for the replacement of synthetic fertiliser with digestate. The data used in the quantification was informed by an extensive literature review and stakeholder outreach.
4. **Monetising the externalities:** The externality metrics were then converted into €/MWh using a **monetisation coefficient**. For example, for several externalities the cost of carbon (€/t CO_2e) traded in the EU Emissions Trading Scheme (ETS) was used to monetise the externality metrics relating to greenhouse gas impact. A **low-high €/MWh range** was calculated for each externality.
5. **Quantifying the externalities per technology:** Finally, an externality value (€/MWh) per technology was calculated based on a weighted average of the biomethane production (MWh) in 2030 and 2050 per feedstock. The biomethane potentials published by Gas for Climate[24] were used for this calculation.

2.3.2 | Quantification of total externality values in 2030 and 2050 per technology

The total externality value (billion € in 2022 prices) was quantified by multiplying the value per MWh of biomethane produced (€/MWh) by the biomethane potential (MWh) per technology in 2030 and 2050 (as published by Gas for Climate).

24 Gas for Climate, *Biomethane production potentials in the EU*, 2022. https://gasforclimate2050.eu/wp-content/uploads/2022/10/Guidehouse_GfC_report_design_final_v3.pdf

3. Environmental externalities

3. Environmental externalities

3.1 | Change in soil health

The maintenance of soil quality is fundamental to farming; its health underpins and drives the entire agricultural sector in the short and long term. Healthy soils are an essential aspect of food security, which is jeopardised by soil degradation and climate change. At present, 33% of the Earth's soils are degraded, and over 90% could become degraded by 2050, according to the FAO[25]. In the EU, an estimated 60% to 70% of soils are already not healthy, according to the European Commission[26]. Degraded soils do not contribute to food production due to low productivity, and can be left barren, leading to further issues such as increased vulnerability to erosion and flooding. Healthy soils therefore provide a whole host of ecosystem services, which range far more broadly than simply food production.

The application of digestate to agricultural soils has been shown to improve a range of soil health indicators. These include improvements in soil organic matter (SOM), soil organic carbon (SOC), soil structure, water retention capacity, cation exchange capacity (CEC)[27], biodiversity and microbial activity, and decreases in soil erosion[28,29,30,31]. The fluctuation in SOC and SOM can influence the fluxes of greenhouse gases, thus providing climate change mitigation services. Various improvements in soil health can also have valuable positive knock-on effects such as increasing yields (and therefore biomass production), reducing water stress in the region, reducing groundwater pollution, and improving pest/disease control. Applying digestate to the soil also recycles a large fraction of the nutrients contained in the feedstock, minimising the need for synthetic fertiliser and contributing to a circular economy.

Some studies have reported negative impacts of waste-derived digestate application, such as an increase in heavy metal and micronutrient content[32,33,34] or a decrease in SOC[35,36]. However, it is understood that these impacts can largely be mitigated through implementing good agricultural practices, such as appropriate timing and quantity of digestate application as well as improving waste management practices.

25 Food and Agriculture Organisation of the United Nations, *Status of the World's Soil Resources*, 2015
26 Questions and Answers on the EU Soil Strategy, 17 November 2021. https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_5917
27 CEC is a soil property that describes its capacity to supply nutrient cations for plant uptake.
28 Möller, *Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review*, Agronomic Sustainability, 2015
29 Dr. Axel Don, Dr. Christopher Poeplau, Prof. Dr. Heinz Flessa, *Soil organic matter management in agriculture Assessing the potential of the 4per1000 initiative Book of abstracts*, 2018
30 Reuland, Sigurnjak, Dekker, Sleutel and Meers, *Assessment of the Carbon and Nitrogen Mineralisation of Digestates Elaborated from Distinct Feedstock Profiles*, Agronomy, 12, 456, 2022
31 Głowacka, Szostak and Klebaniuk, *Effect of Biogas Digestate and Mineral Fertilisation on the Soil Properties and Yield and Nutritional Value of Switchgrass Forage*, Agronomy, 10, 490, 2020
32 Przygocka-Cyna, Witold, *Biogas digestate – benefits and risks for soil fertility and crop quality – an evaluation of grain maize response*, Open Chemistry, vol. 16, no. 1, 2018. https://doi.org/10.1515/chem-2018-0027
33 Roger Nkoa. *Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review*. Agronomy for Sustainable Development, Springer Verlag/EDP Sciences/INRA34 (2), 2014,
34 Dragicevic, Sogn, Eich-Greatorex Susanne, *Recycling of Biogas Digestates in Crop Production – Soil and Plant Trace Metal Content and Variability*, Frontiers in Sustainable Food Systems, Vol 2, 2018
35 Doyeni, Stulpinaite, Baksinskaite, Suproniene, Tilvikiene. *The Effectiveness of Digestate Use for Fertilization in an Agricultural Cropping System*. Plants (Basel),, 10(8), 2021
36 Odlare, Arthurson, Pell, Svensson, Nehrenheim, Abubaker, *Land application of organic waste – Effects on the soil ecosystem*, Applied Energy, Volume 88, Issue 6, 2011

In addition, the implementation of sequential cropping in conjunction with digestate application, as described by the BDR™ concept (developed by the Italian Biogas Consortium) has been demonstrated to provide even further environmental benefits relating to soil quality, soil carbon and biodiversity. The concept furthermore does not impact existing food or feed markets as no additional land is used for biogas production, as illustrated in Figure 3.1 below.

A wider application of BDR™ could therefore be an effective way of increasing sustainable biomethane production across Europe and, coupled with this, make a positive contribution towards promoting sustainable agriculture. The application of BDR™ may not be viable in all regions however, especially countries with more temperate climates than Italy, as a warmer climate is required to fit sequential energy crops into existing crop rotations without significantly impacting the growing period or yield of the food crops. In France, Arvalis' RECITAL project is looking at potential rotations introducing energy cover crops in five different regions with different climates, including the north of France[37]. This project will provide learnings and recommendations for potential suitable rotations in more temperate regions.

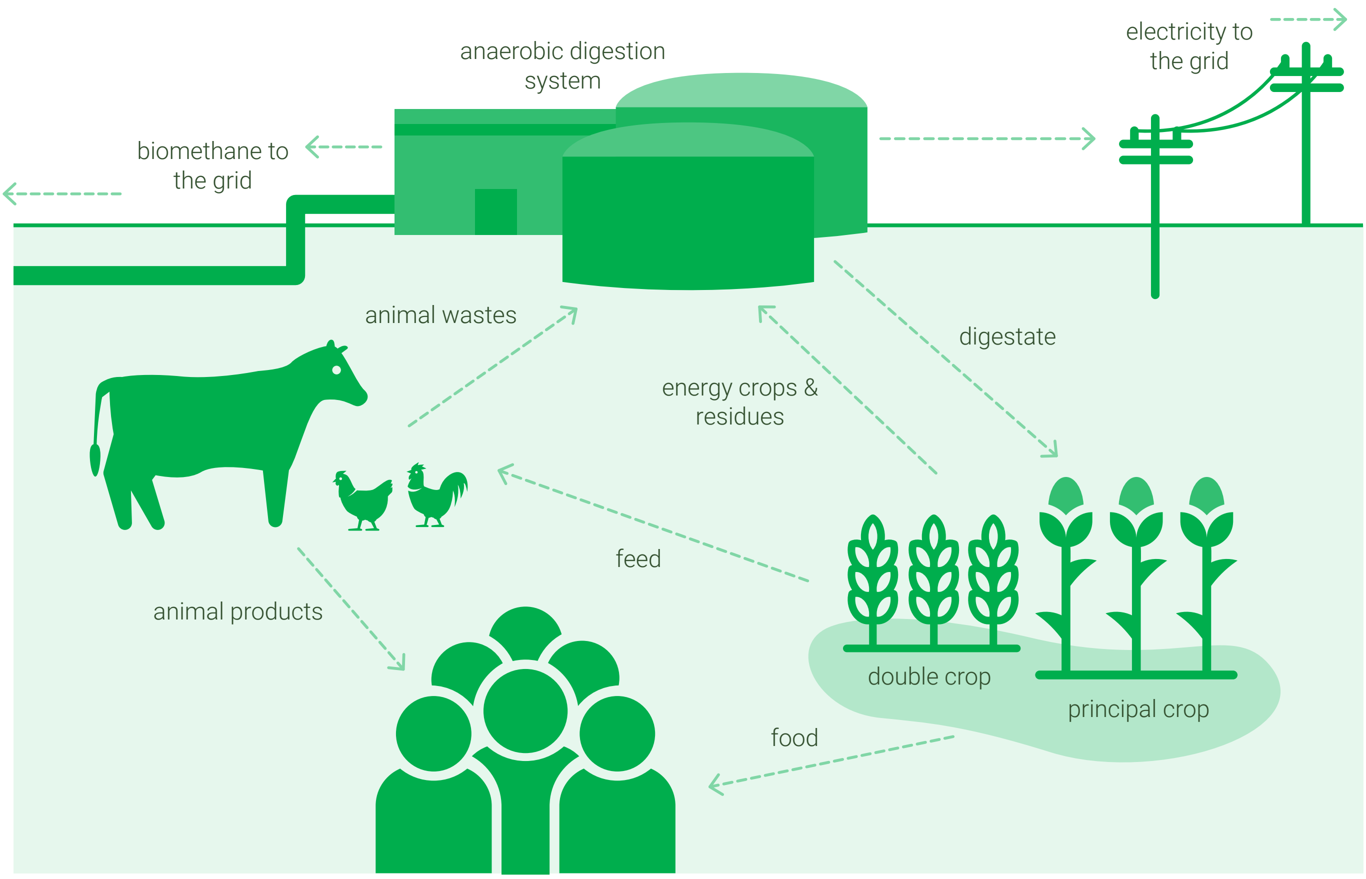


Figure 3.1 | Graphical representation of the Biogasdoneright (BDR™) concept.
Source: BDR™ by the Italian Biogas Consortium

37 Arvalis, *Project RECITAL*. https://www.arvalis.fr/recherche-innovation/nos-travaux-de-recherche/recital, accessed on 09 November 2022

With BDR™, digestate is generally split into a liquid and solid fraction, with the liquid digestate returned to the land, recycling a large fraction of the nutrients, and providing irrigation water as needed (particularly relevant in warmer climates of Europe). The solid digestate is incorporated into the soil, resulting in increased SOC and soil fertility, and farms applying this approach may become more productive over time. These effects are further enhanced by applying conservation agriculture practices including strip tillage, minimum till and sod seeding[38]. Various studies have measured the positive impact on these soil health properties[39,40]. However, sequential cropping is also an agricultural intensification method and could, in some cases, lead to an overall increase in greenhouse gas emissions compared to a single crop system[41]. This can be avoided by establishing good practices and performing a life cycle analysis to identify and remove potential emissions hotspots in the overall system.

In well managed scenarios, biomethane production supports various EU policy initiatives for soil protection[42]. For example, the EU Soil Strategy for 2030 seeks to make sustainable soil management the new normal and to promote sustainable soil management[43], which are also objectives of BDR™. Digestate application and implementation of sequential cropping also contribute to the Soil Thematic Strategy[44] by addressing threats of erosion and organic material decline. The potential for soil carbon sequestration in biomethane supply chains could also significantly contribute to the international "4 per 1000" initiative, which seeks to drive a 0.04% increase in carbon stored in the top 30-40 cm of soils per year to reduce the annual increase in atmospheric carbon dioxide[45]. Such SOC benefits are also recognised in EU policy such as the Renewable Energy Directive recast (REDII). The greenhouse gas emission methodology provides an emission saving from soil carbon accumulation via improved agricultural management (e_{sca}) of up to 25 g CO_2e/MJ biofuel for the entire period of application of the e_{sca} practices[55]. These practices include shifting to reduced or zero-tillage, improved crop rotation, the use of cover crops, including crop residue management, and the use of organic soil improver (e.g. solid digestate), which is relevant to all biomethane feedstocks (except industrial wastewater) and especially sequential crops using the BDR™ concept.

Counterfactual definition

The counterfactual scenario is no biomethane production, and therefore no digestate production and application. For anaerobic digestion, this is relevant for all feedstocks except industrial wastewater. Industrial wastewater is not relevant as although its' digestion does produce digestate, this is typically not spread to land but rather dewatered and disposed of by landfilling or incineration. In the UK, industrial wastewater sludge is typically spread for agricultural benefit[46] under The Sludge Regulations, and accredited under the Biosolids Assurance Scheme, but this is a unique scenario representing a very small fraction of this feedstock across the considered geographies, so it has not been included.

38 Dale, Sibilla, Claudio, Pezzaglia, Pecorino, Veggia, Baronchelli, Gattoni, Bozzetto. *Biogasdoneright™: An innovative new system is commercialized in Italy*. Biofuels, Bioproducts and Biorefining. 10. 2016.
39 BIOGASDONERIGHT®, *Anaerobic digestion and soil carbon sequestration is a sustainable, low cost, reliable and win win BEC-CS solution*. https://www.consorziobiogas.it/wp-content/uploads/2017/05/Biogasdoneright-No-VEC-Web.pdf
40 Szerencsits, Weinberger, Kuderna, Feichtinger, Erhart, Maier, *Biogas from Cover Crops and Field Residues: Effects on Soil, Water, Climate and Ecological Footprint*, International Journal of Environmental and Ecological Engineering, Vol:9 (4), 2015
41 Bacenetti, Fusi, Negri, Guidetti, Fiala. *Environmental assessment of two different crop systems in terms of biomethane potential production*. Sci Total Environ, 2014.
42 European Commission, EU Soil Policy. https://ec.europa.eu/environment/soil/soil_policy_en.htmhttps://ec.europa.eu/environment/soil/soil_policy_en.htm
43 European Commission, *Soil Strategy for 2030*. https://environment.ec.europa.eu/topics/soil-and-land/soil-strategy_en
44 European Commission, *Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - Thematic Strategy for Soil Protection [SEC(2006)620] [SEC(2006)1165]*, 2006. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52006DC0231&from=EN
45 The international "4 per 1000" initiative. https://4p1000.org/discover/?lang=en
46 Department for Environment, Food and Rural Affairs (DEFRA), *Waste water treatment in the United Kingdom*, 2012. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69592/pb13811-waste-water-2012.pdf

In the case of sequential crops that are specifically grown for anaerobic digestion, none of the soil health impacts attributed to digestate and sequential cropping are realised in the counterfactual scenario. This externality does not apply for thermal gasification as no digestate is produced, hence no soil health benefits can be derived from its application.

Quantification method

Quantifying soil health benefits is very challenging. Various studies have attempted to quantify different soil services, however, further developments in this field of study are still required to robustly assign monetary values to the wider socio-economic benefits of healthier soils. Two literature reviews of this topic concluded that only a small number of soil services have been attempted to be quantified, and the approaches often lack the depth needed to fully capture the public good impacts[47,48]. Both concluded that there is an urgent need for improved methodologies and frameworks for valuating soil ecosystem services to better inform decision making and policy.

Soil ecosystem services are generally categorised into production/provisioning services, regulating services, habitat/supporting services and information/cultural services[47]. With regards to this study, the first two categories are most relevant as provisioning services include the production of food and fuel, and regulating services include climate regulation and erosion control. In their literature review, Bartkowski et al. (2020) identified that climate regulation is the most frequently valued due to the relative ease with regards to SOC sequestration. On the other hand, only 5 of the 43 studies assessed attempted to value food, materials or energy production, demonstrating the need for further research in this area.

Due to the lack of well-established methodologies to quantify the value of soil health and soil ecosystem services, this study has instead focused on a qualitative description of this externality. While it may be possible to calculate the value of SOC increase, without also quantifying improvements in SOM, soil structure, water retention, soil fertility, CEC, biodiversity and decrease in soil erosion, this would not capture the full benefit of biomethane production to soils.

The following explores the benefits available, and explores why quantifying their monetary value is difficult:

» **Water retention and water cycling**

  Benefit: Organic rich soils can hold more water. Consequently, less irrigation may be required to meet the water demand of crops, thus reducing costs to the farmer and the risk of water scarcity. Moreover, enhanced water cycling can mitigate against the frequency and intensity of flooding for local communities.

  Value: Benefits to water retention and water cycling are difficult to quantify as these are complex and depend on multiple factors. Agriculturally, soils must retain enough water to meet the crop's water demand, which will depend on the crop type, local climate, and soil type. And economically, if irrigation is required to meet a crop's water demand, the value of soils' water retention relates to the availability (and price) of fresh water. It can be argued that using the price charged for water by utilities would not capture the true value of the benefit, as this price is negligible compared to the social value of water which is essential to human life.

» **Soil fertility**

  Benefit: The nutrients contained within organic feedstocks used in anaerobic digestion are recovered within digestate. When spread to land, digestate fertilises the land, providing a renewable supply of nutrients to crops. Improved fertility can result in higher yields and greater food security within the region.

  Value: Soil fertility is also difficult to quantify as while there are obvious social benefits to improving the soil's ability to produce biomass, the relationship between fertility and societal value is not linear. The greatest benefit can be seen in improving the health and fertility of very poor soils, but when considering healthy soils, the law of diminishing returns will apply to any increases in fertility resulting from biomethane production, as there is a limit to a soil's productivity. Fertility is influenced by many soil properties including organic matter, nutrient content, salinity and many more, and is therefore hard to isolate from other soil health benefits. As with water, there is also the issue of

47 Bartkowski, Bartke, Helming, Paul, Techen and Hansjürgens, *Potential of the economic valuation of soil-based ecosystem services to inform sustainable soil management and policy*, PeerJ 8:e8749, 2020
48 Jónsson, Davíðsdóttir, *Classification and valuation of soil ecosystem services*, Agricultural Systems 145, 2016

the price that should be assigned to soil fertility. Economically, this could be tied to the value of the additional food that can be produced through increased yields. This could be linked to a range of food prices, but again, this would be underestimating the critical role soils play in providing food security and nutrients for sustaining human life.

» **Soil biodiversity**

Benefit: Soil biodiversity provides significant benefits to soil health, making soils more resilient to environmental change. On-farm anaerobic digestion can enhance biodiversity both above ground and within the soil, particularly when sustainable crop production models (e.g. BDR™) are applied. This is driven by the reduction in the need for chemical inputs, such as synthetic fertilisers, which can be displaced by digestate, and herbicides or pesticides, which may be less needed when sequential cropping is deployed and the soil is kept covered.

Value: Quantifying the value of this benefit is challenging. For example, chemical inputs (synthetic fertilisers, herbicides and pesticides) can artificially control agricultural productivity. However, this establishes a dependent system which is vulnerable to external impacts, such as the availability and cost of chemicals, introduction of new pests and diseases, and impacts of climate change. The true value of soil biodiversity relates to its ability to enhance agricultural resilience, and thus withstand existential threats to productivity.

» **Soil erosion**

Benefit: Decreasing soil erosion improves soil's ability to provide numerous ecosystem services, including food production and climate mitigation (by providing greater flood and adverse weather protection). If cultivated, eroded soils will also result in more negative nutrient run-off, leading to freshwater contamination.

Value: Assigning a value to these services is challenging due to the lack of well-established methodologies to evaluate these aspects.

» **Soil organic carbon (SOC)**

Benefit: Increasing SOC can provide climate mitigation services by sequestering carbon in soil. Of the various soil health impacts considered, change in SOC is the most straightforward to quantify. This is because it can be linked to a certain amount of carbon sequestration, which can be converted to a monetary value by applying a cost of carbon.

Value: The value for change in SOC depends on many factors, including soil type (e.g. clay, sandy), initial SOC levels, climate and the specific agricultural practices applied. This can result in a wide range of SOC changes. For example, a range of 0.25-1 tonne C/ha/year is cited in a FAO study[49] which considers the SOC impact of implementing a BDR™ type approach (where sequential cropping is used as a feedstock to produce biomethane, and digestate is returned to the soil). This is applicable for conservation agriculture (which encompasses minimal soil disturbance, permanent soil cover and diversification of crop rotation, all of which are relevant to BDR™) in humid temperate areas (which include several western European countries). This range is supported by evidence from BDR™ field experiments, which showed an annual increase in SOC of 0.5-1 tonne C/ha/year in the first ten years of deploying the method[50].

49 FAO, Sandra Corsi, Theodor Friedrich, Amir Kassam, Michele Pisante and João de Moraes Sà, *Soil Organic Carbon Accumulation and Greenhouse Gas Emission Reductions from Conservation Agriculture: A Literature Review*, Integrated Crop Management Vol.16, 2012

50 Dr. Axel Don, Dr. Christopher Poeplau, Prof. Dr. Heinz Flessa, *Soil organic matter management in agriculture Assessing the potential of the 4per1000 initiative Book of abstracts*, 2018

It is worth noting that any SOC increase is expected to stabilise over time, as the soil reaches a new 'steady-state' equilibrium, and so this externality should not be extrapolated indefinitely, as demonstrated using the RothC soil carbon turnover model by Hillier et al. (2009)[51]. In addition, a return to mainstream agricultural practices such as ploughing can reverse the SOC accumulation, raising concerns about the permanence of such carbon sequestration measures[52]. It is not so straightforward to simply discourage ploughing however, as such occasional, heavier cultivation may still need to be included in any rotation to counter the buildup of perennial weeds and diseases. If some allowance of such practices is not accepted, there runs a risk of isolating parcels of land that traditionally supply fresh produce from biomethane production, as well as inadvertently encouraging heavier use of herbicides as an alternative weed control measure. As long as there is still a net increase in SOC over time, the occasional use of these practices could be acceptable.

The SOC impact of digestate application alone is harder to measure as the rate of increase is much smaller, and therefore must be observed over many years before it becomes measurable. Another method to estimate the SOC potential of digestate is through aerobic incubation experiments, as performed by Reuland et al. (2022)[53]. This study measured the soil carbon mineralisation over 149 days in controlled laboratory conditions, which allows some of the other influencing factors discussed to be isolated. This showed that carbon mineralisation largely stabilised over the 149 days and used a model to extrapolate the data to 350 days to estimate the amount of organic carbon which could be left at the end of this period. Table 3.6 shows the SOC increases that may be achievable by applying digestate from agricultural residues, animal manure, biowaste and sewage sludge.

Table 3.6 | Summary of SOC increase data used for digestate application. Source: Reuland et al. (2022)[84]

Feedstock	SOC increase (g C/ tonne whole digestate)
Agricultural residues	26
Animal manure	10
Biowaste	12
Sewage sludge	25

51 Hillier, Whittaker, Dailey, Aylott, Casella, Richter, Riche, Murphy, Taylor and Smith, *Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses*, GCB Bioenergy, 1: 267-281, 2009

52 Rachid Moussadek, Ngonidzashe Chirinda, Leonardus Vergutz, Kaushik Majumdar, Shamie Zingore, Abdelmohssin El Mokkadem, Amarjit Basra, *Potential and limitations of soil organic carbon sequestration in croplands: the role of sustainable fertility management*, UNFSS White paper, https://www.apni.net/wp-content/uploads/2021/08/UNFSS-SOC-white-paper_Final.pdf

53 Reuland, Sigurnjak, Dekker, Sleutel, Meers, *Assessment of the Carbon and Nitrogen Mineralisation of Digestates Elaborated from Distinct Feedstock Profiles*, Agronomy, 12, 456, 2022

3.2 | Greenhouse gas reduction

Greenhouse gas reductions can be delivered at various stages of the biomethane production process – primarily through the displacement of fossil fuels and synthetic fertilisers, and reductions in fugitive emissions through improved waste management (particularly animal manure[54]).

