# Biogas Systems in Industry: An analysis of sectoral usage, sustainability, logistics and technology development

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# Executive Summary

Biogas is renewable energy source offering dual benefits of sustainability and energy security, within a bioeconomy system. Its integration into industrial sectors supports decarbonisation of energy supply and fosters a circular economy approach, using wastes and residues to diversify energy sources, and transition away from fossil fuel use. The deployment of biogas systems is pertinent to industry sectors generating their own process by-products, such as in the food and beverage sector. System implementation can lead to emissions reductions, cost savings, and improved energy independence in sectors with high energy demands. Industries adopting biogas systems can enhance their sustainability credentials and align with key climate policies such as the EU Green Deal, REPowerEU, and the Renewable Energy Directive. Current challenges to the adoption of biogas in industry, include a stable feedstock supply, proximity to gas infrastructure, and logistics for biogas transport.

Greenhouse gas (GHG) emissions generated from industry may be categorised into Scope 1, Scope 2, and Scope 3 emissions. Scope 1 emissions are direct emissions from an organisation's operations, including fuel combustion and fugitive process emissions. Scope 2 emissions arise indirectly from purchased energy such as electricity or heating and are reported using both market-based and location-based methods. Scope 3 emissions encompass all other indirect emissions, spanning categories like purchased goods, transportation, and waste. In this report, three configurations for biogas integration in industry are proposed to promote sustainability by enabling emissions reductions: 1. industry-owned biogas plants, 2. industry partnerships with external biogas plants, and 3. the use of biomethane from the gas grid through guarantees of origin. The different configurations can have distinct implications in terms of their potential to reduce the emissions in each Scope. The reduction of emissions can be quite nuanced given the variable configurations, and the minimisation of fugitive emissions can often be critical to ensuring system sustainability.

This report provides an overview of biogas production and consumption patterns in ten countries that are members of IEA Bioenergy Task 37. The countries studied are Austria, Denmark, Finland, France, Germany, Ireland, Italy, Norway, Sweden, and the Netherlands. The analysis highlights the production sources, end uses, and industrial applications of biogas, offering insights into its role in decarbonisation efforts. Denmark is exemplified as a country that excels in biomethane grid injection, which can enable industries to adopt biogas systems through use of existing infrastructure and guarantees of origin. In contrast, Sweden can be characterised by a limited gas grid and a focus on biogas use in transportation. However, industrial biogas consumption in Sweden is growing at a significant rate, driven by sectors such as the Food, Beverage, and Tobacco production and Paper and Pulp production, in which both sectors could produce their own by-products/feedstock for biogas production. Comparisons between the ten countries analysed reveal diverse trends. Austria, Denmark, and Ireland have high industrial shares of biogas consumption, primarily for heat production. Sweden, France, and the Netherlands are also significant users, with notable growth in sectors such as Food, Beverage, and Tobacco. Biogas is heavily utilised in sectors with biodegradable by-products, such as Food, Beverage, and Tobacco, and Paper and Pulp. However, rising use in sectors without such by-products, like Chemicals and Petrochemicals, may indicate a growing reliance on externally sourced biogas.

As demonstrated by the country specific analysis, the availability of gas grid infrastructure can be vital to biogas uptake in an industry context. In regions with limited access, alternative delivery options, such as virtual pipelines or physical biogas pipelines, enable decentralised energy solutions. Virtual pipelines, whereby biomethane is transported by truck, provide increased flexibility for biogas end-use, with mobile upgrading units offering shared investment opportunities. Coupling biogas plants with nearby industries can decarbonise operations but need to be strategically planned for effective deployment.

The integration of biorefineries within industry offers a transformative approach to decarbonisation by enabling the circular economy and maximising resource efficiency. Biogas systems are central to this model. Biorefineries convert biodegradable residues into high-value products such as bioenergy, biochemicals, and biomaterials while minimising waste and environmental impact. The model proposed in this report, based at an industry site, includes for production of hydrogen, $CO_2$, and volatile fatty acids from dark fermentation and biomethane from a methanogenic reactor. In a cascading approach, pyrolysis with production of biochar, and power-to-X technologies, are integrated to facilitate closed-loop practices which enable industries to diversify revenue streams and align with their corporate social responsibility. Innovative extensions of the biorefinery concept can also include for novel biogas upgrading methods, including for micro-algae production which may be of considerable economic value. Biorefineries are highly adaptable to industry-specific needs. By leveraging the flexibility and multifunctionality of biorefineries, industries can support decarbonisation while tapping into new economic opportunities and environmental benefits.

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# 1 THE ROLE OF BIOGAS IN INDUSTRY

## 1.1 SUSTAINABILITY AND ENERGY SECURITY

Biogas produced through the anaerobic digestion of organic materials and residues will play an increasingly important role in the future energy landscape as it offers both a renewable energy source and a means of implementing circular economy practices. From an industry standpoint, biogas production may offer both environmental benefits, and opportunities for enhancing energy security. With many industries striving to meet heightened sustainability goals and reduce their carbon footprint, biogas can emerge as a key technology and fuel vector in a successful energy transition.

Biogas systems offer a mature technology to the industrial sector. If energy production is the key focus, the process consists of a standard technological operation whereby organic feedstocks (such as industrial by-products or agricultural residues) are broken down by microorganisms in an oxygen-free environment to produce biogas, which is primarily composed of methane ($CH_4$) and carbon dioxide ($CO_2$). The benefits of integrating anaerobic digestion in industry are tangible. Biogas, if upgraded to biomethane, can reduce direct emissions by offsetting natural gas, or replacing other fossil fuels used in industrial processes. This is particularly relevant to industries with a significant heat demand. Biogas can also reduce indirect emissions if used for electricity production and may lower the dependence on import of grid electricity. Of note is the impact biogas can have on product lifecycle emissions by providing more sustainable supply chains. An example of this would be the use of biomethane as a transport fuel for industry distribution fleets. Industrial operators may benefit in switching to biogas/biomethane not only from a sustainability perspective but also from lower energy costs, and reduced dependency on volatile fossil fuel markets, enhancing energy security.

The logistics of utilising anaerobic digestion systems in industry settings can often be challenging and is dependent on several factors, including for the availability of suitable biomass (or feedstock) within proximity of the site, and the location of existing natural gas grid infrastructure. A key challenge for successful biogas plants is the consistent supply of high-quality feedstock. Industrial operations must investigate effective logistics for feedstock collection, transport, and storage to avoid interruptions in biogas production. Feedstock such as agricultural wastes and residues can potentially be acquired within the vicinity of the site, or the industry may generate their own production by-products that are amenable to anaerobic digestion, for example, as evident in alcohol production processes. For industries located in regions with limited grid infrastructure, alternative methods of biogas / biomethane delivery are required such as physical or virtual pipelines. Physical pipelines are purpose-built pipelines that transport biogas from the biogas plant (or plants) to where it is needed (boiler, CHP, or centralised upgrading facility). Virtual pipelines involve the transportation of compressed biomethane via truck to the end user. Such methods promote more flexible, decentralised energy solutions to expand the penetration of biogas/biomethane energy in industry.

In the future it is expected that advanced anaerobic digestion technologies can be leveraged to provide further value within the industrial context. For example, the continuously stirred tank reactor (CSTR) is currently the most common digester type used in the EU, but different types of digester technologies can potentially be employed. Specifically, two-phase reactors can be employed whereby anaerobic digestion now becomes central to the creation of a multi-output (multi-product) system which can potentially generate new revenue streams. Such configurations epitomise the biorefinery approach where energy (biogas) is produced alongside other biochemicals, biofertilisers, and biomaterials. Further leveraging these diverse products exemplifies how industries can transform its wastes, residues and by-products into high-value outputs, promoting circular economy principles.

This report investigates the current uses of biogas in industry in 10 countries to exhibit the extent of biogas use and the specific industry sectors where the energy is being used. The numerous arrangements /configurations for biogas use in industry, and the limited availability of data, make the analysis of the sector somewhat complex. For example, industry may be located near or far from the gas grid, the industry may have their own digester, or may rely on external digesters for biogas production. This can have consequences in terms of the sustainability of the industry and the logistics of utilising anaerobic digestion as a renewable energy technology. Whilst barriers exist to the uptake of biogas in industry, many opportunities also exist in terms of improved sustainability and enhanced energy security. The aim of this report is to highlight some of the key considerations and nuances that exist in facilitating industrial biogas systems.

## 1.2 ANAEROBIC DIGESTION AND THE CIRCULAR ECONOMY

A linear economy process adopts the strategy of “take, make and discard” and is considered a largely unsustainable model. The circular economy seeks to reuse, recover, recycle, and reintroduce resources back into the value chain using a more sustainable approach. Industry will play a crucial role in enacting circular economy approaches and methods. Decarbonisation of industrial processes can be achieved through anaerobic digestion of residues or by-products, thereby reducing the carbon footprint of the industry’s products, and increasing the energy security of the industry site. This is particularly relevant to food and beverage industries such as alcohol production, whereby the production process has by-products amenable to anaerobic digestion. Thus, it is likely that many food and beverage industries could benefit from implementing circular economy practices.

Biogas plants are flexible and adaptable, and as such can be considered integral components to a circular economy approach. This is evident both in terms of energy production (producing energy from potentially waste and residue materials) and in terms of nutrient recycling. The latter refers to the digestate generated from biogas systems, which is a valuable biofertilizer that can be land-spread for food production. Recycling these nutrients back to soil enhances soil fertility and supports sustainable agriculture, reducing nutrient losses to the environment. Furthermore, anaerobic digestion is fundamentally a waste management strategy that could divert many organic materials generated in industry processes, away from landfills. Thus, the implementation of biogas systems can make industries more self-sufficient, by promoting resource efficiency and energy security, both of which embody the principles of the circular economy in minimising waste and recovering value from used materials. The reader is referred to Liebetrau et al. (2022) for more detail on the role of biogas and biomethane in pathways to net zero.

## 1.3 CLIMATE POLICY PUSH

Improving the economic, environmental, and societal performance of economies and industries is a vital element of progressing toward a more sustainable future. Industries have a corporate social responsibility (CSR) to become “green” and be part of the transition to a net-zero future. Such responsibility includes for reducing the environmental impact of their organisation and delivering on specific sustainability targets. The onus now lies on many industries to provide more sustainable value chains. This can arise through lower carbon emissions associated with the organisation, reduced waste generation, and enhanced resource efficiency. Many industries have begun to invest in renewable technologies and engage with the various stakeholders to make the necessary changes, and enhance the organisational reputation. These attempts have been further boosted by the implementation of specific policies in the EU:

1. European Green Deal 2020

The European (EU) Green Deal was approved in 2020 by the European Commission and aims for Europe to become the first climate neutral continent by 2050. Under the policy initiative, circular economy approaches are to be prioritised with the intention of creating a more sustainable and resource efficient economy. Industry in the EU is responsible for 20% of the EU economy and employs 35 million people (European Commission, 2020). Under the EU Green Deal framework, industrial sectors and value chains will play a key role by reducing their greenhouse gas (GHG) emissions. Furthermore, industry will require a secure, sustainable, and affordable source of energy into the future, which may be facilitated by the transition to a circular economy model (European Commission, 2020). The EU Climate Law 2021(REGULATION (EU) 2021/1119 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, 2021) subsequently outlined the legal requirement to reach climate neutrality in the EU by 2050, with an interim goal of reducing net greenhouse gas emissions by at least 55% compared to 1990 levels, by 2030.

2. REPowerEU Plan

As a result of geopolitical events in the Ukraine, the European Commission implemented a specific policy plan “REPowerEU” (The European Commission, 2022a) in 2022 to reduce import dependence on Russian natural gas and boost energy security in the EU (The European Commission, 2022b). A priority of the REPowerEU Plan is the significant scale up of biomethane production. A target of producing 35bcm of biomethane by 2030 was put forward with increased use in the domestic, agricultural, and industrial sectors. This target was 10 times the current biomethane production in the EU, and corresponds to approximately a 10% substitution of natural gas use. REPowerEU states that biomethane production should be based on the anaerobic digestion of wastes, avoiding the use of food and feed biomass that could lead to land use change issues.

3. Renewable Energy Directive

The amending directive (EU/2023/2413) (European Commission, 2023) of the Renewable Energy Directive has set a legally binding target of a renewable energy share of 42.5% in the EU by 2030. Recognising the key role of bioenergy in this transition, the amending directive highlights the need to ensure that biomass resources are used in a cascading manner to maximise their value (and therefore resource efficiency) by promoting the material use of biomass before its use as a source of energy. Furthermore, the large amount of energy consumed by the industrial sector (responsible for 25% of energy consumption in the EU) for heating and cooling is also highlighted, as 91% is supplied by fossil fuels. The use of biogas produced via anaerobic digestion, or biomethane derived from the upgrading of this biogas, is a potential option to increase renewable energy consumption in industry. The Directive set sustainability criteria for use of biogas in transport (after January 2026) at 65% reduction in greenhouse gas emissions as compared to the fossil fuel displaced; a higher sustainability criteria of 80% was placed on electricity and heat. This is a challenge for use of biogas for industrial heat, as the alterative use in transport is favoured by the Directive, and the carbon footprint will have to be 80% lower than the alternative fossil fuel use. This is even more challenging in that natural gas (used for industrial heat) has a lower footprint than fossil fuels such as diesel for use in heavy transport.

## 1.4 DECARBONISING INDUSTRIES WITH BIOGAS

Based on the policy and the benefits that may be gleaned from biogas integration at industry sites in relation to the circular economy, and creation of more sustainable value chains, industries may wish to adopt biogas technologies. Different configurations exist for industries, in terms of ownership models and sourcing of biogas. Three such potential configurations are outlined below for the purposes of this report:

### Configuration 1: Industry owned biogas plant

In this configuration, the industry uses their own biodegradable by-products or residues (which do not have a use with a higher economic value) to produce biogas in a biogas plant that is under the ownership or control of the industry. The biogas may then be used as a fuel for the production of electricity and/or heat that is then consumed by the industry. The use of biogas to produce heat will reduce or replace the consumption of fossil fuels for heat production. This will reduce the fossil fuel demand of the industry and the associated GHG emissions from fuel combustion. Electricity produced from the biogas, if consumed by the industry will reduce the electricity sourced by the industry from the electricity grid; this can result in a cost (and emissions) saving for the industry.

### Configuration 2: Industry partnered biogas plant

In this configuration, the industry establishes a partnership with an off-site external anaerobic digester that operates using biodegradable residues (for example, agricultural wastes) in the vicinity of the industry site/location. The industry may then directly consume the biogas generated from the plant, or the biogas may be used to produce electricity and or heat by the operator of the plant, which is then sold or transferred to the industry. Alternatively, the biogas is upgraded to biomethane by the biogas plant operator and the biomethane is transferred directly to the industry via a virtual pipeline for use as a fuel for electricity and/or heat production.

### Configuration 3: Industry use of Guarantees of Origin

In this configuration, the industry site is situated on existing natural gas grid infrastructure, and the industry purchases biomethane via the use of guarantees of origin (GoO) and/or certificates for biomethane (“renewable gas”) from the grid. In configuration 3, the gas consumed by the industry is not physically biomethane, rather the guarantees of origin provide certification to the industry that a given share of the gas they consume (which may be 100%) was produced from renewable sources (biomethane).

Figure 1.1 provides a visual representation of the three configurations described above in terms of the options for biogas and/or biomethane use at an industry site. Based on these three configurations, an assessment of the potential GHG emissions savings can be made (see Section 2).

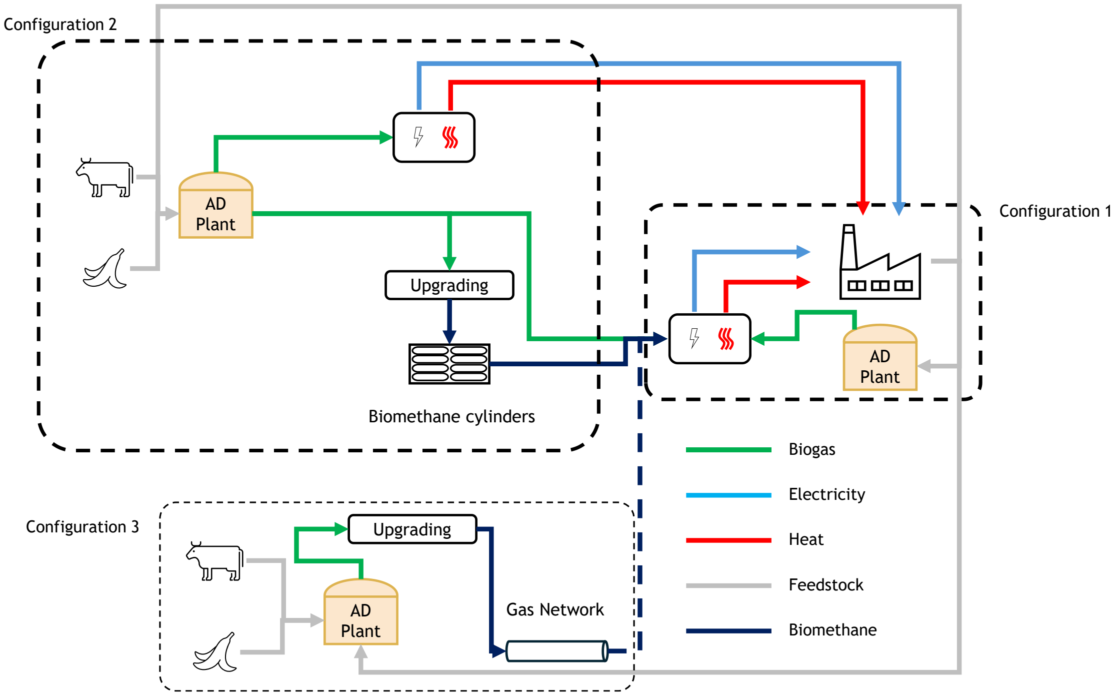


*Figure 1-1 Three configurations for the adoption of biogas in industry*

Configuration 1: Industry owned biogas plant
Configuration 2: Industry partnered biogas plane
Configuration 3: Industry use of guarantees of origin (GoO)

# 2 CATEGORISATION OF GREENHOUSE GAS EMISSIONS

## 2.1 SCOPE 1, SCOPE 2 AND SCOPE 3 GREENHOUSE GAS EMISSIONS

Greenhouse gas emissions from industries/organisations may be classified as “direct” and “indirect” emissions (GHG Protocol, 2013) (World Business Council for Sustainable Development (WBCSD) & World Resources Institute (WRI), 2004). Direct emissions come from sources that are owned or controlled by the industry. Examples of direct GHG emissions would include the emissions from fuel combustion in stationary sources such as boilers and furnaces, fuel combusted by vehicles owned by the industry, as well as (to a lesser extent) fugitive GHG emissions from wastewater treatment, or refrigerant gas used by the organisation. Scope 1 GHG emissions cover all direct GHG emissions from an industry in the form of carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), sulphur hexafluoride ($SF_6$), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). Indirect emissions arise as a consequence of the activities of the industry in question, but are emitted by sources under the ownership or control of another organisation.

Indirect emissions may be classified as Scope 2 emissions, that is, emissions that occur at the location where electricity, heating, and cooling purchased, or acquired by an organisation, are generated. Scope 2 emissions are reported using a market-based approach and a location-based approach. Market based Scope 2 emissions are based on electricity consumed by an organisation, and the emissions intensity of the electricity supplier. As electricity suppliers may avail of GoOs, this can result in the emissions intensity of electricity of some suppliers to be lower than the average emissions intensity of the electricity actually consumed by the industry. Therefore Scope 2 emissions are also reported using allocation-based approaches, whereby the average emissions intensity of grid electricity in the region (or location) where the organisation is located, is used. In the case where an industry purchases, or acquires heating or cooling via a heating or cooling network, the same principle applies - both market-based and location-based Scope 2 GHG emissions need to be reported considering the supplier emissions intensity, and the grid average emissions intensity, respectively.

Scope 3 emissions refer to all other indirect emissions and may be further split into 15 distinct categories including for: purchased goods and services; capital goods; fuel and energy related activities; transportation and distribution; waste generated in operations; business travel; employee commuting; leased assets; processing of sold products; use of sold products; end of life treatment of sold products; franchises; and investments.

The classification of GHG emissions based on the definition of Scope 1, Scope 2, and Scope 3 was adopted by the Global Reporting Initiative (GRI) within GRI standard 305 for the reporting of GHG emissions (Global Reporting Initiative, 2016). Classification using Scope 1, Scope 2, and Scope 3 is also used within the: Corporate Sustainability Reporting Directive (CSRD) (The European Parliament and the Council of the European Union, 2022); and within the European Sustainability Reporting Standard (ESRS) E1 Climate Change (The European Parliament and the Council of the European Union, 2023).

## 2.2 REDUCING EMISSIONS IN INDUSTRY THROUGH BIOGAS / BIOMETHANE GENERATION AND UTIILASTION

Utilisation of biogas may provide a method of reducing Scope 1, Scope 2, and Scope 3 emissions from industries. The following sections outline how the three industrial configurations presented in Figure 1.1 of Section 1.4 may enable the reduction of Scope 1, Scope 2, and Scope 3 GHG emissions.

### 2.2.1 CONFIGURATION 1: INDUSTRY OWNED BIOGAS PLANT

**Scope 1**

In Configuration 1, the industry produces its own biodegradable by-products and uses these resources as feedstock for an on-site anaerobic digester under the industry's control.

The biogas may be used to produce heat in a boiler, or heat and or electricity in a CHP unit, owned or controlled by the organisation. The use of biogas as a fuel would replace or reduce the fossil fuel consumption of the industry. This would therefore reduce the Scope 1 GHG emissions (consisting primarily of $CO_2$, $CH_4$, and $N_2O$) associated with the combustion of fossil fuels by the industry. Similar to the combustion of fossil fuels, the combustion of biogas releases $CO_2$, $CH_4$, and $N_2O$. However, the $CO_2$ released from the combustion of biogas does not count towards the Scope 1 GHG emissions of the industry and is instead reported separately as biogenic $CO_2$. The $CH_4$ and $N_2O$ resulting from the combustion of biogas do contribute to the Scope 1 GHG emissions of the organisation and need to be reported. The $CO_2$ that was contained in the biogas which is released into the exhaust of biogas combustion also does not contribute to the Scope 1 GHG emissions of the industry but can be reported separately as biogenic $CO_2$.

The operation of an anaerobic digester may also result in fugitive $CH_4$ emissions associated with biogas leakage from the digester or digestate storage. These fugitive methane emissions must be accounted for and included in the Scope 1 GHG emissions inventory of the industry. The $CO_2$ contained in any fugitive biogas emissions does not count toward the Scope 1 GHG emissions of the industry.

Scope 1 GHG emission are reduced as the biogas replaces and reduces the combustion of a fossil fuel and therefore reduces the associated Scope 1 GHG from the combustion of said fossil fuel. To maximise the Scope 1 savings associated with biogas combustion in Configuration 1, minimisation of fugitive methane emissions is critical.

**Scope 2**

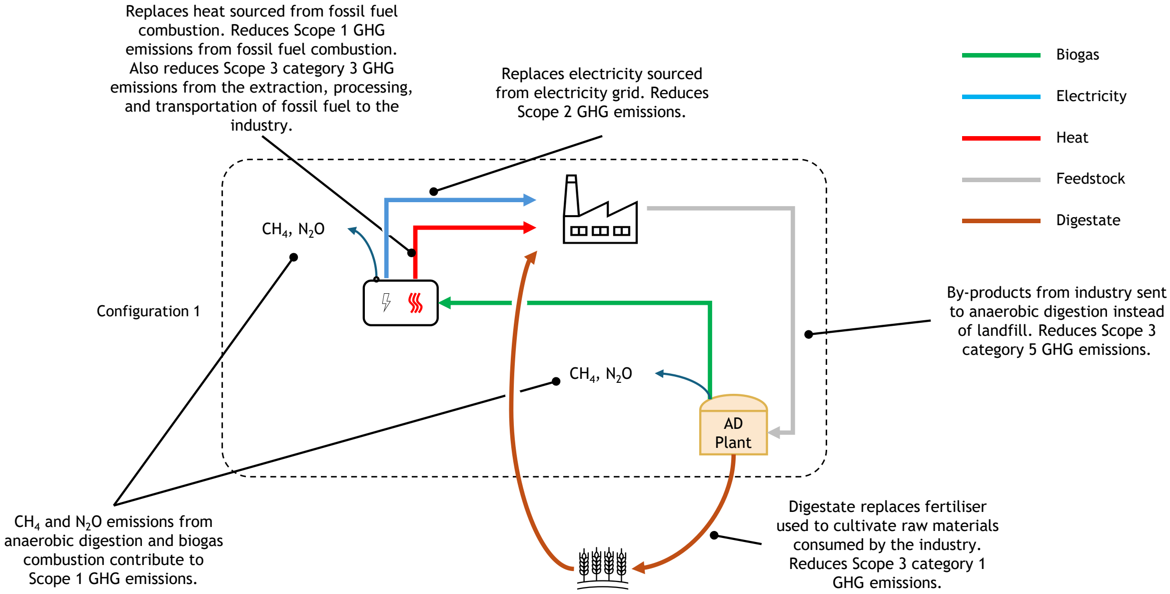
If the biogas generated in Configuration 1 is used to produce electricity that is then consumed by the industry, the amount of electricity that the industry consumes from its electricity supplier is reduced, and the amount of electricity consumed from the electricity grid is reduced. This will in turn reduce both the market-based and location-based Scope 2 GHG emissions of the industry. Alternative methods of reducing market-based Scope 2 emissions include the purchase of electricity from a supplier with a low emissions intensity, however, this will only reduce market-based Scope 2 GHG emissions. Location based emissions may only be reduced by lowering the overall emissions intensity of electricity in the region in which the industry is located, or by reducing the amount of electricity consumed by the industry from the grid. The production and consumption of electricity from biogas in a CHP unit within Configuration 1 is one way to achieve this.

**Scope 3**

Scope 3 GHG emissions may also be reduced through the production and use of biogas from by-products as exhibited in Configuration 1. As the biogas replaces fossil fuel consumption, the upstream GHG emissions associated with the extraction, processing, and transportation of fossil fuel to the industry (Scope 3 category 3: Fuel and energy related activity) will be avoided. Furthermore, the use of by-products from the industry as a feedstock for anaerobic digestion diverts those by-products from waste treatment that would produce GHG emissions such as the landfilling of biodegradable by-products (Scope 3 category 5: waste generated in operations).

Anaerobic digestion can act as a facilitator of the circular economy and can enable the return of biological nutrients to the biosphere in the form of digestate. If the digestate produced from the digester in Configuration 1 is returned to land and used for the cultivation of material consumed by the organisation, this can help close nutrient loops and reduce the consumption of synthetic nitrogen fertilisers in the agricultural sector. This would in turn reduce the GHG emissions intensity of agricultural products, as less synthetic nitrogen fertilisers would be required (synthetic nitrogen fertilisers are primarily derived from ammonia produced via the Haber Bosch process which relies on grey hydrogen produced from natural gas, coal, or oil). This would lower the emissions associated with purchased goods and services (Scope 3 category 1) of organisations which consume agricultural materials.

An additional consideration within Configuration 1 is the production of biomethane from biogas generated by a digester operated by the industry using by-products from said industry. This biomethane may be sold as a vehicle fuel to hauliers or couriers who transport materials for the industry. This would enable the haulier or couriers to replace diesel with biomethane which would in turn reduce the industry's indirect GHG emissions from transportation (Scope 3 category 4: transportation and distribution). However, the combustion of biomethane sold by the industry in vehicles would result in $CH_4$ and $N_2O$ emissions, as well as biogenic $CO_2$ emissions. The biogenic $CO_2$ emissions would not count toward the Scope 3 emissions associated with the use of sold products (Scope 3 category 11) but the emission of $CH_4$ and $N_2O$ would need to be accounted for in the industry's Scope 3 inventory. Figure 2.1 provides a graphical overview of the potential Scope 1, Scope 2 and Scope 3 GHG emission savings and contributions associated within Configuration 1.



Replaces heat sourced from fossil fuel combustion. Reduces Scope 1 GHG emissions from fossil fuel combustion. Also reduces Scope 3 category 3 GHG emissions from the extraction, processing, and transportation of fossil fuel to the industry.

Replaces electricity sourced from electricity grid. Reduces Scope 2 GHG emissions.

By-products from industry sent to anaerobic digestion instead of landfill. Reduces Scope 3 category 5 GHG emissions.

$CH_4$ and $N_2O$ emissions from anaerobic digestion and biogas combustion contribute to Scope 1 GHG emissions.

Digestate replaces fertiliser used to cultivate raw materials consumed by the industry. Reduces Scope 3 category 1 GHG emissions.

*Figure 2-1 Savings and contributions toward Scope 1, Scope 2, and Scope 3 GHG emissions from Configuration 1*

### 2.2.2 CONFIGURATION 2: INDUSTRY PARTNERED BIOGAS PLANT

In Configuration 2 the industry has a partnership agreement with an off-site external biogas plant in the vicinity of the industry. The industry may consume: the biogas directly via a dedicated biogas pipeline; electricity and or heat produced from the biogas by the operator of the anaerobic digester via a direct electrical connection or a direct thermal connection; or biomethane is produced and transferred directly to the industry for use as a fuel.

## Scope 1

If the industry consumes biogas directly from the external biogas plant this will reduce Scope 1 GHG emissions in the same manner as Configuration 1; through the reduction of fossil fuels used by the industry and their associated combustion related GHG emissions.

Alternatively, the biogas producer could upgrade the biogas to biomethane, compress it and store it in biomethane cylinders, that are subsequently transported to the industry via truck (virtual pipeline). This is a good solution where a lack of gas grid infrastructure does not allow for the injection of biomethane. Consumption of the biomethane by the industry would reduce fossil fuel consumption, and the associated combustion related Scope 1 GHG emissions.

Any $CH_4$ or $N_2O$ emissions arising from biogas or biomethane combustion (for the production of heat and/or electricity) would need to be accounted for by the industry (as in Configuration 1). If the industry purchases or acquires heat directly from an externally owned and operated anaerobic digester this would reduce the fossil fuel consumption of the industry and the associated Scope 1 GHG emissions. In Configuration 2, the fugitive emissions associated with biogas leakage, biogas upgrading, digestate storage, or biogas combustion off-site for heat and/or electricity generation do not contribute to the Scope 1 emissions of the industry.

## Scope 2

When the industry partners contract with an externally operated anaerobic digester as per Configuration 2, the acquired biogas or biomethane may be used as a fuel for electricity generation by the industry. As is the case in Configuration 1, consumption of this electricity would reduce both the market-based and location-based Scope 2 GHG emissions of the industry.

If the industry acquires electricity directly from an external anaerobic digester (which has burned the biogas to generate electricity), the amount of electricity consumed from the electricity grid can be reduced. Fugitive emissions associated with the operation of the anaerobic digestion plant, $CH_4$ and $N_2O$ emissions from biogas combustion for electricity production, and any other GHG emissions produced by the digester would contribute to the emissions intensity of the electricity transferred to the industry. If the emissions intensity of this electricity is lower than the emissions intensity of the industry’s electricity supplier, the industry will reduce its Scope 2 market-based GHG emissions. If the emissions intensity of the electricity transferred to the industry is lower than the location-based Scope 2 emissions intensity of electricity, then the industry will reduce its Scope 2 location based GHG emissions. The same approach can be applied to heat purchased or acquired by the industry from an external digester. To maximise the Scope 2 emissions savings within Configuration 2, emissions associated with the production of biogas and electricity by the external anaerobic digester must be minimised.

## Scope 3

In the context of Configuration 2, if an industry consumes biogas or biomethane directly from an external anaerobic digester, it will reduce the consumption of fossil fuels. As in Configuration 1 this will reduce the emissions associated with the extraction, processing, and transportation of fossil fuels to the industry (Scope 3 category 3: fuel and energy related activities). However, the fugitive emissions from biogas leakage, digestate storage, biogas upgrading and transportation (where applicable), and the GHG emissions associated with the production of the biogas or biomethane from by the external anaerobic digester will contribute to the Scope 3 category 3 emissions of the industry. If the quantity of Scope 3 category 3 emissions per unit of energy received in the form of biogas or biomethane is lower than the Scope 3 category 3 emissions per unit of fossil fuel replaced, then the industry will reduce its total Scope 3 category 3 emissions overall. Therefore, it is vital that fugitive emissions from the anaerobic digestion process, digestate storage, and biomethane upgrading and transportation are minimised to reduce its Scope 3 category 3 GHG emissions from the industry's standpoint.

If the external anaerobic digester uses by-products from the industry as feedstock this can reduce the emissions associated with the management of these by-products (Scope 3 category 5) by avoiding their disposal to landfill.

A further consideration that is relevant, particularly to food and beverage industries, is if the external anaerobic digester uses manures and slurries from livestock that are in the value chain of the industry (for example milk processing). Emissions from manure management for livestock in the value chain of the industry contribute to the indirect emissions associated with goods purchased by the industry (Scope 3 category 1: purchased goods and services). If the external anaerobic digester uses manures and slurries from animals in the value chain of the industry as a feedstock, the emissions associated with manure management in open slurry tanks or pits will be reduced, in turn reducing the emissions associated with the livestock, or livestock derived products (such as milk) consumed by the industry. It is often the case that fugitive emissions from the biogas system may be less than the emissions originating from management of the feedstock in the absence of anaerobic digestion. For example an open slurry tank typically emits c. 17% of the biomethane potential of the feedstock, whilst a biogas facility can reduce fugitive emissions to below 2% of the biomethane potential (Liebetrau et al., 2017).

The return of digestate to land used for the cultivation of materials purchased by the industry would also facilitate a reduction in the emissions arising from these purchased goods (Scope 3 category 1: purchased goods and services) in a similar manner to Configuration 1 (the replacement of synthetic nitrogen fertilisers). Figure 2.2 provide a graphic representation of the potential Scope 1, Scope 2 and Scope 3 GHG emissions savings and contributions towards related to Configuration 2.

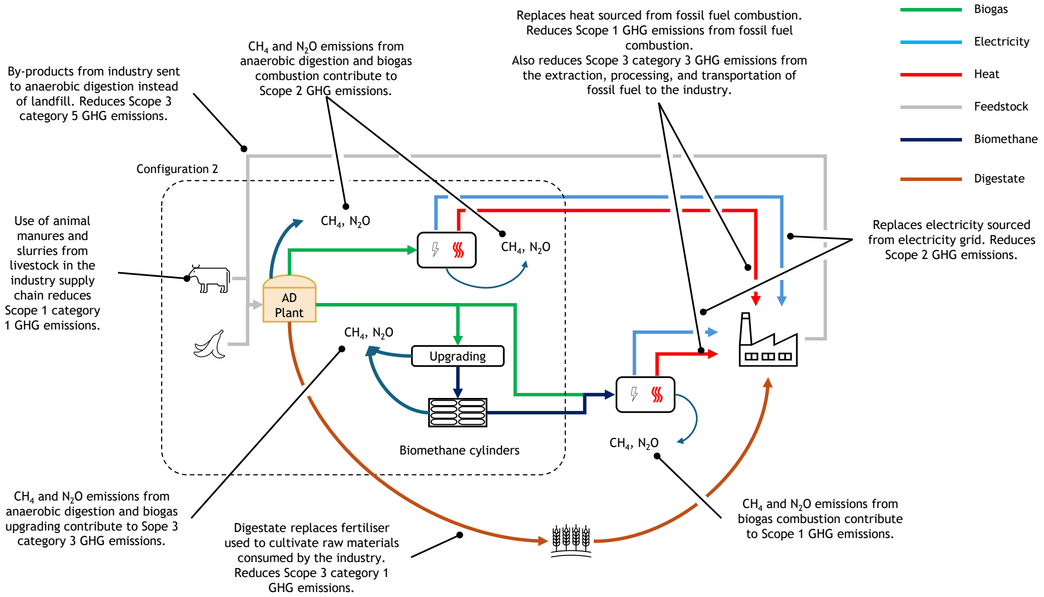


*Figure 2-2 Savings and contributions toward Scope 1, Scope 2, and Scope 3 GHG emissions from Configuration 2*

### 2.2.3 CONFIGURATION 3: INDUSTRY USE OF GUARANTEES OF ORIGIN

**Scope 1**

For Configuration 3, an industry may purchase biomethane (blended with natural gas) from the natural gas grid through the use of guarantees of origin (GoOs) or green gas certificates. This biomethane and natural gas blend may be combusted to produced heat and/or electricity by the industry. As of August 2023, specific guidance on whether this method is a valid approach to reduce Scope 1 GHG emissions from the industry, in accordance with the GHG methodology, is unavailable from the developers of the GHG protocol. The following statement was provided in August 2023 "*In the absence of guidance, companies purchasing certificates may wish to consult with their auditors and consider rules provided by relevant target-setting programs or applicable regulatory schemes in their jurisdiction(s) on how to report these purchases in their reports, while ensuring full transparency and following all GHG accounting and reporting principles.*" (World Resources Institute (WRI), 2024)

Within the European Sustainability Reporting Standard (ESRS) E1 Climate Change, Disclosure Requirement (DR) E1-6 requires undertakings to report their gross Scope 1, Scope 2, Scope 3, and total GHG emissions (The European Parliament and the Council of the European Union, 2023). Calculation guidance (paragraph AR 43) states that for the undertaking's activities that report emissions under the EU ETS, the EU ETS methodology may be used to report on Scope 1 GHG emissions.

Guidance documentation for monitoring and reporting of emissions in the EU ETS (which from the perspective of electricity and heat generation in industry covers facilities where the installed thermal capacity is greater than 20MW) was updated in 2023 and contains a new section (section 6.3.7) relating to "biogas" (in the guidance documentation "biogas" injected into natural grids refers to biomethane) (The European Commission, 2023). The updated guidance states that "*Where biogas is injected into natural gas grids and purchased by an EU ETS operator connected to the same gas grid, the said operator may report that purchased amount of biogas as consumed within his installation, even if the biogas is not physically delivered to the installation. This is done by determining and assigning a biomass fraction to the total gas (natural gas plus biogas) based on the fraction of energy content of biogas in the total gas consumption.*" Assurances and clear demonstration that the double counting of biomethane/biogas is avoided is required and that a single guarantee of origin is disclosed to the biogas/biomethane consumer only. Furthermore, the biogas/biomethane producer and consumer must be connected to the same gas grid and the biogas/biomethane complies with the sustainability criteria outlined in RED-II. This requires an 80% GHG savings as compared to the fossil fuel displaced for industrial heat after January 2026.

The biomass fraction of total gas has an emission factor of zero for $CO_2$ and therefore according to ETS guidance the $CO_2$ from combustion of the fraction of total gas associated with biomethane will not contribute to the industry's Scope 1 GHG emissions but will need to be reported separately as biogenic $CO_2$ emissions. The non-$CO_2$ GHG emissions from combustion ($CH_4$ and $N_2O$ primarily) will need to be accounted for in the industries Scope 1 GHG emission inventory. If this biomethane is replacing natural gas or another fossil fuel consumed by the industry, it will reduce the Scope 1 GHG emissions of the industry associated with the combustion of fossil fuels.

**Scope 2**

Similar to Configurations 1 and 2, the combustion of biomethane by the industry to generate electricity in configuration 3 can reduce the industry's Scope 2 GHG emissions if the amount of electricity consumed from the electricity grid is reduced. This will reduce the market based, and location-based Scope 2 GHG emissions of the industry.

### Scope 3

The GHG emissions associated with the production and transportation of biomethane to the industry via the natural gas grid will need to be accounted for in Scope 3 category 3: fuel and energy related activities.

Similar to Configuration 2, if the industry sends its by-products to be used as feedstock for the anaerobic digester producing the biomethane, this can reduce the GHG emissions associated with the management of waste generated by the industry (Scope 3 category 5: waste generated in operations). If the anaerobic digester accepts animal manures and slurries from livestock in the industry's value chain (as mentioned in Configuration 2) this can also reduce the GHG emissions associated with materials purchased by the industry (Scope 3 category 1). The application of digestate to land which can be used to cultivate raw materials consumed by the industry can also reduce the Scope 3 category 1 emissions of the industry (as outlined in Configuration 2). Figure 2.3 provide a graphic representation of the potential Scope 1, Scope 2 and Scope 3 GHG emissions savings and contributions towards related to Configuration 3.

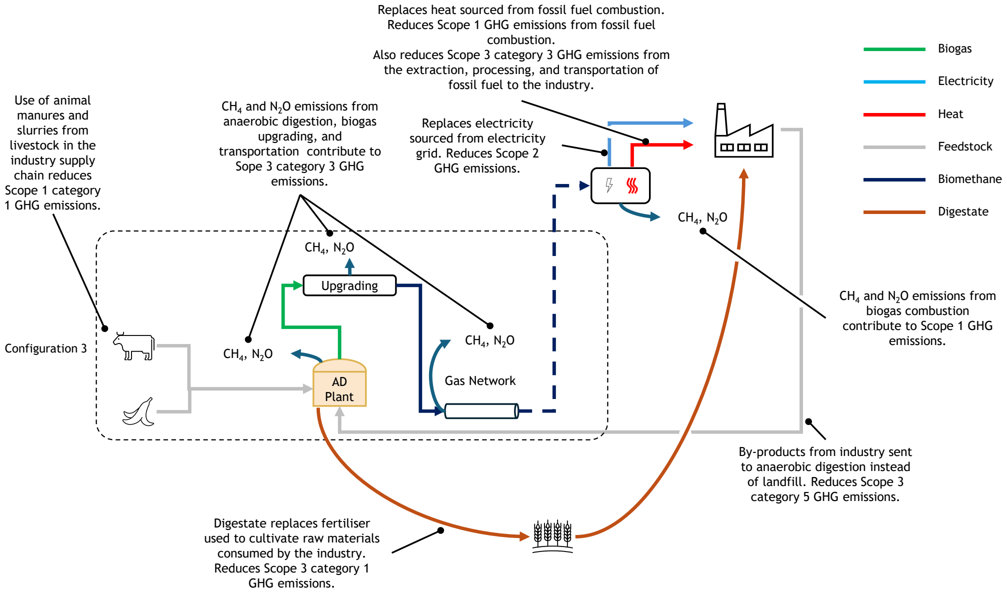


*Figure 2-3 Savings and contributions toward Scope 1, Scope 2, and Scope 3 GHG emissions from Configuration 3*

## 2.3 CURRENT BARRIERS TO BIOGAS ITEGRATION IN INDUSTRY

There are numerous barriers that may exist to the development and deployment of biogas and biomethane systems in industry, ranging from technical and infrastructural challenges, to regulatory and financial hurdles. Firstly, many industries may have entrenched or legacy energy infrastructure that are not configured for natural gas, but for other fossil fuels. This can make the switch to biogas/biomethane difficult as there may be a significant investment required to retrofit the energy infrastructure at the industry site. Additionally, in some cases biogas and biomethane may not meet the requirements of specific industry processes that are reliant on solid fuels for operation. As a result, biogas and biomethane would not be selected as a decarbonisation option in the first place.

If anaerobic digestion is considered a relevant decarbonisation technology by an industry, some further factors must be accounted for. For example, the availability and type of feedstock must be assessed. The feedstock should be attainable year-round to provide a consistent supply chain, and prior investigation should be made regarding the biomethane potential to estimate annual energy production. With regards to infrastructure, some bottlenecks may exist. For instance, if the industry is not located on the gas grid infrastructure, there may be a geographic disconnect between where the biogas/biomethane is produced and where it is needed to be used. Whilst there are methods to overcome this disconnect it may add further logistical considerations and increase overall costs in relation to system development. Another consideration is the production of digestate. Digestate is considered a valuable by-product of anaerobic digestion, but from an industry perspective it may be considered a hindrance if there are not sufficient off-takers (farmers) or a readily available land bank. The industry may consider this beyond the realm of what it does; alternatively, if the industry is part of an agricultural co-operative (producing for example cheese or milk formula) the processing, distribution and application to agricultural land of biofertiliser, may be within their remit.

The regulatory landscape for biogas and its use in industry can vary depending on the region of interest. For the use of biomethane for heat, some countries may adopt a renewable heat incentive, or equivalent support scheme, to drive technology uptake, however this policy is not harmonised across territories. Without such incentivisation, the push for industry to use biogas may not be as tangible in all countries. Industries typically rely on a consistent energy supply; thus, regulatory certainty is of increasing concern for long term investments in renewable energy infrastructure. The facilitation of higher quantities of biomethane in natural gas grid infrastructure, as has been strategised by many countries under the RePowerEU initiative in the EU, will allow industries on the gas grid to utilise biomethane and thus increase penetration of renewable gas use.

Anaerobic digestion systems will also typically require high upfront costs associated with the construction of the digester itself and any biogas upgrading facility requirements. Such financial investment may be quite prohibitive for small and medium-sized enterprises (SMEs), without external financial support. Thus, prudent financial planning by industries must consider this high investment, and assess the potential for return on investment over the project lifetime. A number of considerations would fall under such preliminary economic assessments including: the bankable market price attainable for biogas/biomethane; price volatility; feedstock acquisition cost; discount rate; CAPEX; and OPEX.

Finally, public perception of, and planning authorisation for, biogas plants can be a bottleneck in the development of such facilities, particularly in regions where the technology is not as widely used or understood. Scepticism regarding the hazards of the technology in the locality may arise due to a lack of awareness, and education regarding the process. Community engagement is paramount in the industry pursuit for biogas adoption. Educational initiatives and public outreach that emphasis the environmental benefits of anaerobic digestion may assist in overcoming such issues.

Thus, while anaerobic digestion represents a promising renewable energy technology, its use in industrial settings, must overcome the above bottlenecks to ensure the transition toward cleaner energy sources. Streamlining regulatory processes, providing financial incentives, investing in infrastructure, and developing sustainable feedstock supply chains, are critical steps in fostering the widespread adoption of biogas and biomethane in industrial applications. Only through a coordinated approach can the potential of anaerobic digestion as a renewable energy technology be realised in the industrial sector.

# 3 BIOGAS ENERGY UTILISATION IN INDUSTRY

## 3.1 CLASSIFICATION OF BIOGAS DATA

Biogas plays a crucial role in advancing renewable energy and circular economy goals. The EU is home to some of the global leaders in biogas production, with countries like Germany, Denmark, Italy, and France contributing significantly. Aforementioned policies such as the European green Deal, the Renewable Energy Directive (RED II), and RePowerEU are driving the growth of the biogas sector to promote decarbonisation and energy security. Chapter 2 outlined three potential configurations of biogas integration with industry that may be used to facilitate the reduction of Scope 1, 2, and 3 GHG emissions, specifically in an industry setting. To gain further insight into the current state of play with regards to biogas production and utilisation in a selection of IEA Bioenergy Task 37 countries and their respective industrial sectors, data from EUROSTAT (the statistical office of the EU responsible for publishing high-quality Europe-wide statistics and indicators) was collated. This dataset in relation to biogas production and utilisation specifically details:

1. Total energy supply for biogas: This includes for the indigenous production of biogas (comprised of: biogas from landfill gas; biogas production from sewage sludge at wastewater treatment plants ("*Sewage sludge gas*"); biogas produced from anaerobic digesters excluding those at wastewater treatment plants ("*other biogas from anaerobic fermentation*"); and biogas from thermal gasification processes ("*Biogas from thermal processes*")), biogas imports, biogas exports and changes in stock.
2. The use of biogas across a range of energy activities including the following classifications:
    a. Transformation:
        i. Combustion of biogas to produce:
            1. Electricity only
            2. Heat only: The proportion of biogas used to produce heat that was consumed by the heat producer (self-consumption of heat produced from biogas by an end user) is reported in the final energy consumption of the producer's sector (industry, household, commercial and public services, or agriculture and forestry).
            3. A combination of electricity and heat.
            4. The end use of biogas used in transformation to electricity cannot be disaggregated across industry or other sectors, or within the industry sector based on the available information from EUROSTAT. Furthermore, the end use of heat produced from biogas which was transferred or sold cannot be identified based on information from EUROSTAT.
        ii. Blending of upgraded biogas with natural gas via biomethane injection to natural gas networks.

    b. Final consumption:
        i. This includes for the combustion of biogas in industry for the production and self-consumption of heat
        ii. Biogas used in transport (when upgraded to biomethane),
        iii. Biogas use in other sectors (covering biogas used for the production and self-consumption of heat across households, commercial and public services, and agriculture and forestry).

    c. Energy sector: Combustion of biogas for the operation of equipment to support the transformation of biogas to electricity, heat, or a combination thereof.

d. Distribution losses: biogas losses may occur during transportation and distribution.

As the purpose of this report is to focus on the potential role of biogas to facilitate decarbonisation within industry, the final consumption of biogas in industry will be the emphasis of the following sections that investigate specific countries.

This will include for biogas used by facilities in the industrial sector for the production of heat, that was self-consumed by the facility, comparable to Configuration 1 (if the industry produces the biogas itself from its own by-products). The self-consumption of biogas for heat production (as in Configuration 1) is a key method in reducing the Scope 1 GHG emissions associated with heat production from fossil fuels in industry. It is not possible to determine the total quantity of biogas consumed by industry if the biogas is used in a CHP unit for the production of electricity and heat. Biogas used in electricity production is captured under “Transformation” and it is not possible to disaggregate the amount of biogas used to generate electricity by industries using EUROSTAT data. This may result in an underestimation of biogas consumption by industries as only the biogas used for heat production is disaggregated as final consumption by, and within, industry. Additionally, it is not possible to determine the degree to which Configuration 2 (where an industry obtains biogas, heat, or electricity directly from an external digester) has been implemented using data from EUROSTAT.

Biogas blending with natural gas (following upgrading to biomethane and injection into a natural gas network) may be analogous to Configuration 3. Data related to biogas blending is available from EUROSTAT but no data is available relating to the end use of biogas once blended with natural gas (it is possible to determine the amount of biogas used for blending with natural gas in a country, but it is not possible to determine the sector that biogas is then used in from the EUROSTAT data).

## 3.2 BIOGAS DATA OVERVIEW IN A SELECTION OF IEA BIOENERGY TASK 37 COUNTRIES

Ten countries were included for analysis based on availability of EUROSTAT data. The countries selected were the following IEA Bioenergy Task 37 members: Austria, Denmark, Finland, France, Germany, Ireland, Italy, Norway, Sweden and The Netherlands. Biogas production per capita from anaerobic fermentation (including biogas from landfill, sewage sludge, and non-sewage sludge anaerobic digesters) for the listed countries in 2022 is outlined in Figure 3-1. The figure illustrates that Denmark and Germany are the leading counties as per EUROSTAT data.

The share of biogas consumed across a range of end uses in 2022 for the ten countries is shown in Figure 3-2. End uses include: blending with natural gas (grid injection of biomethane within transformation); electricity and heat generation (including for electricity and heat generation within transformation); use in the energy sector (including biogas flaring); distribution losses (including biogas leakage); final consumption in industry; final consumption in transportation; and final consumption in other sectors.

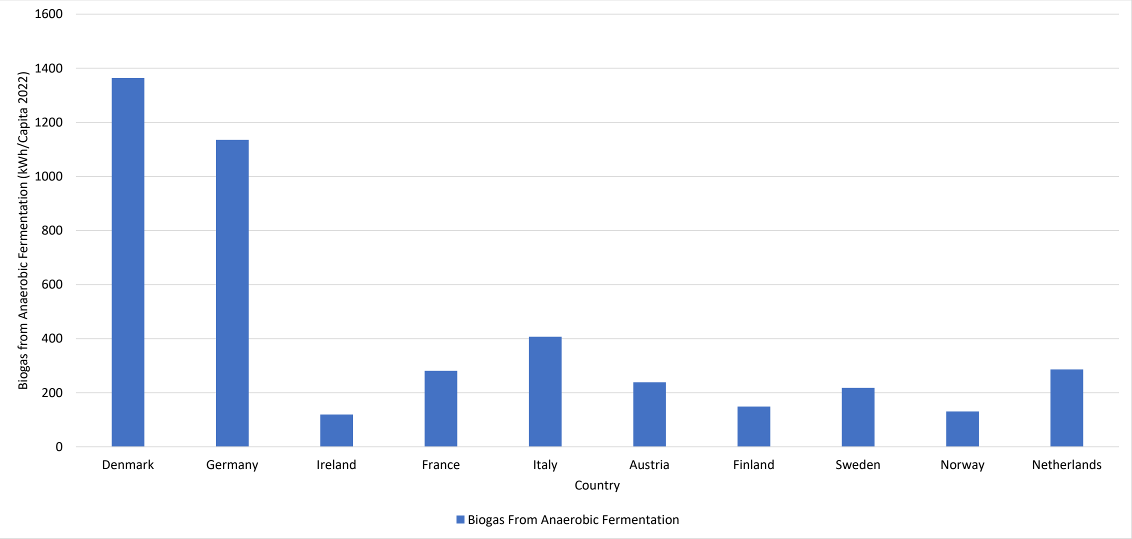


*Figure 3-1 Biogas production (from anaerobic fermentation) per capita in a selection of countries in 2022*

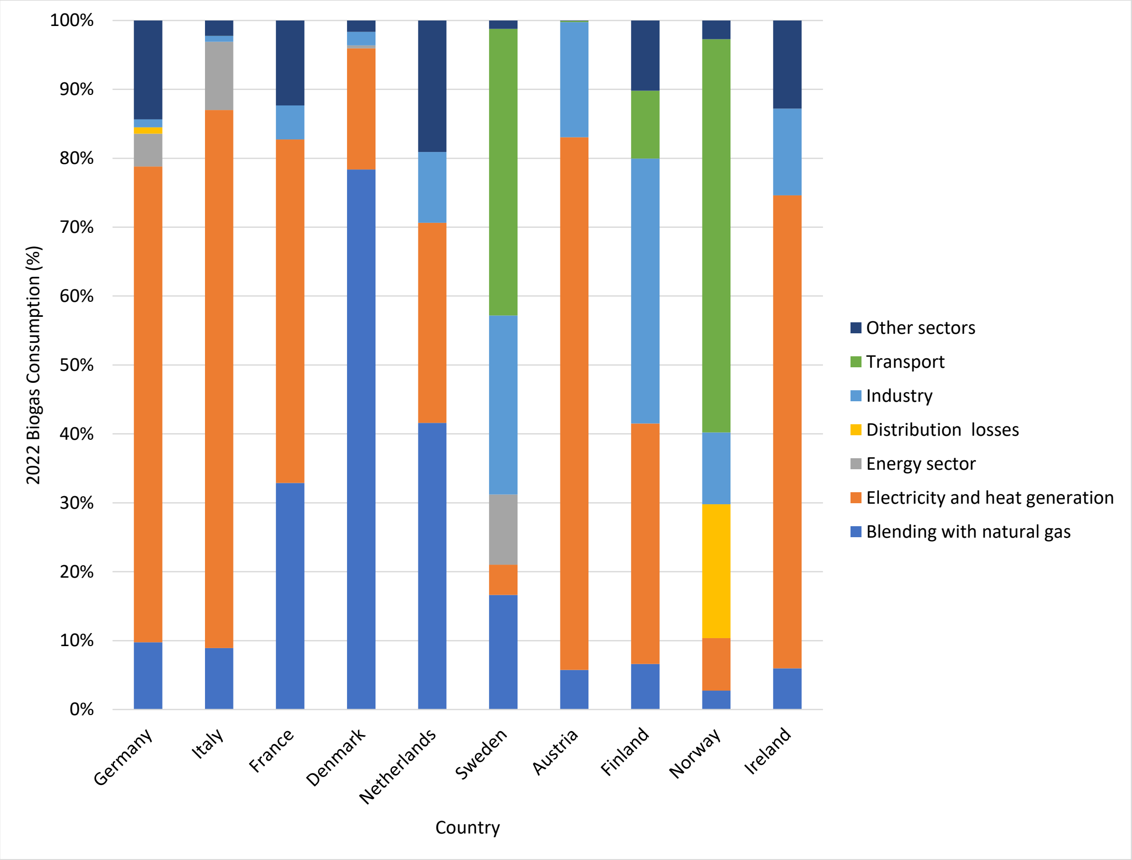


*Figure 3-2 Share of biogas consumption in a selection of countries in 2022*

The country with the largest share of biomethane injection to the gas network in 2022 was Denmark indicating the most potential for industries to avail of a Configuration 3 set up to reduce their GHG emissions through the use of biomethane. While it is not possible to determine how much grid injected biomethane was used by industries in Denmark, this large degree of gird injection can allow for industries to avail of biomethane in systems similar to Configuration 3.