This section explores each of these in more detail.

3.2.1 | Reduction of fossil fuel production and consumption

Biomethane is a versatile renewable energy resource and can be utilised in multiple end-use sectors, namely in transport (road, shipping), heating (for use in industry and buildings) and power production. Biomethane can directly replace the use of fossil fuels in these sectors, with the potential to deliver significant greenhouse gas emission reduction.

Biomethane typically achieves over 80% emission reduction when it replaces fossil fuels, and some pathways even achieve up to 200% emission reduction[55]. This is because, in addition to the emissions avoided from replacing a fossil fuel, a similar amount of greenhouse gases either is effectively removed from the atmosphere (and stored in the land) or is avoided in adjacent systems.

For this externality we focus specifically on the greenhouse gas potential from replacing the use of fossil fuels. The reduction of synthetic fertiliser production emissions through the use of digestate and the reduction in fugitive emissions arising from manure management are treated separately in sections 3.2.2 and 3.2.3 respectively. The potential positive impacts to soil health of biogas production, including the accumulation of soil organic carbon, were covered in section 3.1.

Counterfactual definition

The counterfactual scenario is no biomethane production and no replacement of fossil fuels across the economy. The externality is considered for anaerobic digestion and thermal gasification, and for all feedstocks.

Quantification method

To quantify the greenhouse gas emission reduction, biomethane supply chain emissions [t CO_2e/MWh] were referenced against a fossil fuel comparator [t CO_2e/MWh], which depends on the end-use application (i.e. transport, heating and electricity). For transport, the fossil fuel comparator specified in the EU REDII was applied, while for heating and power the emission factor for natural gas was used as this was viewed as the most representative counterfactual in the long-term. Note that an additional 3.3 to 4.4 g CO_2/MJ was added to the biomethane emission factors for use as a transport fuel to account for compression. The emissions reduction was then converted to a monetary value by multiplying with the average cost of carbon [€/t CO_2e] traded in the EU ETS over 2022 (80 €/t CO_2e was applied)[56].

A representative range (low/high) of biomethane emission factors were identified from literature for each feedstock and technology. These were based on the EU REDII calculation methodology. Emissions relating to feedstock **cultivation** (relevant for sequential crops only), **processing** of the feedstock to produce biogas and further upgrading to biomethane and any **transport** related emissions (including compression if the biomethane for use as a transport fuel).

54 Note that fugitive emissions from improved biowaste management were not included as this represents a relatively small share of biomethane feedstock and strongly depends on the counterfactual scenarios which are varied and not well documented.

55 European Commission, *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)*, Annex VI, 2018.

56 ECX-EUA prices as published by Investing. https://www.investing.com/commodities/carbon-emissions

For **anaerobic digestion**, the typical and default values from Annex VI of the EU REDII were applied for animal manure and biowaste. Closed digestate storage and off gas combustion were assumed to avoid double counting, since these emissions are otherwise included in the Greenhouse gas increase externality calculation (see section 3.3). The UK RTFO Renewable fuel statistics for 2020[57] were used for agricultural residues, industrial wastewater and sewage sludge, while for sequential crops the Italian UNI/TS 11567:2020[58] standard was used.

For **thermal gasification**, the emission factors were based on data published by the JEC consortium[59] and industry insights. The same emission factor was applied for each feedstock due to the lack of available data. This is considered a reasonable assumption given that all of the feedstocks in scope are wastes or residues and therefore cultivation emissions are not relevant.

The quantification was undertaken for each end-use separately since the emissions of biomethane and the fossil fuel comparator differ per end-use application. A weighted average based on an equal share of 33% per sector was then calculated.

3.2.2 | Reduction of synthetic fertiliser production emissions

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)[60]. Digestate can therefore be used as an agricultural fertiliser, replacing synthetic fertiliser.

The production of synthetic fertiliser is responsible for around 1% of global greenhouse gas emissions[61,62]. The production of nitrogen-based fertilisers in particular is very carbon intensive as natural gas is used as both feedstock and process fuel. In 2019, 410 Mt CO_2e were emitted globally from the production of nitrogen-based fertilisers[63]. By displacing synthetic fertiliser, digestate can reduce the overall demand for synthetic fertilisers, hence reducing the amount of synthetic fertiliser produced[64]. This results in a decrease in greenhouse gas emissions. A further benefit is the economic value of replacing synthetic fertiliser with digestate, as discussed in section 4.

Digestate is available in three forms. It is produced by the digestion process as 'whole' and unseparated (a slurry-like material with a typical dry matter content of around 4-7%, although dry matter contents of up 15% can also be observed), but can also be separated into fibrous 'solid' (dry matter content should be greater than 20%) and 'liquid' fractions (dry matter content should be less than 4%)[65]. In come cases, the solid fraction can be subsequently composted.

The amount of synthetic fertiliser that can be displaced by digestate depends on the nutrient content of the digestate. This, in turn, is linked to the feedstock that produced the digestate, and the form of the digestate (i.e. whole, liquid or solid)[66]. Digestate separation is typically undertaken to reduce the weight of digestate making it more economical to transport, to allow digestate to be spread with existing equipment

57 UK Government, *Renewable fuel statistics 2020: Final report*, 2021. https://www.gov.uk/government/statistics/renewable-fuel-statistics-2020-final-report
58 UNI/TS 11567:2020, *Guideline for the qualification of economic operators (organizations) involved in the production chain of biomethane for traceability and mass balance purposes*. https://store.uni.com/en/uni-ts-11567-2020
59 JRC Publications Repository, *JEC Well-to-Tank report v5*, 2020. https://publications.jrc.ec.europa.eu/repository/handle/JRC119036
60 SRUC, *Digestate Information Sheets No.1 – Introduction to Digestate*. https://www.sruc.ac.uk/media/glephuum/digestate_information_sheet_1___introduction_to_digestate.pdf
61 Fertilisers Europe, *Carbon footprinting in the fertiliser industry as an essential part of managing climate change*, 2018. https://www.fertiliserseurope.com/carbon-footprinting-in-the-fertiliser-industry-as-a-means-to-reach-climate-ambitions/
62 The use of fertiliser leads to additional 1.5% greenhouse gas emissions (primarily N_2O) due to soil effects of fertilization.
63 Menegat, Ledo, Tirado, *Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture*, Scientific Reports, 12, 14490, 2022. https://www.nature.com/articles/s41598-022-18773-w
64 A further benefit is a reduction in the demand for natural gas, a key input for fertiliser production.
65 SRUC, *Digestate Information Sheets No.4 – Nutrient Availability*. https://www.farmingandwaterscotland.org/downloads/digestate-information-sheet-4-nutrient-availability/
66 FAS, *Agricultural use of biosolids, compost, anaerobic digestates and other industrial organic fertilisers*, 2019.

(solid digestate can be spread to land with the same machinery as manure) and to improve nutrient standardisation. The solid fraction is typically used before tillage as a soil conditioner. It contains more organic carbon and phosphorous. The liquid fraction is typically used to support crop growth as it contains more nitrogen in the form of readily available NH_{4+}-N.

In addition, thermal gasification technology can be deployed to produce 'biochar', which can serve as a soil improver and partial replacement for synthetic fertiliser, as well as providing a means for long-term storage of carbon in soils. Several initiatives are in development in the Netherlands that are targeting both biomethane and biochar production in an integrated production process[67]. However, since the focus of this study is on dedicated biomethane production the benefits of biochar have not been quantified.

Counterfactual definition

The overarching counterfactual for this externality is that if biomethane were not produced, there would be no anaerobic digestion and therefore no digestate production. However, what this means for the overall synthetic fertiliser demand must be considered on a feedstock-by-feedstock basis as discussed below.

- **Agricultural residues:** without biomethane production, agricultural residues can otherwise be left (or incorporated) on the land, or used for some other application (e.g. animal bedding). In some countries (e.g. central Europe and across the Mediterranean), agricultural residues are also burned in the field as a prevention method for wildfires. While leaving residues on the land has been shown to have some benefits for nutrient cycling[68], those nutrients do not immediately become available to the next crop and may not be easy to quantify. Therefore, farmers do not consider this to contribute to their crops' nutrient requirements and still need to use synthetic fertiliser.
- **Animal manure:** without biomethane production, this feedstock can be directly spread to land and used as an organic fertiliser, thereby also displacing demand for synthetic fertiliser. While digesting manure can change its nutrient availability[69], it is assumed in this study that undigested and digested manure have similar nutrient properties and hence can displace the same amount of synthetic fertiliser. This feedstock is therefore excluded from this externality calculation.
- **Biowaste:** without biomethane production, biowaste can be sent to landfill, incinerated or composted. In some countries, such as France, landfilling of biowaste is not permitted.
- **Industrial wastewater:** digestate produced from industrial wastewater is not suitable for application as an organic fertiliser and so is excluded from this externality calculation.
- **Sequential crops:** sequential crops produced specifically for biomethane production would not be grown at all in the counterfactual case as there would be no demand for the feedstock. The digestate produced from the anaerobic digestion of sequential crops is cycled back to the land to return the nutrients removed during their growth. Therefore, this feedstock does not displace synthetic fertiliser and is excluded from this externality calculation.
- **Sewage sludge:** anaerobic digestion is one of the most widely used sewage sludge treatment methods, with dewatering followed by incineration or landfilling being the other two main pathways[70]. In the UK, around two thirds of sludge is treated by anaerobic digestion[71]. The use of sewage sludge in Europe is controlled by the EU 'Sewage Sludge Directive'[72]. This states that sewage sludge normally has to be treated before being applied to land, with anaerobic digestion being one of the treatment options.

67 https://www.gasunie.nl/en/projects/eemsgas; https://stercore.nl/en/; http://torrgas.nl/
68 Torma, Vilček, Lošák, Kužel & Martensson, *Residual plant nutrients in crop residues – an important resource*, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 68:4, 2018 4
69 Möller & Müller, *Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review.* Engineering in Life Sciences. 12. 242-257, 2012.
70 Communication from SUEZ, September 2022.
71 The Official Information Portal on Anaerobic Digestion, Feedstocks. https://www.biogas-info.co.uk/about/feedstocks/
72 European Union, *Directive 86/278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture*, June 1986. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01986L0278-20220101&from=EN

After anaerobic digestion, sludge can be used as an agricultural fertiliser according to, and if in compliance with, national regulations. There are restrictions on the timings and crop types for which sewage sludge can be used as a fertiliser. The use of sewage sludge as a fertiliser is restricted based on its heavy metal concentration. There are limits for seven heavy metals that may be toxic, such as cadmium, copper, nickel, lead, zinc, mercury, and chromium. These limits refer to the fertiliser itself and the applied soil. Additional restrictions for sludge under these heavy metal thresholds are in place, prohibiting its use shortly before harvesting. Local regulations may also include limits on organic compounds and pathogens. Digestate from sewage sludge is already used as part of the European New Circular Economy Action Plan. In 2018, 33% of the sewage sludge produced in the European Union was recorded as having been used for agriculture[73].

Quantification method

To quantify this externality requires information about the amount and type of synthetic fertiliser displaced, the emission factor of those synthetic fertilisers and the monetary value of the emissions. Digestate provides three key macro nutrients for plant growth, N, P and K, although it should be noted that the proportion of these three nutrients may be more challenging to control compared to synthetic fertilisers, and therefore requires careful management. Most synthetic fertilisers usually provide only one or two of these nutrients, so a unit of digestate can displace more than one type of fertiliser. The amount of synthetic fertiliser displaced must therefore be calculated by looking at the total quantity of nutrients displaced. The equation below sets out the calculation method for this externality that was applied for each N, P and K component of the digestates, to give an overall value in €/MWh[74].

The amount of fertiliser displaced depends on how much digestate is produced (digestate yield), how much nutrient it contains (nutrient content) and how much of this is available to plants (nutrient availability). This differs by feedstock and whether the digestate is in whole, liquid or solid form. As this study is focused on the potential replacement value, whole digestate data was used and assumed to represent the total nutrient potential of digestate.

The amount of digestate produced depends on the amount of feedstock digested (which is linked to the biogas yield), and the feedstock conversion ratio. A mass conversion rate of around 85% is representative and was applied in this study[75,76].

The nutrient content depends on the feedstock and can vary significantly from one plant to another. The variability in digestate nutrient data was used to produce a low and high range for this externality (see Table 3.7).

$$\text{Synthetic fertiliser emissions } [t\ CO_2 / t\ \text{fertiliser}] \times \frac{\text{Digestate nutrient content } [t\ NPK / t\ \text{digestate}]}{\text{Digestate nutrient content } [t\ NPK / t\ \text{digestate}]} \times \text{Digestate yield } [t\ \text{digestate} / MWh\ \text{biomethane}] \times \text{Cost of carbon } [€ / t\ CO_2e]$$

Equation 3.1 | Calculation methodology for Reduction of synthetic fertiliser production emissions (anaerobic digestion only)

73 Eurostat, *Sewage sludge production and disposal from urban wastewater*. https://ec.europa.eu/eurostat/databrowser/view/TEN00030__custom_3555502/default/table?lang=en
74 Note that the quantification is based on the displacement of macro nutrients only. Secondary nutrients and micronutrients are not considered as they have comparatively less commercial value.
75 Biofertiliser Certification Scheme, *Application of digestate to land as biofertiliser vs. waste. Fee Comparison – England*, 2021. https://www.biofertiliser.org.uk/pdf/BCS-cost-benefit-analysis.pdf
76 WRAP, *Enhancement and treatment of digestates from anaerobic digestion*, 2012.

Multiple data sources were identified for food-based and farm-based digestate properties. The Scottish Government's Farm Advisory Service[77] and UK Agriculture and Horticulture Development Board (AHDB)[78] give the same values, which are also fairly consistent with those given by WRAP[79]. These were taken as the low range for the biowaste and agricultural residue feedstock, respectively. Tambone et al. (2017)[80] studied the nutrient content of digestates from 13 feedstock combinations containing energy crops and agricultural residues. The highest of these values were taken as the high range for the agricultural residue feedstock. A publicly available digestate database[81] was also analysed to verify these ranges and to provide the high range for digestate from the biowaste feedstock. Finally, for sewage sludge, the digestate nutrient content range was taken from the ISO/TC 275 standard on Sludge recovery, recycling, treatment and disposal, specifically the section regarding land application[82].

Table 3.7 | Summary of whole/raw digestate nutrient values used for low and high range

Feedstock	Agricultural residues		Biowaste		Sewage sludge	
Range	Low	High	Low	High	Low	High
N (kg/t)	3.6	6.7	4.8	5.22	3.0	5.0
P_2O_5 (kg/t)	1.7	3.4	1.1	1.48	3.0	6.0
K_2O (kg/t)	4.4	4.4	2.4	1.62	0.3	0.7

77 Scottish Government Farm Advisory Service, *Technical Note TN699 Agricultural use of biosolids, composts, anaerobic digestates and other industrial organic fertilisers*, 2019. https://www.fas.scot/downloads/tn699-agricultural-use-of-biosolids-composts-anaerobic-digestates-and-other-industrial-organic-fertilisers/

78 Agriculture and Horticulture Development Board, *Nutrient Management Guide (RB209): Section 2 Organic Materials*, 2021, https://ahdb.org.uk/knowledge-library/rb209-section-2-organic-materials

79 WRAP, *Field experiments for quality digestate and compost in agriculture*, 2016. https://wrap.org.uk/sites/default/files/2020-09/WRAP-WRAP_DC-Agri_research_summary.pdf

80 Tambone, Orzi, D'Imporzano, Adani, Solid and liquid fractionation of digestate: *Mass balance, chemical characterization, and agronomic and environmental value*, Bioresource Technology, Volume 243, 2017. https://www.sciencedirect.com/science/article/pii/S0960852417312464

81 Reuland; Sigurnjak; Michels; Dekker; Meers; *Digestate and the Liquid Fraction of Digestate Compositional Properties*, 2021. https://zenodo.org/record/5526416#.Yv-e7RxByUk

82 ISO/TC 275/WG 4, *Sludge recovery, recycling, treatment and disposal, Land application*. https://www.iso.org/committee/4493530.html

Nutrient availability is different for each of the three key nutrients. The amount of readily available nitrogen (RAN) for plant uptake depends on the amount of N in NH_4^+-N form and was taken to be 80% based on the AHDB data. This depends on the feedstock and the conditions of digestion. It is worth noting that RAN content is linked to N volatilisation and hence loss of N to the atmosphere. Solid digestate can contain high levels of RAN so it is advised to incorporate this into the soil as quickly as possible, ideally within 24 hours[83]. The amount of digestate P and K readily available for plant uptake is around 50% and 90% respectively[84].

Each nutrient provided by the digestate can displace a different synthetic fertiliser. For example, the digestate N could reduce the consumption of ammonium nitrate (NH_4NO_3) or urea (CH_4N_2O) as a synthetic fertiliser. There are multiple chemical compositions of synthetic fertiliser available for each nutrient. This study assumes that the most widely used synthetic fertilisers in the EU27 and UK are displaced by digestate. Based on an analysis of the FAO 'Fertilisers by Product' dataset for the EU27 and UK in 2019, these are urea for N, phosphate rock for P and muriate of potash for K.

Urea contains a 46% N content, the highest of all dry fertiliser products[85]. **Phosphate rock** in its untreated form is not very soluble but is used to manufacture more effective phosphate fertilisers. The most common phosphate fertilisers in Europe are single superphosphate (SSP), triple superphosphate (TSP), monoammonium phosphate (MAP), diammonium phosphate (DAP) and ammonium polyphosphate liquid[86]. DAP is the most widely used phosphorous fertiliser in the world and was applied in this study[87]. DAP contains 46% P_2O_5[88]. **Muriate of potash** contains 60-62% K_2O, and for the purpose of this study we have applied a value of 61%[89,90]. The emission factors for the production of those fertilisers are based on the standard values published by the European Commission in the context of the EU REDII[91].

Finally, these emissions were converted to a monetary value by multiplying with a cost of carbon of 80 €/t CO_2e.

3.2.3 | Reduction of fugitive emissions from manure management

When raw (solid) manure or raw (liquid) slurry is stored, waiting to be spread on the fields, it releases gases in the atmosphere as result of bacterial activity. Methane is the main gas released by manure decomposition, but also nitrogen compounds such as nitrous oxide (N_2O), ammonia (NH_3) and nitrogen oxides are released[92].

At present, 24% of global greenhouse gas emissions arise from the food, agriculture and land use sector. Manure management (in particular from open storage systems) is a significant driver of these emissions, representing 2% of the sector's methane emissions and 28% of its nitrous oxide emissions[93]. This is even higher in Europe, where methane emissions from manure represented almost 10% of total methane emissions in 2017 (or 17% of the methane emissions in agriculture which is the largest contributing sector)[94].

83 SRUC, *Digestate Information Sheets No.3 – Application methods*. https://www.sruc.ac.uk/media/hkcanzo1/digestate_information_sheet_3___application_methods.pdf
84 SRUC, *Digestate Information Sheets No.4 – Nutrient Availability*. https://www.farmingandwaterscotland.org/downloads/digestate-information-sheet-4-nutrient-availability/
85 Agrico Canada, *Urea*. https://www.agricocanada.com/fertilisers/urea/
86 Fertilisers Europe, *Types of fertiliser*. https://www.fertiliserseurope.com/fertilisers-in-europe/types-of-fertiliser/
87 Indorama, *Phosphate Fertilisers*. https://www.indorama.com/products/phosphate-fertilisers
88 Agrico Canada, *Diammonium Phosphate*. https://www.agricocanada.com/fertilisers/dap/
89 Agrico Canada, *Muriate of Potash 60%*. http://www.agricocanada.com/fertilisers/muriate-of-potash-60/
90 Agrico Canada, *Muriate of Potash 62%*. https://www.agricocanada.com/fertilisers/muriate-of-potash-62/
91 European Commission, *Commission Implementing Regulation (EU) 2022/996 of 14 June 2022 on rules to verify sustainability and greenhouse gas emissions saving criteria and low indirect land-use change-risk criteria (Text with EEA relevance)*, 2022. https://eur-lex.europa.eu/eli/reg_impl/2022/996
92 JRC, *Solid and gaseous bioenergy pathways: input values and GHG emissions: Calculated according to methodology set in COM(2016) 767: Version 2*, 2017. https://publications.jrc.ec.europa.eu/repository/handle/JRC104759
93 Project Drawdown, *Farming our way out of the climate crisis*, 2020. https://drawdown.org/sites/default/files/pdfs/Drawdown-Primer_FoodAgLandUse_Dec2020_01c.pdf
94 European Environment Bureau, *EEB input to DG AGRI on the urgency to establish binding measures to reduce methane emissions from agriculture*, 2020, https://eeb.org/wp-content/uploads/2020/07/EEB-input_EU-methane-strategy-to-reduce-emissions-from-agriculture.pdf

Using manure as a feedstock for biomethane production can therefore play an important role in helping to reduce fugitive emissions from the agricultural sector, while also providing an important contribution to the control of pathogens. Importantly, biogas is the most efficient manure treatment method that can do so, with composting offering similar benefits, but to a lesser extent. Similar benefits will be realised when organic waste streams in other sectors, such as food waste are treated via anaerobic digestion. This has relevance considering the recently launched Global Methane Pledge which aims to reduce global methane emissions by at least 30% from 2020 levels by 2030[95].

Counterfactual definition

The main alternatives to using manure as a feedstock for anaerobic digestion are landspreading of untreated manure (with or without long-term storage), manure composting (which can be subsequently spread to land), separation and incineration[96].

There is variable evidence on the greenhouse gas impact of composting manure as this depends on the composting method. To mitigate this uncertainty and to provide a conservative estimate, the proportion of manure that is currently composted was excluded from this quantification. Limited information on manure incineration could be identified, although it appears to be more common for poultry litter as it can be more easily collected from poultry shed floors. Cattle manure from feedlots also has potential for incineration, but issues arise due to dirt incorporated in the manure, leading to high ash levels. The most common manure management method identified is storage and spreading[97], therefore this was analysed as the counterfactual scenario.

Quantification method

To quantify this externality requires information on the greenhouse gas emissions of untreated manure, the biomethane yield of manure and the associated monetary cost of emissions as indicated below.

$$\text{Untreated manure emissions } [t\ CO_2e / t\ manure] \times \text{Biomethane manure requirements } [t\ manure / MWh] \times \text{Cost of carbon } [€ / t\ CO_2e]$$

Equation 3.2 | Calculation methodology for Reduction of fugitive emissions from manure management (anaerobic digestion only)

95 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/en/statement_21_5766

96 Manure treatment and utilisation options, R.W. Melse PhD & F.E. de Buisonjé BSc

97 Loyon Laurence, *Overview of Animal Manure Management for Beef, Pig, and Poultry Farms in France, Frontiers in Sustainable Food Systems*, 2018. https://www.frontiersin.org/articles/10.3389/fsufs.2018.00036

The EU REDII allocates a greenhouse gas credit for using manure as a feedstock of 54 kg CO_2e/t fresh matter relating to improved manure management emissions reduction[98]. This value was determined by the JRC and is based on a manure fresh matter content of 90%[99], and was applied for both the low and high range quantification.