The country with the largest share of biogas use for final consumption in industry in 2022 was Finland. However, as the source of biogas (landfill, sewage sludge, other anaerobic fermentation, and thermochemical biogas production from gasification) within final consumption cannot be disaggregated, and the share of biogas production from thermochemical sources in Finland is high (Appendix C Figure: B-1), it was not possible to determine if the final consumption of biogas in Finland is produced via anaerobic digestion, or via gasification. The country with the next highest share of biogas final consumption in industry was Sweden and this may indicate the use of biogas in systems more aligned to Configuration 1. Of interest is that the final consumption of biogas in transport in Sweden represented the largest end use of biogas.

Both Denmark and Sweden will be discussed in detail in the following section with regards to total indigenous biogas production, biogas end use, and the final consumption of biogas in industry. A similar discussion is also available for the remaining eight countries (Germany, Italy, France, The Netherlands, Austria, Norway, and Ireland) in Appendices A to H.

## 3.3 SWEDEN

As per Figure 3-3, Swedish biogas production was primarily from anaerobic digestion (56.5% in 2022) and biogas from sewage sludge (40.6%). Landfill gas contributed 2.9% of biogas production and no biogas production from gasification was recorded for 2022.

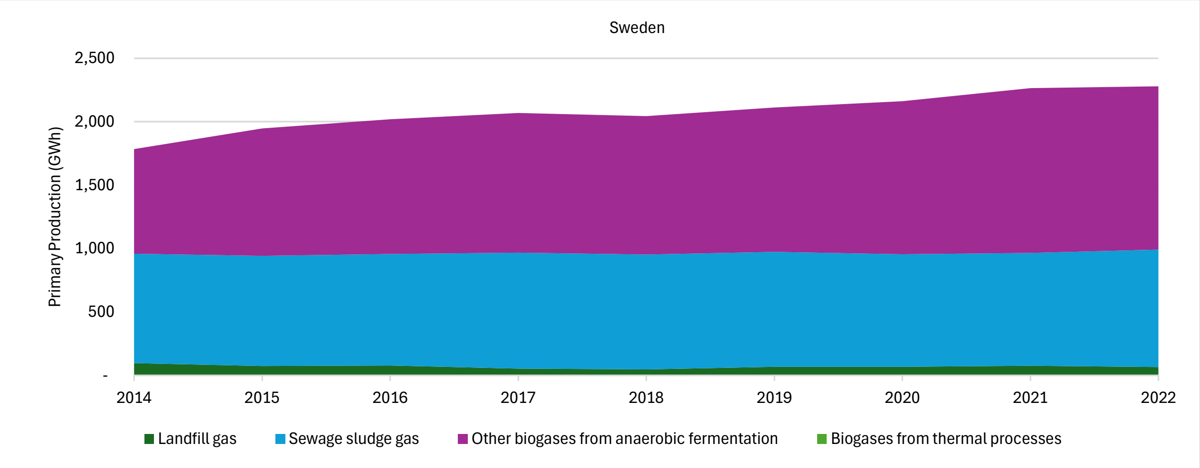


*Figure 3-3 Sources of indigenous biogas production in Sweden*

From 2014 – 2022 the average annual growth rate of biogas production in Sweden was 3.2% (Table 3-1). This was driven by an increase in biogas production from anaerobic digestion plants (5.9%), an increase in biogas from sewage sludge (0.9%), and a reduction in biogas from landfills (-2.3%). The majority of growth in biogas production in Sweden has been associated with biogas from anaerobic digestion plants.

*Table 3-1 Average annual growth rate of biogas production in Sweden*

| 2014 - 2022 | **Biogas** | Biogas from anaerobic fermentation | Landfill gas | Sewage sludge gas | Other biogas from anaerobic fermentation | Biogas from thermal processes |
|---|---|---|---|---|---|---|
| Average Annual Growth Rate (%) | 3.2 | 3.2 | -2.3 | 0.9 | 5.9 | - |

Figure 3-4 illustrates the breakdown of total biogas energy supply in Sweden in 2022.

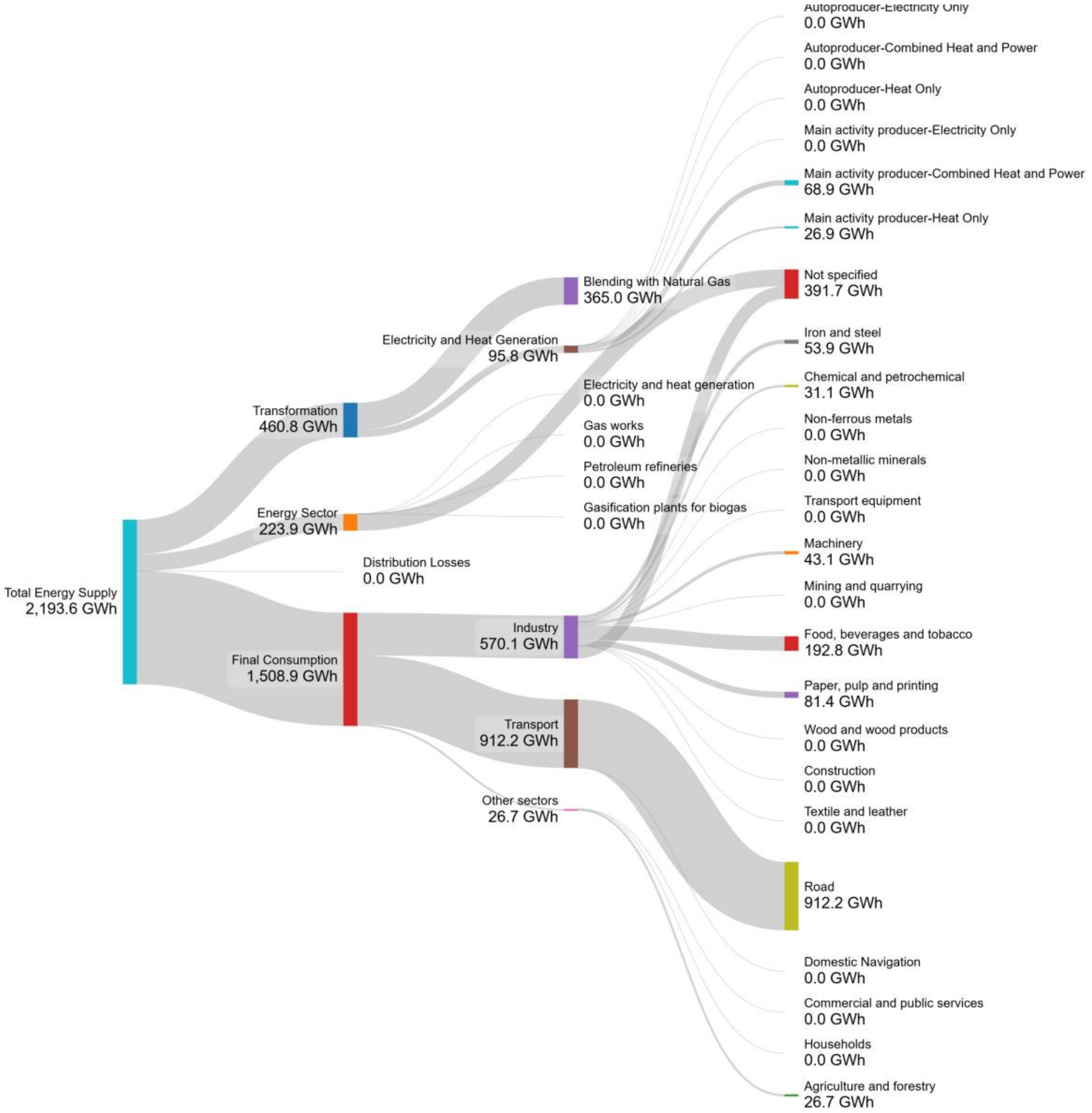


*Figure 3-4 Total biogas energy supply and use in Sweden*

Sweden has a very limited gas grid network that is restricted to certain parts of the country and thus the country adapted to use biomethane primarily as a transport fuel in heavy duty vehicles (Persson & Svensson, 2014). From an industrial perspective, use of biomethane as a transport fuel can enable a reduction in the Scope 3 GHG emissions if the biomethane is used to fuel vehicles in the upstream and/or downstream industry supply chains.

Within biogas final consumption (1,509 GWh in 2022), Industry contributed 37.8% (570 GWh) of demand and experienced an average growth rate of 45.8% from 2018 – 2022. Within Industry the majority of biogas final consumption was consumed in Food, Beverage, and Tobacco sector (33.8% in 2022 with an average annual growth of 44%), Paper Pulp and Printing (14.3 %, with an average annual reduction of -1.5 %), and Iron and Steel (9.5 % with a major increase in use in 2021 and 2022).

A full breakdown of the relevant industrial sectors for Sweden is shown in Figure 3-5 for the years 2018-2022.

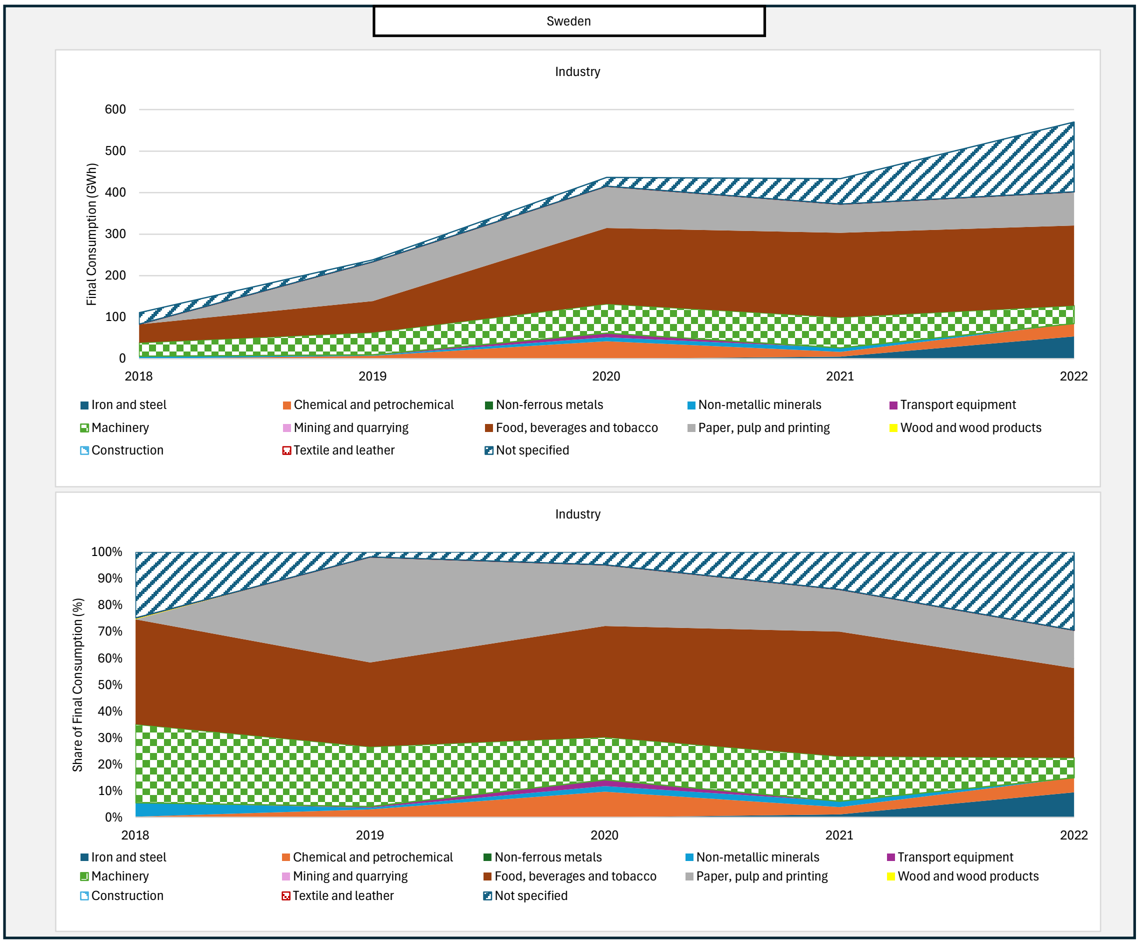


*Figure 3-5 Industry final consumption and sectoral share of biogas in Sweden from 2018-2022*

## 3.4 DENMARK

Denmark is a global leader in biomethane, with c. 70 large producers injecting biomethane into the gas grid, with 39% of gas consumption in the form of biomethane (IEA, 2023). As per Figure 3-6, 95% of biogas in Denmark in 2022 was produced by anaerobic digestion plants, excluding those at wastewater treatment plants in the form of "*Sewage sludge gas*" which contributed 4.1 % of biogas production. Landfill gas contributed 0.5 % of biogas production in 2022 with no recorded biogas from gasification ("*Biogas from thermal processes*").

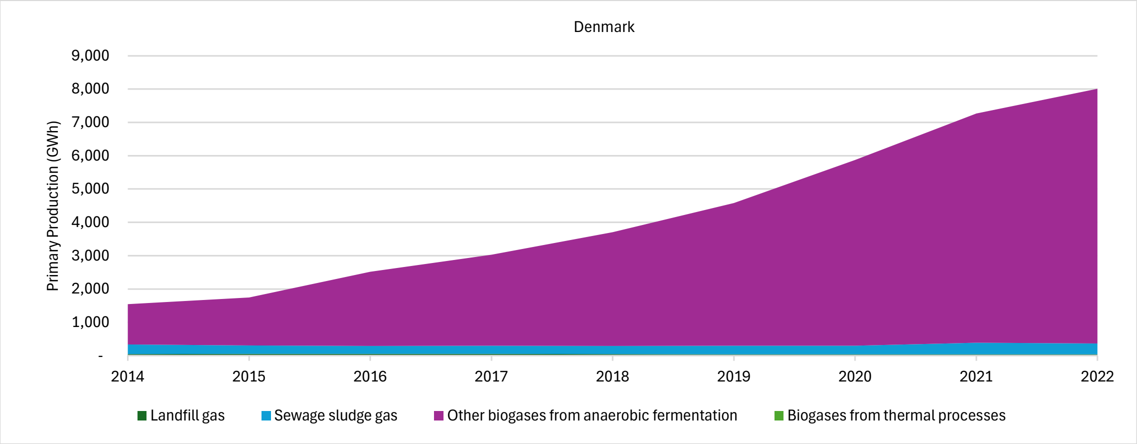


*Figure 3-6 Sources of indigenous biogas production in Denmark*

From 2014 – 2022 the average annual growth rate of biogas production in Denmark was 23.2% (Table 3-2). This was driven by an increase in biogas production from anaerobic digestion plants (23.2%), indicative of a significant uptake of biogas systems in Denmark.

*Table 3-2 Average annual growth rate of biogas production in Denmark*

| 2014 - 2022 | **Biogas** | Biogas from anaerobic fermentation | Landfill gas | Sewage sludge gas | Other biogas from anaerobic fermentation | Biogas from thermal processes |
|---|---|---|---|---|---|---|
| Average Annual Growth Rate (%) | 23.2 | 23.2 | - 3.1 | 2.5 | 26.4 | - |

Figure 3-7 illustrates the breakdown of total biogas energy supply in Denmark in 2022. The largest use of biogas in Denmark is blending with natural gas which represented 82% of total biogas use. The quantity of biogas used for blending with natural gas in Denmark has increased steadily from 1961GWh in 2019 to 6281GWh in 2022 with an annual average growth rate of 27.5%. Whilst it is not possible to determine where the biogas that was blended with natural gas is ultimately used, the large amount of blending can enable industries to implement biogas systems analogous to Configuration 3 whereby they purchase biomethane through the gas network and reduce their GHG emissions.

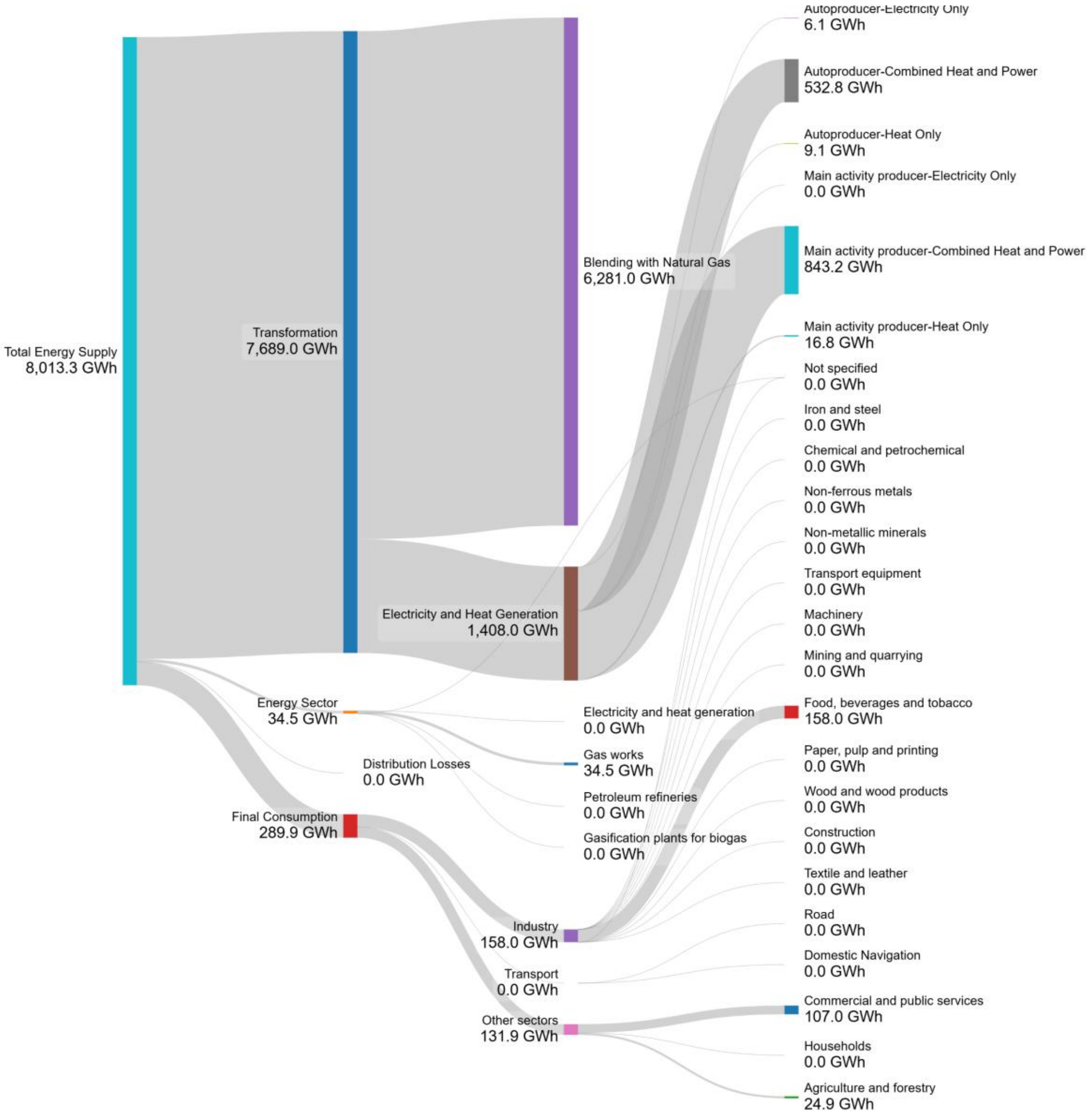


*Figure 3-7 Total biogas energy supply and use in Denmark*

Within final consumption (289.9 GWh in 2022), Industry accounted for 54.5% (158 GWh) and experienced an average growth rate of 23.3% from 2018 – 2022. This was primarily associated with a large increase from 101.5 GWh in 2018 to 240.1 GWh in 2019, followed by a reduction to current levels. Industry was responsible for 78% of the final consumption of biogas in 2020, but this reduced to 45% in 2021, with an increase in recent years to the current share. According to EUROSTAT data, final consumption of biogas in industry (100%) in Denmark was associated with the Food, Beverage, and Tobacco sector in 2022, with an annual average growth rate of 23.3%.

A full breakdown of the relevant industrial sectors for Denmark is shown in Figure 3-8 for the years 2018-2022.

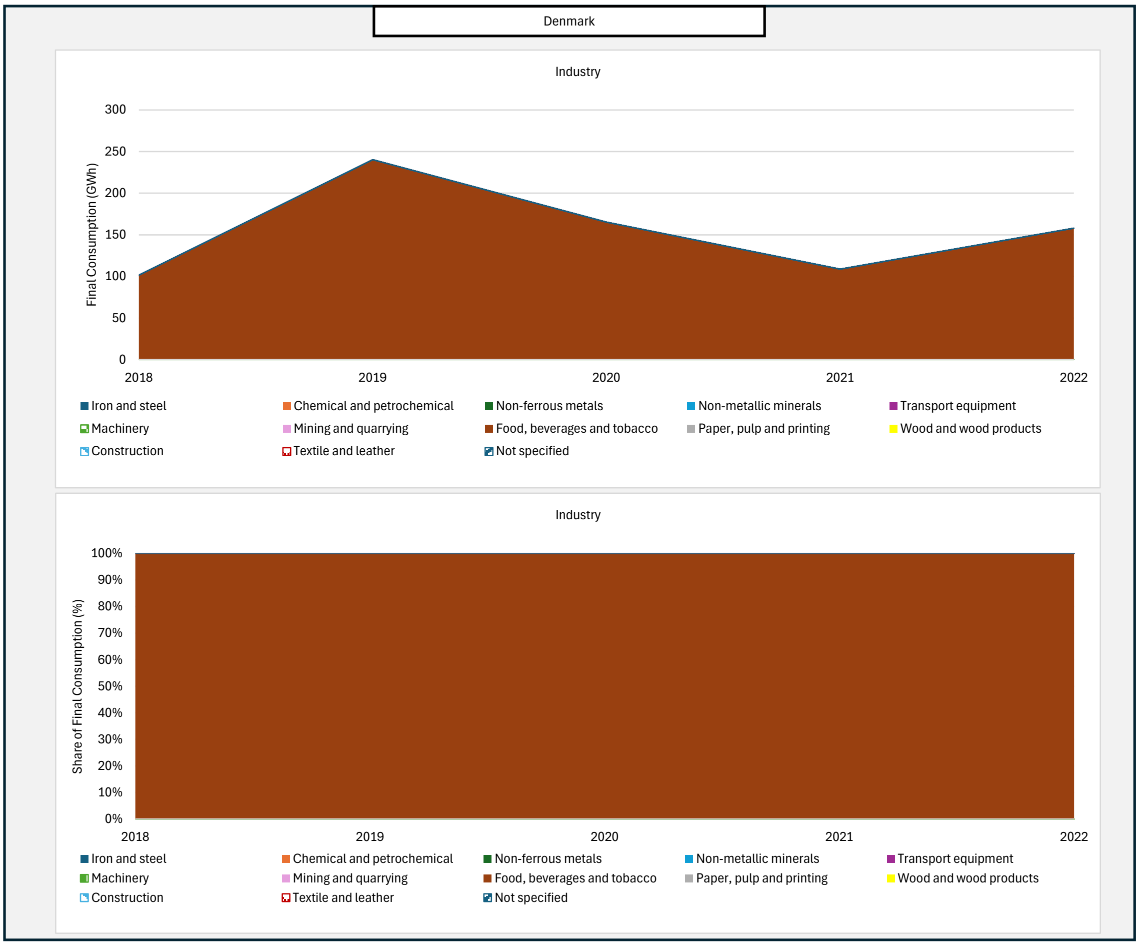


*Figure 3-8 Industry final consumption and sectoral share of biogas in Denmark from 2018-2022*

## 3.5 COUNTRY COMPARISON

A comparison of the share of final consumption of biogas attributed to Industry in 2022, and the annual average growth rate of biogas use in Industry from 2018-2022 is provided in Figure 3-9.

For Austria (99%), Denmark (66%), and Ireland (50%), (Figure 3-9) Industry is responsible for 50% or more of biogas final consumption, however growth rates of biogas use in industry vary widely between these countries. Of the countries documented in this report, Denmark experienced the second highest annual average growth rate of biogas used in Industry (23%), Ireland experienced the third highest average annual growth rate (12%), whilst Austria experienced the 6th highest growth rate (8%). Within these three countries, Industry plays a major role in the final consumption of biogas (primarily for heat production) and this role is increasing as evidenced by the average annual growth rates outlined.

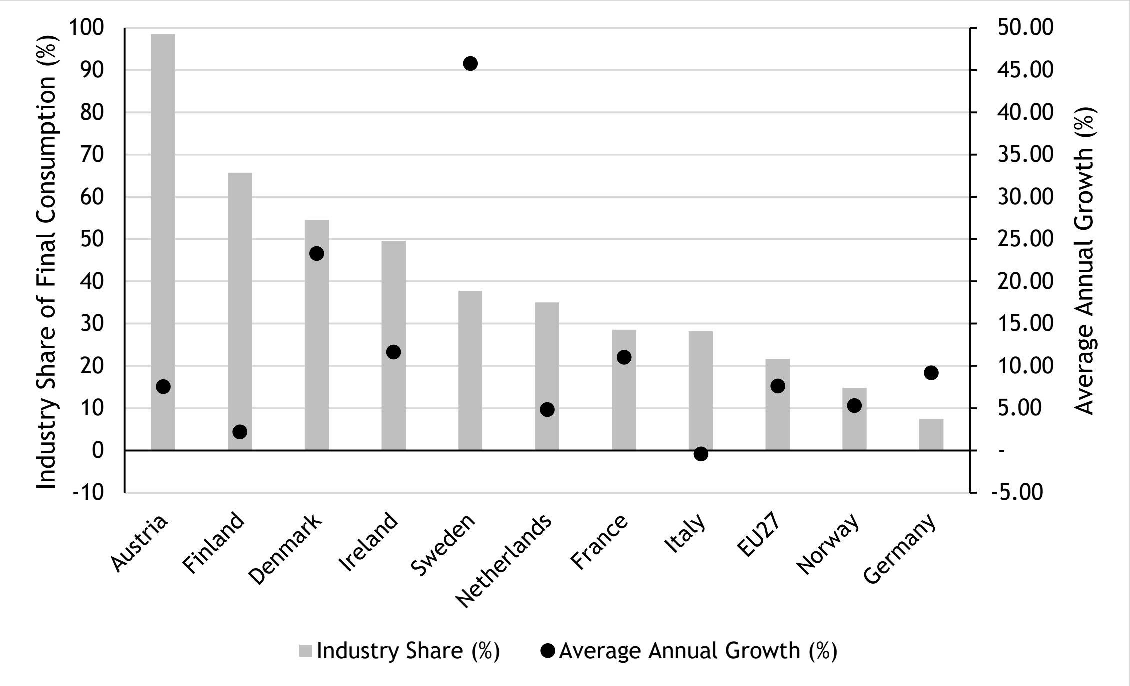
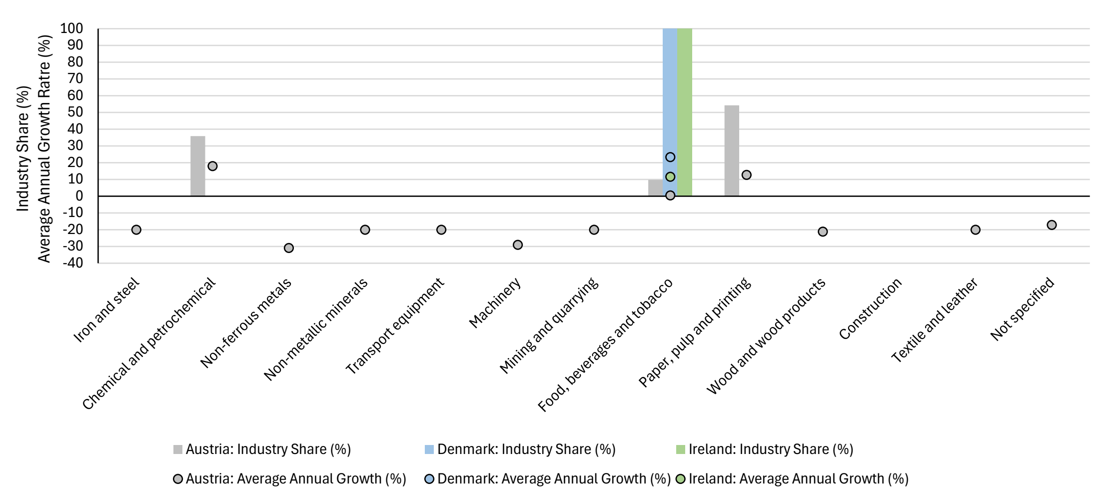


*Figure 3-9 Comparison of Biogas Final Consumption and Growth in Industry*

Industrial biogas consumption in Austria is primarily associated with the Paper, Pulp, and Printing sector (54% in 2022), the Chemical and Petrochemical sector (36% in 2022), and the Food, Beverage, and Tobacco sector (9% in 2022). In Denmark and Ireland, the main use of biogas in Industry is within the Food, Beverage, and Tobacco sector (100% in 2022). This highlights the prevalence of biogas use in Industry sectors where biodegradable by-products and residues are available for use as feedstock for anaerobic digestion. Growth of biogas use in the Food, Beverage, and Tobacco sector within Denmark (23%) and Ireland (12%) shows a growing use of biogas in this sector as companies seek to decarbonise their operations. In contrast to this, the growth of biogas use in the Food, Beverage, and Tobacco sector in Austria is much lower (0.5%), however there is growth in biogas use in the Paper, Pulp, and Printing sector (13%) which is another sector where by-products and residues suitable for biogas production may be considered plentiful. A further point of difference is the consumption of biogas in the Chemical and Petrochemical sector within Austria (36%) along with a strong growth average annual growth rate of 18% which is absent in both Denmark and Ireland (Figure 3-10).