Linear extrapolation was applied to calculate the greenhouse gas credit for manures from different livestock types with different dry matter contents, as summarised in Table 3.8. The biomethane yield using different types of manure were taken from Scarlat et al. (2018)[100].

Finally, these emissions were converted to a monetary value by multiplying with a cost of carbon of 80 €/t CO_2e.

A weighted average of the different manure types was calculated based on the future potential of each in 2030 and 2050, as estimated by Gas for Climate[101]. The distribution is 34% cattle, 20% dairy cows, 11% pigs, 5% sheep/goats and 29% poultry.

Table 3.8 | Summary of manure assumptions per livestock type for greenhouse gas reduction externality calculation

Manure type	Cattle	Dairy cows	Pigs	Sheep / goats	Poultry	Source
Fresh matter (%)	90%	90%	94%	70%	80%	Gas for Climate
Greenhouse gas credit ($t\ CO_2$ / t fresh manure)	0.0540	0.0540	0.0324	0.1620	0.1080	European Commission /JRC
Biomethane yield ($m^3\ CH_4$ / t fresh manure)	13.6	15.6	14.4	48.0	51.2	Scarlat et al. (2018)

98 European Commission, *DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)*, 2018.
99 Giuntoli, Agostini, Edwards and Marelli, *Solid and gaseous bioenergy pathways: input values and GHG emissions: Calculated according to methodology set in COM(2016) 767: Version 2*, EUR 27215 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-64811-3 (print),978-92-79-64810-6 (PDF), doi:10.2790/98297 (print),10.2790/27486 (online), JRC104759.
100 Scarlat et al., *A spatial analysis of biogas potential from manure in Europe, Renewable and Sustainable Energy Reviews*, Volume 94, 2018, https://doi.org/10.1016/j.rser.2018.06.035
101 Gas for Climate, *Biomethane production potentials in the EU*, 2022. https://www.europeanbiogas.eu/wp-content/uploads/2022/07/GfC_national-biomethane-potentials_070722.pdf

3.3 | Greenhouse gas increase

Although biomethane typically leads to an overall reduction in greenhouse gas emissions when it replaces fossil fuels, such as natural gas or diesel, fugitive emissions arising from the production process can negatively impact the scale of the greenhouse gas performance. This negative effect is amplified by the high global warming potential of methane, which is directly released to the atmosphere when biogas or biomethane leaks occur. Furthermore, fugitive emissions also directly impact the economic performance of production since every unit of biomethane lost also represents lost revenue.

Fugitive emissions can arise from leaks in the digester or upgrader equipment, pipework and pressure valves, or from the storage of digestate, particularly if this is open or not gas tight. For anaerobic digestion, fugitive emissions rate can be influenced by the size, age, quality and upgrading technology of the facility. Several studies and organisations have carried out emissions measurement campaigns at anaerobic digestion plants and found methane emissions rate as low as 0.1% and as high as 10% of total methane production[102,103,104,105]. On average however, most plants tend to have emissions rates around 3%[102,106]. Those on the higher end of the spectrum tend to be farm-based plants and older plants.[102] Measurement methods include Gaussian plume modelling, tracer gas dispersion and static chamber methods. Implementing monitoring systems such as regular checks of safety valves and methane measurement campaigns to detect, quantify and repair any leaks will help to minimise these emissions.

The EvEmBi research project, supported by the European Biogas Association (EBA), has been developing a European-wide voluntary monitoring system for greenhouse gas emission reduction across the biogas and biomethane sectors. This has included workshops to share knowledge and research results with the project consortium, which includes academic bodies, bioenergy focused non-profits, biogas associations and biogas operators. The project will improve the database on methane emissions from biogas plants and assess mitigation strategies, partly by evaluating emissions from biogas plants in countries where voluntary programmes are already in place or under development (Denmark, Austria, Germany Switzerland and Sweden). A key outcome will be the determination of comparable and representative methane emission factors, which is seen as pivotal to harmonise the uncertainty estimates towards emission mitigation strategies. Best Available Techniques (BAT) adopted in other Member States have also been found to be an effective way of reducing fugitive emissions[107]. Measures to reduce methane emissions have been included in technical regulations such as the TRAS-120 in Germany[108].

Another key project in this field is MetHarmo (European harmonisation of methods to quantify methane emissions from biogas plants), funded via ERA-NET and supported by EBA. This project aimed to develop a common procedure to quantify methane emissions from biogas plants, using both on-site and ground-based remote sensing methods[109]. MetHarmo demonstrated that a well-managed biogas plant produces minimal methane emissions, further supporting the argument for deploying BAT.

102 Bakkaloglu, Lowry, Fisher, France, Brunner, Chen, Nisbet, *Quantification of methane emissions from UK biogas plants*, Waste Management, Volume 124, 2021. https://doi.org/10.1016/j.wasman.2021.01.011

103 Reinelt, McCabe, Hill, Harris, Baillie, Liebetrau, *Field measurements of fugitive methane emissions from three Australian waste management and biogas facilities*, Waste Management, Volume 137, 2022

104 Fredenslund, Scheutz, *Total methane loss from biogas plants, determined by tracer dispersion measurements*. Proceedings Sardinia, 2017

105 Wechselberger, *Performance of biogas plants towards methane emissions*, European Biogas Conference, 2021

106 European Biogas Association, *Fugitive Methane Emissions from the Biogas sector, Impact scenarios for the EU biogas sector*

107 Clauß, Reinelt, Liebetrau, Vesenmaier, Reiser, Flandorfer, et al., *Recommendations for reliable methane emission rate quantification at biogas plants*, 2019.

108 European Biogas Association, *Methane emission mitigation strategies: Information sheet for biogas industry*, 2020. https://www.europeanbiogas.eu/wp-content/uploads/2020/05/Methane-emission-mitigation-strategies-info-sheet-for-biogas-industry.pdf

109 European Biogas Association, *EBA supporting the MetHarmo project – European harmonisation of methods to quantify methane emissions from biogas plants*. https://www.europeanbiogas.eu/eba-supporting-the-metharmo-project-european-harmonisation-of-methods-to-quantify-methane-emissions-from-biogas-plants/

3.3.1 | Fugitive emissions from anaerobic digestion plants arising during the digestion and upgrading processes

This section focuses on fugitive emissions from anaerobic digestion and thermal gasification plant structures and equipment only. These include emissions and leakages from receiving tanks or buffer tanks, particularly in the case of manure and biowastes, from gas diffusion through digester holder membranes, leakages, or pressure relief valves, from gas pipelines, especially around joints, and from compressors and other moving parts in the upgrading unit. The exhaust gas can also contain residual methane depending on the efficiency of the upgrading process. Fugitive emissions from digestate storage are considered as a separate sub-externality in section 3.3.2.

Counterfactual definition

Fugitive emissions can arise in the anaerobic digestion or thermal gasification production processes for any feedstock. The counterfactual is that no biomethane is produced, hence there are no anaerobic digestion or thermal gasification plants, and subsequently that no additional fugitive emissions are generated. Therefore, this externality applies for all the technologies and feedstocks in scope.

Quantification method

A recent measurement campaign measured and analysed fugitive emissions rates from different anaerobic digestion plant components, giving a range of values, shown in Figure 3.2[110]. This shows that, excluding digestate storage, the majority of emissions occur in the substrate receiving and storage phase and the biogas utilisation phase. The greatest variation in emissions is seen across the different utilisation and upgrading technologies, therefore the value of this externality was calculated for each of the upgrading technologies and scaled to their respective market share. The ranges shown in the figure were used to calculate the low and high externality estimates. Note that fugitive emissions from combined heat and power (CHP) units will not be included as these systems typically powered by biogas, rather than biomethane which is the focus of this study.

$$\left(\text{Digester leakage rate* } [t\ CO_2e\ /\ MWh] + \text{Upgrader leakage rate* } [t\ CO_2e\ /\ MWh] \right) \times \text{Cost of carbon } [€\ /\ t\ CO_2e]$$

*This depends on several factors including the size, age and quality of the facility, as well as the feedstock (as this affects the CO_2 to CH_4 ratio of the biogas produced).

Equation 3.3 | Calculation methodology for Fugitive emissions from digestion and upgrading in anaerobic digestion plants

110 ERA-NET Bioenergy, DBFZ, *Evaluation and reduction of methane emissions from different European biogas plan concepts – EvEmBi, ERA-NET Bioenergy Thematic Online Seminar*, October 2022. https://eranetbioenergy.net/wp-content/uploads/2022/01/ERA-NET_Bioenergy_18012022_Highlights_EvEmBi_Wechselberger.pdf

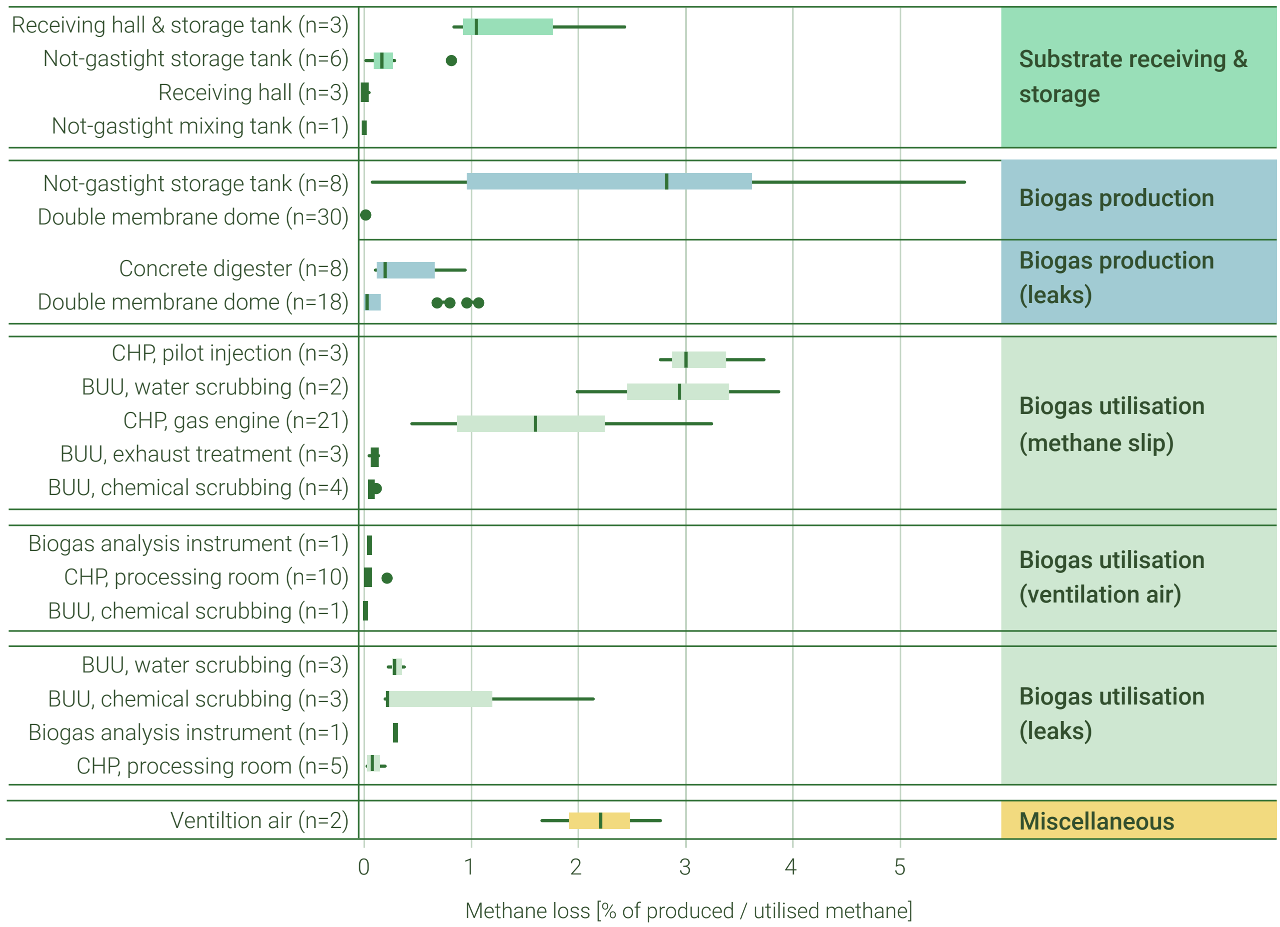


Figure 3.2 | Fugitive emission rates for anaerobic digestion plants. Source: ERA-NET[110]

The ERA-NET data provides leakage rates specifically for two upgrading technologies, water scrubbing and chemical scrubbing. Three additional technologies are commonly deployed in the market. These are membrane separation, pressure swing absorption and cryogenic separation (see Figure 3.3). While cryogenic separation currently only represents a very small share of the upgrading market, its deployment is expected to grow significantly in the medium to long term as demand for bio-LNG in transport increases. Meanwhile, physical scrubbing has the second smallest share, but its market share is declining and so was not considered. Leakage rates for membrane separation and pressure swing absorption were taken from a recent study by Bakkaloglu et al. (2022)[111] as shown in Figure 3.4 below. Finally, a leakage range of 0% to 2% was used for cryogenic separation, based on Adnam et al. (2019)[112]. The leakage rates were converted to carbon dioxide equivalents by multiplying by methane's global warming potential weighting of 28, and then converted to a monetary value by multiplying by the cost of carbon traded in the EU ETS.

111 Bakkaloglu, Cooper, Hawkes, *Methane emissions along biomethane and biogas supply chains are underestimated*, One Earth, Vol 5, Issue 6, 2022. https://doi.org/10.1016/j.oneear.2022.05.012
112 Adnan, Ong, Nomanbhay, Chew, Show, *Technologies for Biogas Upgrading to Biomethane: A Review*. Bioengineering (Basel). 6(4):92, 2019.

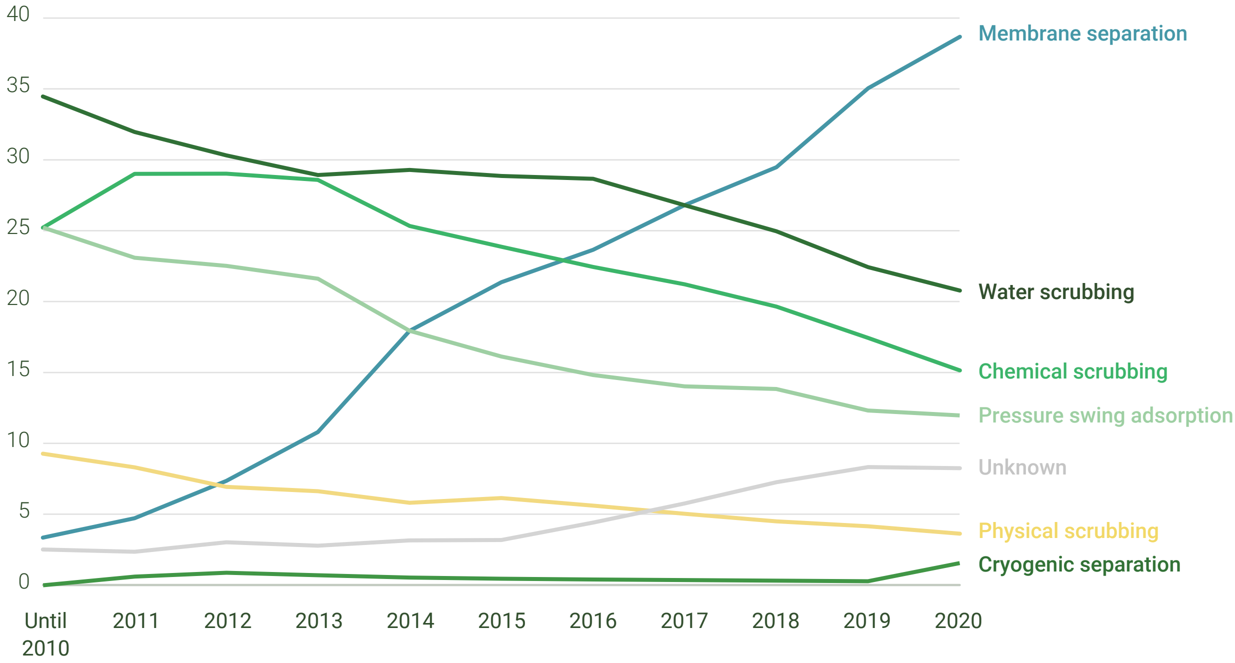


Figure 3.3 | Cumulative change in biogas-biomethane upgrading techniques based on number of plants in Europe. ("Unknown" signifies the upgrading technology is not known). Source: Gas for Climate[113]

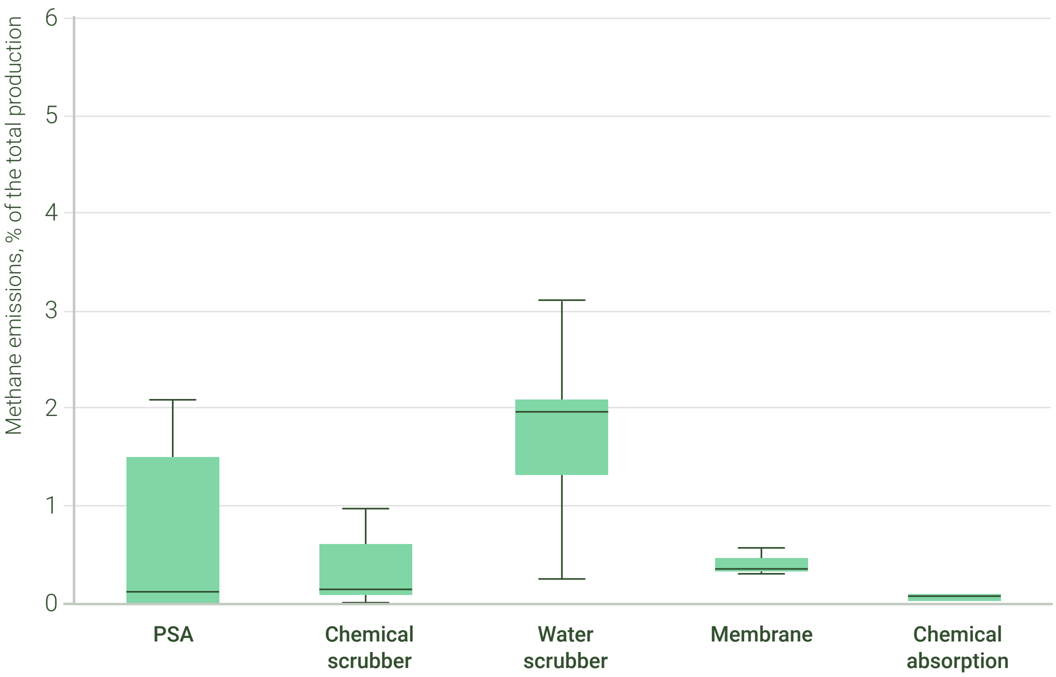


Figure 3.4 | Fugitive emission rates for different upgrading technologies. Source: Bakkaloglu et al. (2022)[111]

113 Gas for Climate, *Market state and trends in renewable and low-carbon gases in Europe*, 2020. https://gasforclimate2050.eu/wp-content/uploads/2020/12/Gas-for-Climate-Market-State-and-Trends-report-2020.pdf

As biomethane production from thermal gasification is a less commercially mature technology, there is currently limited information available concerning fugitive emissions. It is expected that these will be lower on average compared to anaerobic digestion plants, due to the larger size of plants expected to be constructed in future. As these plants will usually be subject to ATEX[114] constraints, it would not be surprising to see a value close to zero if off-gas is reutilised in combustion[115]. To illustrate this, a leak rate of 0% and 0.5% was used as the basis for the low and high externality calculations, respectively.

3.3.2 | Fugitive emissions from digestate storage

This externality focuses specifically on fugitive emissions from digestate storage. These emissions have historically been problematic for the anaerobic digestion sector due to open storage of digestate. This can lead to significant emissions of methane resulting from the continued anaerobic digestion of the residual biodegradable organic matter[116]. This can be minimised by ensuring that organic matter is nearly fully degraded by increasing the digestion time. In Germany for example, there are regulations on retention time and an option to demonstrate emissions are below a certain threshold, under which open digestate storage is permitted. This is useful in certain scenarios, such as small plants, where it may not be economic to cover the entire storage volume. Closed, gas-tight digestate storage prevents these emissions from escaping to the atmosphere by connecting to the gas system to allow the methane formed to be recovered. Finally cooling the digestate will also reduce emissions as methane production decreases at temperatures below 17°C[117].

According to the EBA[117], several countries have already put measures in place to mitigate these emissions. Mandatory recommendations on closed digestate storage for all new plants and minimum digestion time are in place in some European countries, such as France, Germany and Switzerland.

Counterfactual definition

Digestate storage emissions can occur from any feedstock. The counterfactual is that no biomethane is produced, hence no digestate is produced and no additional fugitive emissions are created. Therefore, this externality applies for all anaerobic digestion feedstocks.

Quantification method

To quantify this externality relative to a unit of biomethane production requires data on the amount of digestate produced per unit of biomethane, the emission rate of digestate storage and the monetary value of those emissions.

$$\text{Digestate storage leakage rate } [t\ CO_2e / t\ digestate] \times \text{Digestate yield* } [t\ digestate / MWh\ biomethane] \times \text{Cost of carbon } [€ / t\ CO_2e]$$

* Digestate yield differs by feedstock

Equation 3.4 | Calculation methodology for Fugitive emissions from digestate storage (anaerobic digestion only)

114 European Commission, *Internal Market, Industry, Entrepreneurship and SMEs, Equipment for potentially explosive atmospheres (ATEX)*. https://single-market-economy.ec.europa.eu/sectors/mechanical-engineering/equipment-potentially-explosive-atmospheres-atex_en
115 Communication from ENGIE, October 2022.
116 United Nations Framework Convention on Climate Change, Clean Development Mechanism, Methodological Tool "Project and leakage emissions from anaerobic digesters", 2012. https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-14-v1.pdf
117 European Biogas Association, *Methane emission mitigation strategies – information sheet for biogas industry*, 2020. https://www.europeanbiogas.eu/methane-emission-mitigation-strategies-information-sheet-for-biogas-industry/

As discussed in section 3.2.2 the feedstock to digestate mass conversion factor of the anaerobic digestion process is taken to be 85% on average. Given the biomethane yield of each feedstock, the digestate yield per MWh of biomethane produced was calculated as follows.

$$\frac{1}{\text{Biomethane yield}\left(\frac{\text{MWh}}{\text{t feedstock}}\right)} \times \text{Digestate conversion factor}\left(\frac{\text{t digestate}}{\text{t feedstock}}\right)$$

Equation 3.5 | Calculation methodology for Digestate yield applied in Equation 3.4

The emission rate from digestate depends on the digestion time, and the storage method. For open storage, the EvEmBi study discussed in section 3.3.1 gives an interquartile range of 1% to 3.5% of total biomethane production. For closed storage, emissions may be negligible in certain situations, but small leaks can sometimes still occur. A range of 0% to 1.3% was therefore applied, with the upper value coming from an IEA study which looked at methane emissions from biogas plants[118].

The share of facilities implementing open and closed digestate storage is not available at a European level. Older facilities are more likely to have open storage systems, while newer facilities are more likely to have closed storage systems, as digestate storage emissions have been increasingly highlighted as an issue in recent years. It is expected that the proportion of facilities with closed storage will continue to increase, as new plants are likely to have to use this type of storage system in order to meet the more stringent REDII greenhouse gas reduction requirements, unless manure is used as a substrate. It will become increasingly difficult for biomethane producers to meet the REDII and future REDIII greenhouse gas reduction requirements without switching to closed storage. As a conservative estimate, this study has assumed that 30% of storage will be open, with a 70% majority being closed.

The leakage rates were converted to carbon dioxide equivalents, and then to a monetary value by multiplying by a cost of carbon of 80 €/t CO_2e.

118 IEA, *Methane emissions from biogas plants: Methods for measurement, results and effect on greenhouse gas balance of electricity produced*, 2017. https://www.ieabioenergy.com/blog/publications/methane-emissions-from-biogas-plants-methods-for-measurement-results-and-effect-on-greenhouse-gas-balance-of-electricity-produced/

4. Economic externalities

4. Economic externalities

4.1 | Improved energy security

Europe is heavily reliant on energy imports, including natural gas. Until recently, Russian natural gas made up a large share of energy imports to the EU27 with 155 bcm, representing 38% of total consumption (see Figure 4.5).

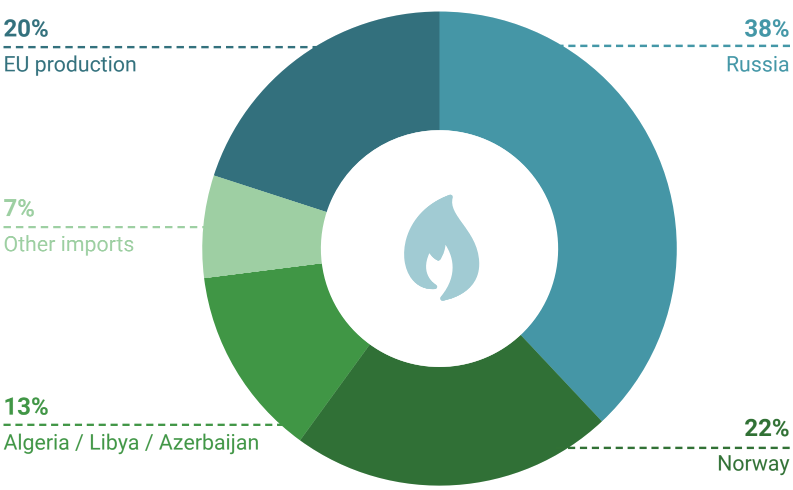


Figure 4.5 | EU27 dependency on natural gas imports in 2020[119]

In light of Russia's invasion of Ukraine in February 2022, the European Commission published REPowerEU, a plan to make Europe independent from Russian fossil fuels well before 2030, starting with replacing the 155 bcm of natural gas. The plan also sets a target to reduce natural gas imports by two thirds in 2022. The EU27 is well on track to meeting this aim. According to the European Commission, Russian natural gas imports decreased to 28% in the second quarter (Q2) of 2022, with pipeline imports having a share of 23% which decreased further still to 10% in August 2022[120].

119 Gas for Climate, *Action plan for implementing REPowerEU*, 2022. https://gasforclimate2050.eu/wp-content/uploads/2022/04/Gas-for-Climate-Action-Plan-for-implementing-REPowerEU_v2.pdf#:~:text=On%20March%208%2C%202022%2C%20in,2030%20(see%20Figure%205).

120 European Commission, *Quarterly report – On European gas markets*, 2022. https://ec.europa.eu/info/sites/default/files/energy_climate_change_environment/overall_targets/documents/quarterly_report_on_european_gas_markets_q2_2022_final_0.pdf

Although Russian imports have decreased, overall imports of natural gas to the EU27 increased by 3% in Q2 2022 (compared to Q2 2021). Imports of LNG have increased significantly reaching 35.6 bcm in Q2 2022 (compared to 23.8 bcm in Q2 2021). Four countries dominate supply, delivering over 80% of EU27's imports. The largest import partner is the USA with 16 bcm. Russia still remains the second largest import partner with 6.5 bcm, followed by Qatar (4.6 bcm) and Nigeria (2.7 bcm). LNG imports bring the opportunity to allow more diversified import partners as they are not limited to pipeline routes. However, dedicated infrastructure is required to receive LNG and regasify it back to natural gas, which is not yet widely available across Europe.

Energy consumption in Europe reduced in 2022 compared to 2021 resulting from energy savings and an overall reduction in gas use. However, over time this period domestic gas production also decreased[121]. This highlights that Europe will likely continue to be heavily reliant on natural gas imports in the coming years.

Not only geopolitical crises, such as the Russian invasion of Ukraine, can lead to energy supply disruptions. The restarting of the global economy in 2021 following the covid-19 pandemic resulted in a rapid increase in demand for commodities like natural gas. Supply has struggled to keep pace with the increased demand. As a result of both crises, natural gas prices increased more than ninefold from €20/MWh to around €180/MWh between March 2021 and March 2022. This threatens the competitiveness of Europe's industries and increases the risk of energy poverty for households.

Biomethane can directly replace natural gas (e.g. in industrial heating), or otherwise serve as a substitute for other fossil fuels (e.g. in transportation) depending on the end-use application. Renewable gases, such as biomethane, are seen to play a key role in meeting the REPowerEU ambition. Specifically, the REPowerEU plan sets a target of 35 bcm (370 TWh) of biomethane production per year by 2030 in the EU27. This is equivalent to replacing around 20% of the Russian natural gas imports in 2020[122].

Current production costs for biomethane range from €55-€110/MWh[123] depending on the feedstock, technology and plant scale, which is competitive against current natural gas prices (see Figure 4.6). As domestically produced biomethane reduces the need to import natural gas, it can directly improve Europe's energy independence and security, and cushion against exposure to volatile natural gas prices.

121 European Commission, *Quarterly report – On European gas markets*, 2022. https://ec.europa.eu/info/sites/default/files/energy_climate_change_environment/overall_targets/documents/quarterly_report_on_european_gas_markets_q2_2022_final_0.pdf

122 European Commission, *REPowerEU: A plan to rapidly reduce dependency on Russian fossil fuels and fast forward the green transition*, 2022. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

123 Costs are expressed on a Levelised Cost of Energy (LCOE) basis. This takes into account both capital and operational costs over the lifetime of a biomethane plant, referenced against the energy that can generated over this period.

Figure 4.6 | Natural gas price development since 2021[124] and LCOE of biomethane[125,126]

Counterfactual definition

The counterfactual considered for this externality is importing natural gas to Europe (EU27 and UK). The externality is analysed separately for biomethane produced from both anaerobic digestion and thermal gasification technologies. All feedstocks are considered to be in scope.

Quantification method

Determining the economic value of improved energy security is extremely challenging to quantify, in part due to many different factors that may be considered which can in some cases be subjective (e.g. fear of power outages). In this study we quantify improved energy security by comparing the levelised cost of energy (LCOE) for biomethane [€/MWh] to the natural gas price peaks [€/MWh] observed in 2021 and 2022 relative to the baseline prices in those years. Through this approach we aim to provide an estimate of the economic value that locally produced biomethane could deliver as an alternative to imported natural gas, thereby reducing exposure to volatile price increases.

$$\left(\text{Natural gas price peak } [€ / \text{MWh}] - \text{Natural gas price baseline } [€ / \text{MWh}]\right) - \text{Biomethane LCOE } [€ / \text{MWh}]$$

Equation 4.6 | Calculation methodology for Energy security

124 Dutch TTF natural gas price. https://www.investing.com/commodities/dutch-ttf-gas-c1-futures-historical-data
125 Gas for Climate, *The future role of biomethane*, 2021. https://gasforclimate2050.eu/wp-content/uploads/2021/12/The_future_role_ of_biomethane-December_2021.pdf
126 EBA, *Gasification – A Sustainable Technology for Circular Economies*, 2021. https://www.europeanbiogas.eu/wp-content/uploads/2021/11/Gasification-A-Sustainable-Technology-for-Circular-Economies.pdf

The 2021 price peak (180 €/MWh) occurred in December 2021 and is related to the economy ramp up following the global Covid-19 pandemic. This peak price compares to a baseline price of 50 €/MWh in 2021. Two price peaks have occurred in 2022, the first (227 €/MWh) occurred in March directly following the Russian invasion of Ukraine, and the second (339 €/MWh) in August. This compares to a baseline price of 115 €/MWh for 2022 (average between January and July). We applied the March price peak to provide a more conservative estimate.

For this quantification, natural gas commodity prices based on the Dutch TTF[127] (leading European benchmark price index) were applied. The assumed LCOE for biomethane were 55-100 €/MWh[128] for anaerobic digestion and 85-110 €/MWh for thermal gasification[129].

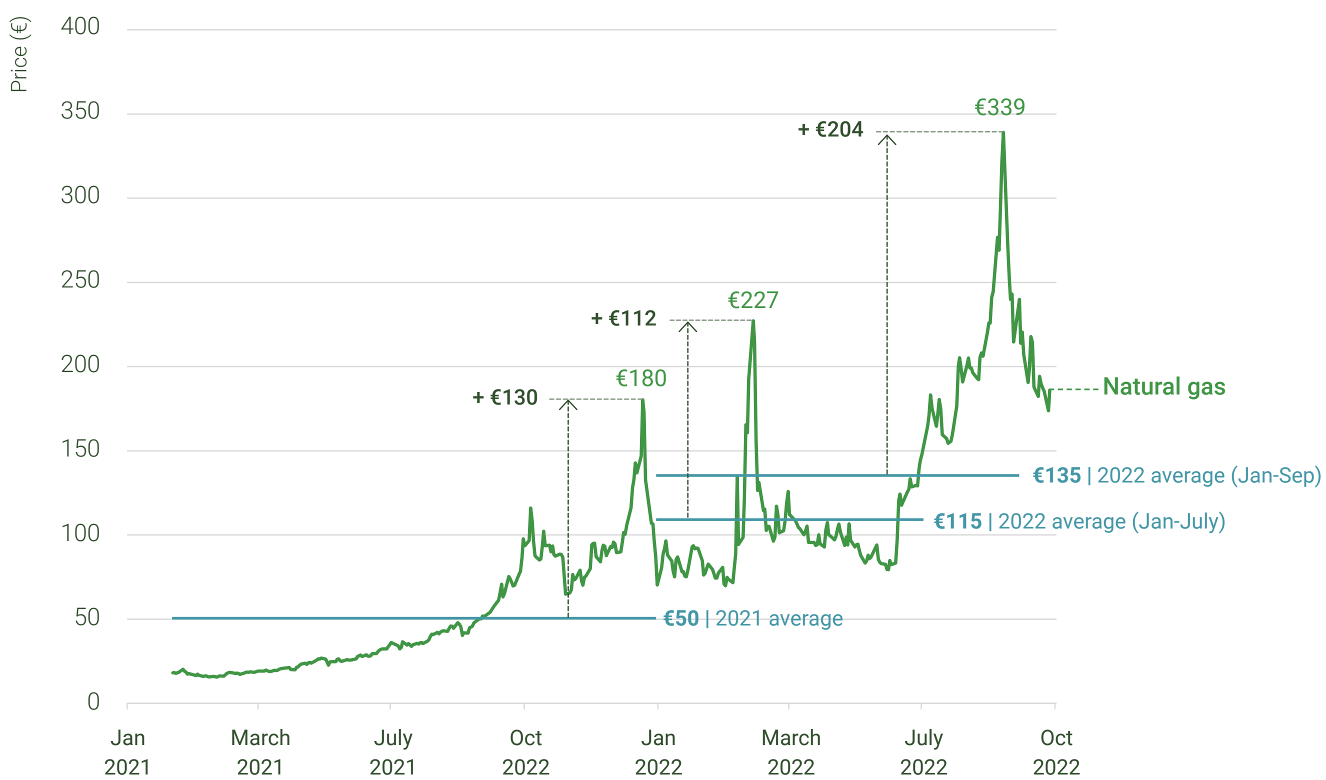


Figure 4.7 | Natural gas price development since 2021 (average yearly prices and price peaks are indicated)

127 Prices exclude CO_2 compliance costs.
128 Gas for Climate, *The future role of biomethane*, 2021. https://gasforclimate2050.eu/wp-content/uploads/2021/12/The_future_role_ of_biomethane-December_2021.pdf
129 EBA, *Gasification – A Sustainable Technology for Circular Economies*, 2021. https://www.europeanbiogas.eu/wp-content/uploads/2021/11/Gasification-A-Sustainable-Technology-for-Circular-Economies.pdf

4.2 | Provision of biogenic carbon dioxide

Biogas produced via anaerobic digestion contains around 55% to 65% methane by volume, the remainder being mainly biogenic CO_2 with a short carbon cycle. During the upgrading of biogas to biomethane, the CO_2 and other gas impurities are removed. Currently, the CO_2 is typically released to the atmosphere, but could instead be captured and either utilised or stored[130].

To be utilised or stored, the CO_2 stream needs to be further processed. After separating the CO_2 stream, it is first filtered and dried to remove impurities and water vapour. In a next step, any biomethane which was not captured in the upgrading process is recovered, increasing the overall biomethane yield of the plant. Finally, the CO_2 stream is compressed or liquified and transported by pipeline, ship or (for shorter distances) by truck[131,132].

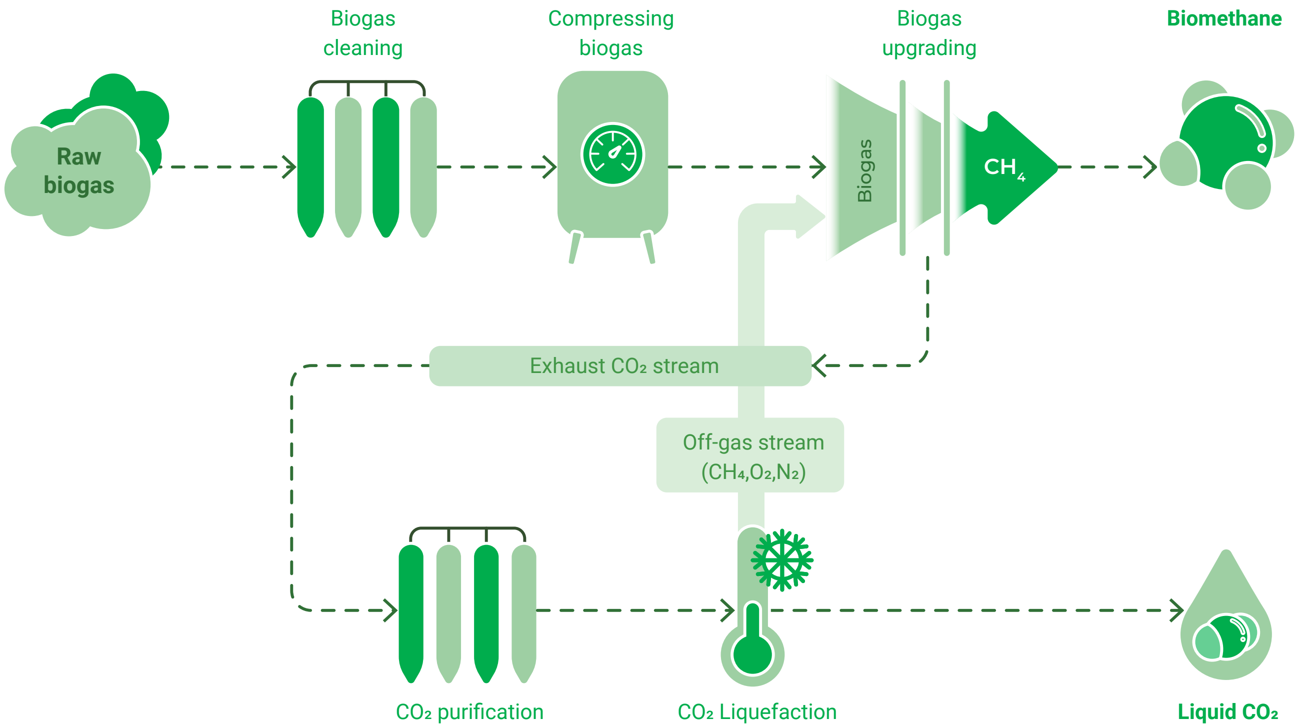


Figure 4.8 | Technical scheme of biomethane upgrading via membrane separation and cryogenic CO_2 liquifaction[133]

130 Carbon capture and utilisation is typically referred to as CCU, whereas carbon capture and storage is typically referred to as CCS.
131 Pentair, *Biogas Upgrading – Biocomplete*, Product leaflet, 2020
132 IEA, *About CCUS*, 2021. https://www.iea.org/reports/about-ccus
133 Pentair, *Biogas Upgrading – Biocomplete*, Product leaflet, 2020

Biomethane produced via **thermal gasification** can yield a relatively pure biogenic CO_2 stream. Here, biogenic or waste feedstocks are first 'gasified' to produce syngas[134] and following this 'conditioned' to remove any trace compounds. The cleaned syngas then undergoes a water-shift reaction, this produces CO_2 that can be captured. A methanation step follows, producing mostly CH_4 and water vapour, but also potentially CO_2. The gas is then purified to remove the water, as well as any residual CO_2. As with anaerobic digestion, any captured CO_2 can either be utilised or stored. Because the CO_2 must already be separated, little additional technology is required for integration of CCU or CCS[135].

CO_2 utilisation:
CO_2 is utilised as a feedstock in multiple industrial applications, including the food industry (to freeze, chill or pack food), beverage carbonation, metal fabrication, fire suppression and stimulating plant growth in greenhouses (see Figure 4.9). As CO_2 used today is mainly fossil-based, biogenic CO_2 could provide a sustainable alternative and importantly generate an additional income stream for biomethane producers. Emerging markets for CO_2 include the production of synthetic fuels or chemicals, for example where CO_2 is reacted with renewable hydrogen to produce renewable methane or methanol, as well as in the manufacture of novel cements[136]. If not utilised, the biogenic CO_2 can otherwise be captured and stored permanently, leading to negative emissions.

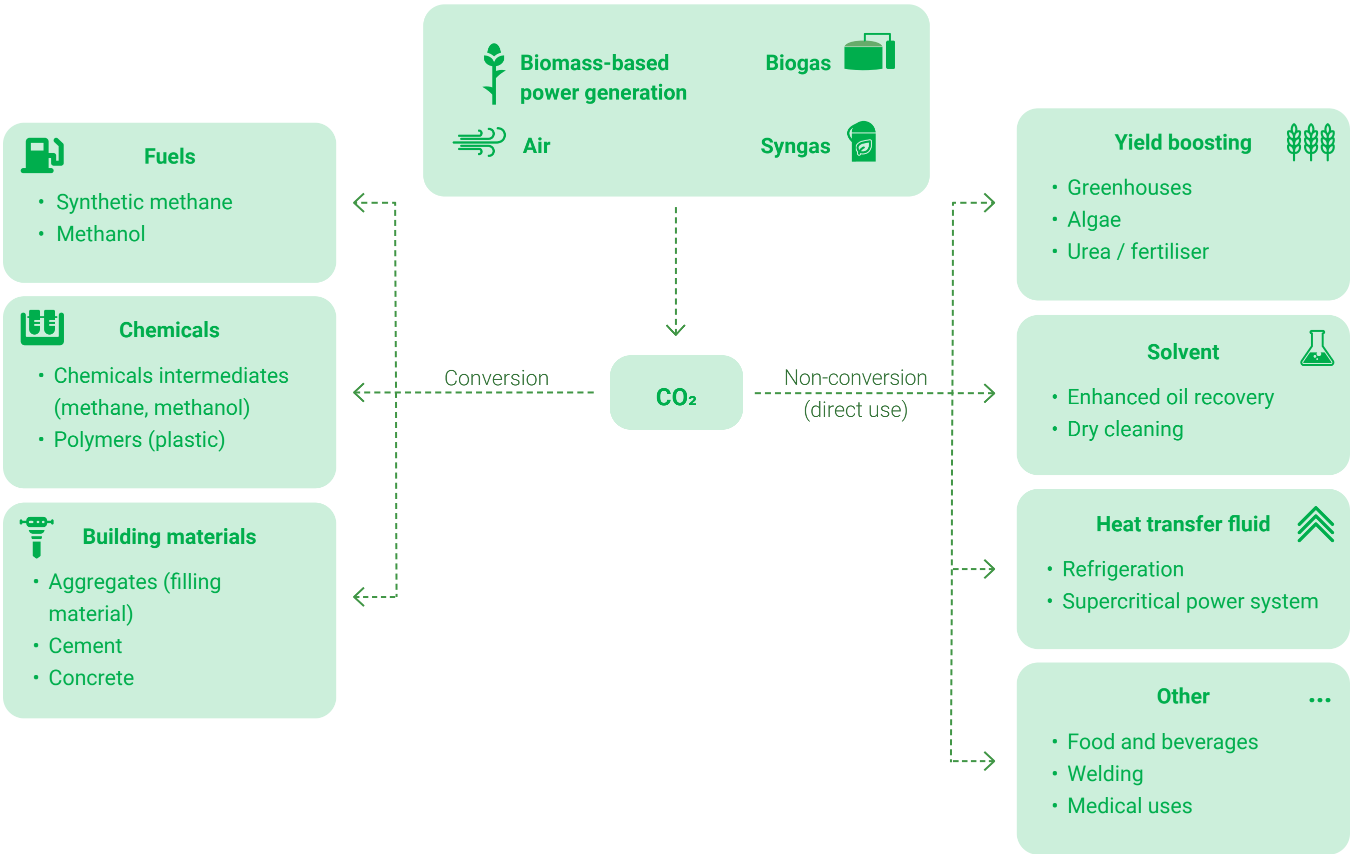


Figure 4.9 | Applications of CO_2 use. Source: IEA[135]

134 Syngas is a mixture of methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2) and hydrogen (H_2).
135 BEIS, *Innovation Needs Assessment for Biomass Heat*, 2018. https://www.gov.uk/government/publications/innovation-needs-assessment-for-biomass-heat
136 IEA, *Putting CO_2 to Use*, 2019. https://www.iea.org/reports/putting-co2-to-use

There are multiple examples of utilising captured CO_2 from biogas upgrading plants across Europe. For example, in Denmark, biomethane producer Nature Energy is capturing 16 kt CO_2/year at its Korskro plant. This is equivalent to 25% of the annual demand for CO_2 in Denmark and is primarily used in the food and beverage industry[137]. In Italy, Biogas Wipptal is capturing the CO_2 in its biomethane plant in Vipiteno. Here, the CO_2 is used in the beverage industry and in the production of dry ice[138]. Revis Bioenergy is planning a biomethane facility in Cloppenburg, Germany where 87 kt CO_2/year will be captured and liquified. This facility is planned to be operational by 2023[139].