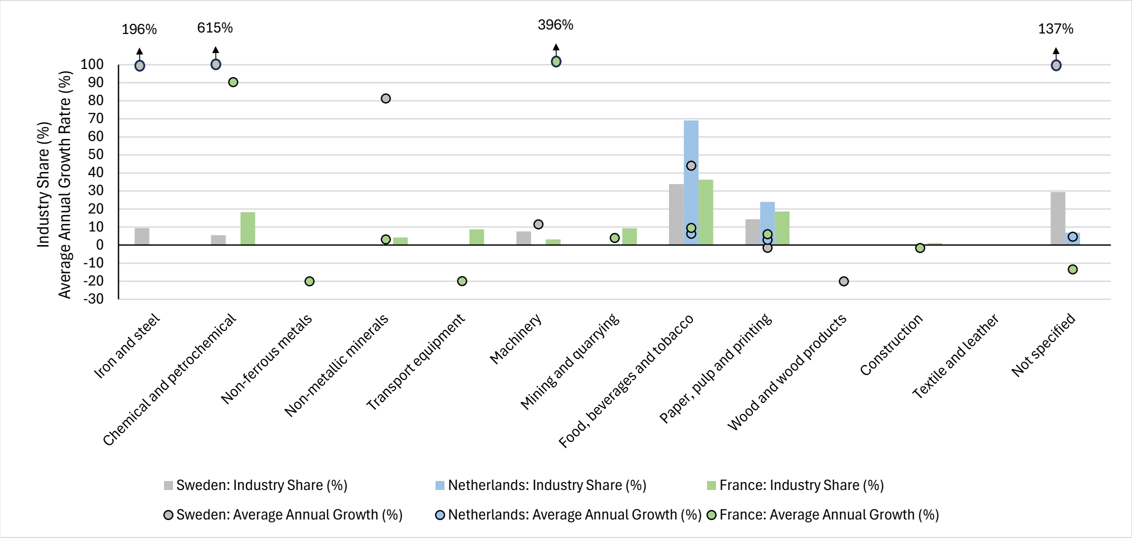
Sweden (38%), The Netherlands (35%), and France (29%) have the next highest share of biogas final consumption in Industry. Average annual growth rates vary widely, Sweden has the highest growth rate of any country in this report (46%), France has the fourth highest growth rate (11%), whilst The Netherlands had the third lowest average annual growth rate (4.8%).



*Vertical bars represent the share of biogas final consumption in Industry in 2022.*
*Circular markers represent the annual average growth rate over the period 2018 - 2022 (inclusive)*
*Figure 3-10 Biogas Final Consumption and Growth in Industry: Austria, Denmark, and Ireland.*

The final consumption of biogas in Industry is primarily in the Food, Beverage, and Tobacco sector within Sweden (34%), The Netherlands (69%), and France (36%) where by-products and residues suitable for anaerobic digestion are available (Figure 3-11). The use of biogas in this sector is also growing across all three countries with Sweden exhibiting an annual average growth rate of 44%, followed by France at 9.5%, and The Netherlands at 6%, indicative of the growing importance of biogas use in this sector. The second largest Industrial sector in terms of biogas final consumption across all three countries is the Paper, Pulp, and Printing sector (again, a sector with biodegradable by-products and residues suitable for anaerobic digestion), however the average annual growth of biogas use in this sector is lower than that of the Food, Beverage, and Tobacco sector for all three countries (Figure 3-11).

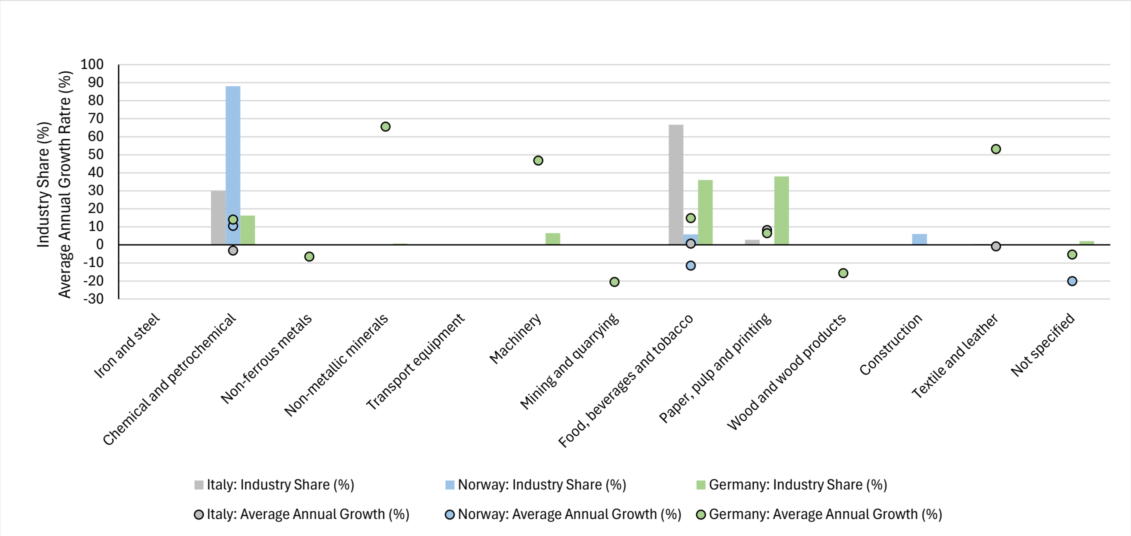
Outside of these two sectors biogas use has also grown in the Iron and Steel sector, the Chemical and Petrochemical sector, and the Machinery sector in Sweden in recent years. The use of biogas in these sectors would aid in their decarbonisation by replacing fossil fuels. The exact source of the biogas used in these sectors is not available from EUROSTAT data but owing to the lack of biodegradable materials from these sectors it is possible that the biogas is purchased from offsite producers either through the gas network, or via a virtual biomethane pipeline. Similarly, biogas use in France has also grown in recent years in the Chemical and Petrochemical sector, Non-metallic Minerals, Transport Equipment, Machinery, and Mining and Quarrying. These sectors do not typically produce biodegradable materials suitable for anaerobic digestion, but the growing use of biogas indicates that biogas produced from an external source is being used to aid in the decarbonisation of these sectors.



*Vertical bars represent the share of biogas final consumption in Industry in 2022.*
*Circular markers represent the annual average growth rate over the period 2018 - 2022 (inclusive)*
*Figure 3-11 Biogas Final Consumption and Growth in Industry: Sweden, Netherlands, and France*

Industry biogas final consumption in Italy (28% in 2022), Norway (15% in 2022), and Germany (7% in 2022; Figure 3-12) is the lowest of the countries considered in this report, however biogas final consumption is growing in Norway (average annual growth 5.3%) and Germany (average annual growth of 9.2%) indicating the growing role that biogas is playing in decarbonising industry. This is contrasted with a minor reduction in biogas final consumption in industry in Italy (average annual growth of -0.4%) primarily caused by a reduction from 2018 to 2019 (since then biogas consumption has grown albeit rather slowly).

Industrial biogas use in Italy is primarily in the Food, Beverage, and Tobacco sector (67%), in Germany biogas is used primarily in the Paper, Pulp, and Printing sector (38%) and the Food, Beverage and Tobacco sector (36%), while in Norway the majority of biogas use in Industry is in the Chemical and Petrochemical sector (88%) (Figure 3.37). The Chemical and Petrochemical sector in Italy (30%) and Germany (16%) represent the second and third largest users of biogas in industry, respectively (Figure 3-12). As is the case for most of the prior countries in this report, biogas use is high in sectors where biodegradable by-products and residues are available for use as feedstock in anaerobic digestion. Of interest is the share of biogas final consumption in the Chemical and Petrochemical sector which does not typically generate by-products or residues suitable for anaerobic digestion. This indicates that biogas may be sourced externally in efforts to decarbonise this sector.



*Vertical bars represent the share of biogas final consumption in Industry in 2022.*
*Circular markers represent the annual average growth rate over the period 2018 - 2022 (inclusive)*
*Figure 3-12 Biogas Final Consumption and Growth in Industry: Italy, Norway, and Germany*

Overall, the Food, Beverage, and Tobacco sector is responsible for the largest share of Industry biogas final consumption in Denmark, Ireland, France, Italy, The Netherlands, and Sweden. The Paper, Pulp, and Printing sector is responsible for the largest share of Industry biogas consumption in Germany and Austria. Both of these sectors generated by-products and residues which are suitable for biogas production via anaerobic digestion and as such the large share of industry biogas final consumption attributed to them is unsurprising.

As outlined in Section 2.2.1 facilities in the Food, Beverage, and Tobacco sector, as well as the Paper, Pulp, and Printing sector, may use their own biodegradable by-products for biogas production in anaerobic digesters owned by the facility themselves (Configuration 1). This biogas may then be used to reduce Scope 1, Scope 2, or Scope 3 GHG emissions. It may also be possible for facilities in these sectors to send their by-products to an offsite anaerobic digester in their locality under the control or ownership of a separate entity as was outlined in Configuration 2. Additional biodegradable feedstock may also be processed by this digester. The use of biogas from this offsite digester (delivered to the industry facility via a dedicated biogas pipeline, or a virtual biomethane pipeline), or the use of heat and electricity procured from this offsite digester may also reduce the Scope 1, Scope 2, and Scope 3 GHG emissions of the facility. Finally, the biodegradable by-products may be transported to an anaerobic digester at a remove from the industry and combined with additional by-products to produce biogas that is then upgraded to biomethane and injected into the natural gas network. The industry which produced these biodegradable by-products may then avail of a contractual agreement (such as a guarantee of origin) to procure the biomethane produced in order to reduce their Scope 1, Scope 2, and Scope 3 GHG emissions.

The Chemical and Petrochemical sector is responsible for the largest share of biogas final consumption in Norway, it is the second largest consumer in Austria and Italy, and it is the third largest user in France and Germany. This sector does not generate by-products or residues which are typically used for biogas production, and the increase in biogas consumption in this sector could indicate an increase in the acquisition of biogas from external sources by industries in the Chemical and petrochemical sector as they seek to decarbonise their operations.

These external sources of biogas may be aligned with Configuration 2 or Configuration 3 as outlined in Sections 2.2.2 and 2.2.3. In Configuration 2 the industry would obtain the biogas directly via a dedicated biogas pipeline from an anaerobic digester in close proximity to the industry, or, via a dedicated virtual biomethane pipeline delivering biomethane to the industry. As the biogas and biomethane are delivered directly to the industry in Configuration 2, guarantees of origin (or equivalent contractual frameworks) may not be required when assessing the reduction in Scope 1 GHG emissions from the combustion of this biogas or biomethane. If the industry obtained biomethane through the natural gas network, then a contractual framework (similar to a guarantee of origin) is required to provide assurance to the share of biomass gas (that has a $CO_2$ emission intensity of zero) purchased by the industry, if it is operating in the EU-ETS for the purpose of reporting Scope 1 GHG emissions under the Corporate Sustainability Reporting Directive (CRSD) within the EU. The rise of biogas use in industrial sectors that do not produce biodegradable by-products suitable for anaerobic digestion indicates the growing role that biogas is playing in the decarbonisation of the wider industrial sector.

# 4 DELIVERY OF BIOGAS ENERGY TO THE END USER

## 4.1 LOGISTICAL CONSIDERATIONS OF ANAEROBIC DIGESTION

The configuration of anaerobic digestion systems can vary due to several logistical considerations. However, the characteristics of a biogas plant are most typically dependent on the feedstock utilised and the end-use of the biogas (or biomethane) produced. Alongside such technical and logistical considerations of a biogas plant, considerable community engagement is also typically made to address any concerns and ensure social acceptance prior to system development.

As described in Chapter 2, there are nuances in relation to the utilisation of biogas in industry. Configuration 1 was indicative of an industry that generates its own by-products, organic wastes and residues and utilises such resources in their own on-site anaerobic digestion system. Configuration 2 and Configuration 3 implied that the industry is coupled with an off-site digester in the locality that operates on feedstock that may not be generated at the industry site (agricultural wastes and residues) but the energy generated is supplied to the industry site. Regardless of whether the biogas plant is on-site or off-site, it is important that a constant supply of feedstock is available for continuous operation of the digester. For example, having only seasonal availability of feedstock such as animal slurry (for example in an off-site digester in Configuration 2 or Configuration 3), as would be typical in pasture-based farming systems such as those in Ireland, has been shown to increase the greenhouse gas emissions of the biomethane produced and require increased digestate recirculation to maintain digester operation (Ó Céileachair et al., 2022). The digester should also be situated as close as possible to the feedstocks to minimise transportation requirements and improve sustainability. Depending on the feedstock, some form of mechanical pre-treatment may be required. For example, lignocellulosic crops such as grass may need to be macerated to smaller particle sizes to optimise the digestion process and ensure sufficient mixing (Wall et al., 2015). Furthermore, adequate storage systems for the feedstocks should be in place to ensure year-round, uninterrupted supply.

Different digester technologies can be implemented. The continuously stirred tank reactor (CSTR) is the most common type of anaerobic digester. However, designs can also include for two-phase and two-stage systems to maximise the potential energy or value from the feedstock. A two-stage process could include for the same reactor type in series, for example a CSTR followed directly by a second CSTR; the feedstock would pass through both with the majority of the digestion taking place in the first reactor. A two-stage system can prolong the retention time of material in the system to ensure maximum biogas production. Furthermore, the second stage digester can also operate as a digestate storage system (with residual biogas capture) until land application of digestate is permitted. For two-stage systems it is typical that all microbial reactions occur in both reactors.

In a two-phase system the microbial processes are typically separated (Guneratnam et al., 2017) – hydrolysis and acidogenesis occurring in the first reactor (optimised at a pH of about 5.5 and high organic loading rate with inhibition of methanogenesis) followed by acetogenesis and methanogenesis in the second reactor (optimised at a pH of 7.5 with a low organic loading rate). This can again be two CSTRs in series or can include for two different reactor types which can process the solid and liquid components of the feedstock separately, for example, a leach bed reactor (LBR) combined with an upflow anaerobic sludge blanket (UASB) i.e., a dark fermentation reactor followed by a methanogenic reactor (Nizami & Murphy, 2011). Such two-phase systems have the advantage of potentially diversifying beyond just energy production in anaerobic digestion by facilitating the production of high-value-added products such as bioplastics or biobased chemicals (see Chapter 5). The two-phase approach emphasises the variability and flexibility of anaerobic digestion, which can progress from a primarily single product technology (biogas) to a multi-product technology (biogas, biobased products, digestate valorisation and $CO_2$ utilisation).

Digestate management is also a significant consideration of anaerobic digestion plants. Although rich in nutrients (N, P and K) and considered an effective biofertiliser, digestate management can be a significant barrier to the economic and environmental performance of a biogas plant (O'Shea et al., 2022). Currently, the most common digestate management practise is land spreading as a biofertiliser. However, if incorrectly managed it can lead to an oversupply of nutrients and contribute to the pollution of waterways via run off or leaching; this may require digestate to be transported greater distances from the biogas plant so as not to breach strict nutrient application limits. With over 90% moisture content, digestate transportation can be an added challenge, further increasing barriers to digestate use. Digestate management strategies will therefore be critical to facilitate the sustainable growth of the biogas sector.

As indicated in Chapter 2, the biogas produced from the digester can be utilised via a number of potential options (end-uses) depending on the biogas plant configuration:

1. Biogas can be used directly in a boiler for the generation of renewable heat;
2. Biogas is used directly in a combined heat and power (CHP) unit for the production of electricity and heat;
3. Biogas is upgraded to biomethane and used as a source of heat at a remove from the site, or as a transport fuel;
4. Biogas is upgraded to biomethane and injected to the natural gas grid for use where required.

The size and scale of the biogas plant is relative to which of the options above is selected for biogas end-use. Traditionally, smaller biogas plants of up to 0.5MW capacity would most likely not upgrade the biogas due to the lower volumes of production and the subsequent high cost of biogas upgrading (Diaz Huerta et al., 2023). Alternatively, if the digester is being developed primarily for electricity production, then there is no need to upgrade to biomethane as biogas can be used in a CHP. Larger anaerobic digestion systems of up to 10MW are more suited to biomethane production due to the high volumes of production and the greater flexibility of biomethane as an energy carrier.

### 4.1.1 AVAILABILITY OF GAS GRID INFRASTRUCTURE

Biogas comprises of primarily methane (50-60%) and carbon dioxide (40-50%), with small amounts of other gases such as hydrogen sulphide. The process of purifying biogas to produce biomethane (>97% methane) is termed upgrading. While biogas can be burned directly for heating or electricity generation, it must be upgraded to natural gas quality (biomethane) before it can be compressed for injection to natural gas grid infrastructure. Biomethane has a composition equivalent to that of fossil fuel natural gas and can be used for the same purposes.

As mentioned, the location of available feedstocks will often dictate the siting of a biogas plant, as transporting feedstocks over long distances can be economically and environmentally unsustainable. This is particularly true for high water content feedstocks such as animal slurries and manures. For agricultural biogas plants it may be the case that the biogas plant is remote from any natural gas grid, or simply the region has a very limited gas grid infrastructure such as Sweden. Integrating anaerobic digestion with the gas grid however has the benefit of connecting the technology with the wider energy system and enables the use of biomethane by industries which do not generate biodegradable by-products suitable for the production of biogas in onsite anaerobic digesters (as outlined in Configuration 3). In essence, connection with existing gas grid infrastructure provides for increased opportunities for distribution and utilisation of the biomethane produced, beyond the vicinity of the biogas plant. This potentially increases the energy security of the biogas plant as there is a constant outlet for the product and the operator is not reliant on a local off-taker. Furthermore, the direct injection of biomethane aligns with many countries ambitions and policies to decarbonise their gas networks and transition away from fossil gas (Liebetrau et al., 2021).

If an anaerobic digestion plant producing biomethane cannot be connected with the gas grid infrastructure, it will most likely need to supply the gas (biogas or biomethane) to a nearby large energy consumer. This can involve its own complexities such as a gas demand that can vary seasonally (higher summer or winter demand). This situation can affect the operational characteristics and logistics of an on-farm biogas plant (Ó Céileachair et al., 2022). Without access to the gas grid, the transportation of gas from the biogas plant to the end user involves complex logistical planning, including decisions on whether to upgrade the gas and determining its final use.

### 4.1.2 DECENTRALISED BIOMASS RESOURCES

Agricultural biomass is an important feedstock for anaerobic digestion. In countries such as Germany, France, Italy, and Denmark, all of which have a strong tradition of anaerobic digestion uptake, agricultural residues make up the majority of the feedstock used (International Energy Agency, 2024)). Agricultural feedstocks include for crop residues, animal manures and slurries, catch crops and energy crops, although the latter is now regarded as less favourable. With the context of a rural setting, such agri-derived feedstock may not be in the vicinity of a gas grid network. Such feedstocks can thus be considered decentralised biomass, that is, located at a considerable distance from suitable gas grid infrastructure that would allow for easy transportation and distribution of biomethane. This can extend to the point whereby the use of biomethane can become logistically challenging or uneconomical.

A previous study investigated the decentralised agricultural biomass resource in Ireland (Ó Céileachair et al., 2021). Whilst ‘decentralised’ has no defined distance, a range of distances were analysed from the existing gas grid network in Ireland, with the quantity of biomass analysed also. Over 56% of the total national biomethane resources in Ireland, associated with agricultural feedstocks, was found to be in excess of 5 km from the national gas grid, and over 29% of the total national biomethane resources in Ireland was over 15 km from grid infrastructure. This can be particularly challenging for animal slurry as a feedstock due to its low solids content – transporting such feedstock to a digester located in proximity to the gas grid may be impractical. Increasing the number of vehicle movements required for the transportation of remote feedstocks to biogas plants situated on the gas grid can potentially be detrimental to the environmental (and economic) sustainability of such systems, and the potential for increased objections by the public.

What constitutes as “decentralised” may be somewhat ambiguous and differ depending on the country of analysis. In Ireland, the national gas grid network is developed to serve large anchor tenants such as power stations or large industry energy users. Many urban centres in the vicinity of these users have been connected to the grid. Agricultural feedstocks, which are in abundance, are often located in rural areas away from the gas grid. Figure 4-1 and Figure 4-2 depict illustrations of the dairy slurry and grass feedstock resource in Ireland, respectively, and the associated biomethane resource at a distance of over 15km from existing gas grid infrastructure. Furthermore, Table 4-1 illustrates an origin-destination matrix of percentage of national gross (on-farm) biomethane resource in Ireland at varying distances from gas grid but within specific distances of large industry energy users who could avail of this resource. With such resources, it would be prudent to couple with local industry to potentially decarbonise remote of any gas grid network.

*Table 4-1 Origin-destination matrix of percentage of national gross (on-farm) biomethane resource in Ireland at varying distances from gas grid and within specific distances of large industry energy users (adapted from Ó Céileachair et al., 2021)*

| | | | | | |
|---|---|---|---|---|---|
| **Distance from Large Industry Energy User** | **<20km** | | | | **14.4%** |
| | <15km | | | 17.3% | 12.3% |
| | <10km | | 16.1% | 12.3% | 8.6% |
| | <5km | 9.7% | 7.4% | 5.7% | 3.9% |
| | | >5km | >10km | >15km | >20km |
| | | **Distance from Gas Grid Infrastructure** | | | |

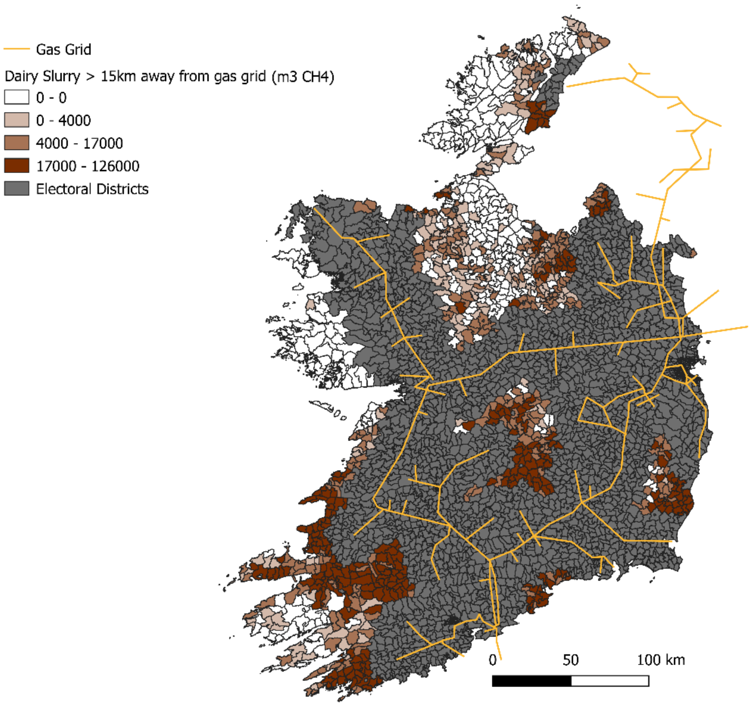


*Figure 4-1 Biomethane resource from dairy slurry feedstock resource in Ireland at distances greater than 15km from existing gas grid infrastructure (adapted from Ó Céileachair et al., 2021)*

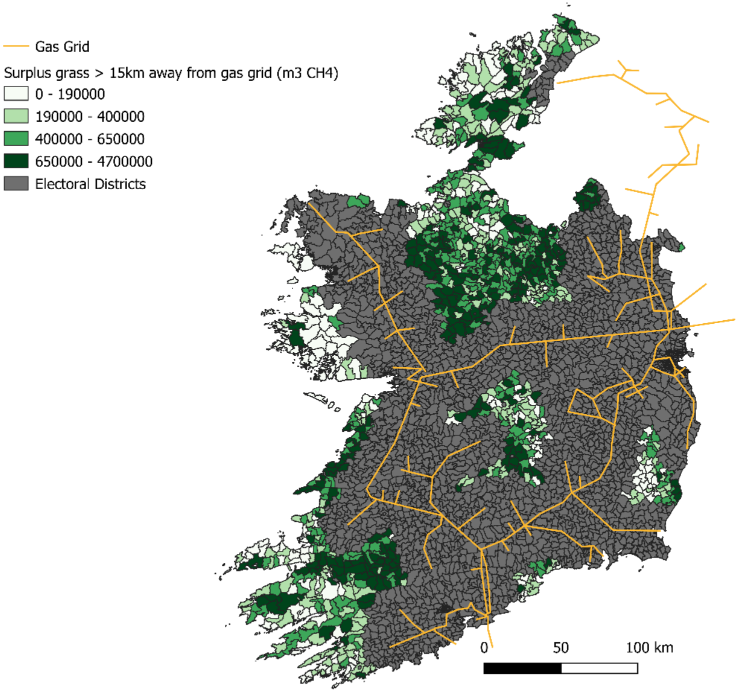


*Figure 4-2 Biomethane resource from grass feedstock resource in Ireland at distances greater than 15km from existing gas grid infrastructure (adapted from Ó Céileachair et al., 2021)*

### 4.1.3 COUPLING OF LARGE INDUSTRY ENERGY USERS WITH BIOGAS SYSTEMS

Large industries with significant energy demand that are situated away from gas grid infrastructure can potentially be coupled with biomethane generated from decentralised biomass located within the vicinity of the industry site. This is analogous to Configuration 2 outlined in Chapter 2, Section 2.2.2. This use of biomethane in industries provides a means for industry decarbonisation (by reducing Scope 1, Scope 2, and Scope 3 emissions) whilst also providing an outlet for decentralised biogas plants. The potential synergy of coupling industry and decentralised biogas plants can facilitate a higher penetration of anaerobic digestion plants (as a climate mitigation technology), utilising resources that may have previously been considered as not favourable, and facilitating the use of biogas and biomethane by industries which do not produce biodegradable by-products suitable for anaerobic digestion. It is likely that in such instances the biogas plant would be situated in proximity to the industry site (Configuration 2) and could avail of feedstock from the immediate vicinity of the site, within 2.5km of the large energy user. Figure 4-3 shows a flow diagram of some of the different biogas/biomethane end-use possibilities in relation to industry use.