Demand for biogenic CO_2 is forecast to increase as the production of various products (e.g. plastics, lubricants and niche fuels) seek renewable sources of carbon.

CO_2 storage:
Considering the biogenic origin of CO_2 from anaerobic digestion and gasification, its permanent storage delivers Greenhouse Gas Removals (GGR; also known as Carbon Dioxide Removals, CDR). Such removals are essential to the delivery of Net Zero targets, due to their ability to offset unavoidable emissions. For example, the UK's Net Zero Strategy (2021) forecasts a need of 76-81 Mt CO_2e of GGR per year by 2050.

With respect to **storing** CO_2, UK biomethane producer Future Biogas is partnering with technology provider Pentair to install 25 CCS units at its existing biomethane plants and newly developed plants. Combined, these facilities will have the capacity to capture around 200 kt CO_2/year from 2024 rising to 400 kt CO_2/year by 2035. At each site, the CO_2 will be captured, liquified and transported to port facilities in the Humber by road tanker. This biogenic CO_2 will then be supplied to the Northern Lights project[140], a major initiative to permanently store CO_2 under the North Sea. Backed by the Norwegian government, liquid CO_2 will be collected from the Humber's temporary storage and shipped to an injection site in Norway, where it will be pumped into geological stores kilometres below the North Sea[141,142].

The EBA (2022) estimated the theoretical potential for biogenic CO_2 in Europe in 2030 and 2050 assuming that all biogas is upgraded to biomethane and all of the resulting biogenic CO_2 is fully captured. A potential of 46 Mt biogenic CO_2 could be available in 2030, based on 35 bcm biomethane production (as targeted under REPowerEU), which is equivalent to the greenhouse gas emissions of Sweden in 2020[143].

Counterfactual definition

The counterfactual considered for this externality is that there is no biomethane production, and consequently that biogenic CO_2 is not captured. Hence, for biogenic CCU the counterfactual is that fossil CO_2 is instead used in industrial applications, and for biogenic CCS that there is no CO_2 storage. As described above, this externality is applicable to both anaerobic digestion and thermal gasification technologies, and all feedstocks are considered to be in scope.

Quantification method

To quantify this externality, we estimate the **economic value of the biogenic CO_2** captured including any **recovered biomethane** during the CO_2 separation process (for anaerobic digestion), and deduct the **costs for purifying and liquifying** the CO_2 stream from the upgrading facility (for anaerobic digestion) or from the syngas (for gasification), as indicated in Figure 4.10 below.

137 IEA Bioenergy, *Production of food grade sustainable CO_2 from a large biogas facility*, 2020. https://www.ieabioenergy.com/wp-content/uploads/2020/11/Case-Story-CO2-recovery-Denmark-November-2020.pdf
138 https://www.biogas-wipptal.com/en/
139 Revis Bioenergy, 2021. https://www.gruene-kraftstoffe-kuestenkanal.de/rohstoffe-erzeugnisse/
140 https://www.equinor.com/energy/northern-lights
141 https://www.futurebiogas.com/beccs/
142 https://www.futurebiogas.com/pentair-and-future-biogas-join-forces-to-help-reduce-the-uks-co2-footprint/
143 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

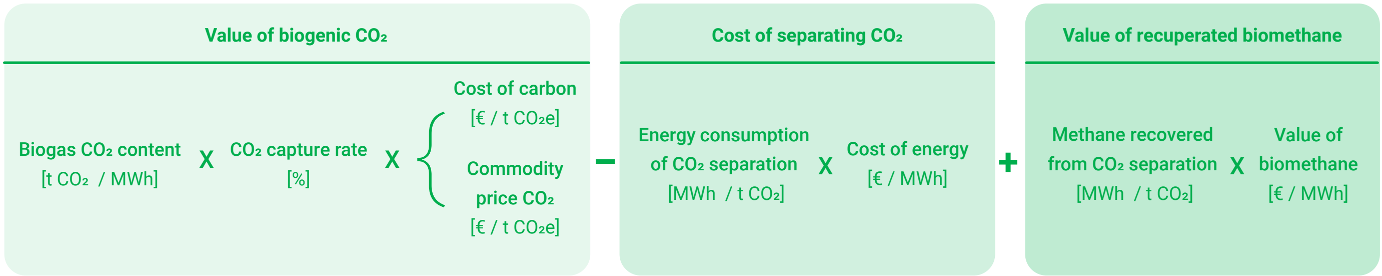


Figure 4.10 | Calculation methodology for biogenic CO_2 arising from anaerobic digestion

The economic value of biogenic CO_2 was determined by multiplying the biogas or syngas CO_2 content [t CO_2/MWh] by the CO_2 capture rate during upgrading or gasification [%] and the CO_2 price [€/t CO_2e].

The CO_2 content in biogas ranges from 35% to 45% depending on the feedstock. A capture rate of 90% CO_2 was assumed, since the biogas upgrading process does not fully capture all of the CO_2 produced and also due to additional CO_2 losses that occur during purification and liquefaction. For thermal gasification, a CO_2 content of 0.29 t CO_2/MWh biomethane and a capture rate of 100% was assumed[144].

The operational cost of purifying and liquifying the CO_2 was calculated based on the electricity consumed for these processes[145] [MWh/t CO_2] multiplied by the cost of electricity [€/MWh]. The economic value of the recovered biomethane was quantified based on the amount of methane recovered during CO_2 processing [MWh/t CO_2] multiplied by the LCOE of 70 €/MWh for biomethane from anaerobic digestion. For thermal gasification, the electricity consumption of CO_2 liquefaction was taken as 0.076 MWh/MWh biomethane.

A key modelling assumption is the **biogenic CO_2 price**. Historically CO_2 commodity prices have typically traded at around 100 €/t CO_2 across Europe but have risen significantly over the past year reaching 1,000 €/t CO_2 or more[146,147]. This has resulted from reduced CO_2 supply following the temporary closure of synthetic fertiliser plants, due to the very high natural gas prices. It is anticipated that CO_2 commodity prices are not likely to remain at such high levels in the long term. A price of 200 €/t CO_2 was therefore seen as a reasonable estimate for the purpose of this study[148]. The value of stored biogenic CO_2 is likely to be higher than the CO_2 commodity price, reflecting the additional benefit of delivering negative emissions. A value of 300 €/t CO_2 was applied in this study and based on projects listed on the Puro.Earth marketplace for GGR. Current prices range from €150-500/t CO_2 for biochar projects (temporary storage) and €400/t CO_2 for a biogenic CO_2 storage project[149]. A price of 300 €/t CO_2 was considered to be a representative estimate for the purpose of this study.

Finally, the low-high externality values were determined by assuming a **capture application share** since it is not realistic to assume that all biomethane plants will apply carbon capture in the future.

144 GoGreenGas, *BioSNG Demonstration Plant – Project Close-Down Report*, 2018
145 The electricity consumption was determined by comparing an upgrading process with CO_2 liquification (membrane separation + cryogenic liquefaction) with an upgrading process without CO_2 capture (membrane separation).
146 https://www.theguardian.com/business/2022/sep/02/food-producer-warns-of-price-shock-as-carbon-dioxide-price-quadruples
147 https://www.vrt.be/vrtnws/en/2022/09/02/beer-production-in-belgiun-threatened-due-to-co2-shortage/
148 Note that at this time there is no price premium for biogenic CO_2.
149 Puro.Earth, *Carbon Removal Certificate (CORC) supplier listing*, 2022. https://puro.earth/CORC-co2-removal-certificate/?carbon_removal_method%5B0%5D=7363

The **share of utilisation and storage** was estimated by comparing the European CO_2 demand with the CO_2 potential. Applying the EBA potential estimates above to the biomethane potentials we have used in this study[150], would result in a biogenic CO_2 potential of 59 Mt/year in 2030 and 215 Mt/year in 2050. Compared to this potential, the demand is estimated to be 47 Mt/year[151] in 2030 and 73 Mt/year in 2050[152].

In the short to medium term (2030) we assume that CO_2 utilisation (80%) will remain the principal application for biogenic CO_2, with CO_2 storage (20%) representing the balance (CCS projects will take longer to develop and may not be feasible in all geographies). In the long term (2050), CO_2 is likely to be increasingly valued as a commodity for storage as it can play an important role in delivering significant negative emissions across Europe. Coupled with the constraints on CO_2 demand for utilisation, we estimate a share of 33% for utilisation and 66% for storage respectively. An average share of 60% utilisation and 40% storage was assumed for the purpose of this study.

4.3 | Organic waste processing

Biomethane production from organic waste feedstocks provide waste processing and energy generation services. This can reduce the treatment costs of waste producers, or otherwise improve the overall economics of the operation. Importantly, this also plays a valuable role in contributing to the circular economy by recycling organic wastes and turning them into useful products, including renewable energy and nutrient rich digestate that can be returned to the soil.

To fully demonstrate the value of this externality, we considered that the primary function of biomethane production systems is energy generation, with organic waste processing being considered to be a 'free' co-service. Therefore, none of the capital or operational costs of biomethane facilities were attributed to this co-service. When calculating the value of this externality, the costs of the biomethane production facility have not been deducted from the benefits of organic waste processing, as they are considered in the biomethane product cost, and to also count them towards organic waste processing would constitute double counting.

Counterfactual definition

Organic waste can be converted into biomethane by both anaerobic digestion and gasification technologies. The counterfactual scenario depends not on the production technology but on the feedstock considered. It is defined by the waste processing pathways of the different organic waste feedstocks in the absence of biomethane production. Sequential crops were excluded as they are not a waste feedstock, but a biomass stream which is produced specifically for biomethane production.

For **agricultural residues**, the key counterfactual is incorporation into soil or use in existing markets, such as animal bedding or feed. These uses do not have significant processing costs attached and therefore this feedstock was excluded in the calculation for this externality.

For **animal manure**, a European Commission study[153] found that only 8% of livestock manure was processed, while the remainder was handled by the conventional method of storage and land spreading[154]. Landspreading was therefore taken as the key counterfactual for this externality. The cost of manure landspreading is expected to be broadly similar to the cost of spreading manure digestate. Therefore, biomethane production using manure does not lead to cost savings compared to the counterfactual, and so this feedstock was also excluded in the calculation for this externality.

150 Gas for Climate, *Biomethane production potentials in the EU*, 2022. https://www.europeanbiogas.eu/wp-content/uploads/2022/07/GfC_national-biomethane-potentials_070722.pdf
151 IEA, *Putting CO_2 to use*, 2019. https://www.iea.org/reports/putting-co2-to-use
152 Gas for Climate, *Market state and trends in renewable and low-carbon gases in Europe*, 2021
153 Foged, Lyngsø, Flotats, Bonmati Blasi, Palatsi, Magri and Martin Schelde, *Inventory of manure processing activities in Europe*. Technical Report No. I concerning "Manure Processing Activities in Europe" to the European Commission, Directorate-General Environment. 2011.
154 Environmental and Energy Study Institute, *Fact Sheet | Biogas: Converting Waste to Energy*, 2017. https://www.eesi.org/papers/view/fact-sheet-biogasconverting-waste-to-energy

Biowaste comprises the organic fraction of municipal solid waste, which includes food waste, green waste (garden leaves and grass) and paper and cardboard that is not otherwise utilised. The key counterfactuals for this feedstock are composting and landfilling. It should be noted that landfilling of biowaste is not permitted in certain countries, such as France. However, data on the share of biowaste going to compost and landfill could not be obtained, therefore a 50%-50% split was assumed. For the composting counterfactual, the introduction of anaerobic digestion is typically additional to composting and serves as a pre-treatment phase[155]. Digestion was assumed to reduce the substrate mass, and therefore the mass of material to be composted, by 15%, as discussed in section 3.3.2. It was therefore assumed that biomethane production for the composted fraction of biowaste reduces the counterfactual cost by 15%.

For **industrial wastewater**, the key counterfactual is aerobic treatment.[156] Adding an anaerobic digestion pre-treatment stage reduces organic load, and hence electricity consumption (which is the main cost driver for aerobic treatment) by 75-85%[156]. As a conservative estimate it was therefore assumed that biomethane production from industrial wastewater reduces the counterfactual cost by 75%.

For **sewage sludge**, anaerobic digestion is already widely used as a treatment method. The other key counterfactuals are dewatering the sludge before sending it to for incineration or landfilling.[157] Data on the share of sewage sludge going to incineration and landfill could not be obtained, therefore a 50%-50% split was assumed. Adding an anaerobic digestion pre-treatment stage reduces sludge volume by 33%, reducing the amount of material that has to be dewatered and incinerated or sent to landfill[157]. It was therefore assumed that biomethane production from sewage sludge reduces the counterfactual waste management costs by 33%.

Quantification method

To quantify this externality on a per MWh basis, we estimate the counterfactual costs avoided per tonne of feedstock diverted to biomethane production. This is represented by the equation below.

For biowaste, the assumed costs of the counterfactual waste management methods were 60-75 €/tonne feedstock for composting and 100-110 €/tonne feedstock for landfill, based on discussions with industry experts[157]. For industrial wastewater, the cost of aerobic treatment was taken to range from 0.36[158] to 0.49[159] €/m^3 feedstock. These values were taken from two studies looking at the economics of industrial wastewater treatment plants in the Spanish food industry. Therefore, they should be considered to provide a rough estimate of this externality rather than a precise value, as actual costs will vary depending on region, plant size, industry, treatment method and other factors. The costs were adjusted for inflation with respect to their publication dates to estimate the present value. For sewage sludge, the cost of landfill was assumed to be the same as for biowaste, and the cost for incineration was taken to be 110-120 €/tonne feedstock, also based on expert input[157].

As discussed in the counterfactual section, for composted biowaste, industrial wastewater and sewage sludge, biomethane production does not fully displace the counterfactual waste processing facilities, but rather is added as a pre-treatment phase which serves to reduce the mass/volume of material which still needs to be processed. Therefore, a cost reduction factor was applied in the calculation for those feedstocks, corresponding to the reduction in mass/volume due to anaerobic digestion, as outlined in the counterfactual section.

155 Communication from European Biogas Association, September 2022.

156 European Biogas Association, *The role of biogas production from industrial wastewaters in reaching climate neutrality by 2050*, April 2021. https://www.europeanbiogas.eu/wp-content/uploads/2021/04/Paper-The-role-of-biogas-production-from-wastewater-in-reaching-climate-neutrality-by-2050.pdf

157 Communication from SUEZ, September 2022.

158 Román Sánchez, Molina Ruiz, Casas López, Sánchez Pérez, *Effect of environmental regulation on the profitability of sustainable water use in the agro-food industry*, Desalination 279, 2011.

159 Román Sánchez, Sánchez Pérez, Carra, *Promoting environmental technology using sanitary tax: The case of agrofood industrial wastewater in Spain*, Environmental Engineering and Management Vol.13, No. 4, 2014.

Feedstock input*
[t feedstock / MWh biomethane]

X

Cost of counterfactual waste management
[€ / t feedstock]

* Based on specific biomethane yields per feedstock

Equation 4.7 | Calculation methodology for Organic waste processing (anaerobic digestion only)

4.4 | Replacement of resources

As discussed in section 3.3.2, anaerobic digestion of organic feedstocks produces biogas and digestate as a co-product. Digestate is a nutrient rich substance that can readily replace the use of synthetic fertiliser, although its deployment may require more careful management compared to synthetic fertiliser due to the variability in the proportion of available key macro nutrients (N, P and K). Replacing synthetic fertiliser creates additional value for the biomethane producer (as well as to society) since it reduces the demand for synthetic fertiliser.

Fertiliser is applied to around 134 million hectares of agricultural land in the EU, equivalent to 75% of the total[160]. The main applications are for wheat and coarse grains production (26% and 25% of fertilised land use respectively).[161] A detailed breakdown is provided in Figure 4.11 below.

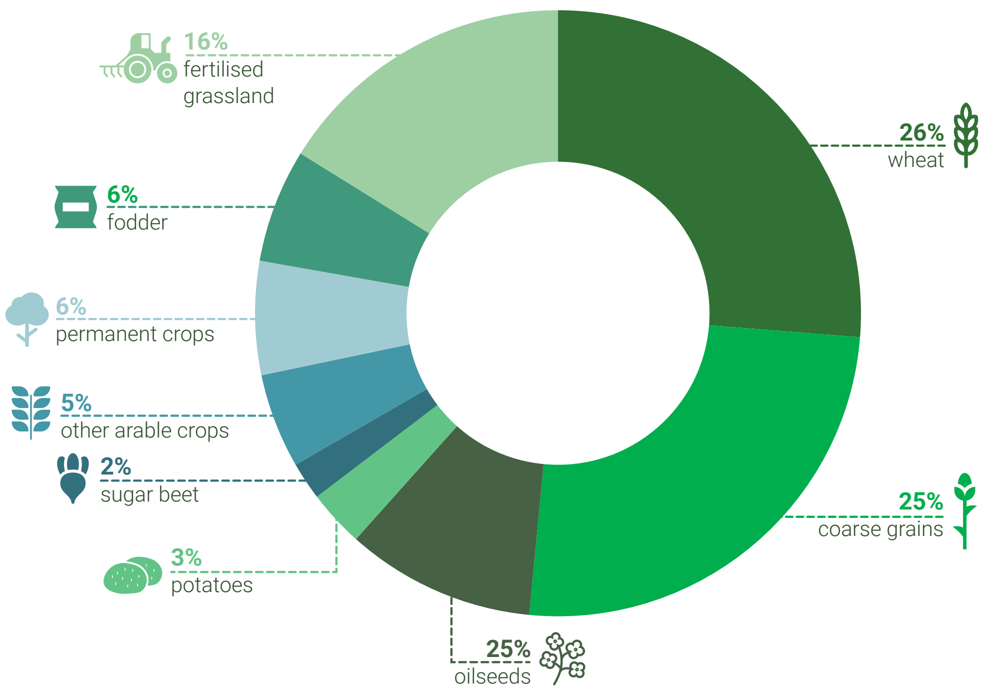


Figure 4.11 | Fertiliser consumption by crop type in the European Union. Source: Fertilisers Europe[161]

160 Fertilisers Europe, *Forecast of food, farming and fertiliser use in the European Union 2021-2031*, 2022. https://www.fertiliserseurope.com/wp-content/uploads/2021/12/Forecast-2021-31-Studio-final-web.pdf
161 Fertilisers Europe, *Fertiliser Industry Facts & Figures 2022*, 2022. https://www.fertiliserseurope.com/wp-content/uploads/2022/09/Industry-Facts-and-Figures-2022.pdf

According to the European Commission 180 Mt of digestate were produced in the EU27 and UK in 2016, of which 120 Mt (67%) was derived from agricultural feedstocks (manure, agricultural residues, energy crops) and 46 Mt (26%) from the organic fraction of mixed MSW (mechanical biological treatment)[162]. The nutrient content of this digestate is estimated to contain around 0.84 Mt of nitrogen, 0.36 Mt of phosphate and 0.64 Mt of potash[163]. In comparison, over the last three growing seasons, an average of 11.2 Mt nitrogen, 2.7 Mt phosphate and 3.1 Mt potash were applied as synthetic fertiliser (see Figure 4.12 below)[164]. Most of the digestate from agricultural feedstocks and biowaste is already used as organic fertiliser.

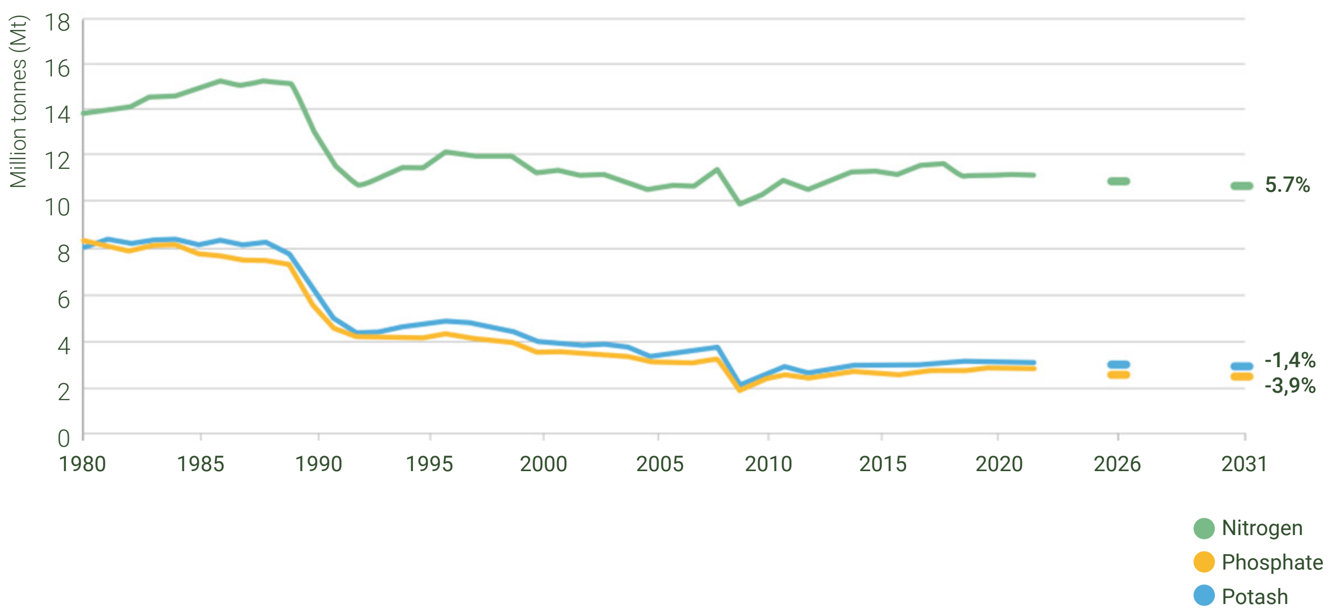
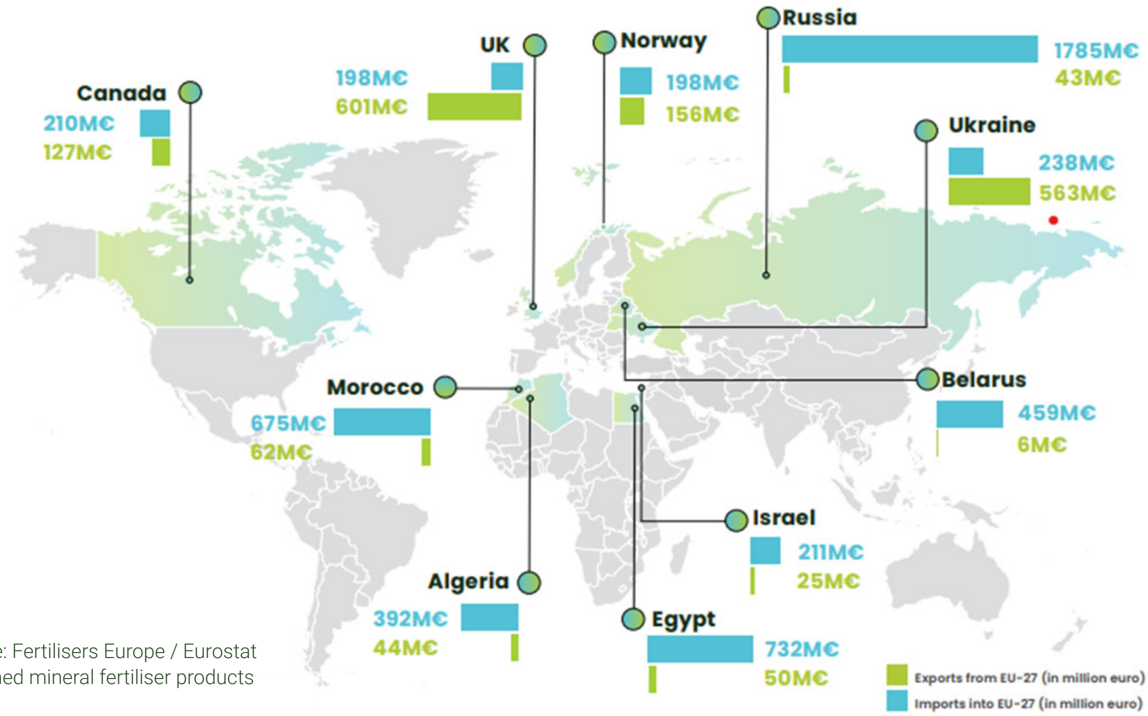


Figure 4.12 | Fertiliser consumption in the EU. Source: Fertilisers Europe[164]

162 European Commission, *Digestate and compost as fertilisers: Risk assessment and risk management options*, 2019.
163 Guidehouse assumption based on average nutrient content of farm and food-based digestate.
164 Fertilisers Europe, *Forecast of food, farming and fertiliser use in the European Union 2021-2031*, 2022.

The use of digestate is actively promoted and regulated through certification schemes in some countries across Europe. For example, in Sweden, the use of digestate has been incentivised since 1999 through the Certifierad återvinning (Certified recycling)[165] fertiliser quality assurance program. In the UK, the Biofertiliser Certification Scheme (BCS) has set quality specifications for digestate known as the Publicly Available Specification 110 (PAS110)[166]. This allows users to be confident that the digestate is of consistent and sufficiently high quality.



Source: Fertilisers Europe / Eurostat
*Finished mineral fertiliser products

Figure 4.13 | Overview of key EU trade partners in fertiliser trade in 2021. Source: Fertilisers Europe[167]

165 European Biogas Association, *Open market for digestate from anaerobic digestion*, 2016. https://www.europeanbiogas.eu/wp-content/uploads/2016/03/Uppsala.pdf
166 Biofertiliser Certification Scheme, *Background of the REAL's Biofertiliser Certification Scheme*. https://www.biofertiliser.org.uk/overview/background
167 Fertilisers Europe, *2022 Fertiliser Industry Facts and Figures*, 2022. https://www.fertiliserseurope.com/wp-content/uploads/2022/09/Industry-Facts-and-Figures-2022.pdf

Europe is highly dependent on the import of fertilisers. Key import counties in 2020 include Russia, Belarus, Morocco, Egypt and Canada (see Figure 4.13). While just 32% of the EU27's consumption of nitrogen fertiliser was imported in 2020, 65% of phosphate and 88% of potash were imported[167]. Recognising this, the European Commission has listed phosphate rock, which is used to produce phosphate-based fertiliser, as a 'critical raw material' because risks of supply shortage and their impacts on the economy are higher than those most other raw materials[168]. Digestate could provide a valuable alternative to these imports, improving Europe's security of supply and trade balance. Additionally, given that the fertiliser industry is the main natural gas consuming industry in Europe, replacement with digestate has the added benefit of further reducing Europe's dependency on imported natural gas.

Counterfactual definition

The counterfactual scenario used to quantify this externality is no biomethane production and therefore no digestate production, hence the need to continue to use synthetic fertiliser. The externality is only considered for anaerobic digestion.

Agricultural residues, biowaste and sewage sludge were all considered to be in scope. Animal manure, industrial wastewater and sequential crops were excluded, as discussed in section 3.3.2.

Quantification method

The quantification method is broadly similar to the quantification of greenhouse gas reduction arising from the reduction of synthetic fertiliser production. As described in section 3.3.2, digestate and synthetic fertiliser are compared on an N, P, K basis. However, instead of quantifying the emissions of the replaced fertiliser, for this externality the costs of synthetic fertiliser were applied.

As described in section 3.3.2, the most commonly used fertilisers are **urea** (for nitrogen), **muriate of potash** (for potassium) and **diammonium phosphate** (for phosphorus). The price development between 2018 and 2022 year to date of these three fertiliser types are shown in Figure 5.14. Urea and muriate of potash prices are taken from the AHDB[169], and for phosphorus-based fertiliser, the US diammonium phosphate spot prices are used[170].

To quantify this externality, the lowest and highest price during the last 3 years was used for each fertiliser. The lowest prices occurred in the end of 2019/beginning of 2020 (Urea: 208 €/t, muriate of potash: 262 €/t, diammonium phosphate: 213 €/t), while the highest prices occurred in the first half of 2022 (Urea: 763 €/t, muriate of potash: 1,061 €/t, diammonium phosphate: 621 €/t).

$$\text{Digestate yield* [t digestate / MWh biomethane]} \times \frac{\text{Digestate nutrient content* [t NPK / t digestate]}}{\text{Fertiliser nutrient content** [t NPK / t fertiliser]}} \times \text{Cost of synthetic fertiliser [€ / t fertiliser]}$$

* Digestate yield / nutrient content differs by feedstock, as well as between solid vs liquid digestate.
** Fertiliser nutrient content differs per type of fertiliser (fertiliser selection informed by Fertilisers Europe.

Equation 4.8 | Calculation methodology for Biogenic CO_2 arising from anaerobic digestion

168 European Commission, *Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*, 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474&from=EN
169 AHDB, *GB-fertiliser prices*. https://ahdb.org.uk/GB-fertiliser-prices
170 US Diammonium Phosphate Spot Price (Gulf). https://ycharts.com/indicators/us_diammonium_phosphate_spot_price_gulf

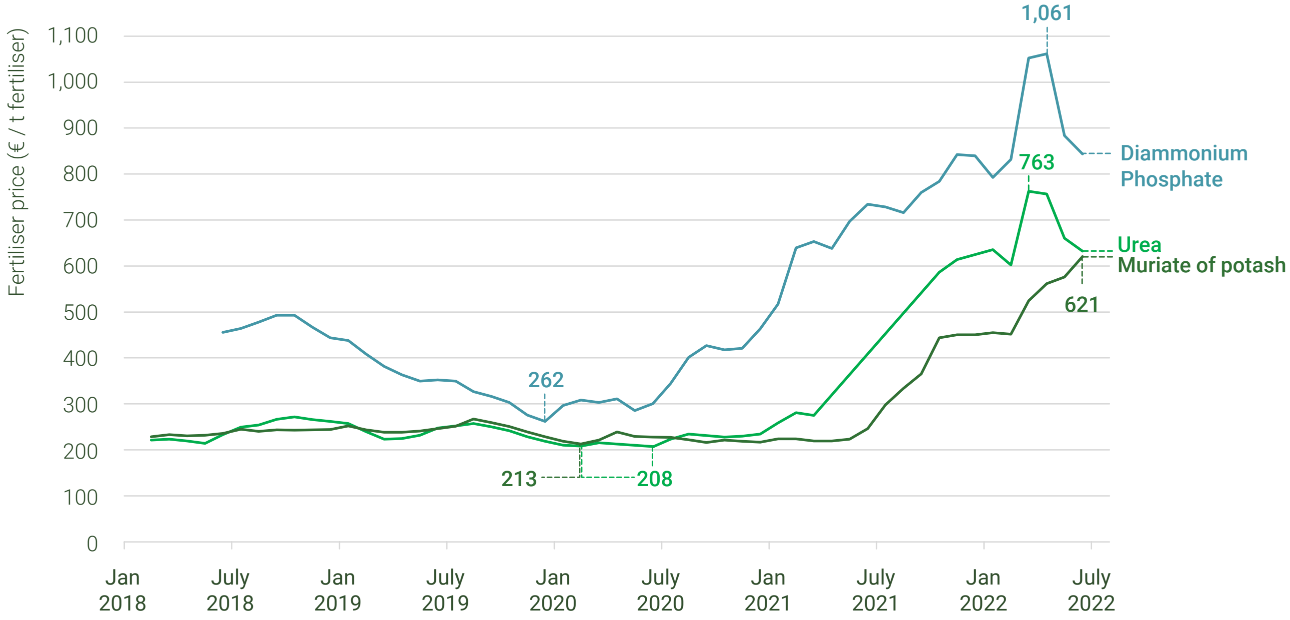


Figure 4.14 | Fertiliser price development for urea, muriate of potash and diammonium phosphate between 2018 and July 2022[171,172]

171 AHDB, *GB-fertiliser prices*. https://ahdb.org.uk/GB-fertiliser-prices
172 US DAP Spot Price. https://ycharts.com/indicators/us_diammonium_phosphate_spot_price_gulf

5. Social externalities

5. Social externalities

5.1 | Job creation

Biomethane production can serve to stimulate the creation of jobs throughout the value chain. These jobs include both **direct** and **indirect jobs**. Direct jobs are created in the planning and construction of plants as well as in the operation and maintenance of the plants. Indirect jobs include jobs created along the value chain, such as in logistics operations (feedstock and digestate collection, storage, pre-processing and transport) and farming activities (growing feedstock and spreading digestate). Many of these jobs are permanent and sustained throughout the lifetime of the plant, although some are temporary and limited to the construction phase only. In total, a European biomethane industry could support the creation of 280,000-490,000 jobs in 2030 and up to 1,130,000-1,810,000 jobs in 2050. **Induced jobs** are additionally created across the economy as a direct consequence of the creation of the direct and indirect jobs.

As biomethane production through anaerobic digestion will primarily involve a more decentralised production model based on agricultural wastes, residues and sustainable crops, its deployment is expected to bring new employment benefits to rural regions across Europe. This offers significant benefits to many countries in Europe, including in southern and eastern Europe, where rates of rural unemployment are highest and importantly higher than in urban areas[173]. In contrast, it is expected that biomethane production from thermal gasification will lead to employment benefits in more centralised production facilities and largely located near to sustainable forest-based industries or urban areas from which the feedstock will be collected.

Estimates of the number of jobs that could be created in a future biomethane industry have been assessed by a number of organisations, including the EBA, NNFCC and Gas for Climate. In these studies, the overall number of jobs created is estimated over the lifetime of a biomethane facility and referenced to the total production of biomethane over that lifetime.

The EBA assessed the number of direct and indirect jobs based on current deployment. This analysis draws on existing studies, as well as estimates provided by several European national biogas associations. Hence, this assessment is based a range of plant sizes, end use applications and upgrading technology. The average **employment ratio** (the number of jobs created per unit of energy produced) was calculated as **1.09 jobs created per GWh** of biogas and biomethane produced, of which 0.32 relates to direct jobs and 0.77 indirect jobs[174]. This translates into an estimated 208,071 total jobs in the sector in 2020, based on a production of 190,891 TWh.

173 According to Eurostat, in 2015 the lowest employment rates for rural areas – less than 60% - were recorded in Italy, Greece, Spain, Croatia and Bulgaria. Much higher unemployment rates were recorded for rural areas (compared with cities) in Bulgaria, Lithuania and Slovakia in 2015. See: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Statistics_on_rural_areas_in_the_EU#Rural_development_2014.E2.80.932020

174 Depending on the source, the total employment rate ranges from 0.56 to 1.92 jobs/GWh. The number of direct jobs ranges from 0.07 to 1.18 jobs/GWh and the number of indirect jobs from 0.22 to 1.56 jobs/GWh.

The NNFCC estimated the number of jobs created in the UK biogas sector in 2020. These are assigned to each activity in the value chain: plant design/development, construction and commissioning, operation and maintenance and UK feedstock supply. Three energy supply scenarios were modelled: 320 MW_{el} (2.09 TWh), 450 MW_{el} (3.04 TWh) and 579 MW_{el} (3.99 TWh)[175]. A total of 1,358 to 2,457 created jobs were estimated, which is equal to an employment ratio of **0.62 to 0.65 jobs/GWh**. (The study authors indicate that since small-scale anaerobic digestion plants are considered, scaling effects might reduce the number of jobs if larger capacity plants were modelled.) Direct jobs created in development, construction and operation and maintenance make up around 88% of the total (0.54 to 0.57 jobs/GWh), with the balance being indirect jobs in UK feedstock (0.07 to 0.08 jobs/GWh). The jobs related to development and construction are not sustained throughout the lifetime of the plant but are applicable for approximately two years. This was accounted for in the study by annualising the number of jobs in these sectors compared to an average 20 years' plant lifetime[176].

Finally, the Gas for Climate study estimated the potential for job creation in 2050 for biomethane produced through both anaerobic digestion and gasification technologies. The study estimated that the production of 660 TWh of biomethane through anaerobic digestion could create 200,000 to 275,000 direct jobs and another 300,000 to 400,000 indirect jobs. This equates to an employment ratio of **0.76 to 1.02 jobs/GWh**.The production of 350 TWh of biomethane through thermal gasification could create 100,000 to 150,000 direct jobs and another 150,000 to 200,000 indirect jobs. This equates to an employment ratio of **0.71 to 1.00 jobs/GWh**. For anaerobic digestion, around one-third of the jobs result from the development of the plants, mainly in two sectors: machinery and equipment construction and construction work. Two-thirds of the jobs are related to the facility's ongoing operations, including running the plant and the sourcing of the required biomass in the agriculture sector. The temporary jobs in the plant development are annualised over the lifetime of the project[177].

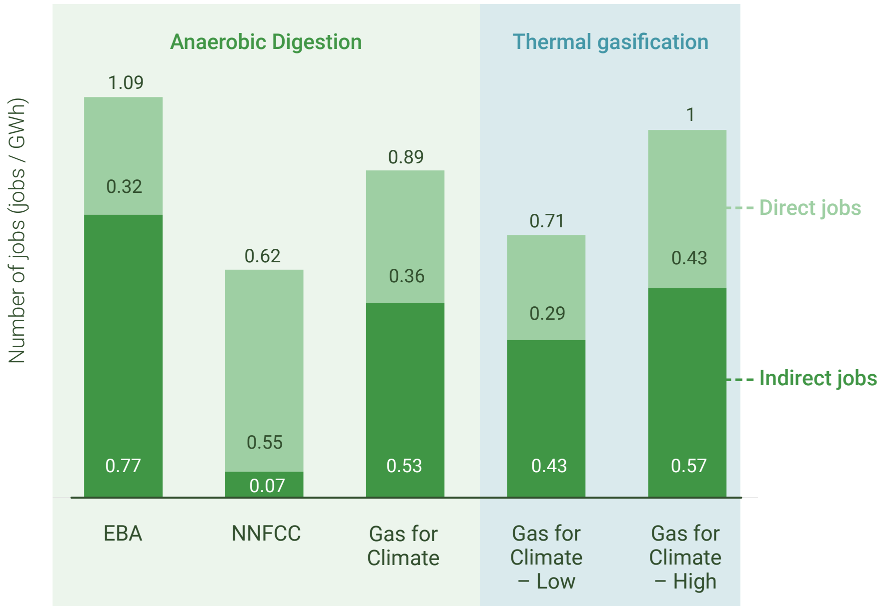


Figure 5.15 | Number of jobs in the biomethane industry depending on the technology, evaluated by the EBA, NNFCC and Gas for Climate

175 Estimated generation of biogas via anaerobic digestion. Assumed full load hours: 6,500 to 6,800 hours per year.
176 NNFCC, *UK jobs in the bioenergy sectors by 2020*, 2012. https://www.gov.uk/government/publications/jobs-in-the-bioenergy-sectors-by-2020
177 Gas for Climate, *Job creation by scaling up renewable gas in Europe*, 2019. https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-Job-creation-by-scaling-up-renewable-gas-in-Europe.pdf

The differences in the split between direct and indirect jobs in the three studies can be explained by a number of reasons, one of them being a different definition of direct and indirect jobs (see Figure 5.15). The Gas for Climate study applies a wider definition of indirect jobs, taking basic material manufacturing (e.g. steel manufacturing) into account, which leads to a high number of indirect jobs. For the NNFCC study, only agricultural jobs in the feedstock production are treated as indirect jobs. The EBA analysis only accounts for on-site jobs connected to the operation of the biomethane plant as direct jobs, the remainder is seen as indirect (excluding basic material manufacturing). Additionally, the basis for including temporary jobs is also likely to account for differences between the studies.

Quantification method

To evaluate this externality, a counterfactual scenario with no biomethane production and therefore no created jobs is considered. This externality is applicable to both anaerobic digestion and gasification technologies, and all feedstocks are considered to be in scope.To quantify the value of job creation, the number of jobs created [jobs/GWh biomethane] is multiplied by the wage associated with the job [€/job]. We have based the total number of jobs assessed in the three studies, with a low/high range of 0.62 to 1.09 jobs/GWh for anaerobic digestion and 0.71 to 1.00 jobs/GWh for thermal gasification. As these studies use different definitions of direct and indirect jobs, a split between these categories was not considered, as it would lead to a distortion of the results. Induced jobs were not considered as this data could not be readily identified at a European level.

The value per job created can be evaluated in different ways, including the avoided cost of unemployment, the overall economic benefit or the earnings of the employed worker. The **avoided cost of unemployment** was used as the basis in an analysis undertaken by ENEA[178] for the French biomethane sector. However, using this approach at a European level is challenging, and not feasible in the context of this study, as the costs of unemployment vary widely per country due to different social security standards. The **overall economic benefit** depends on multiple factors (wages and subsequent spending on the wider economy) and is therefore difficult to quantify per job created. An alternative approach is to apply the monetary value per job type, based on the **earnings of the employed worker**.

In the quantification of this externality, we have therefore applied the earnings of the employed worker based on the average salary. The differences in salary for different sectors relevant to the biomethane value chain activities, namely construction, industry and agriculture, were based on respective shares in the NNFCC study[179].

Jobs created in biomethane industry / GWh [jobs / GWh]	X	Value per job created [€ / job]

Equation 5.9 | Calculation methodology for Jobs creation

178 ENEA, *Renforcer la compétitivité de la filière biomethane francaise*, 2018.
179 Eurostat, *Unit labour costs at industry level - compensation of employment (Eurostat NAMA_10_LP_A21).*

6. Results

6. Results

This chapter provides the calculated (net) benefit per unit of biomethane produced (€/MWh) and the total benefit (€) for 2030 and 2050 for each of the selected externalities.

6.1 | Value of biomethane benefits per technology

The externalities studied bring significant additional value for biomethane production beyond renewable energy provision. Figure 6.16 shows the calculated low and high estimates of biomethane externalities per externality and technology in €/MWh. The total externality benefits for anaerobic digestion are broadly similar and of the same order of magnitude as the total externality benefits estimated for thermal gasification.

Anaerobic digestion delivers an additional benefit of **84-175 €/MWh** of biomethane produced, while **thermal gasification** delivers an additional **benefit of 80-162 €/MWh**. Importantly, these benefits outweigh the current cost of producing biomethane through these technologies (55-100 €/MWh and 85-110 €/MWh for anaerobic digestion and thermal gasification respectively).

The higher externality value for anaerobic digestion largely results from the higher greenhouse impact due to reducing fugitive emissions in agriculture, benefits from the application of digestate (replacing synthetic fertiliser) and organic waste processing, as well as a lower cost of production which increases the overall value of energy security. Fugitive emissions from biomethane production and digestate storage do not make a significant impact to the overall results.

However, the relative share of each externality varies between the low and high scenarios, and also between the technologies. For **anaerobic digestion**, the shares in the low scenario are relatively evenly spread. Job creation (33%), greenhouse impact (28%), provision of biogenic CO_2 (15%) and energy security (14%) make up over 80% of the total. In the high scenario, energy security (43%) and job creation (28%) dominate.

For **thermal gasification**, job creation (40%) and the provision of biogenic CO_2 (37%) make up the highest share of the low scenario, with the balance largely made up of greenhouse gas impact (20%). In the high scenario, the shares are more evenly spread with energy security providing a greater contribution (28%).

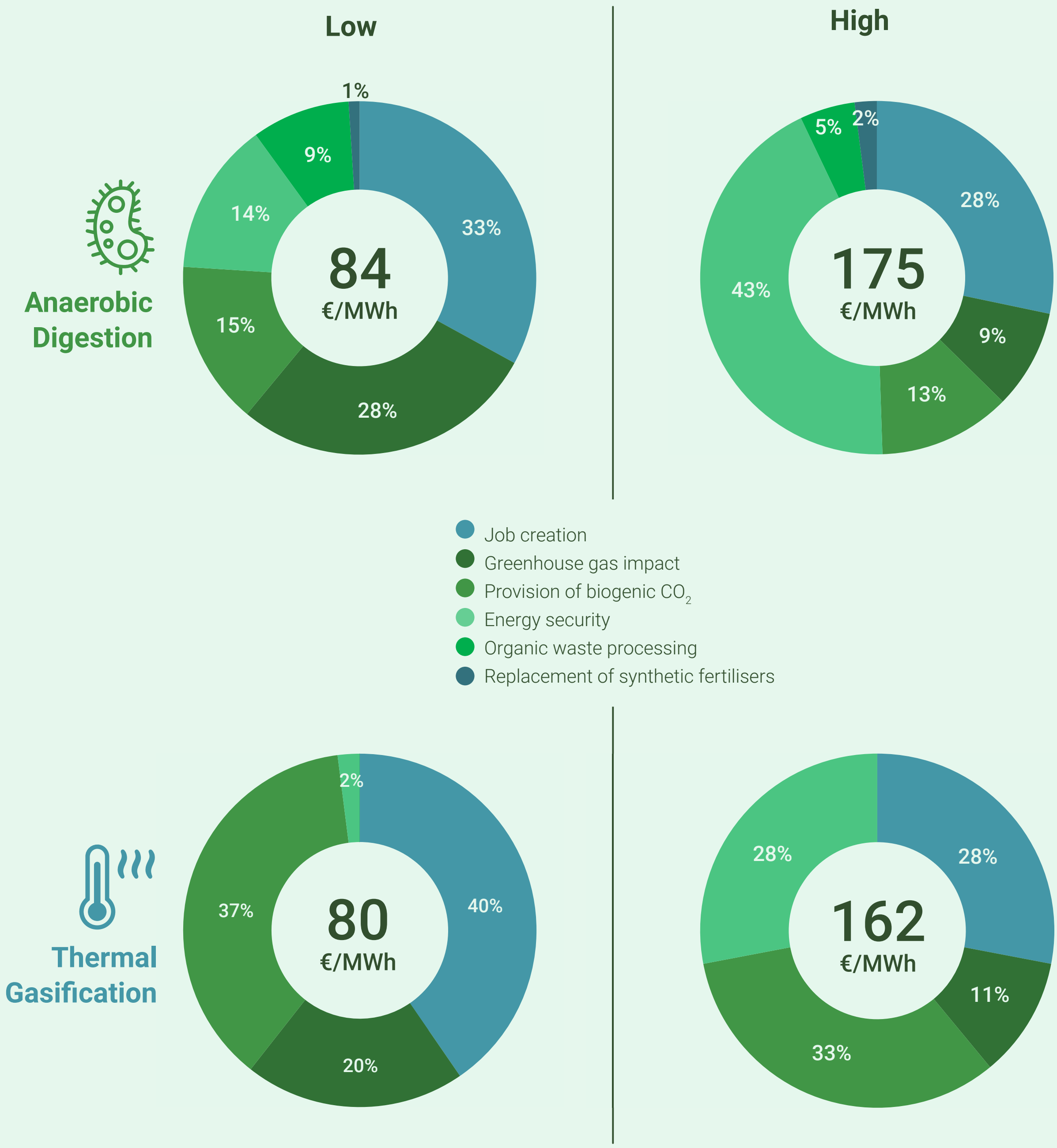


Figure 6.16 | Low and high estimates of biomethane externalities categorised by externality and technology (€/MWh).