Previous work by O'Ceileachair et al. (2021) proposed two decentralised biomethane facilities in Ireland at two industry sites (A and B) situated at 19 km and 36 km respectively from the Irish natural gas grid (Ó Céileachair et al., 2021). The biomethane resource within a 2.5km radius of the industry sites was quantified and compared to the existing fuel consumption of industry A (ca. 27 TJ) and industry B (ca. 17 TJ). The use of biomethane would require both industries to switch current fuel systems onsite (from oil based energy systems to gas) but was shown to reduce Scope 1 emissions by 322 $tCO_2/a$ at industry A and by 268 $tCO_2/a$ at industry B.

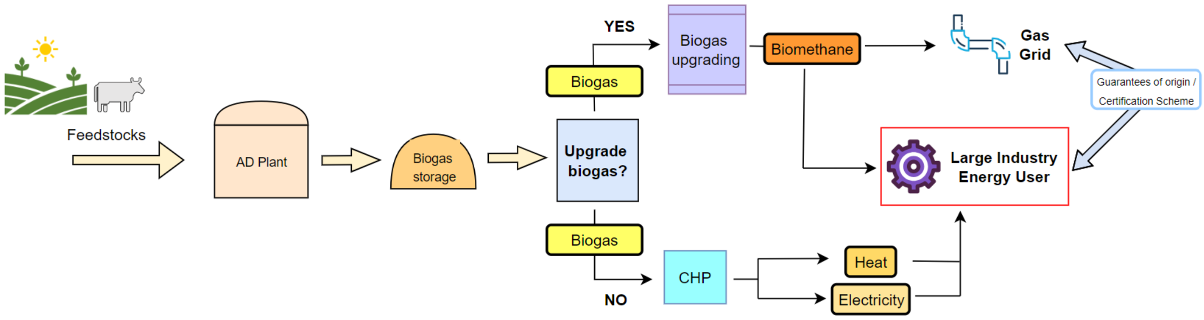


*Figure 4-3 Biogas and biomethane end-use potential with industry use*

## 4.2 ALTERNATIVE BIOGAS AND BIOMETHANE DELIVERY METHODS

### 4.2.1 BIOGAS PIPELINES

Biogas plants that are located at a distance from gas grid infrastructure can be connected (together and to a centralised industry user) via dedicated biogas pipelines. These localised pipelines represent a type of micro-grid infrastructure that can be utilised to transport biogas in areas where it is not possible to connect to national gas grid networks. This would prompt a type of “hub and pod” model whereby smaller biogas plants (pods) within a region are connected and produce biogas for a hub – which could be an industry with a demand for biogas to replace fossil fuels, or a centralised biogas upgrading facility for biomethane. The latter has proved successful in the Netherlands whereby a number of digesters deliver biogas via pipeline to a central refining and injection point (IEA Bioenergy Task 37, 2017). In effect, it offers a solution that may be cost optimal for smaller anaerobic digestion systems that cannot avail of economies of scale associated with biogas upgrading facilities. Such a model could also enable the further use of biogas and biomethane by industries which do not produce by-products suitable for anaerobic digestion (Configuration 2 and Configuration 3).

The development of biogas pipeline infrastructure at a regional level requires optimisation of logistics, specifically the physical layout of the desired pipeline that connects the biogas plants to the end user. To reduce costs, the optimal solution would be to build pipelines with the shortest path, however this is not always feasible due to property constraints, land access or otherwise. In an Irish context, a previous study investigated the design of biogas pipelines through a specific case study that considered an area of ca. 120 km$^2$ in Ireland (Ó’Céileachair et al., 2024). The area under analysis was assumed to have ten biogas plants and one end user for the biogas. To connect the biogas plants, two design layouts were considered:

1. Steiner Minimum Spanning Tree (Steiner MST) which uses Steiner points to create the shortest length of pipeline (shortest network connection) to connect the ten biogas plants with no constraints on where the pipeline can be routed;
2. Road Network Minimum Spanning Tree (Road Network MST) which connects ten biogas plants following the road network (to minimise land access issues) until the end user is reached.

Two heuristic approaches were also considered as part of the study with the intention of either maximising biogas flowrate or minimising the total biogas pipeline length:

1. Biogas output heuristics which connect the biogas plants in order of largest to smallest in terms of biogas production;
2. Proximity heuristics which, for example would connect the biogas plants in order of their proximity to the biogas end user.

The results of the methodological study showed that Steiner MST designs (implying the shortest network configuration) will result in shorter pipeline lengths which will minimise cost, however land access costs may be a significant barrier with such an approach. Road network MST configurations could increase traffic disruption while the biogas pipeline is being developed which may lead to increased objections from residents and businesses, however permission for such construction may be more straightforward. In relation to heuristics, biogas output may be important if a desired biogas production rate (and sufficient gas flow) is required for a centralised upgrading facility. Proximity heuristics should be used for minimising overall pipeline costs, this may be particularly relevant to biogas operators if the cost of such a distribution development was to fall upon them.

### 4.2.2 VIRTUAL PIPELINES

An alternative method to physical pipelines that connect biogas plants to an end user (or industry site) are virtual pipelines. Virtual pipelines are a method of gas delivery for biomethane, although it is also possible for biogas. The gas is transported compressed, via gas cylinders by truck to the point of use (as outlined previously in Configuration 2). Such an approach aligns once more to areas with limited natural gas grid infrastructure availability and can facilitate the use of biomethane by industries that do not produce by-products suitable for anaerobic digestion. Typically, in virtual pipeline approaches (as opposed to physical pipeline approaches), on-site biogas upgrading is initially undertaken on-site at the biogas plants. In a conventional virtual pipeline, typical biogas upgrading technologies are used at the biogas plant and the haulier collects the biomethane – this is shown in Figure 4-4. In this case the onus of responsibility rests on the biogas plant operator to produce high quality biomethane.

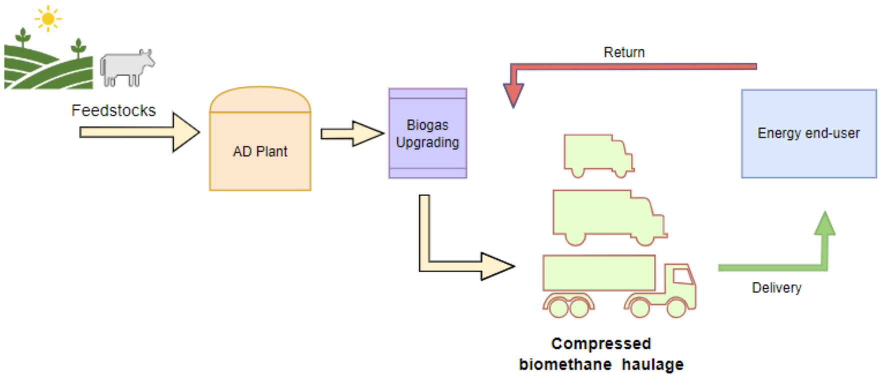


*Figure 4-4 Transport of biomethane to energy end-user (industry) via haulage truck (adapted from Ó Céileachair et al., 2023)*

However, another option is the provision of mobile biogas upgrading units in which a truck loaded with a pressure swing absorption upgrading system travels to a number of biogas plants within a region and upgrades the biogas at each site and transports all of the collected biomethane to the end user – this is shown in Figure 4-5. This latter approach offers a shared financial risk for the upgrading unit between a number of biogas plants that may be located in proximity.

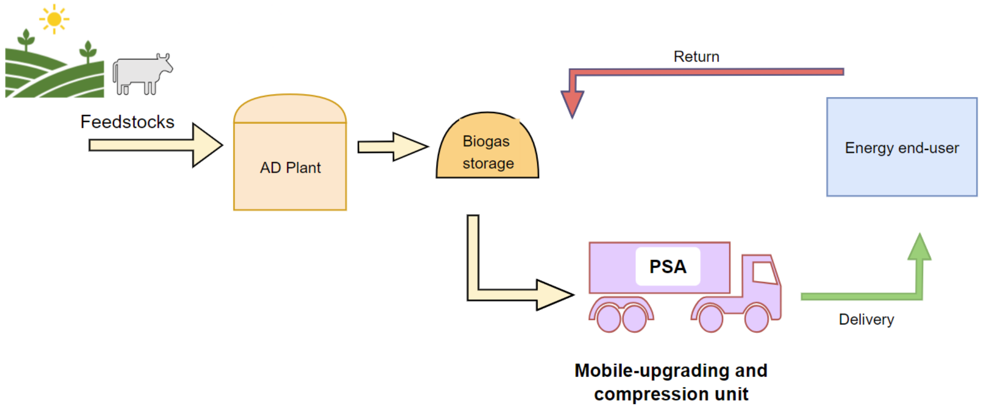


*Figure 4-5 Mobile upgrading of biogas and transport of biomethane to energy end-user (industry) (adapted from Ó Céileachair et al., 2023)*

Of significant importance in the creation of virtual pipelines is optimisation of the route taken by the truck(s) in collecting the biomethane from the biogas plants. Shorter travel distances will equate to lower greenhouse gas emissions generated from transportation, thus increasing the sustainability of the biomethane produced. Vehicle routing problem (VRP) techniques have previously been used to optimise the logistics of biomethane collection and transportation by (Ó Céileachair et al., 2023). In that study, 7 scenarios were explored for virtual biomethane pipelines considering a range of factors such as truck capacity, the number of end users (termed depots), and whether conventional biogas upgrading, or mobile biogas upgrading is employed. The objective of the study was to minimise transportation requirements for a virtual pipeline serving 100 biogas plants contained within a land area of 400 km$^2$. The analysis indicated some key considerations when developing virtual pipelines:

- Conventional virtual pipeline systems (whereby biogas upgrading is undertaken at the biogas plant using conventional technologies) hold an advantage of relatively short visit times to the biogas plant;
- Larger haulage trucks (45ft vehicles) can allow greater flexibility regarding collection scheduling due to their larger capacity for biomethane storage, but may be unsuitable if road infrastructure is poor;
- Mobile upgrading systems require significantly longer visits to the biogas plants due to their slow upgrading capacity which may prove to be logistically impractical;
- Biomethane collected via mobile upgrading systems had higher transport emissions than conventional virtual pipelines in the scenarios investigated since more overall routes (truck movements) were required.

# 5 BEYOND BIOGAS TO BIOREFINERY

## 5.1 INDUSTRY DECARBONISATION THROUGH A BIOREFINERY APPROACH

A biorefinery approach can facilitate the circular economy through the conversion of biodegradable residues into valuable products, whilst minimising waste and environmental impact by enabling the cascading use of biological nutrients. In the biorefinery model, the valuable products generated can include for bioenergy, biochemicals, and biomaterials. This supports the concept of extracting maximum value from biomass, which enhances resource efficiency, and initiates closed loop (zero waste) practices. In effect, industries can gain from increased energy and material security through the minimisation of fossil fuel use, while also potentially diversifying their revenue streams through new products. Ultimately the biorefinery approach is indicative of sustainable value chains, and from an industry perspective, promotes corporate social responsibility in the green transition.

Anaerobic digestion can be positioned central to the circular economy philosophy, and the implementation of a biorefinery within industry. The technology can be considered more than just an energy production technology. The products generated at biogas plants can include for methane ($CH_4$), carbon dioxide ($CO_2$), and digestate, and when including for different reactor configurations and technology coupling, can be expanded to produce volatile fatty acids, hydrogen ($H_2$), biochar, and micro-algae. The flexibility of anaerobic digestion, in terms of accepting a variety of feedstock, and generating a specific end product, makes it a suitably versatile process that can be integrated into sustainable biorefineries.

Figure 5.1 gives an example illustration of a cascading biorefinery configuration in an industry setting based on the implementation of an anaerobic digester. Aligning with previous chapters, the set-up illustrates an industry that generates its own by-products amenable to anaerobic digestion, and thus represents Configuration 1. The model provides a climate conscious approach for the industry whereby feedstocks are processed to produce an on-site renewable source of heat that can potentially replace fossil natural gas. However, along with producing heat the biorefinery also includes many other useful technologies to increase valorisation. The following sections give a brief description of the different aspects of the example biorefinery shown in Figure 5-1.

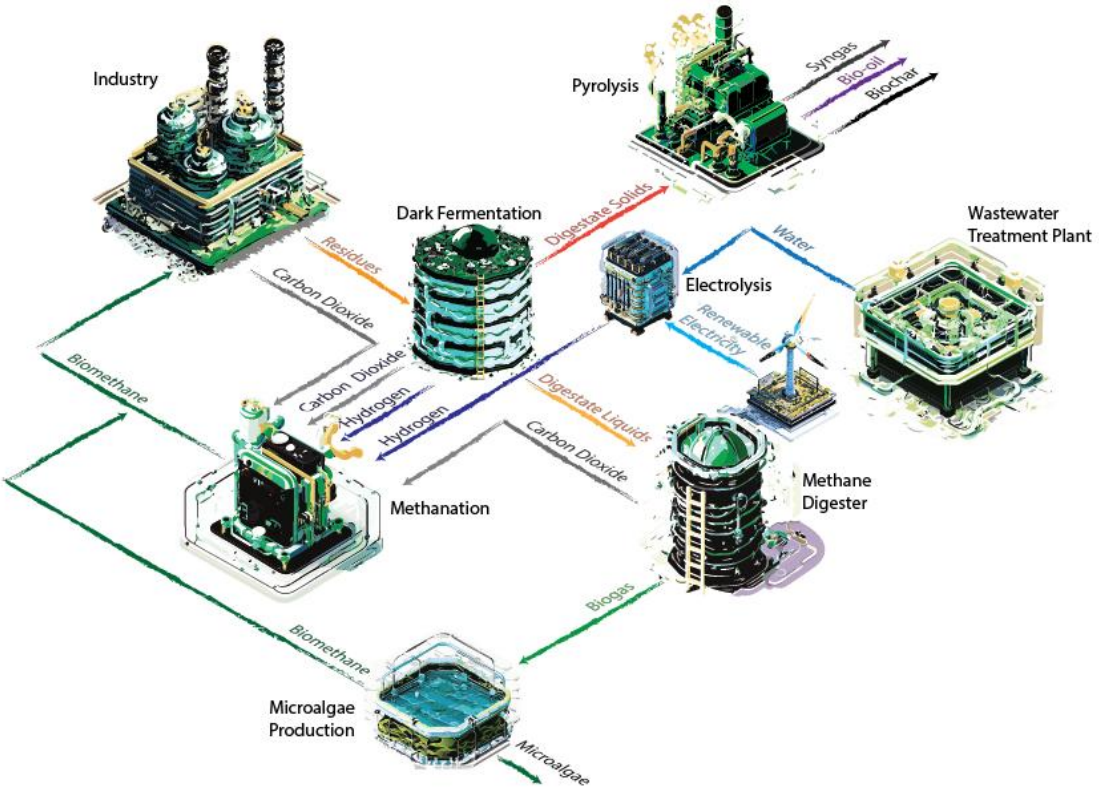


*Figure 5-1 Cascading biorefinery through anaerobic digestion in industry*

## 5.2 TWO-PHASE ANAEROBIC DIGESTION SYSTEM

In the biorefinery proposed in Figure 5-1, a two-phase anaerobic digestion system is utilised. This includes for a dark fermentation (first phase) reactor and a methanogenic (second phase) reactor. Dark fermentation converts the organic matter in the absence of oxygen and light to biological hydrogen, $CO_2$ and volatile fatty acids (VFAs) – in effect, the reactor achieves the hydrolysis and acidogenesis steps of the anaerobic digestion process at a low pH, a high organic loading rate and a low hydraulic retention time. Hydrogen is a clean fuel in that its only by-product in combustion is water, and so is deemed a key energy carrier for deep decarbonisation. Many countries have now introduced hydrogen strategies and see this vector as having a crucial role in deep decarbonisation (Liebetrau et al., 2021). However, it must be noted that the energy return, in terms of energy in the hydrogen product, is relatively low.

Carbon dioxide is now recognised as a valuable commodity from anaerobic digestion. The $CO_2$ from dark fermentation is biogenic and should be captured rather than discharged. When we consider power to X fuels, whereby renewable electricity is converted to hydrogen ($H_2$) through water electrolysis, and onto methane ($CH_4$) and methanol ($CH_3OH$) through reaction with $CO_2$, the source of the $CO_2$ in the renewable hydrocarbons must be sustainable. The options are biogenic $CO_2$ or $CO_2$ from Direct Air Capture (DAC). The cost of $CO_2$ from DAC is of the order of €400/t and as such this may be considered the upper limit on the value of biogenic $CO_2$. The cost of capture of $CO_2$ from biomethane is low (about €30/t) and as such profit can be made off the $CO_2$ by-product (Murphy et al., 2024).

VFAs are short chain hydrocarbons which include for acetic acid and propionic acid. These VFAs can be readily converted to biogas/biomethane by methanogenic archaea in the methane reactor. However long chain acids, such as butyric acid and caproic acid, if isolated, can act as platform chemicals for synthesis into higher value products. While the VFAs may generate more financially attractive products than biogas, much work is currently underway investigating the ability to produce consistent VFA profiles from the fermentation of organic feedstocks and the development of separation technologies to recover VFAs, that are not cost prohibitive. Microbial chain elongation is one such process which can convert short chain acids to long chain acids.

The methanogenic reactor, operating at close to neutral pH, accepts the liquid effluent from the dark fermenter which is rich in VFAs, and produces biogas. The composition of the biogas typically sees elevated methane levels (70-80%) since the methanogenic reactor undertakes the acetogenesis and methanogenesis stages of the anaerobic digestion process.

Innovative methods that combine both biogas production and the production of biomaterials, such as polyhydroxyalkanoates (PHAs) or biobutanol, can potentially provide further opportunities for biomass valorisation, however challenges remain. The cost of producing biomaterials through such methods are often quite a bit higher than conventional petrochemical methods. However, increased consumer demand for sustainable materials may drive investment in this area.

## 5.3 NOVEL BIOGAS UPGRADING THROUGH MICRO-ALGAE PRODUCTION

Biogas upgrading is undertaken to increase the methane content of biogas by removal of $CO_2$, and further removal of impurities in raw biogas, making it suitable as a substitute to natural gas. Conventional techniques for biogas upgrading are physicochemical methods such as chemical scrubbing and pressure swing absorption. However biological methods such as photosynthetic biogas upgrading can be used in a novel biorefinery approach. This is illustrated after the methanogenic digester in Figure 5.1 where the biogas is upgraded to biomethane whilst producing a valuable product in the form of micro-algae. This is a two-step process consisting of a bubble column and photobioreactor. Initially $CO_2$ and hydrogen sulphide ($H_2S$) are removed by absorption in a carbonate rich alkaline medium in a bubble column as the biogas is passed through it. A high $CO_2$ absorption rate can be achieved at the optimal pH and alkalinity of the solution combined with suitable liquid-to-gas flowrates. Subsequently, the $CO_2$ which has been captured in bicarbonate form, is consumed by microalgae in a photobioreactor and carbonates are regenerated. This process of capturing and reusing $CO_2$ aligns well with circular economy initiatives in industry. The micro-algae biomass generated during $CO_2$ removal can be harvested and utilised in a variety of applications such as “superfoods”. The production of Spirulina powder as an alternative food-based protein generated from biogas upgrading has previously been shown to be a promising option from a cost and emission savings perspective when looking at anaerobic digestion biorefinery applications (Bose et al., 2022). Furthermore, compared to conventional biogas upgrading techniques, such biological methods can be considered less energy intensive.

## 5.4 DIGESTATE MANAGEMENT THROUGH THE PRODUCTION OF BIOCHAR

Digestate management can be a significant hurdle to the economic and environmental performance of biogas plants. The most common digestate management practice is land spreading as a biofertiliser. However, this necessitates that sufficient land is available for application. In the development of large industrial-based digesters this may be of issue; agreements with farmers, and nutrient management balances will need to be secured to optimise use of the digestate. Oversupply of nutrients can lead to pollution of waterways; thus, it may be required to transport digestate away from the biogas plant so as not to breach strict nutrient application limits (such as those set in the EU under the Nitrates Directive). Furthermore, transportation can be an economic burden due to the high moisture content of digestate. Nutrient recovery options are sought so that digestate is not viewed as a constraint but a valuable product in the wider bioeconomy, and specifically where industry may benefit.

In the biorefinery approach presented, thermochemical production of biochar from dry digestate is suggested as an alternative approach to direct land application of digestate. This requires anaerobic digestion to be coupled with pyrolysis to produce biochar, bio-oil and syngas. Biochar, primarily comprised of carbon, has been acknowledged by the Intergovernmental Panel on Climate Change (IPCC) as a promising negative emissions technology due to its soil carbon sequestration properties. As pyrolysis necessitates dry feedstock (with less than 5% moisture), a solid-liquid separation step (and further drying of the solid fraction) would be required. Such biochar has previously been assessed as an additive for enhanced biogas production in anaerobic digestion through direct interspecies electron production (Deng et al., 2021), and as an aid to microbial chain elongation (Wu et al., 2022). However, its use as a soil amendment has been recognised as important from a sustainability perspective. This improves the soil organic content, and increases photosynthesis and crop yields. As such it draws $CO_2$ from the atmosphere and is deemed a negative emission technology. The surface area per gramme of biochar has been measured up to 200 $m^2/g$ (Hackula et al., 2024). This is hugely beneficial for holding water in drought and flood situations. Biochar is a more valuable product than digestate. Ensuing the economic value of biochar is realised is a challenge for the industry.

## 5.5 THE UTILISATION OF HYDROGEN AND BIOGENIC CARBON DIOXIDE

Industries striving to reach net-zero greenhouse gas emissions will potentially utilise a number of decarbonisation technologies to satisfy their requirements. This may include for the generation of renewable electricity from wind turbines and further, the production and use of e-fuels (through electrolysis), initially through green hydrogen. The integration of renewably produced hydrogen into the biorefinery model leads to a cascading approach whereby further synergies can be gleaned through technology coupling. One example of this is if the hydrogen produced from electrolysis (supplied with renewable electricity) is combined with $CO_2$ from anaerobic digestion (both from the first and second phase reactors) in a biomethanation reactor to generate more methane. This occurs through a Sabatier reaction mediated through hydrogenotrophic methanogenic archaea ($4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$) and is a means of carbon capture and utilisation. Ideally hydrogen would be used directly as a fuel as this is the most efficient route in terms of energy utilisation. For example, if the industry had a distribution fleet, the vehicles could be converted to operate off hydrogen in fuel cell vehicles. However, there are benefits to pursuing a further step to produce methane. Firstly, the hydrogen provides a means of carbon utilisation by converting the carbon dioxide in the biogas to e-methane (which is additional to that produced in biomethane). The e-methane and biomethane can be directed to the industry site to offset natural gas consumption without requiring a change to hydrogen compliant infrastructure. Else these fuels may be used in heavy haulage reducing scope 3 emissions of a food and beverage industry. Furthermore, it is also possible to combine hydrogen with $CO_2$ to produce methanol ($CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$). Methanol is an emerging as liquid energy carrier for hydrogen storage, and this may be particularly applicable to power generation in industry or the maritime sector as an alternative low carbon marine fuel.

## 5.6 FLEXIBILITY OF BIOREFINERY CONFIGURATION

Industrial anaerobic digestion systems can be configured in numerous ways depending on the specific on-site feedstocks, logistics, land availability, energy requirements, and desired product outputs. The flexibility of these systems allows them to be tailored to meet the unique needs of different industries. In the example proposed in Figure 5.1, the biorefinery is designed with bioenergy and biomaterials as key priorities, favouring the production of methane, micro-algae, and biochar. Methane provides renewable energy, while micro-algae and biochar contribute to high-value products for agricultural and environmental applications. However, biorefineries are adaptable, and different configurations can be developed based on alternative goals. For example, VFAs could be prioritised instead of methane production. VFAs serve as building blocks for chemical manufacturing or as food additives, changing the operational design to focus on chemical outputs. Additionally, $CO_2$ from the digestion process could be diverted for food-grade uses, such as drink carbonation, rather than converted into methane for energy. This option may be more viable in industries with a focus on food or beverage production. Similarly, hydrogen generated on-site can be used directly as a clean transport fuel, aligning with sustainability goals for reducing carbon emissions in transportation. In essence, industrial biorefineries can provide customised solutions that align with market demands, environmental sustainability objectives, and the available resources. This flexibility allows industries to maximize the value of their feedstocks while supporting diverse economic and environmental objectives.

# 6 CONCLUSION

Biogas systems play a pivotal role in an industrial context by offering a sustainable and versatile energy solution, which can address some key environmental concerns such as reducing dependency on fossil fuels. The deployment of biogas systems in industries not only enhances energy security but can also support circular economy principles by turning waste and residues into valuable resources. This supports the provision of more sustainable value chains and a reduction in Scope 1, Scope 2 or Scope 3 greenhouse gas emissions, depending on the configuration of the biogas system with the industry. Three such configurations were proposed in this report. Biogas has the capability to enable GHG emission reductions across all three scopes and as such is an effective tool for industries aiming to reduce GHG emissions.

The utilisation of biogas across IEA Bioenergy Task 37 member countries exemplifies its potential in industrial and energy applications. This report investigated biogas production across 10 Task 37 member countries whereby trends in biogas utilisation were established. Denmark lays emphasis on biogas upgrading to biomethane for injection into the natural gas grid, demonstrating a seamless integration with existing energy networks; they have effected a 39% substitution of natural gas with of the order of 70 large scale gas grid injection points (IEA, 2023). This approach can lead to industries using guarantees of origin to utilise biogas to decarbonise. Conversely, Sweden has a limited gas grid network and focuses on using biogas for transportation. However, biogas is also utilised in various industrial sectors that generate their own by-products which can be used for digestion. Such examples underline how tailored approaches to biogas utilisation can align with specific national priorities, regulatory frameworks, and resource availability.

Grid injection of biomethane enables distribution to a broad range of consumers further enhancing energy accessibility and utility. However, if industries are located at a distance from gas grid infrastructure, alternative approaches can be implemented regarding the delivery of biogas energy to end-users. This report outlines strategies such as dedicated biogas pipelines or virtual pipelines in such instances. These decentralised biogas distribution methods may involve complex logistical planning, but also offer an opportunity to expand the penetration of biogas in industry.

As the biogas sector evolves, industries may be able to adopt an integrated biorefinery approach which can maximise resource efficiency through a circular economy approach. A cascading biorefinery configuration is presented in the report that diversifies the output of biogas plants beyond energy. Such facilities can incorporate the production of bio-based chemicals, biofertilisers, and biomaterials, further enhancing the technology's economic and environmental value. Transitioning to biorefineries represents a paradigm shift, allowing industries to go beyond energy solutions and embrace comprehensive sustainability strategies.

In conclusion, biogas systems in industry exemplify the intersection of environmental stewardship and energy innovation. By addressing greenhouse gas emissions across Scope 1, 2, and 3, enabling diverse applications across the EU, and efficiently delivering energy to end-users, biogas stands as a cornerstone of industrial decarbonisation. Furthermore, the shift towards biorefineries promises to unlock new dimensions of sustainability, fostering a resilient and resource-efficient industrial future.

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# Appendices

## A Norway

As per Figure: A-1, the majority of biogas in Norway (60 % in 2022) was produced by anaerobic digestion plants (excluding those at wastewater treatment plants in the form of "*Sewage sludge gas*" which contributed 26% of biogas production). Landfill gas contributed 14.3 % of biogas production in 2022 and no biogas from gasification ("*Biogas from thermal processes*") was recorded in 2022.