6.2 | Value of biomethane benefits per feedstock

Figure 6.17 and Figure 6.18 below provide a breakdown of the externality values by individual feedstock and technology, compared to the weighted average value for all feedstocks in the low and high scenarios.

The calculated values for **anaerobic digestion** vary between the feedstocks, although the values for the majority of the feedstocks (agricultural residues, biowaste, industrial wastewater and sequential crops) are broadly similar. Exceptions are animal manure and, in particular, sewage sludge. The higher values for animal manure largely result from the inclusion of reduction of fugitive emissions due to improved manure management of 28 €/MWh (leading to a much higher greenhouse gas impact value). The higher values for sewage sludge are largely driven by the very high value for organic waste processing (156-171 €/MWh). The processing of sewage sludge is relatively expensive, and anaerobic digestion provides a cost-effective solution to reduce these costs. Also, the lower biogas yield per tonne of feedstock for sewage sludge has an impact, as a large amount of sludge is processed for every MWh produced. However, since sewage sludge has a small share of the overall biomethane feedstock in 2030 (3%) and 2050 (1%), this has a minor impact on the overall externality value.

The underlying assumptions applied for **thermal gasification** were the same for all of the feedstocks in scope, and consequently the calculated externality values are also the same for all feedstocks.

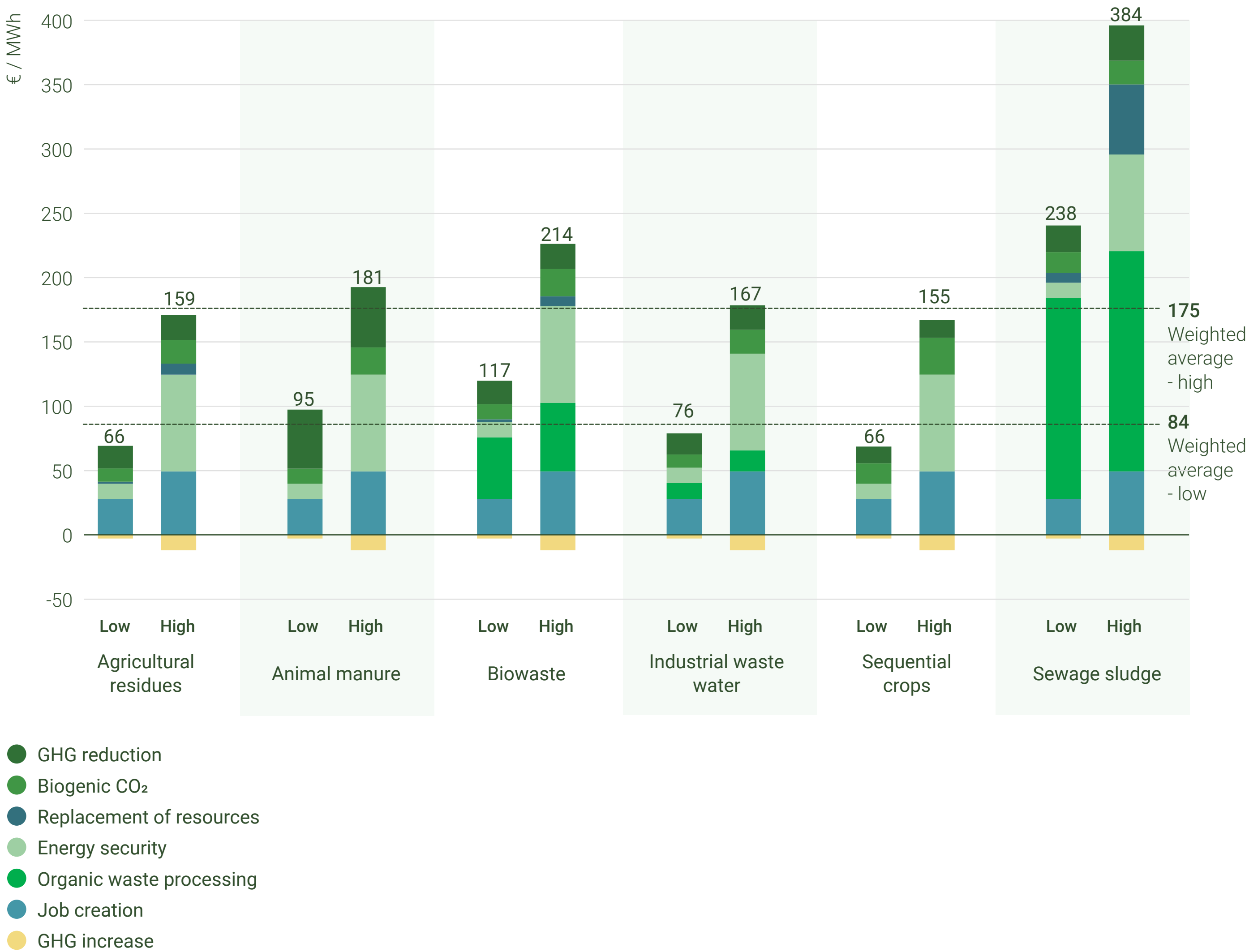


Figure 6.17 | Anaerobic digestion: Externality benefit per feedstock for each externality (€/MWh)

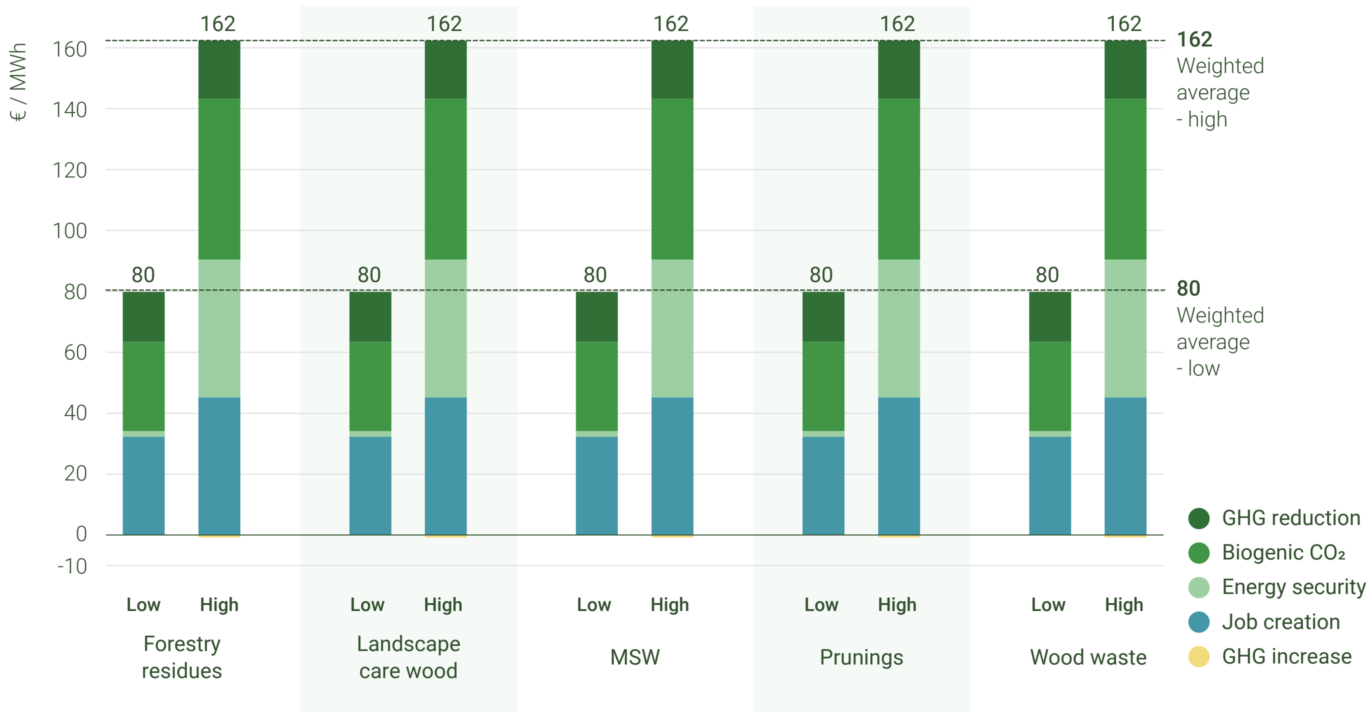


Figure 6.18 | Thermal gasification: Externality benefit per feedstock for each externality (€/MWh)

6.3 | Future economy-wide benefits of biomethane production in Europe

The total estimated benefits are significant and demonstrate the value that biomethane production can deliver to the European economy (see Figure 6.19 and Figure 6.20 below). As explained in chapter 2, these benefits were calculated by multiplying the externality values per technology by the assumed biomethane potentials in these years. These benefits are considered to be an underestimate since this scope of this study has specifically focussed on a selection of the externalities presented in chapter 1. Furthermore, as discussed in section 3.1 the benefits to soil health were not quantified due to the lack of well-established methodologies available today that can robustly assign monetary values to these benefits.

In **2030**, the additional economy-wide benefits of biomethane production to the EU27 and UK range from **€38-78 billion per annum** and almost entirely relate to **anaerobic digestion** (€35-73 billion). This technology is already widely deployed across Europe today and will further scale-up to 2030. In contrast, biomethane production from **thermal gasification** is expected to be fully commercially available from 2030 onwards. As such, biomethane production **from gasification** in 2030 will likely be available in significantly lower volumes compared to anaerobic digestion.

In **2050**, the additional economy-wide benefits of biomethane production to the EU27 and UK range from **€133-283 billion per annum**. The share between the two technologies is more balanced as thermal gasification is expected to make a significantly larger contribution in this timeframe. **Anaerobic digestion** represents around 60% of the total (€77-168 billion) and **thermal gasification** 40% (€57-115 billion).

As a frame of reference, the values in the high scenarios in 2030 and 2050 approximately correspond to the gross domestic products (GDPs) of Luxembourg and Finland in 2021, respectively[180].

180 Statista, *Gross domestic product at current market prices of selected European countries in 2021*, 2022. https://www.statista.com/statistics/685925/gdp-of-european-countries/

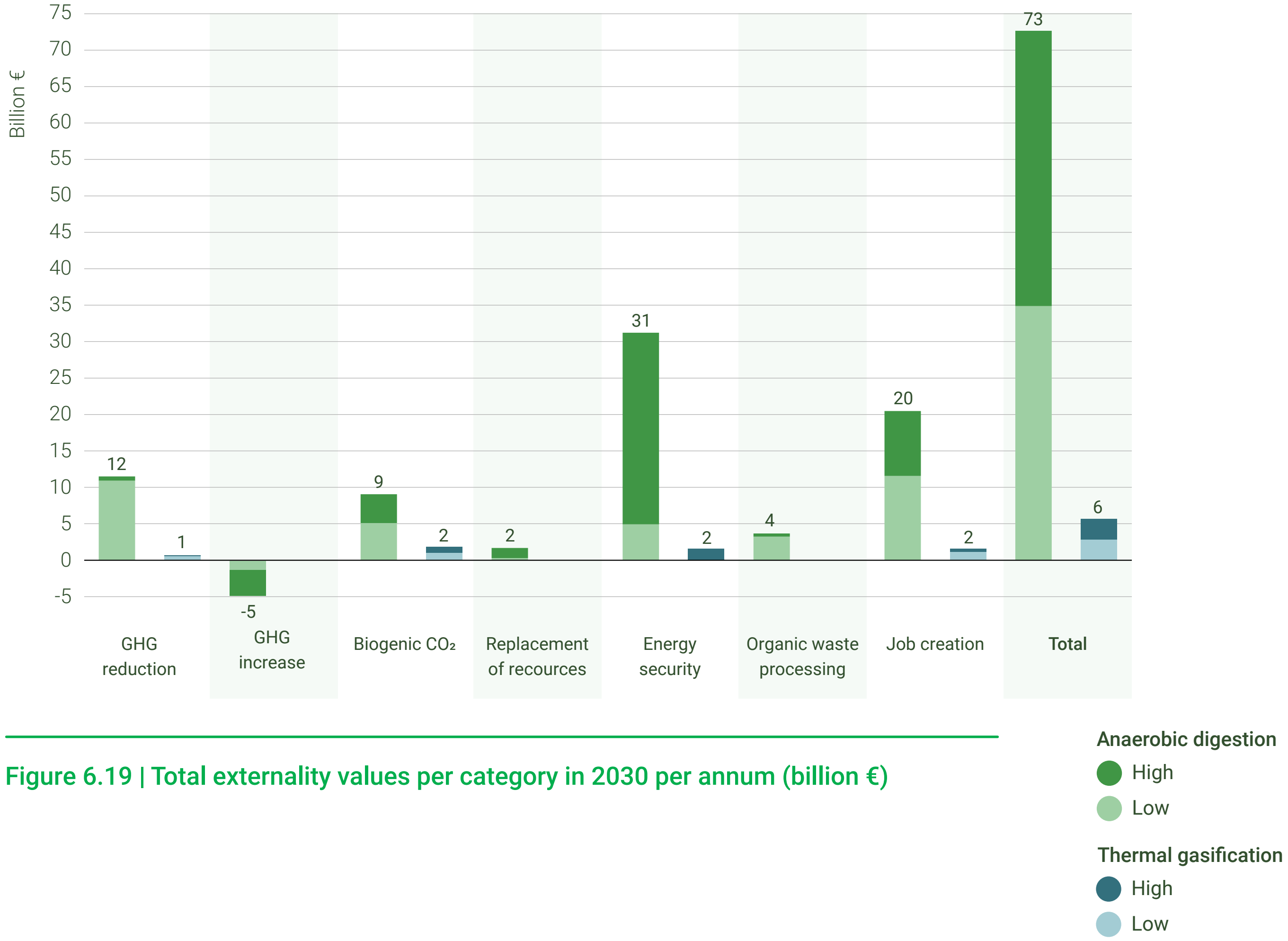


Figure 6.19 | Total externality values per category in 2030 per annum (billion €)

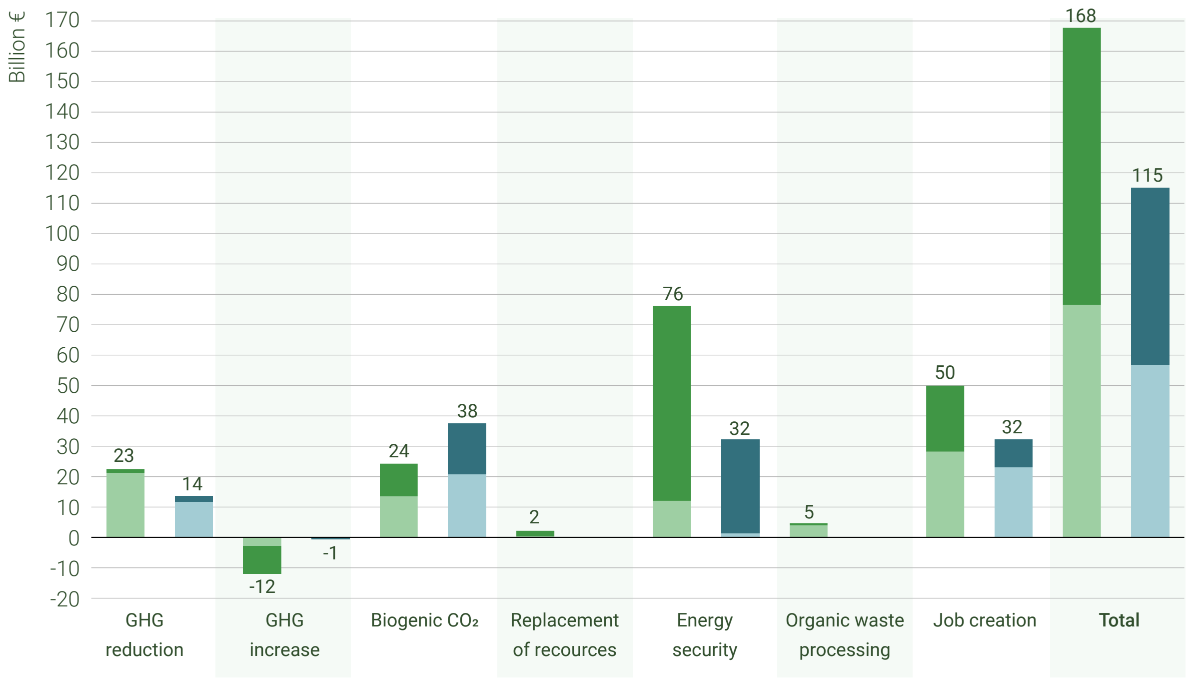


Figure 6.20 | Total externality values per category in 2050 per annum (billion €)

6.4 | Conclusions

This study clearly highlights that biomethane production can provide significant benefits beyond renewable energy provision. These benefits are varied and cover multiple **environmental, economic and social** aspects, as summarised below. Importantly, many of these benefits are unique compared to other renewable energy sources.

- **Soil health:** Biogas production from anaerobic digestion produces a nutrient rich digestate. Application of digestate to agricultural soils has been shown to improve a range of soil health indicators and to sequester organic carbon in the soil. Its organic rich composition can support the recovery of degraded soils, necessary for long-term agricultural sustainability. Applying digestate to the soil also recycles a large fraction of the nutrients contained in the feedstock, reducing the need for fossil-derived synthetic fertiliser and contributing to a circular economy. Deployment of sequential crops can also reduce soil erosion as the land is covered year-round.
- **Greenhouse gas emissions impact:** Biomethane is a versatile renewable energy vector. It can be used in multiple end-use sectors, including transport (road, shipping), heating (for use in industry and buildings) and power production. Biomethane can directly replace the use of fossil fuels in these sectors, with the potential to deliver significant greenhouse gas emissions reduction. Furthermore, fugitive emissions in the agricultural sector can largely be avoided by using manure as a feedstock for biomethane production, thereby providing a valuable solution to support efforts to reduce global methane emissions (for example, as part of the Global Methane Pledge which aims to reduce global methane emissions by at least 30% from 2020 levels by 2030[181]). Similar benefits will be realised when organic waste streams in other sectors, such as biowaste, are treated via anaerobic digestion. Finally, replacing synthetic fertiliser use with digestate also reduces greenhouse gas emissions, since the production of synthetic fertilisers is very energy intensive (in particular nitrogen-based fertilisers, as natural gas is used as both feedstock and process fuel).
- **Energy security:** Europe is heavily reliant on energy imports, including natural gas. Domestically produced biomethane can reduce the need to import gas and directly improve Europe's energy independence and security. This can help cushion against exposure to volatile natural gas prices, protecting the competitiveness of Europe's industries and reducing the risk of energy poverty for households. The role that biomethane can play in strengthening Europe's energy independence and security has been duly recognised by the European Commission in the REPowerEU[182] plan, which sets a target of 35 billion cubic metres (bcm) of biomethane production per year by 2030 in the European Union (EU27).
- **Provision of biogenic carbon dioxide:** Biomethane production through both anaerobic digestion and thermal gasification can produce a pure biogenic CO_2 stream. Biogenic CO_2 can be used as a feedstock in multiple industrial applications, largely displacing fossil CO_2 sources, or in emerging applications such as renewable fuels, chemicals and algae production. Alternatively, it can be permanently stored within geological features (e.g. closed saline aquifers below

181 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/en/statement_21_5766
182 European Commission, *REPowerEU: A plan to rapidly reduce dependency on Russian fossil fuels and fast forward the green transition*, 2022. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

the sea) to deliver Greenhouse Gas removals (GGR; also known as Carbon Dioxide Removals, CDR). Such removals are essential to the delivery of Net Zero targets, due to their ability to offset unavoidable emissions in other sectors.

- **Organic waste processing:** Biomethane production from organic waste feedstocks provides waste processing services, as well as energy generation services, which can improve the overall economics of the operation. Importantly, this also plays a valuable role in contributing to the circular economy by recycling organic wastes and turning them into useful products, including renewable energy and nutrient rich digestate that can be returned to the soil.
- **Job creation:** Biomethane production can contribute to the creation of between 1.1 and 1.8 million jobs across the value chain in Europe by 2050. As biomethane production through anaerobic digestion will involve a more decentralised production model based on agricultural wastes, residues and sustainable crops, its deployment is expected to bring new employment benefits especially to rural regions across Europe. In contrast, it is expected that biomethane production from thermal gasification will lead to employment benefits in more centralised production facilities and largely located near to sustainable forest-based industries or urban areas from which the feedstock will be collected.

Action is needed to realise these benefits

To fully realise these benefits will require a concerted effort from the biomethane industry, policy makers and regulators alike. We recommend that focus should be directed at the following areas:

1. **Ensure benefits are recognised by policy makers:** Policy makers at both the European and national level should recognise the benefits that biomethane can deliver (additional to renewable energy provision) and ensure that agriculture, climate, energy and waste policy enables these benefits to be fully realised by biomethane producers.

   European level: The European Commission could consider developing an EU strategy for energy transition in rural areas to support biomethane production, as recommended in the REPowerEU Biomethane Action Plan[183]. Anchoring the 35 bcm biomethane production target proposed in the REPowerEU plan in the revision of the EU REDII would also serve to strengthen this target, supporting Europe's energy security. The environmental benefits of sustainable sequential cropping cultivation for biomethane should also be recognised, for example, by including this agronomic practice as an 'eco-scheme' under the common agricultural policy (CAP)[184].

   National level: Countries should develop an overall vision for the long-term role of biomethane in their energy system and economy, as recommended in the Biomethane Action Plan. The strategy should recognise the rural and circular economy benefits that biomethane can bring in the national context and put in place a supportive regulatory framework to enable this. Financial incentives (including loans or tax credits), support or market mechanisms and targets should be implemented accordingly to provide greater market security for biomethane producers, thereby improving the bankability of projects. Furthermore, actions should be taken to remove any barriers that may prevent, or hinder, the scale-up of biomethane production (such as reducing the time for permitting and granting access to inject in to the gas grid). The Gas for Climate manual to develop and implement national biomethane strategies may serve as a useful reference source in this respect[185].