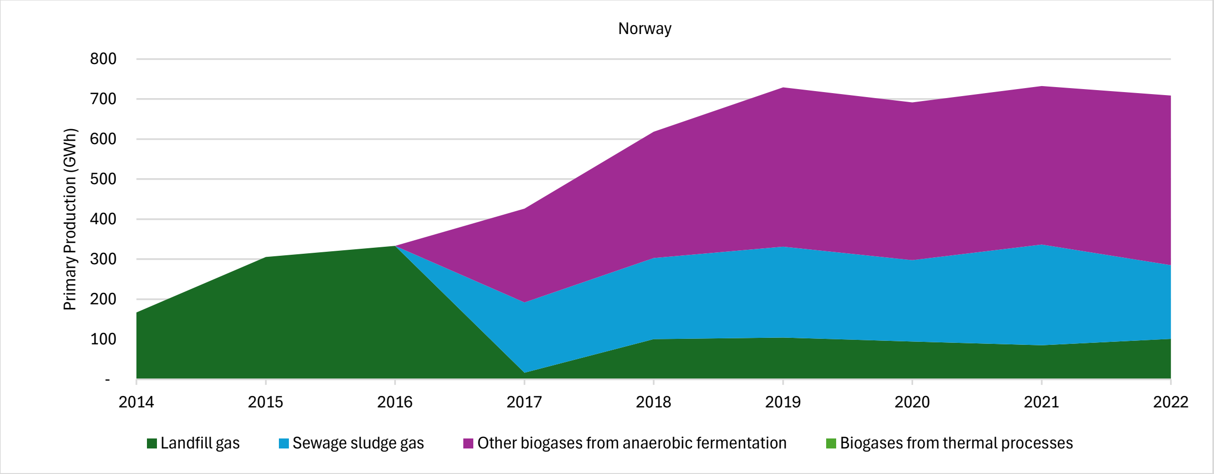

*Figure: A-1 Sources of indigenous biogas production in Norway*

From 2014 – 2022 the average annual growth rate of biogas production in Norway was 22.6% (Table: A-1). This was driven by an increase in biogas production from anaerobic digestion plants (13.5%) as well as an increase in biogas from sewage sludge (2.7%), and biogas from landfill gas (64.3%).

*Table: A-1 Average annual growth rate of biogas production in Norway*

| 2014 - 2022 | **Biogas** | Biogas from anaerobic fermentation | Landfill gas | Sewage sludge gas | Other biogas from anaerobic fermentation | Biogas from thermal processes |
|---|---|---|---|---|---|---|
| Average Annual Growth Rate (%) | 22.6 | 22.6 | 64.3 | 2.7 | 13.5 | - |

Figure: A-2 illustrates the breakdown of total biogas energy supply in Norway in 2022.

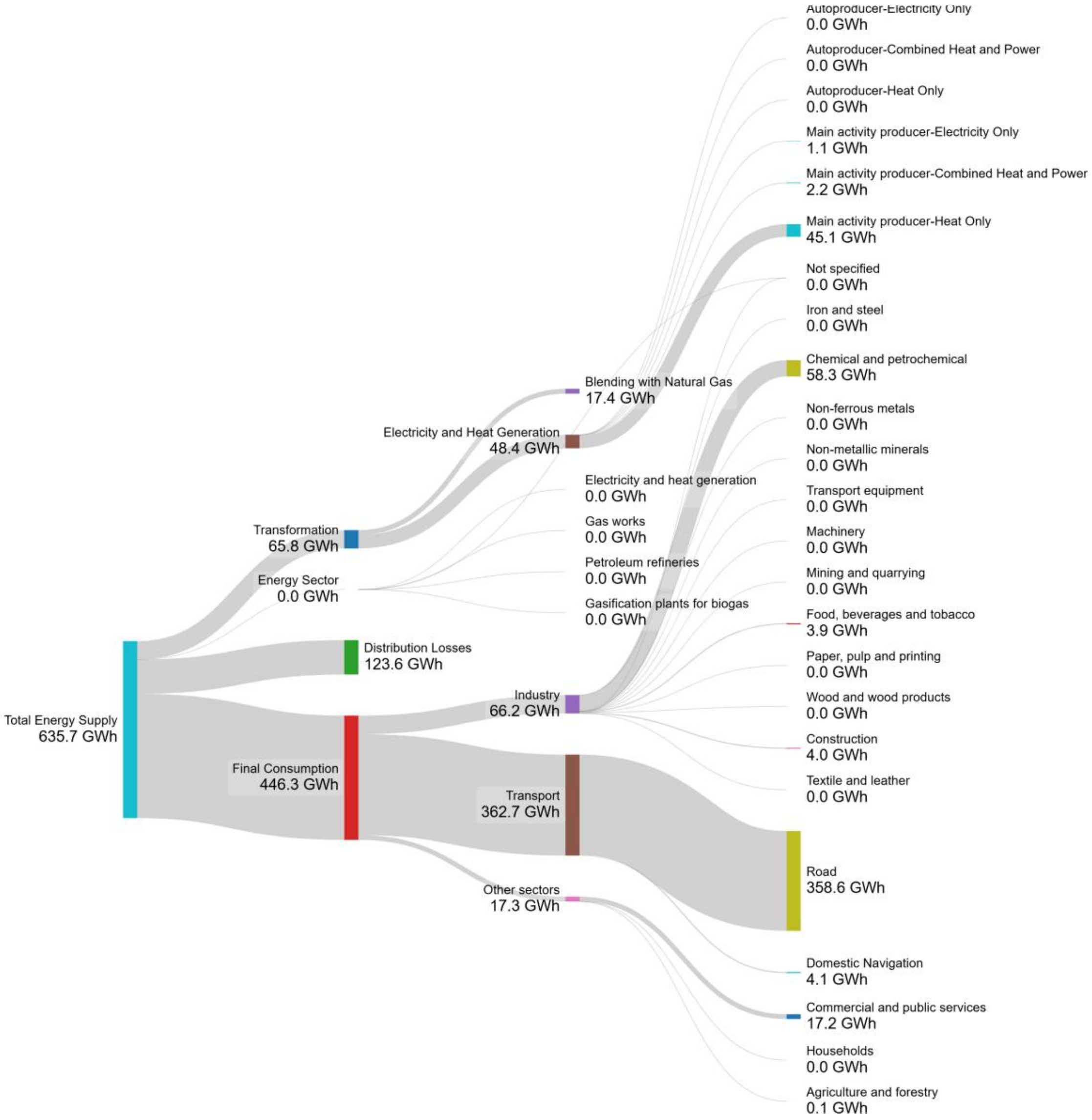

*Figure: A-2 Total biogas energy supply and use in Norway*

Within final consumption (446.3 GWh in 2022) industry contributed 14.8 % (66.2 GWh) of demand and experienced an average growth rate of 5.3 % in the period 2018 – 2022. Within Industry the majority of biogas final consumption was in the Chemical and Petrochemical sector (88.1%) in 2022 with an average growth of 10.7%, The first use of biogas in construction was recorded in 2021 at 0.003 GWh, which increased to 4 GWh in 2022. Food Beverages and Tobacco was responsible for 5.9 % of biogas demand, an average reduction of -11.4%.

A full breakdown of the relevant industrial sectors for Norway is shown in Figure: A-3 for the years 2018-2022.

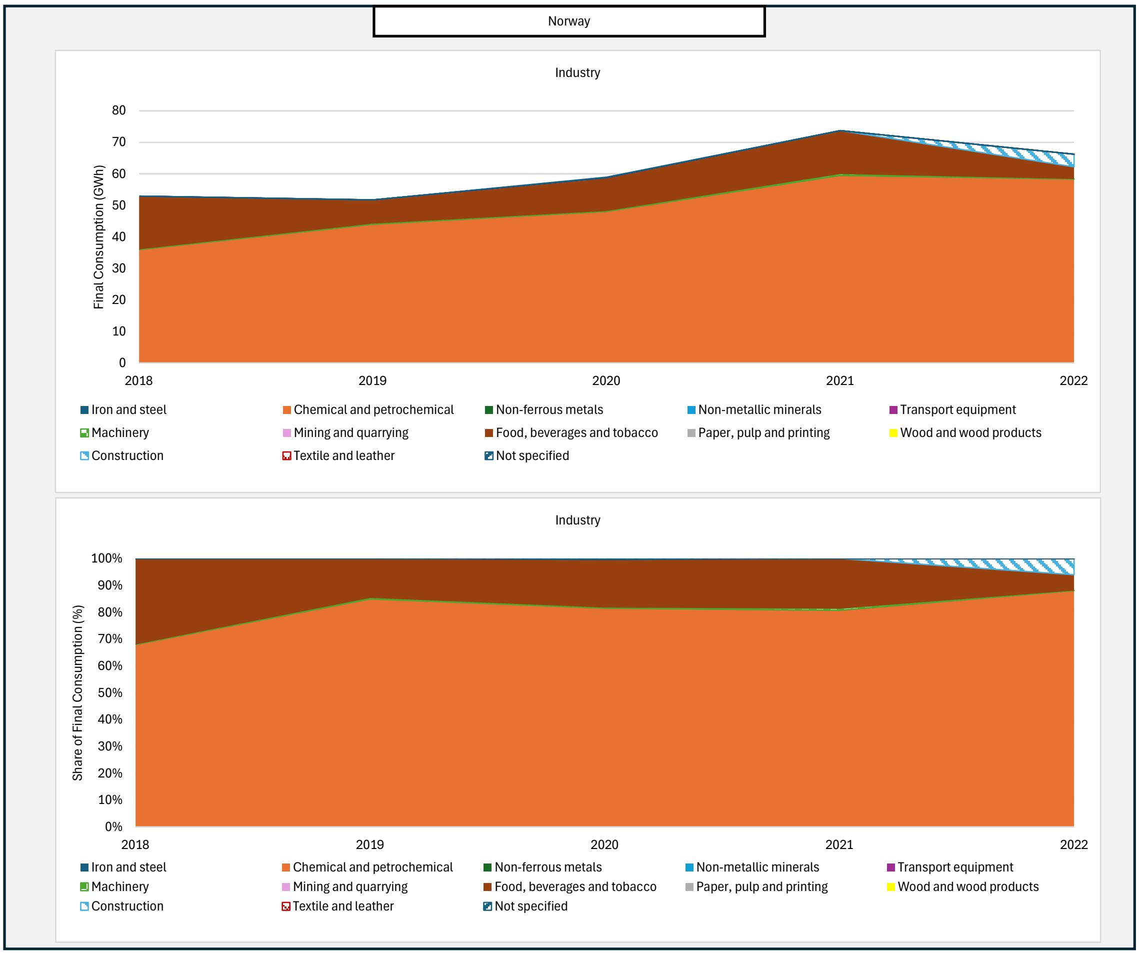

*Figure: A-3 Industry final consumption and sectoral share of biogas in Norway from 2018-2022*

# B Finland

As per Figure: B-1, biogas production in Finland in 2022, came primarily from gasification (56.7%), anaerobic digestion plants (24.6%), landfill gas (6.2%), and biogas from sewage sludge (9.6%). The major role played by biogas from thermal processes in Finland contrasts with other countries in this report where the majority of biogas was produced via biological processes (anaerobic digestion in anaerobic digestion plants, landfills, and the management of sewage sludge).

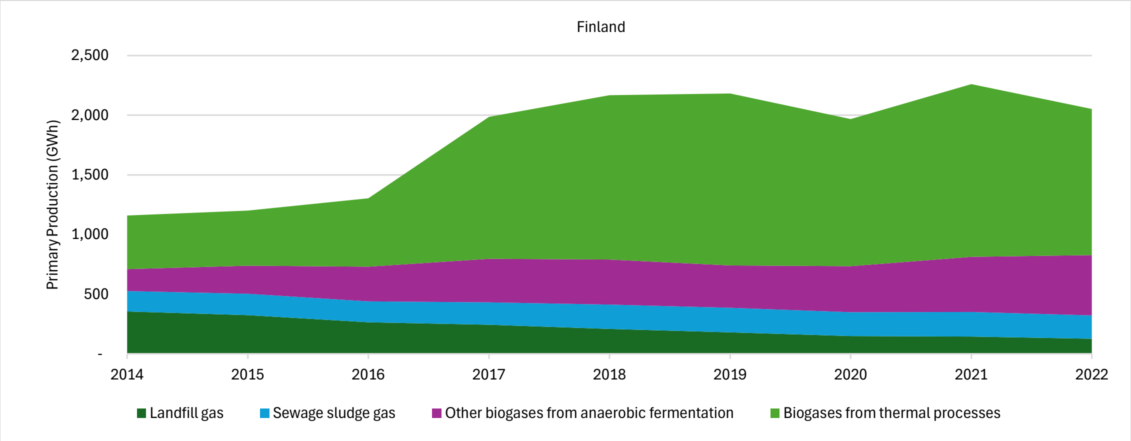

*Figure: B-1 Sources of indigenous biogas production in Finland*

From 2014 – 2022 the average annual growth rate of biogas production in Finland was 8.8% (Table: B-1). This was driven by an increase in biogas production from anaerobic digestion plants (14%), an increase in biogas from sewage sludge (1.8%), and a reduction in biogas from landfills (-12%). The majority of growth in biogas from anaerobic processes in Finland has been associated with biogas from anaerobic digestion plants. Biogas from thermal processes (gasification) was the main contributor to total biogas production in Finland (17.8%).

*Table: B-1 Average annual growth rate of biogas production in Finland*

| 2014 - 2022 | **Biogas** | Biogas from anaerobic fermentation | Landfill gas | Sewage sludge gas | Other biogas from anaerobic fermentation | Biogas from thermal processes |
|---|---|---|---|---|---|---|
| Average Annual Growth Rate (%) | 8.8 | 2.1 | - 12.0 | 1.8 | 14.0 | 17.8 |

Figure: B-2 illustrates the breakdown of total biogas energy supply in Finland in 2022.

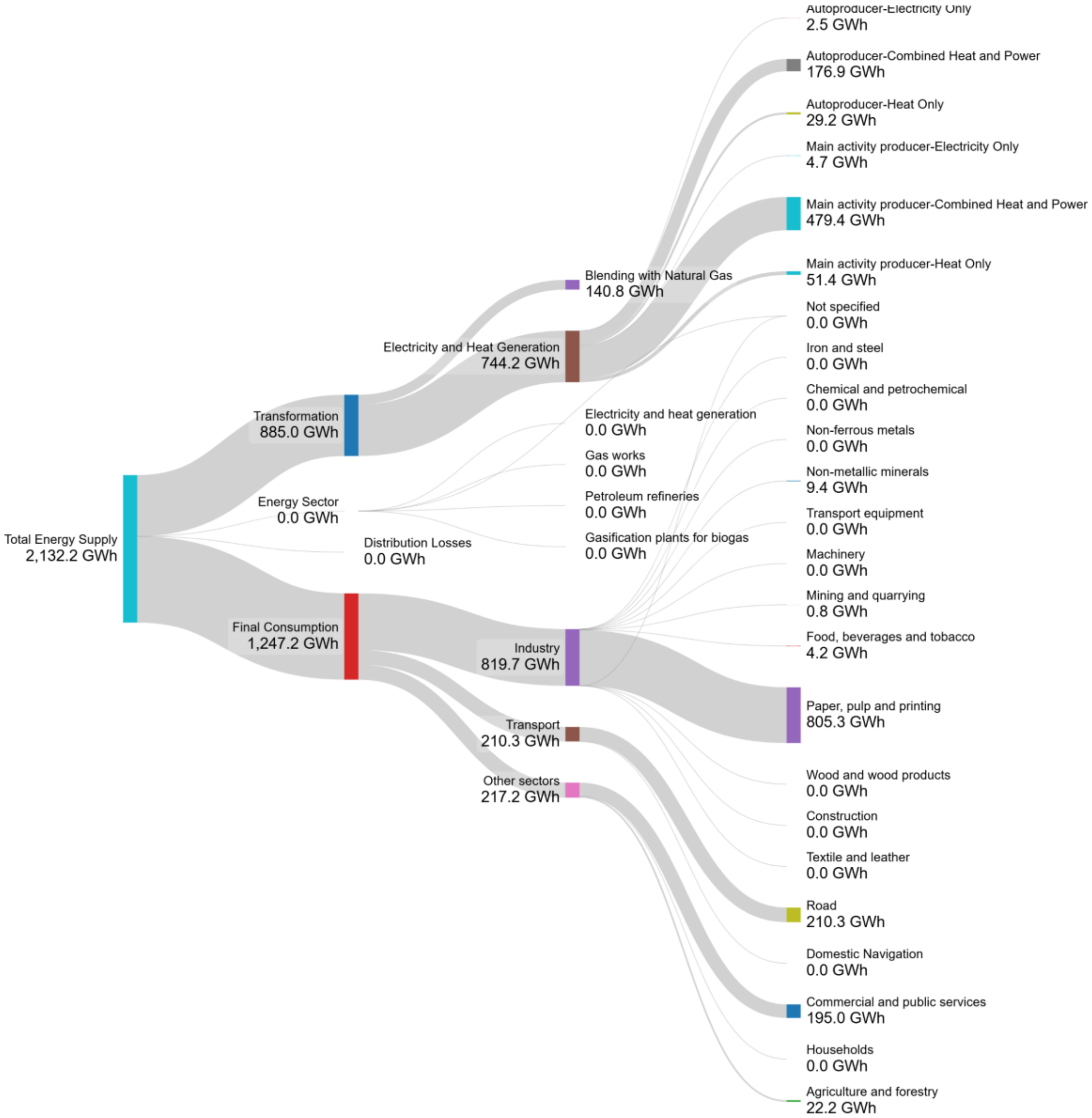

*Figure: B-2 Total biogas energy supply and use in Finland*

The source of biogas used under final consumption is not available from EUROSTAT data. It is not possible to differentiate between biogas produced from biological processes (anaerobic digestion) and biogas produced from thermal processes (gasification). The following discussion should bear this in mind.

Within biogas final consumption (1,247 GWh in 2022), Industry contributed 65.7% (820 GWh) to demand and experienced an average growth rate of 2.2% from 2018 – 2022. Within Industry the majority of biogas final consumption was in the Paper, Pulp and Printing sector (98.2%, with an average annual growth of 3.31%).

A full breakdown of the relevant industrial sectors for Finland is shown in Figure: B-3 for the years 2018-2022.

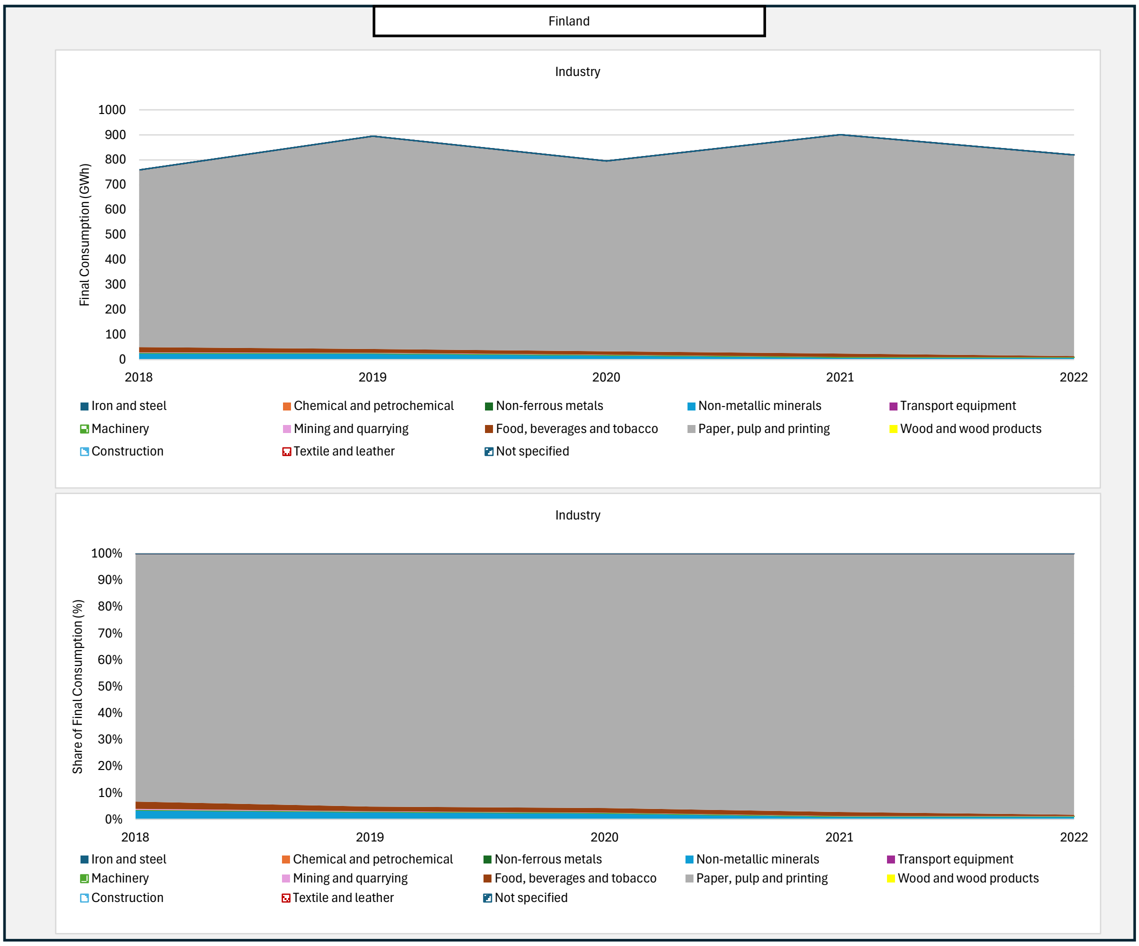

*Figure: B-3 Industry final consumption and sectoral share of biogas in Finland from 2018-2022*

# C Austria

As per Figure: C-1, 76% of biogas in Austria in 2022 was sourced from anaerobic digestions plants, excluding those at wastewater treatment plants in the form of "*Sewage sludge gas*" which contributed 22.4% of biogas production. Landfill gas contributed 1.2% of biogas production in 2022 with no biogas from gasification ("*Biogas from thermal processes*").

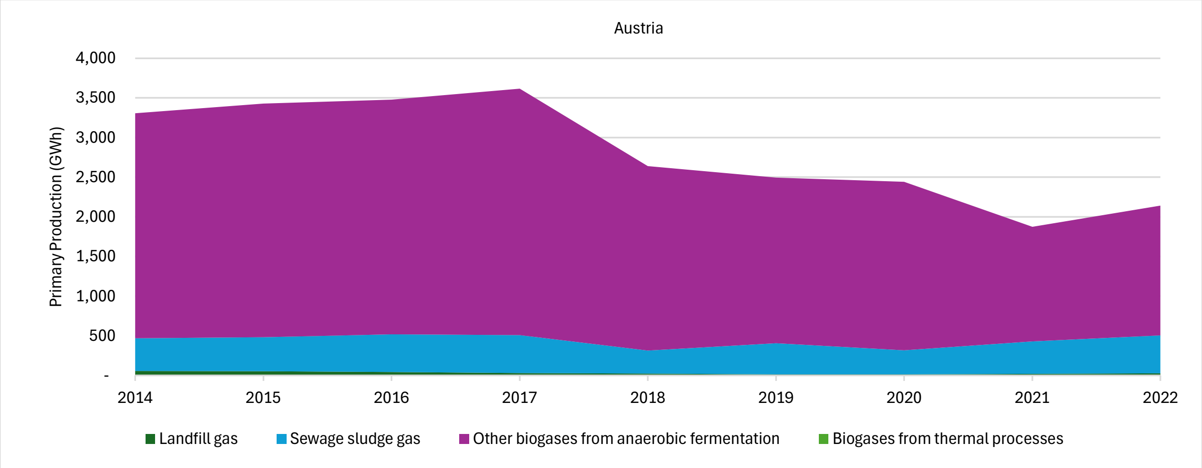

*Figure: C-1 Sources of indigenous biogas production in Austria*

From 2014 – 2022 the average annual growth rate of biogas production in Austria was -4.3% (Table: C-1). This was driven by a reduction in biogas production from anaerobic digestion plants (-4.3%).

*Table: C-1 Average annual growth rate of biogas production in Austria*

| 2014 - 2022 | **Biogas** | Biogas from anaerobic fermentation | Landfill gas | Sewage sludge gas | Other biogas from anaerobic fermentation | Biogas from thermal processes |
|---|---|---|---|---|---|---|
| Average Annual Growth Rate (%) | -4.3 | - 4.3 | - 5.6 | 5.0 | - 5.4 | - |

Figure: C-2 illustrates the breakdown of total biogas energy supply in Austria in 2022.

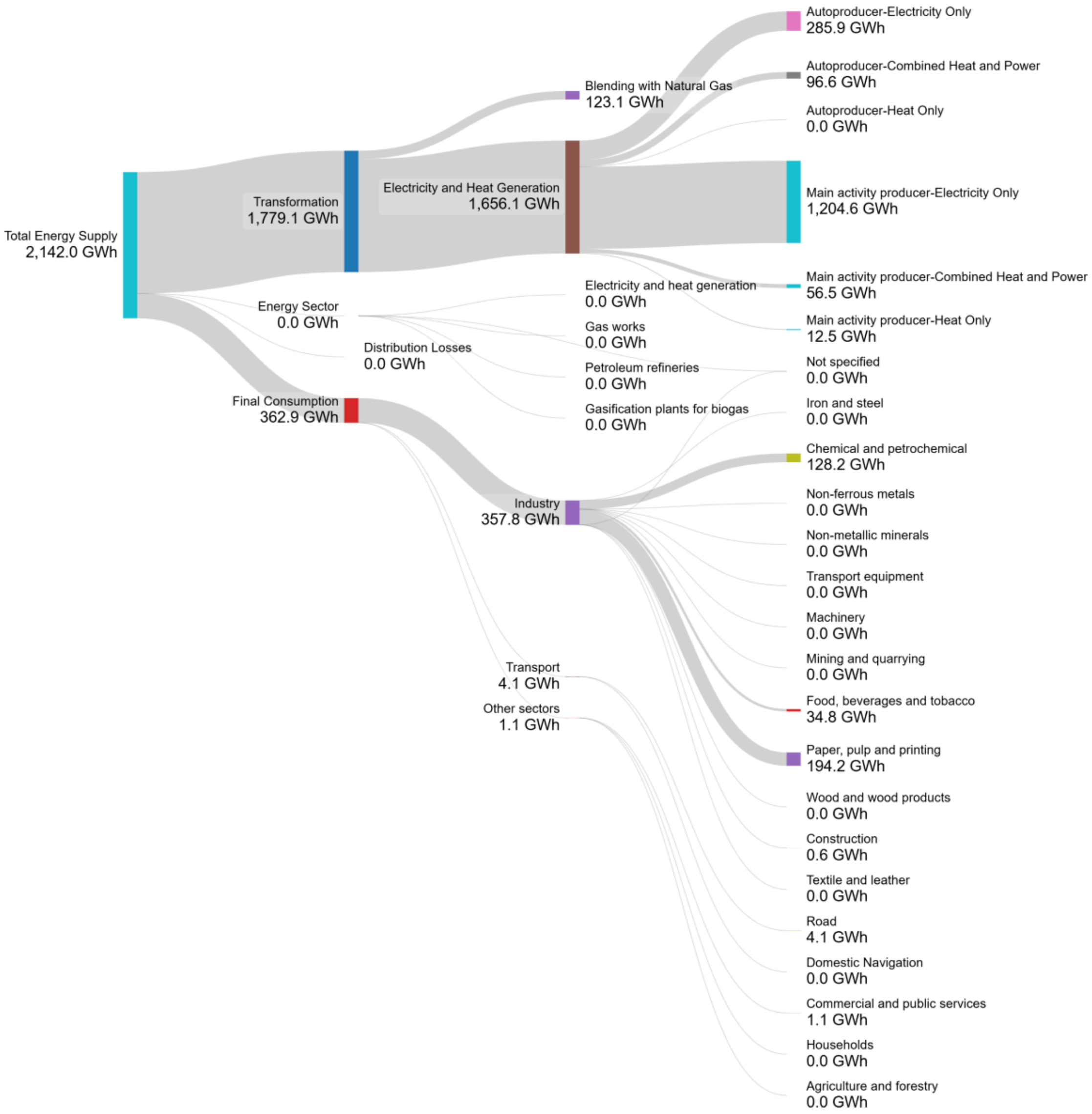

*Figure: C-2 Total biogas energy supply and use in Austria*

Within final consumption (363 GWh in 2022), Industry (denoted as biogas used for the production of self-consumed heat) accounted for 98.6% (358 GWh) and experienced an average growth rate of 7.5 % from 2018 – 2022. Interestingly, final consumption of biogas in industry reduced from 2018 (288.6 GWh) to 2020 (200.1 GWh), and subsequently increased to 294.9 GWh in 2021 and 357.7 GWh in 2022. The majority of final consumption was in Paper, Pulp, and Printing (54.3%) in 2022, with an average growth rate of 12.75%. The Chemical and Petrochemical sector in Austria also accounted for a substantial share of the final consumption of biogas (35.8%), with an average annual growth rate of 18%. Food, Beverage and Tobacco was the third largest user of biogas in terms of final consumption (34.8 GWh, 9.7% in 2022) and experienced a moderate annual average growth rate of 0.54% from 2018 to 2022.