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

184 https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/new-cap-2023-27_en; https://agriculture.ec.europa.eu/news/commission-publishes-list-potential-eco-schemes-2021-01-14_en

185 Gas for Climate, *Manual for National Biomethane Strategies*, 2022. https://gasforclimate2050.eu/wp-content/uploads/2022/09/2022-Manual-for-National-Biomethane-Strategies_Gas-for-Climate.pdf

2. **Mobilise waste and residue feedstocks:** The mobilisation of waste and residue feedstocks, such as animal manure and biowaste, should be prioritised as these feedstocks offer the highest greenhouse gas saving benefit, as well as supporting job creation. Support should be provided at the national level to facilitate the collection and aggregation of these feedstocks, with a particular focus on animal manure given the significant benefit of reducing fugitive emissions in agriculture when this feedstock is used for biomethane production. The banning of landfilling or incineration of biowaste from 2024 provides an immediate opportunity to unlock additional sustainable feedstock for biomethane production, where the greatest societal benefit can be realised. Finally, municipal and industrial wastewater sludges should be fully utilised for biomethane production.

3. **Incentivise sustainable agricultural production:** Sustainable sequential crops can play an important role in the scale-up of biomethane production to 2050, and similarly realise significant economy wide benefits. To date, sequential crops for biomethane production have been deployed commercially in Italy and successfully tested in France. A further scale-up requires research to test to what extent this can be implemented in more temperate parts of Europe, and in particular in key European agricultural regions such as Germany, Romania and Poland. Large-scale training and awareness-raising programmes would need to be implemented for farmers in all countries in which sequential cropping is targeted. In conjunction with this, the benefits of sustainable agricultural methods such as no or low-till, and application of digestate should also be promoted. Funding to invest in specialist machinery should be allocated from the rural development measures under the CAP[186].

4. **Support further commercialisation of thermal gasification:** Biomass gasification with biomethane synthesis exists at demonstration scale. However, the potential to scale up is large in the mid-term (2030 and beyond). This technology could realise benefits of €115 billion annually in 2050 if production is scaled-up. Setting out a long-term policy framework that supports biomethane from gasification and provides investors with the confidence to support this technology is needed. Such a framework should also target continuous cost reductions to minimise societal costs.

5. **Maximise valorisation of biomethane co-products:** The valorisation of biogenic CO_2 and digestate co-products provides producers with an opportunity to generate additional revenue streams and improve the overall business case of biomethane production. The benefit for biogenic CO_2 could be worth at least 12 €/MWh for anaerobic digestion and up to 52 €/MWh for thermal gasification alone. Similarly, the value of digestate as an alternative product to synthetic fertilisers could be worth an additional 4 €/MWh. Maximising these benefits will place the industry on a sustainable path to subsidy independence in the long-term.

186 European Commission, *Agriculture and rural development*. https://agriculture.ec.europa.eu/common-agricultural-policy/rural-development/measures_en

Biogenic carbon dioxide: To ensure that the benefits for biogenic CO_2 can be realised it is critical that biogas is first upgraded to biomethane in the case of anaerobic digestion. Efforts to create greater awareness of the commercial opportunities of biogenic CO_2 provision within the biomethane sector are also necessary. Policy makers can support the market development by putting in place a policy framework that values biogenic CO_2 as a commodity above that of CO_2 arising from fossil origin. The European Commission's proposal for the certification of carbon removals[187] is a helpful first step in this regard. Further action is required, however, to establish a policy mechanism that values the certificates, for example, through linkage to the EU ETS. Additionally, a range of CEN/ISO quality standards should be made available in order to optimise the market potential for biogenic CO_2 across all applications.

Digestate: Internal market barriers must be removed to ensure that digestate can be recognised as a product (i.e. organic fertiliser), and not a waste, in order to realise greatest value. Industry quality standards, such as those in Sweden and the UK, should be established in all markets to allow users to be confident that the digestate is of consistent and sufficiently high quality. Further efforts should also be targeted on the processing of digestate to create more customised nutrient mixes. Synergies of combining digestate production with composting should also be explored as a future circular economy strategy for organic municipal solid waste management.

187 European Commission, *European Green Deal: Commission proposes certification of carbon removals to help reach net zero emissions*, 30 November 2022. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7156

7. Annexes

A | Externalities analysed per feedstock for Anaerobic digestion

	Agricultural residues	Animal manure	Biowaste	Industrial wastewater	Sequential crops	Sewage sludge
GHG reduction						
Reduction of fossil fuel emissions	✓	✓	✓	✓	✓	✓
Reduction of synthetic fertiliser production emissions	✓	✓	✓	✓	✓	✓
Reduction of fugitive emissions from manure management		✓				
GHG increase						
Fugitive emissions from biomethane production	✓	✓	✓	✓	✓	✓
Fugitive emissions from digestate storage	✓	✓	✓	✓	✓	✓
Biogenic CO_2						
Carbon capture and storage	✓	✓	✓	✓	✓	✓
Carbon capture and utilisation	✓	✓	✓	✓	✓	✓
Replacement of resources						
Replacement of synthetic fertiliser	✓		✓			✓
Energy security						
Replacement of imported natural gas	✓	✓	✓	✓	✓	✓
Organic waste processing						
Organic waste processing			✓	✓		✓
Job creation						
Jobs created in biomethane value chain	✓	✓	✓	✓	✓	✓

B | Externalities analysed per feedstock for Thermal gasification

	Forestry residues	Landscape care wood	MSW (organic fraction)	Prunings	Wood waste
GHG reduction					
Reduction of fossil fuel emissions	✓	✓	✓	✓	✓
Reduction of synthetic fertiliser production emissions					
Reduction of fugitive emissions from manure management					
GHG increase					
Fugitive emissions from biomethane production	✓	✓	✓	✓	✓
Fugitive emissions from digestate storage					
Biogenic CO_2					
Carbon capture and storage	✓	✓	✓	✓	✓
Carbon capture and utilisation	✓	✓	✓	✓	✓
Replacement of resources					
Replacement of synthetic fertiliser					
Energy security					
Replacement of imported natural gas	✓	✓	✓	✓	✓
Organic waste processing					
Organic waste processing					
Job creation					
Jobs created in biomethane value chain	✓	✓	✓	✓	✓

C | Biomethane potentials in 2030 and 2050

Table 7.9 | Biomethane potential for anaerobic digestion per feedstock in TWh

	Anaerobic digestion						
	Agricultural residues	Animal manure	Biowaste	Industrial wastewater	Sequential crops	Sewage sludge	Subtotal
Total 2030	**107.3**	**142.2**	**20.7**	**42.2**	**91.6**	**11.0**	**415.1**
Share	26%	34%	5%	10%	22%	3%	100%
Total 2050	**172.9**	**202.9**	**15.7**	**121.7**	**488.2**	**10.9**	**1012.3**
Share	17%	20%	2%	12%	48%	1%	100%

Table 7.10 | Biomethane potential for thermal gasification per feedstock in TWh

	Thermal gasification					
	Forestry residues	Landscape care wood	MSW (organic fraction)	Prunings	Wood waste	Subtotal
Total 2030	**10.3**	**3.9**	**8.7**	**1.2**	**11.0**	**35.0**
Share	29%	11%	25%	3%	31%	100%
Total 2050	**229.5**	**77.2**	**143.0**	**28.9**	**233.2**	**711.8**
Share	32%	11%	20%	4%	33%	100%

D | Assumptions

Greenhouse gas reduction

Factor / parameter	Value and unit	Source
Reduction of fossil fuel emissions		
Fossil fuel emission factor	**Heating and power:** 66 gCO_2e/MJ (natural gas assumed)	European Commission, Implementing Regulation 2022/996, Annex IX[188]
	Transport: 94 gCO_2e/MJ	European Commission, Renewable Energy Directive recast, Annex VI[189]
Fossil fuels displaced	**Heating:** 33% **Power:** 33% **Transport:** 33%	As agreed with the EBA and project Steering Committee
Biomethane emission factors	**Agricultural residues:** 14.6 - 19.0 g CO_2e/MJ	Based on UK RTFO Statistics 2020[190]
	Animal manure: 11.9 - 16.2 g CO_2e/MJ	European Commission, Renewable Energy Directive recast, Annex VI[189]
	Biowaste: 13.4 - 18.6 g CO_2e/MJ	European Commission, Renewable Energy Directive recast, Annex VI[189]
	Industrial wastewater: 11.0 - 21.0 g CO_2e/MJ	Based on UK Renewable Fuel Statistics 2020[190]
	Sequential crops: 29.0 - 32.9 g CO_2e/MJ	UNI/TS 11567:2020[191]
	Sewage sludge: 11.1 - 22.0 g CO_2e/MJ	Based on UK Renewable Fuel Statistics 2020[190]
	Forestry residues: 10.5 - 21.0 g CO_2e/MJ	JEC Well-to-Tank report v5 (2020)[192]
	Landscape care wood: 10.5 - 21.0 g CO_2e/MJ	JEC Well-to-Tank report v5 (2020)[192]
	MSW (orhanic fraction): 10.5 - 21.0 g CO_2e/MJ	JEC Well-to-Tank report v5 (2020)[192]
	Prunings: 10.5 - 21.0 g CO_2e/MJ	JEC Well-to-Tank report v5 (2020)[192]
	Wood waste: 10.5 - 21.0 g CO_2e/MJ	JEC Well-to-Tank report v5 (2020)[192] WTT
	Compression for transport fuel: 3.3 - 4.6 g CO_2e/MJ	Renewable Energy Directive recast, Annex VI[189]

188 European Commission, *Commission Implementing Regulation (EU) 2022/996 of 14 June 2022 on rules to verify sustainability and greenhouse gas emissions saving criteria and low indirect land-use change-risk criteria (Text with EEA relevance)*, 2022. https://eur-lex.europa.eu/eli/reg_impl/2022/996
189 European Commission, *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)*, Annex VI, 2018.
190 UK Government, *Renewable fuel statistics 2020: Final report, 2021*. https://www.gov.uk/government/statistics/renewable-fuel-statistics-2020-final-report
191 UNI/TS 11567:2020, *Guideline for the qualification of economic operators (organizations) involved in the production chain of biomethane for traceability and mass balance purposes*. https://store.uni.com/en/uni-ts-11567-2020
192 JRC Publications Repository, *JEC Well-to-Tank report v5*, 2020. https://publications.jrc.ec.europa.eu/repository/handle/JRC119036

Factor / parameter	Value and unit	Source
Reduction of synthetic fertiliser production emissions		
Synthetic fertiliser emission factors	**Nitrogen (urea):** 1.935 kg CO_2e/t fertiliser **Phosphorus (diammonium phosphate):** 1.552 kg CO_2e/t fertiliser **Potassium (muriate of potash):** 413 kg CO_2e/t fertiliser	European Commission, Implementing Regulation 2022/996 Annex IX[188]
Fertiliser nutrient content	**Nitrogen (urea):** 46 % **Phosphorus (diammonium phosphate):** 46 % **Potassium (muriate of potash):** 61 %	AGRICO Canada[193]
Digestate nutrient content	See Section 3.2.2, Table 3.7	
Digestate nutrient availability	**Nitrogen:** 80 % **Phosphorus:** 50 % **Potassium:** 90 %	SRUC[194]
Digestate yield	0.85 t digestate/t feedstock (representative value applied for all feedstocks)	BioFertiliser Certification Scheme[195]
Reduction of fugitive emissions from manure management		
Share of manure per livestock type	**Cattle:** 48 % **Dairy cows:** 25 % **Pigs:** 16 % **Sheep / goats:** 3 % **Poultry:** 9 %	Gas for Climate (2022)[196]
Manure solid content	**Cattle:** 10 % **Dairy cows:** 10 % **Pigs:** 6 % **Sheep / goats:** 30 % **Poultry:** 20 %	Gas for Climate (2022)[198]
Untreated manure emissions	**Emissions:** 0.054 t CO_2e / t manure	European Commission, Renewable Energy Directive recast, Annex VI[189]
	Default dry matter content: 10%	JRC (2016)[197]
Biomethane manure emissions	**Cattle:** 13.6 m^3 CH_4/t fresh manure **Dairy cows:** 15.6 m^3 CH_4/t fresh manure **Pigs:** 14.4 m^3 CH_4/t fresh manure **Sheep / goats:** 48.0 m^3 CH_4/t fresh manure **Poultry:** 51.2 m^3 CH_4/t fresh manure	Scarlat et al. (2018)[198]

193 Agrico Canada. https://www.agricocanada.com/standard-fertilizers/193 https://www.agricocanada.com/fertilisers/
194 SRUC, *Digestate Information Sheets No.4 – Nutrient Availability*. https://www.farmingandwaterscotland.org/downloads/digestate-information-sheet-4-nutrient-availability/
195 Biofertiliser Certification Scheme, *Application of digestate to land as biofertiliser vs. waste. Fee Comparison – England*, 2021. https://www.biofertiliser.org.uk/pdf/BCS-cost-benefit-analysis.pdf; WRAP, Enhancement and treatment of digestates from anaerobic digestion, 2012.
196 Gas for Climate, *Biomethane production potentials in the EU*, 2022. https://gasforclimate2050.eu/wp-content/uploads/2022/10/Guidehouse_GfC_report_design_final_v3.pdf
197 Giuntoli, Agostini, Edwards and Marelli, *Solid and gaseous bioenergy pathways: input values and GHG emissions: Calculated according to methodology set in COM(2016) 767: Version 2*, EUR 27215 EN, Publications
198 Scarlat et al., *A spatial analysis of biogas potential from manure in Europe*, Renewable and Sustainable Energy Reviews, Volume 94, 2018. https://doi.org/10.1016/j.rser.2018.06.035

Greenhouse gas increase

Factor / parameter	Value and unit	Source
Fugitive emissions from biomethane production		
Digester leakage rate [% of biomethane produced]	**Receiving hall and storage tank:** 1.0 % - 2.5 % **Digester:** 0.1% - 1.2 %	ERA-NET (2022)[199]
Biomethane upgrading technology [% of technology deployed]	**Chemical scrubbing:** 29 % **Cryogenic separation:** 7% **Membrane separation:** 12% **Pressure swing absorption:** 22% **Water scrubbing:** 30 %	Gas for Climate (2020)[200]
Upgrader methane loss [% of biomethane produced]	**Chemical scrubbing:** 0.0 % – 0.1 %	ERA-NET (2022)[199]
	Cryogenic separation: 0.0 % - 2.0 %	Adnam et al. (2019)[201]
	Membrane separation: 0.4 % - 0.7 %	Bakkaloglu et al. (2022)[202]
	Pressure swing absorption: 0.0 % - 2.4 %	Bakkaloglu et al. (2022)[202]
	Water scrubbing: 2.0 % - 3.8 %	ERA-NET (2022)[199]
	Exhaust treatment: 0.0 % - 0.2 %	ERA-NET (2022)[199]
	Processing room: 0.2 % - 2.2 %	ERA-NET (2022)[199]
Fugitive emission from digestate storage		
Digestate storage leakage rate	**Open storage:** 1.0 % - 3.5 %	ERA-NET (2022)[199]
	Closed storage: 0.0 % - 1.3 %	IEA (2017)[203]
Digestate storage type	**Open storage:** 30 % **Closed storage:** 70 %	As agreed with the EBA and project Steering Committee

199 ERA-NET Bioenergy, DBFZ, *Evaluation and reduction of methane emissions from different European biogas plan concepts – EvEmBi, ERA-NET Bioenergy Thematic Online Seminar*, October 2022.
200 Gas for Climate, *Market state and trends in renewable and low-carbon gases in Europe*, 2020. https://gasforclimate2050.eu/wp-content/uploads/2020/12/Gas-for-Climate-Market-State-and-Trends-report-2020.pdf
201 Adnan, Ong, Nomanbhay, Chew, Show, *Technologies for Biogas Upgrading to Biomethane: A Review*. Bioengineering (Basel). 6(4):92, 2019. https://pubmed.ncbi.nlm.nih.gov/31581659/
202 Bakkaloglu, Cooper, Hawkes, *Methane emissions along biomethane and biogas supply chains are underestimated*, One Earth, Vol 5, Issue 6, 2022. https://doi.org/10.1016/j.oneear.2022.05.012
203 IEA, *Methane emissions from biogas plants: Methods for measurement, results and effect on greenhouse gas balance of electricity produced*, 2017. https://www.ieabioenergy.com/blog/publications/methane-emissions-from-biogas-plants-methods-for-measurement-results-and-effect-on-greenhouse-gas-balance-of-electricity-produced/

Improved energy security

Factor / parameter	Value and unit	Source
Biomethane LCOE	**Anaerobic Digestion:** 55-100€/MWh	As agreed with the EBA and project Steering Committee
	Anaerobic Digestion: 55-100€/MWh **Thermal Gasification:** 85-110 €/MWh	EBA (2021)[204]
Natural gas price	**2021 peak:** 180 €/MWh (21.12.2021) **2021 baseline:** 50 €/MWh (average 2021) **2022 peak:** 227 €/MWh (7.03.2022) **2022 baseline:** 115 €/MWh (average January-July 2022)	Investing, Dutch TTF price[205]

Provision of biogenic carbon dioxide

Factor / parameter	Value and unit	Source
Biogas CO_2 content	**Agricultural residues:** 35% **Animal manure:** 38% **Biowaste:** 38% **Industrial wastewater:** 35% **Sequential crops:** 45% **Sewage sludge:** 35%	Future Biogas
Syngas CO_2 content	0.290 t CO_2/MWh	GoGreenGas (2018)[206]
CO_2 capture rate	90%	Guidehouse assumption
Energy consumption (Anaerobic digestion)	**Membrane separation:** 0.25 kWh/Nm³ biogas **Membrane separation and cryogenic liquefaction:** 0.36 kWh/Nm³ biogas	Future biogas
Energy consumption (Thermal gasification)	**Liquefaction after thermal gasification:** 76 kWh/MWh biomethane	GoGreenGas (2018)[206]
Methane recovered	100% of 0.7% losses	IBased on Bakkaloglu et al. (2022)[207]; Pentair (2020)[208]

204 EBA, *Gasification – A Sustainable Technology for Circular Economies*, 2021. https://www.europeanbiogas.eu/wp-content/uploads/2021/11/Gasification-A-Sustainable-Technology-for-Circular-Economies.pdf
205 Dutch TTF natural gas price. https://www.investing.com/commodities/carbon-emissions-historical-data
206 GoGreenGas, *BioSNG Demonstration Plant – Project Close-Down Report*, 2018.
207 Bakkaloglu, Cooper, Hawkes, *Methane emissions along biomethane and biogas supply chains are underestimated*, One Earth, Vol 5, Issue 6, 2022. https://doi.org/10.1016/j.oneear.2022.05.012
208 Pentair, *Biogas Upgrading – Biocomplete, Product leaflet*, 2020. https://biogas.pentair.com/en/our-solutions/sgs-product-biogas-upgrading-biocomplete

Factor / parameter	Value and unit	Source
Carbon price	**Commodity price:** 200 €/tCO_2e **Storage price:** 300 €/tCO_2e	As agreed with EBA and project Steering Committee
Electricity price	144.5 €/MWh	Eurostat (2021)[209]
Biomethane LCOE	**Anaerobic Digestion:** 78 €/MWh (average of 55-100 €/MWh)	As agreed with EBA and project Steering Committee
	Thermal Gasification: 98 €/MWh (average of 85-110 €/MWh)	EBA[211]

Organic waste processing

Factor / parameter	Value and unit	Source
Counterfactual	**Biowaste:** **Composting:** 100% **Anaerobic digestion volume reduction:** 15%	GH assumption BioFertiliser Certification Scheme[195]
	Industrial wastewater: **Anaerobic treatment:** 100% **Anaerobic digestion volume reduction:** 75%	Guidehouse assumption EBA[210]
	Sewage sludge: **Incineration:** 50% **Landfill:** 50% **Anaerobic digestion volume reduction:** 33%	GH assumption GH assumption SUEZ
Cost of counterfactual waste treatment	**Aerobic treatment:** 0.36-0.49 €/m³ wastewater	Roman et al. (2011)[211]; Roman et al. (2014)[212]
	Landfill: 100-110 €/t waste	SUEZ, Guidehouse assumption
	Compost: 60-75 €/t waste	SUEZ, Guidehouse assumption
	Incineration: 110-120 €/t waste	SUEZ, Guidehouse assumption

209 Eurostat, *Electricity price statistics 2021*, 2022. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_non-household_consumers
210 European Biogas Association, *The role of biogas production from industrial wastewaters in reaching climate neutrality by 2050*, April 2021. https://www.europeanbiogas.eu/wp-content/uploads/2021/04/Paper-The-role-of-biogas-production-from-wastewater-in-reaching-climate-neutrality-by-2050.pdf
211 Román Sánchez, Molina Ruiz, Casas López, Sánchez Pérez, *Effect of environmental regulation on the profitability of sustainable water use in the agro-food industry*, Desalination 279, 2011.
212 Román Sánchez, Sánchez Pérez, Carra, *Promoting environmental technology using sanitary tax: The case of agrofood industrial wastewater in Spain*, Environmental Engineering and Management Vol.13, No. 4, 2014.

Replacement of resources

Factor / parameter	Value and unit	Source
Digestate yield	0.85 t digestate / t feedstock	BioFertiliser Certification Scheme[195]
Digestate nutrient content	See assumptions for Reduction of synthetic fertiliser production emissions	
Fertiliser nutrient content	See assumptions for Reduction of synthetic fertiliser production emissions	
Cost of synthetic fertiliser	**Urea:** 208-763 €/t	AHDB[213]
	Diammonium phosphate: 262-1061 €/t	US DAP Spot price[214]
	Muriate of potash: 213-621 €/t	AHDB

Job creation

Factor / parameter	Value and unit	Source
Jobs created	**Anaerobic Digestion:** 0.62 jobs/GWh 1.09 jobs/GWh	NNFCC (2012)[215] EBA (2021)[216]
	Thermal Gasification: 0.71 jobs/GWh 1.00 jobs/GWh	Gas for Climate (2019)[217]
Value per job created	**Agriculture:** 11.2 €/h **Construction:** 21.1 €/h **Industry:** 25.3 €/h	Eurostat[218]

213 AHDB, *GB-fertiliser prices*. https://ahdb.org.uk/GB-fertiliser-prices
214 US DAP Spot Price. https://ycharts.com/indicators/us_diammonium_phosphate_spot_price_gulf
215 NNFCC, *UK jobs in the bioenergy sectors by 2020*, 2012. https://www.gov.uk/government/publications/jobs-in-the-bioenergy-sectors-by-2020
216 European Biogas Association, *Statistical Report 2021*, 2021. https://www.europeanbiogas.eu/eba-statistical-report-2021/
217 Gas for Climate, *Job creation by scaling up renewable gas in Europe*, 2019. https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-Job-creation-by-scaling-up-renewable-gas-in-Europe.pdf
218 Eurostat, *Unit labour costs at industry level - compensation of employment (Eurostat NAMA_10_LP_A21)*.

Beyond energy – monetising biomethane's whole-system benefits

February 2023

Guidehouse

EBA European Biogas Association