A full breakdown of the relevant industrial sectors for Austria is shown in Figure: C-3 for the years 2018-2022.

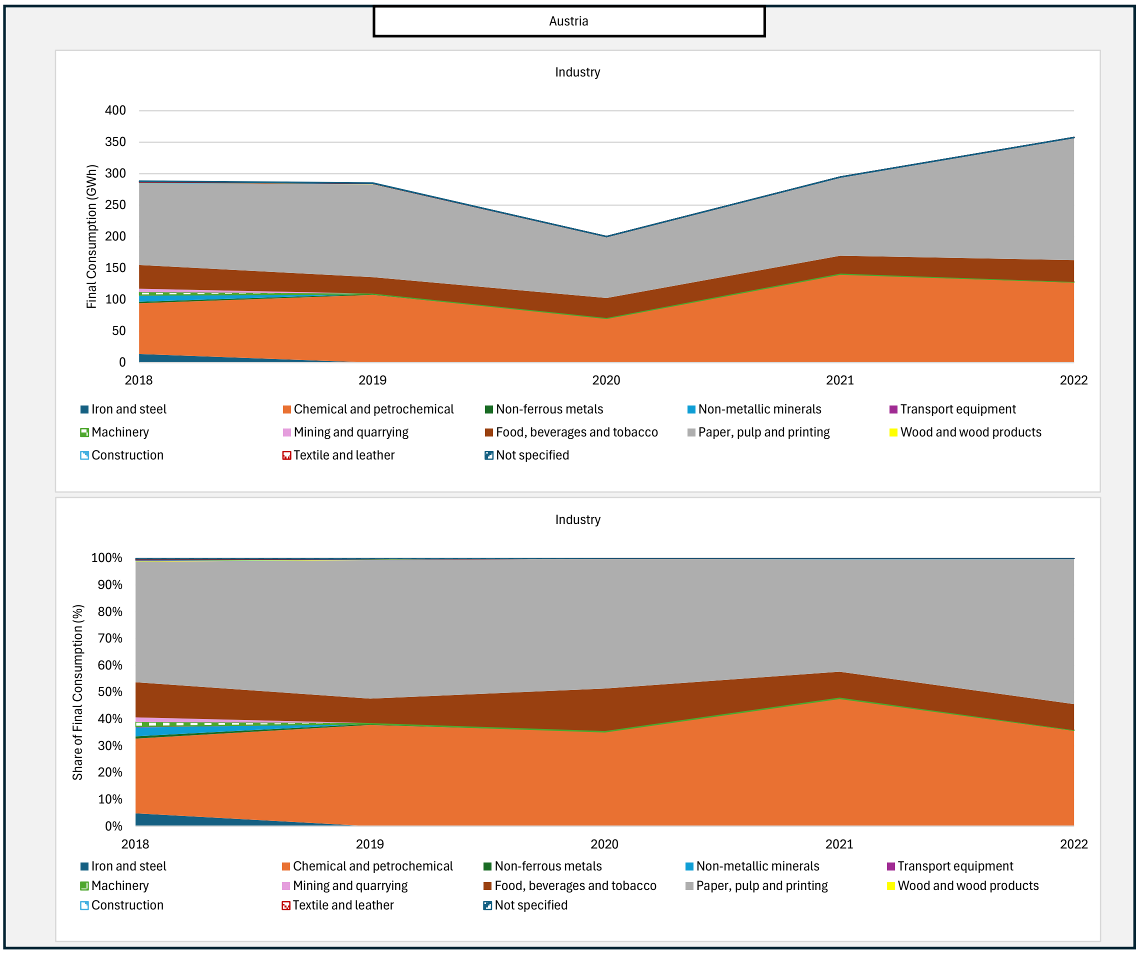

*Figure: C-3 Industry final consumption and sectoral share of biogas in Austria from 2018-2022*

# D Ireland

As per Figure: D-1, 48.7% of biogas in Ireland in 2022 was "*Landfill gas*", followed by 33.3% produced by anaerobic digestions plants, whilst wastewater treatment plants in the form of "*Sewage sludge gas*" contributed 18 % of biogas production.

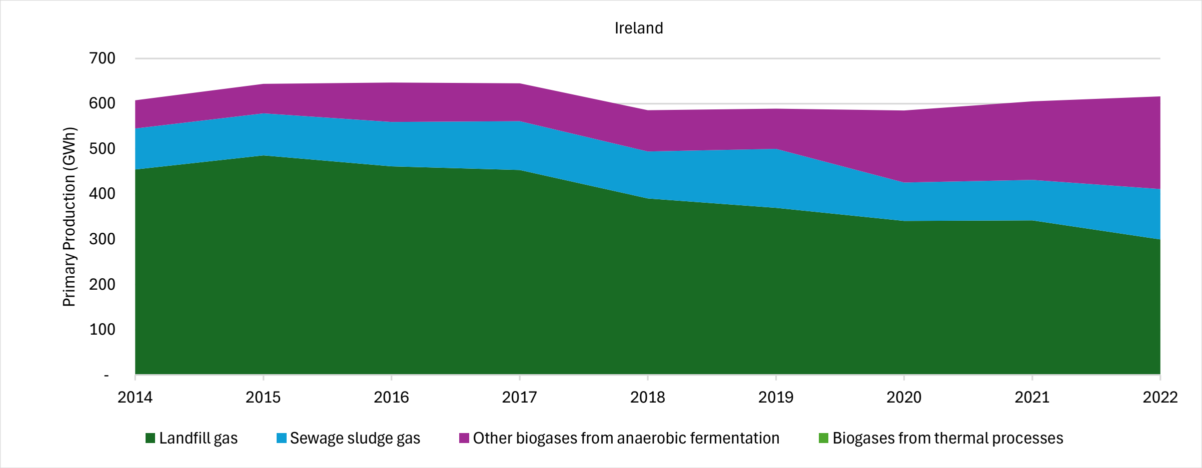

*Figure: D-1 Sources of indigenous biogas production in Ireland*

Biogas from landfill gas had an annual average growth rate of -4.9% and biogas from anaerobic digestion plants had an annual average growth rate of 18.3%, indicating the change of emphasis with regards to the biogas sector in Ireland (Table: D-1).

*Table: D-1 Average annual growth rate of biogas production in Ireland*

| 2014 - 2022 | **Biogas** | Biogas from anaerobic fermentation | Landfill gas | Sewage sludge gas | Other biogas from anaerobic fermentation | Biogas from thermal processes |
|---|---|---|---|---|---|---|
| Average Annual Growth Rate (%) | 0.3 | 0.3 | -4.9 | 4.3 | 18.3 | - |

Figure: D-2 illustrates the breakdown of total biogas energy supply in Ireland in 2022.

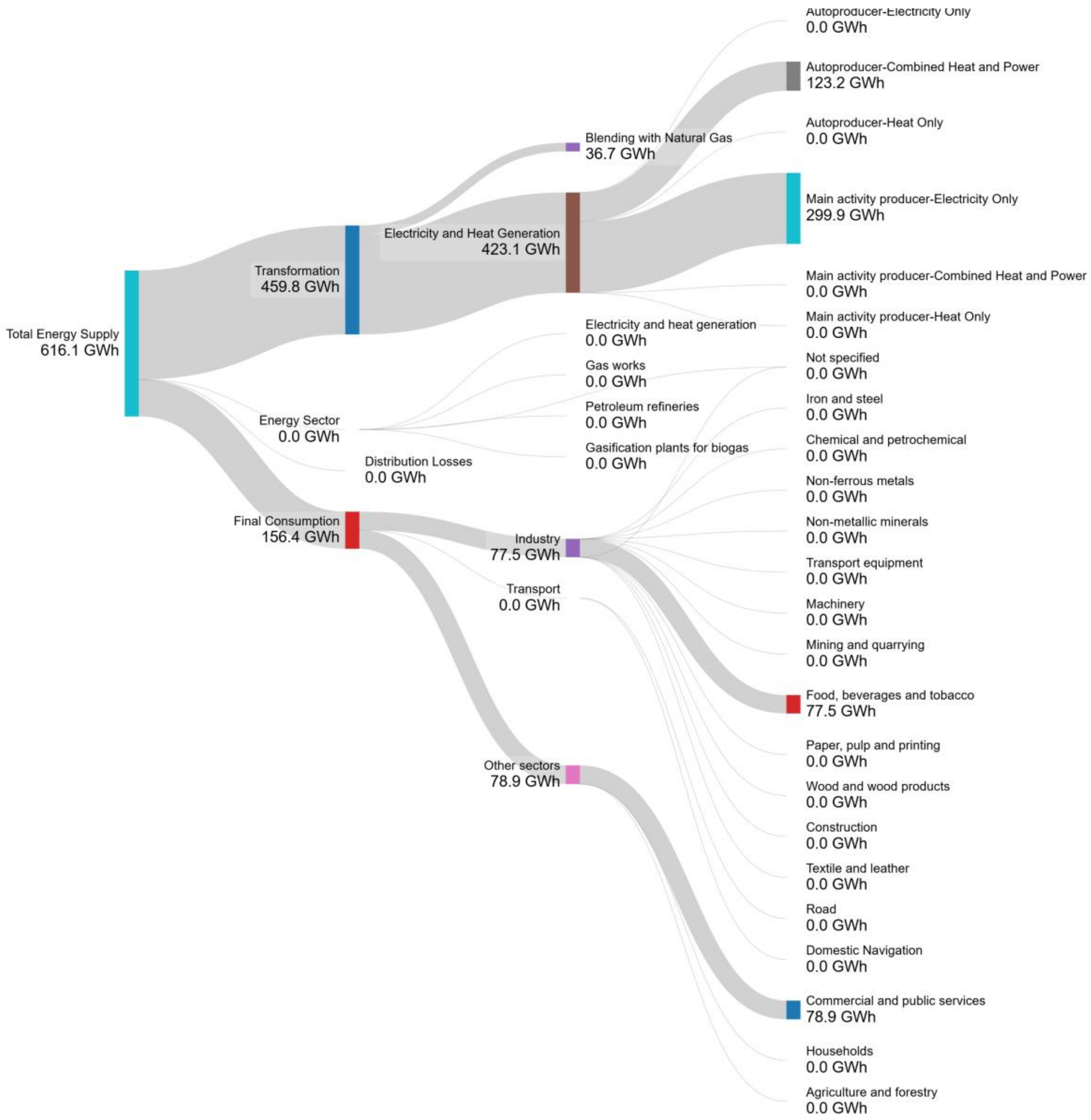

*Figure: D-2 Total biogas energy supply and use in Ireland*

Within final consumption (156 GWh in 2022) Industry (biogas used for the production of self-consumed heat) contributed 49.6% (77.5 GWh) of final consumption (lower than Austria, and similar to Denmark) and experienced an average growth rate of 11.7% from 2018 – 2022. According to EUROSTAT data, all final consumption of biogas in industry (100%) in Ireland was associated with the Food, Beverage, and Tobacco sector in 2022, with an annual average growth rate of 11.7 %.

A full breakdown of the relevant industrial sectors for Ireland is shown in Figure: D-3 for the years 2018-2022.

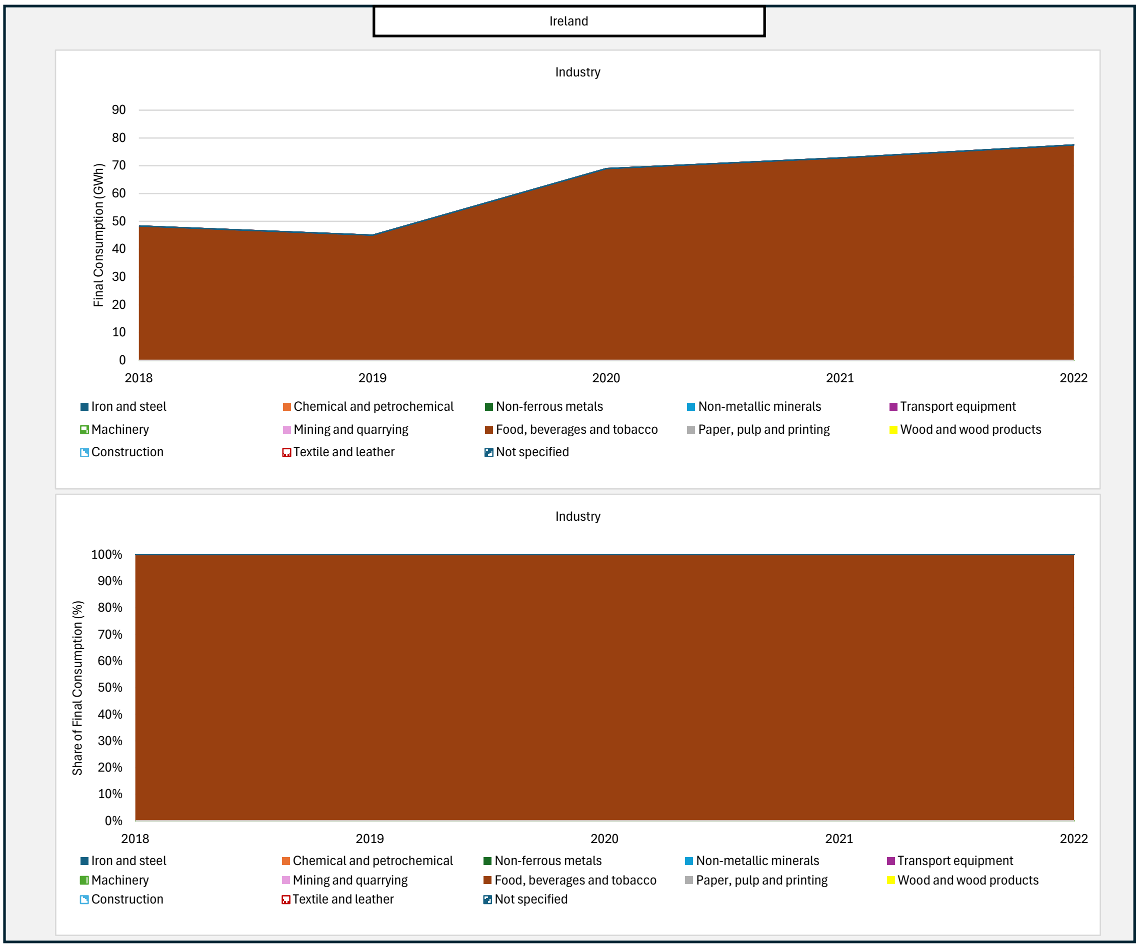

*Figure: D-3 Industry final consumption and sectoral share of biogas in Ireland from 2018-2022*

# E The Netherlands

As per Figure: E-1, 83% of biogas in The Netherlands in 2022 was produced by anaerobic digestions plants, followed by "*Sewage sludge gas*" from wastewater treatment plants which contributed 14.6%. Landfill gas contributed 2.5% of biogas production in 2022 with no biogas production from gasification.

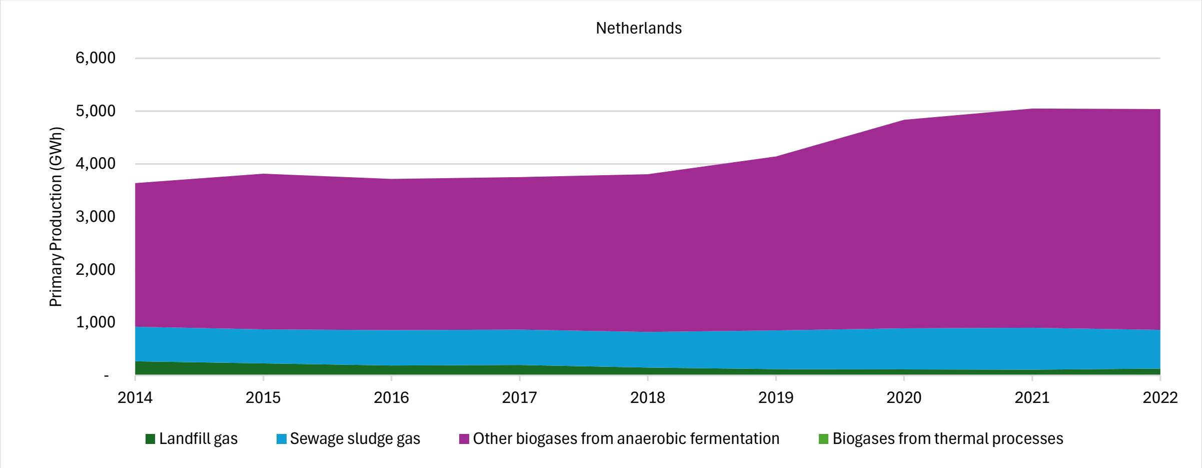

*Figure: E-1 Sources of indigenous biogas production in The Netherlands*

From 2014 – 2022 the average annual growth rate of biogas production in The Netherlands was 4.3% (Table: E-1). This was driven by an increase in biogas production from anaerobic digestion plants (5.7%) as well as an increase in biogas from sewage sludge (1.5%), and a reduction in biogas from landfills (-7.9%).

*Table: E-1 Average annual growth rate of biogas production in The Netherlands*

| 2014 - 2022 | **Biogas** | Biogas from anaerobic fermentation | Landfill gas | Sewage sludge gas | Other biogas from anaerobic fermentation | Biogas from thermal processes |
|---|---|---|---|---|---|---|
| Average Annual Growth Rate (%) | 4.3 | 4.3 | - 7.9 | 1.5 | 5.7 | - |

Figure: E-2 illustrates the breakdown of total biogas energy supply in The Netherlands in 2022.

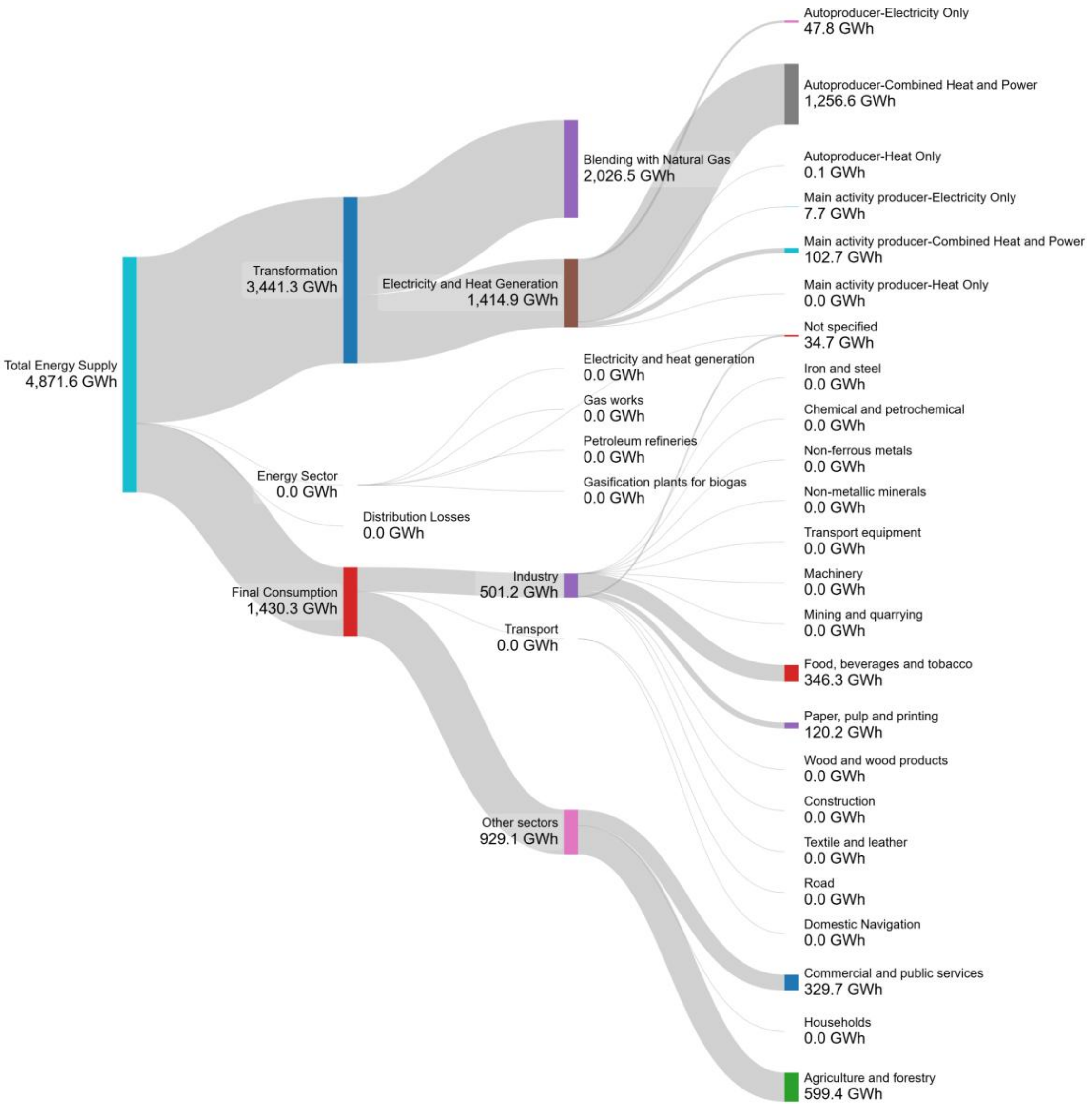

*Figure: E-2 Total biogas energy supply and use in The Netherlands*

Within final consumption (1,430 GWh in 2022) industry using biogas for the production of self-consumed heat contributed 35% and experienced an average growth rate of 4.8% in the period 2018 – 2022. However, final consumption of biogas reduced from 533 GWh in 2021 to 501 GWh in 2022. The majority of biogas final consumption in industry was used in Food, Beverages, and Tobacco sector (69.1%), and Paper, Pulp, and Printing (24%) in 2022, sectors which had an average annual growth rate of 6.3% and 2.9%, respectively. This highlights the increasing role of biogas in these sectors where biodegradable materials suitable for digestion are available.

A full breakdown of the relevant industrial sectors for The Netherlands is shown in Figure: E-3 for the years 2018-2022.

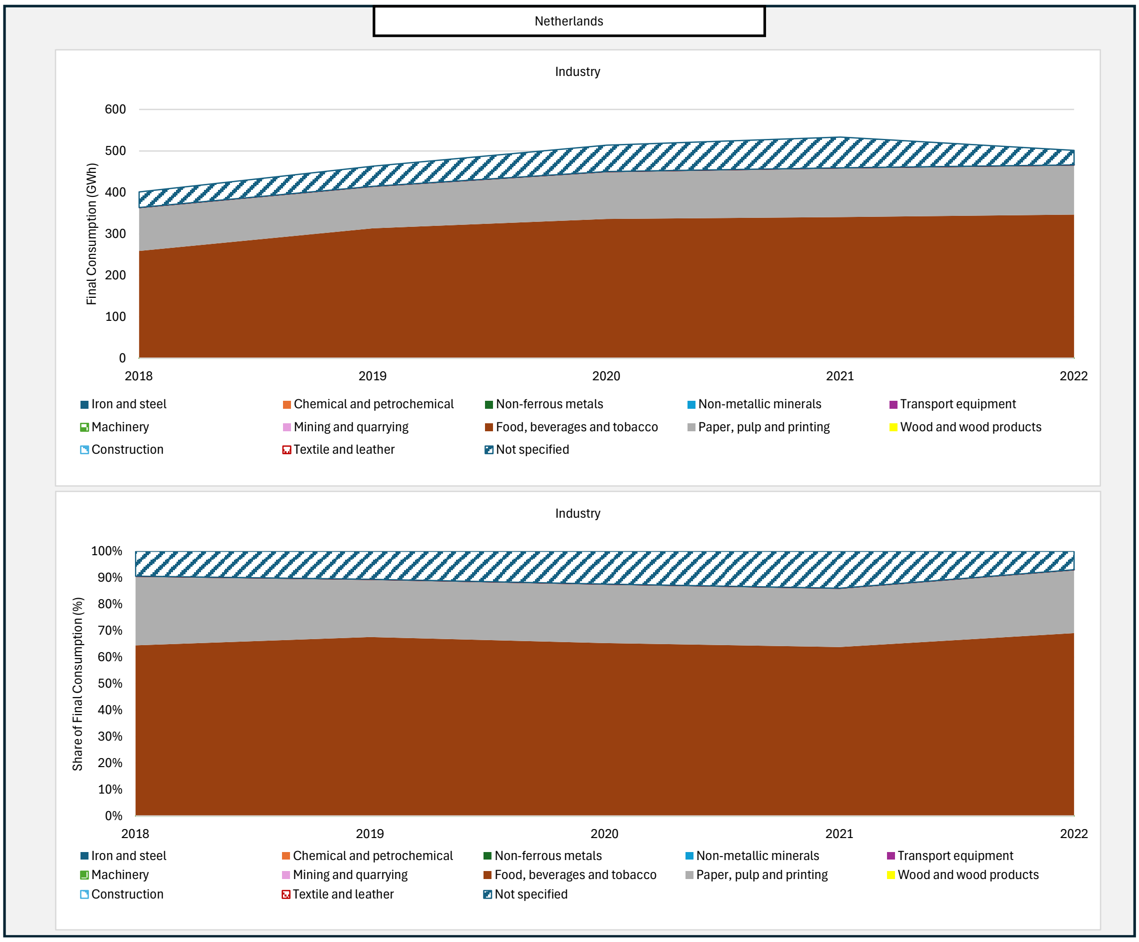

*Figure: E-3 Industry final consumption and sectoral share of biogas in The Netherlands from 2018-2022*

## F Italy

As per Figure: F-1, biogas production in Italy was primarily from anaerobic digestions plants which contributed 85%. "*Sewage sludge gas*" from wastewater treatment plants contributed just 2.3% of biogas production whilst the remainder was made up of Landfill gas at 12.2% of biogas production in 2022, and 0.3% of biogas from gasification.

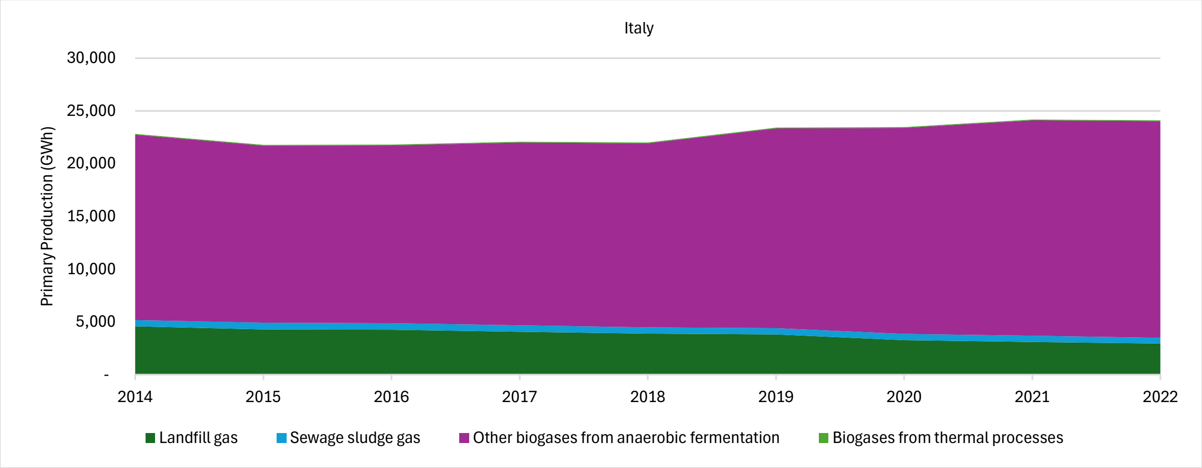

*Figure: F-1 Sources of indigenous biogas production in Italy*

From 2014 – 2022 the average annual growth rate of biogas production in Italy was 0.7% (Table: F-1). However, there was a distinct difference between the average annual growth rates of different biogas sources. Biogas from anaerobic digestion grew by 2% on average, and biogas from gasification grew by 1.3% on average. Biogas from landfills reduced by -5.3% on average, and biogas from sewage sludge reduced by 1% on average.

*Table: F-1 Average annual growth rate of biogas production in Italy*

| 2014 - 2022 | **Biogas** | Biogas from anaerobic fermentation | Landfill gas | Sewage sludge gas | Other biogas from anaerobic fermentation | Biogas from thermal processes |
|---|---|---|---|---|---|---|
| Average Annual Growth Rate (%) | 0.7 | 0.7 | - 5.3 | - 1.0 | 2.0 | 1.3 |

Figure: F-2 illustrates the breakdown of total biogas energy supply in Italy in 2022.

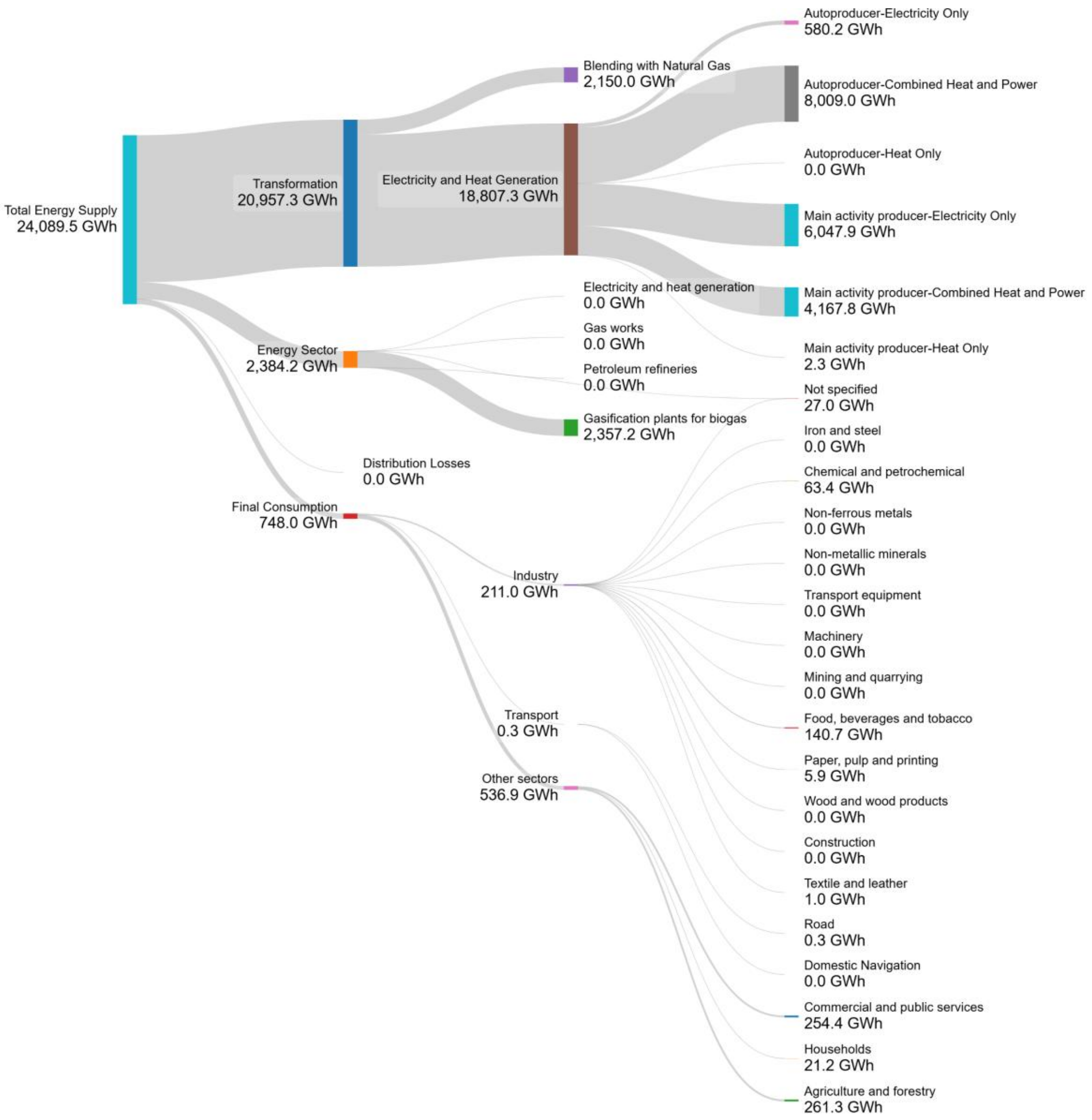

*Figure: F-2 Total biogas energy supply and use in Italy*

Within final consumption (748 GWh in 2022), industry was responsible for 28% (211 GWh) and experienced an annual average growth rate of -0.4% from 2018 – 2022. This reduction was primarily seen between 2018 and 2019, followed by an increase from 2020 to 2021. Within industry, the majority of biogas final consumption was in Food, Beverages, and Tobacco (66.7%), and the Chemical and Petrochemical sector (30%). Paper, Pulp, and Printing was responsible for a minor portion of final consumption (2.8%) in 2022. Average annual growth rates in these sectors were 0.7%, -3.1%, and 8.3% respectively.

A full breakdown of the relevant industrial sectors for Italy is shown in Figure: F-3 for the years 2018-2022.

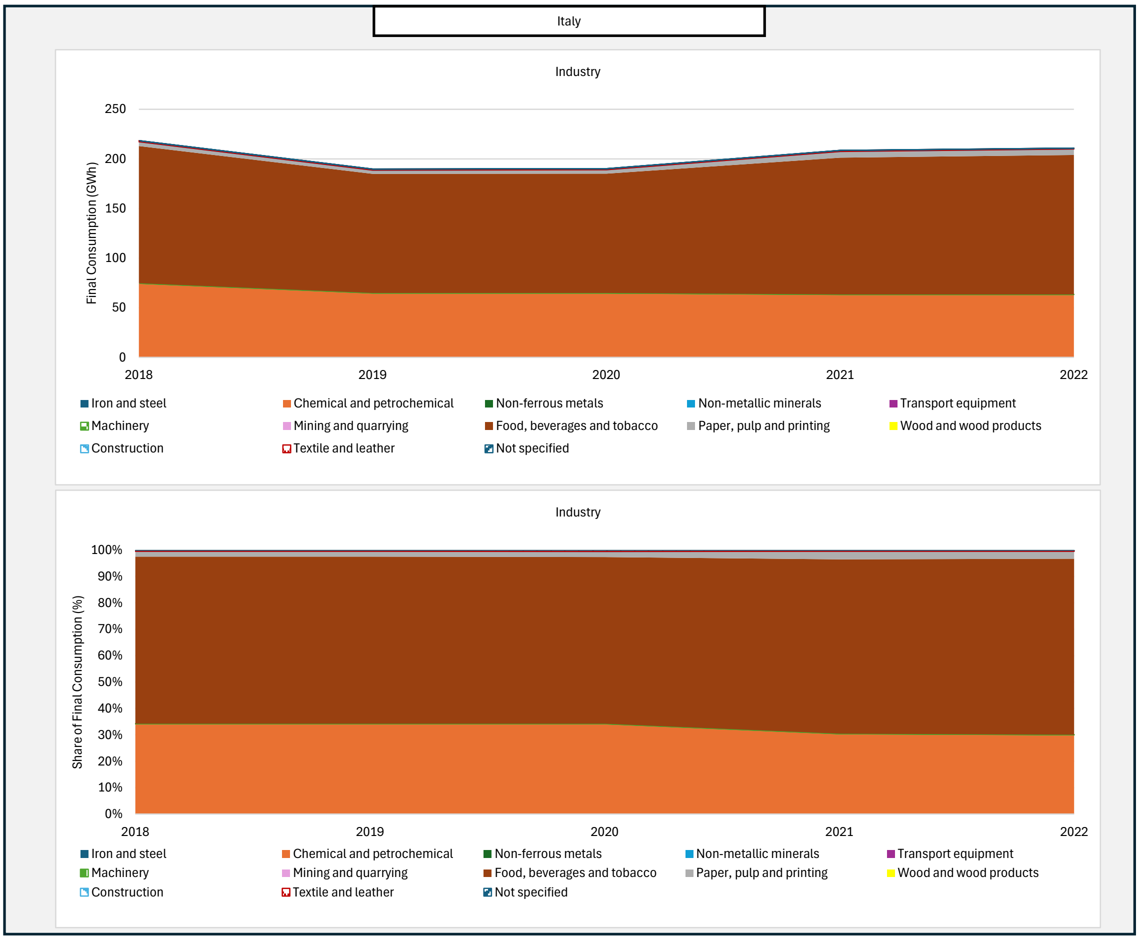

*Figure: F-3 Industry final consumption and sectoral share of biogas in Italy from 2018-2022*

# G France

As per Figure: G-1, biogas production in France was primarily from anaerobic digestion contributing 74.4% in 2022. Landfill gas contributed 22.6% of biogas production, and biogas from sewage sludge was responsible for 3%. No biogas production from gasification was recorded for 2022.

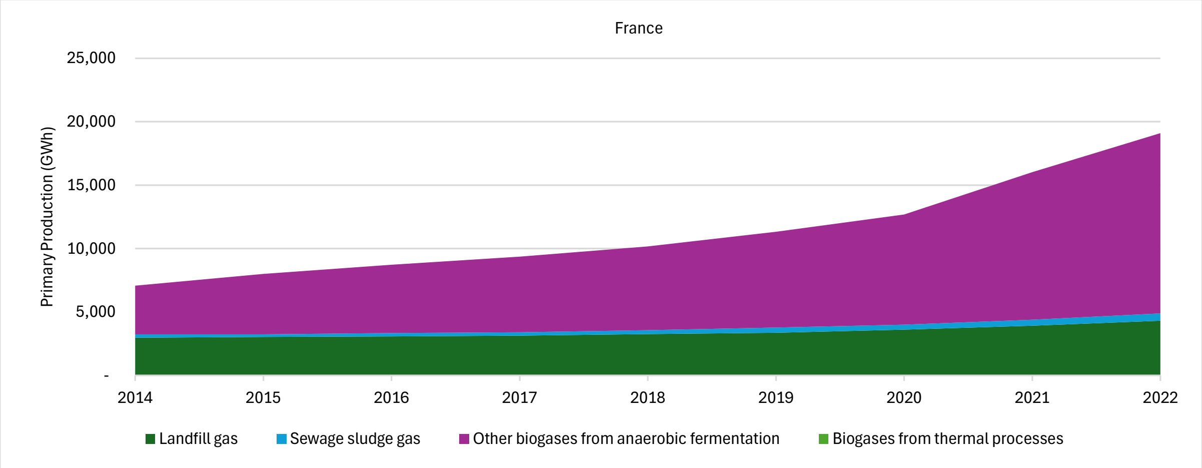

*Figure: G-1 Sources of indigenous biogas production in France*

From 2014 – 2022 the average annual growth rate of biogas production in France was 13.4% (Table: G-1). This was driven by an increase in biogas production from anaerobic digestion plants (18%), an increase in biogas from sewage sludge (11.7%), and biogas from landfills (4.8%). The majority of growth in biogas production in the France has been associated with biogas from anaerobic digestion plants.

*Table: G-1 Average annual growth rate of biogas production in France*

| 2014 - 2022 | **Biogas** | Biogas from anaerobic fermentation | Landfill gas | Sewage sludge gas | Other biogas from anaerobic fermentation | Biogas from thermal processes |
|---|---|---|---|---|---|---|
| Average Annual Growth Rate (%) | 13.4 | 13.4 | 4.8 | 11.7 | 18.0 | - |

Figure: G-2 illustrates the breakdown of total biogas energy supply in France in 2022.

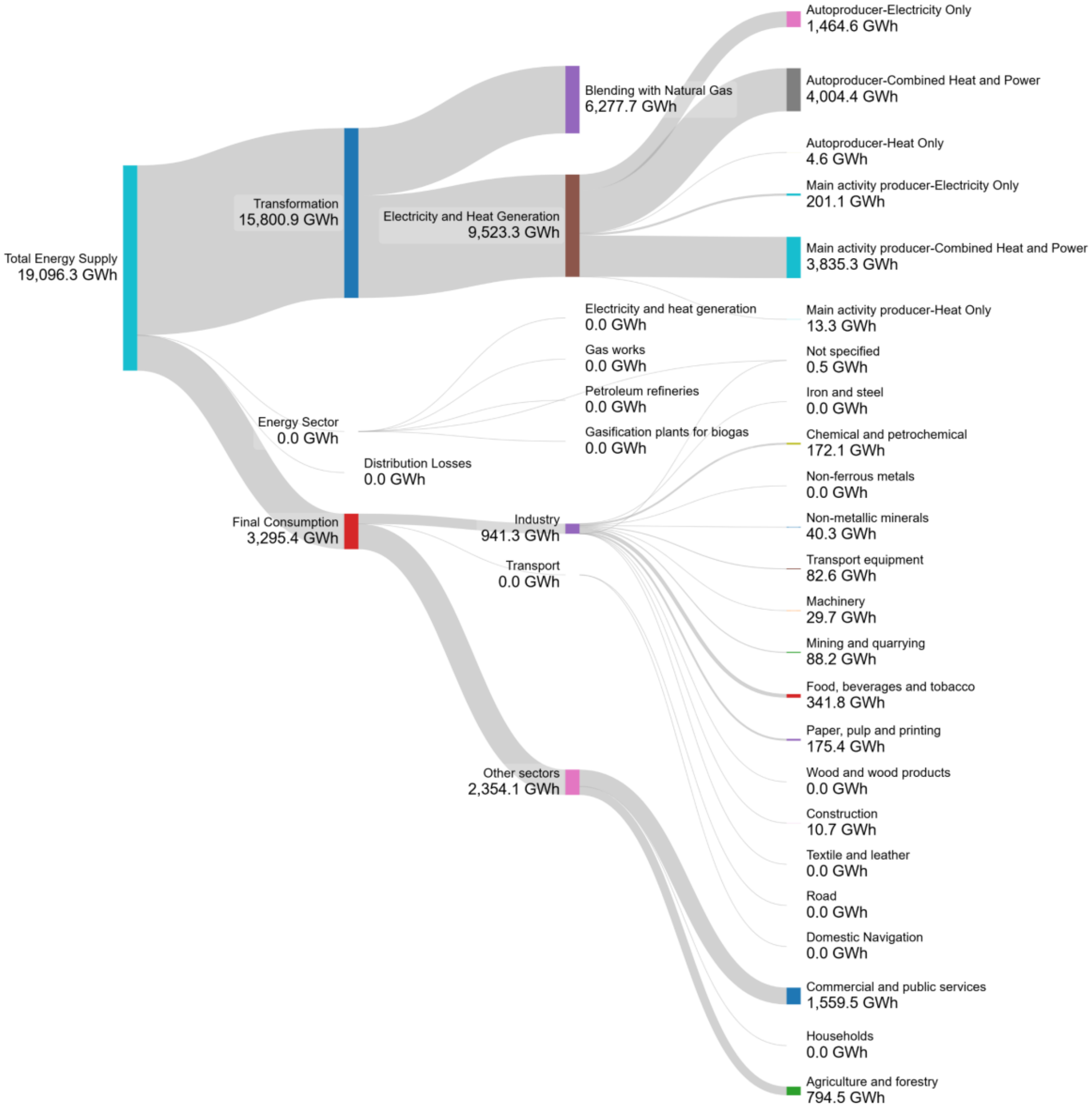

*Figure: G-2 Total biogas energy supply and use in France*

Within final consumption (3,295 GWh in 2022), Industry contributed 28.6% (941 GWh) of final consumption and experienced an average growth rate of 11% in the period 2018 – 2022, indicative of a significant increase. The majority of biogas final consumption was in Food, Beverages, and Tobacco (36.3%), Paper, Pulp, and Printing (18.6%), and Chemical and Petrochemical (18.3%) in 2022. Average annual growth rates of 9.5%, 6.1%, and 90.4% were recorded, respectively. This highlights the increasing role of biogas in these sectors where biodegradable materials suitable for anaerobic digestion are available. Industrial final consumption of biogas in France can be considered more diverse than in other EU countries discussed.

A full breakdown of the relevant industrial sectors for France is shown in Figure: G-3 for the years 2018-2022.

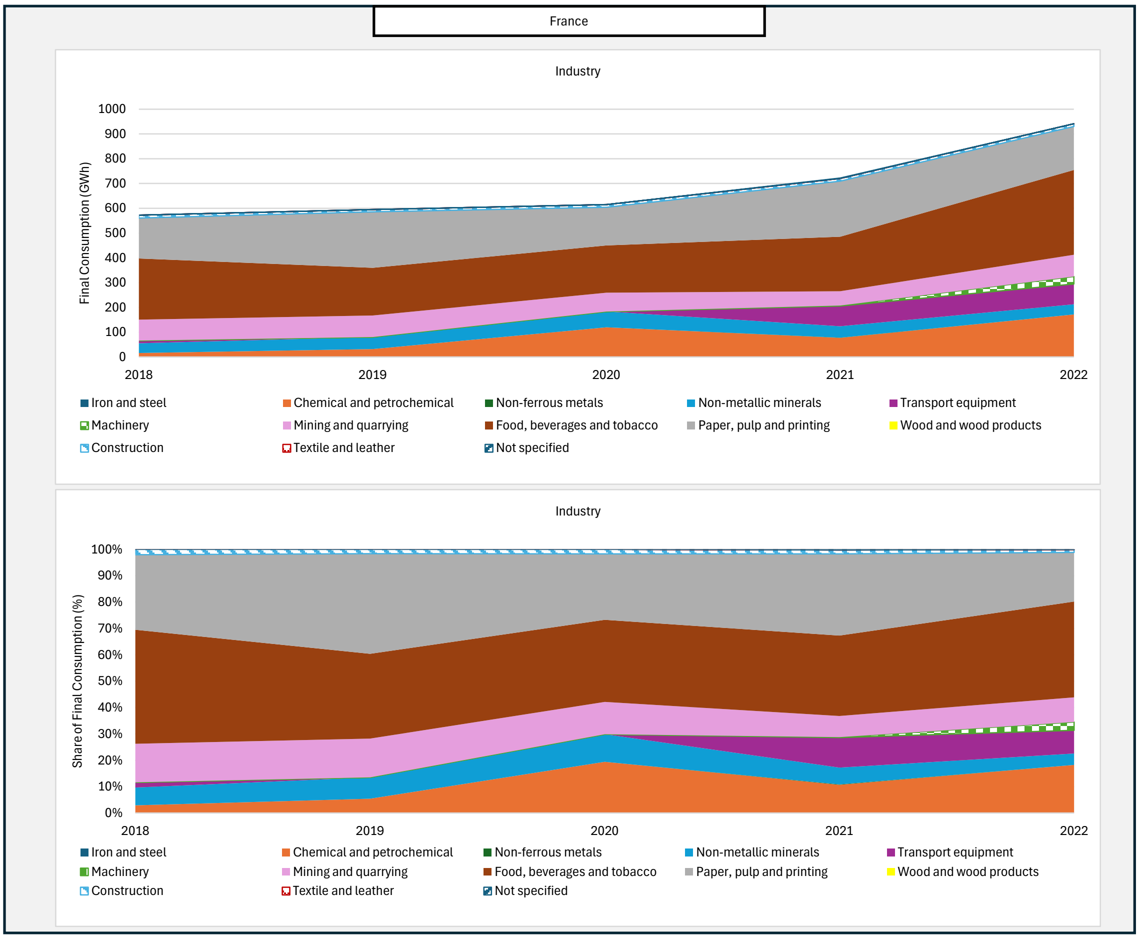

*Figure: G-3 Industry final consumption and sectoral share of biogas in France from 2018-2022*

# H Germany

As per Figure: H-1, the majority of biogas production in Germany in 2022 was sourced from anaerobic digestion plants at 93%, followed by sewage sludge (5.8%), and 1.4% from landfill gas. Biogas production from gasification was not recorded in 2022.

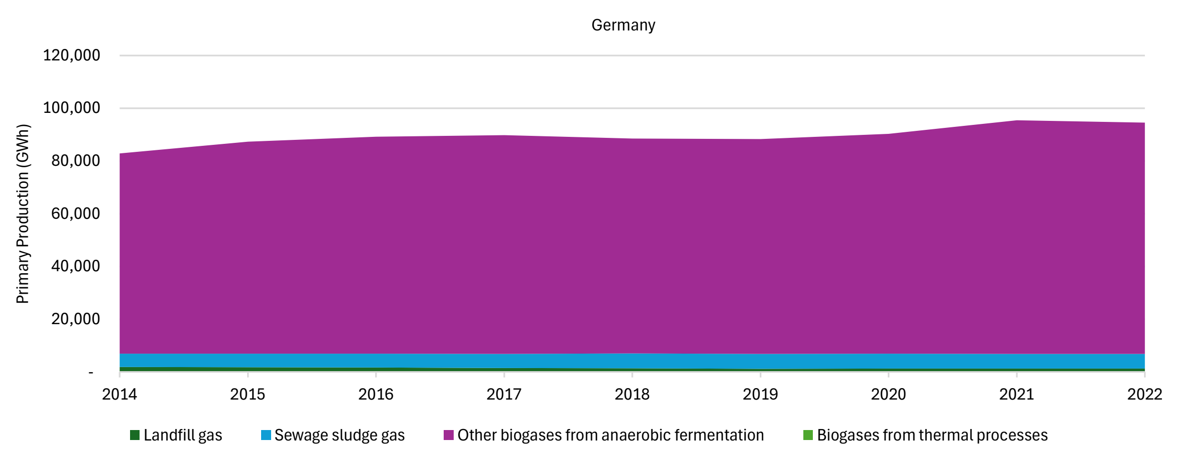

*Figure: H-1 Sources of indigenous biogas production in Germany*

Total biogas production in Germany grew by an average of 1.7% from 2014 – 2022 (Table: H-1), primarily associated with an average growth rate of 1.9% in biogas from anaerobic digestion, and 1% average growth rate in biogas from sewage sludge. Landfill gas experience an average reduction of -4.2% from 2014 – 2022.

*Table: H-1 Average annual growth rate of biogas production in Germany*

| 2014 - 2022 | **Biogas** | Biogas from anaerobic fermentation | Landfill gas | Sewage sludge gas | Other biogas from anaerobic fermentation | Biogas from thermal processes |
|---|---|---|---|---|---|---|
| Average Annual Growth Rate (%) | 1.7 | 1.7 | - 4.2 | 1.0 | 1.9 | - |

Figure: H-2 illustrates the breakdown of total biogas energy supply in Germany in 2022.

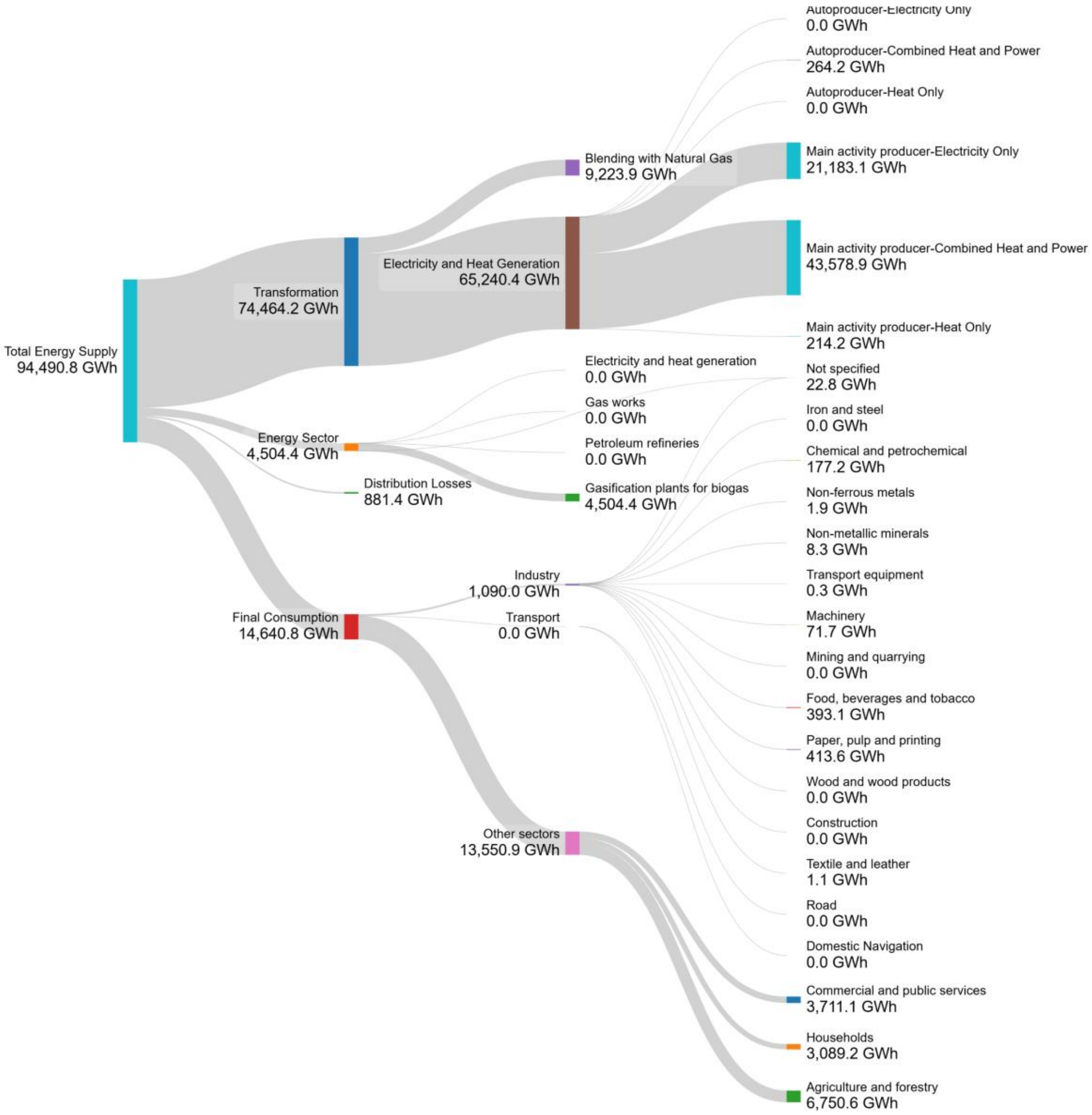

*Figure: H-2 Total biogas energy supply and use in Germany*

Within final consumption (14,641 GWh in 2022) Industry contributed 7.4% of final consumption and experienced an average growth rate of 9.2% from 2018 – 2022. Within Industry the majority of biogas final consumption was in Food, Beverages, and Tobacco (36.1%), Paper, Pulp, and Printing (38%), and Chemical and Petrochemical (16.3%) in 2022. Average annual growth rates of 14.9%, 6.5%, and 14.1% were recorded, respectively. The Food, Beverages, and Tobacco sector experienced a reduction in biogas final consumption from 2018 (241.9 GWh) to 2021 (208.9 GWh), followed by a significant increase in 2022 to 393.1 GWh. This highlights the large and increasing role of biogas in these sectors where biodegradable materials suitable for digestion are available.

A full breakdown of the relevant industrial sectors for Germany is shown in Figure: H-3 for the years 2018-2022.

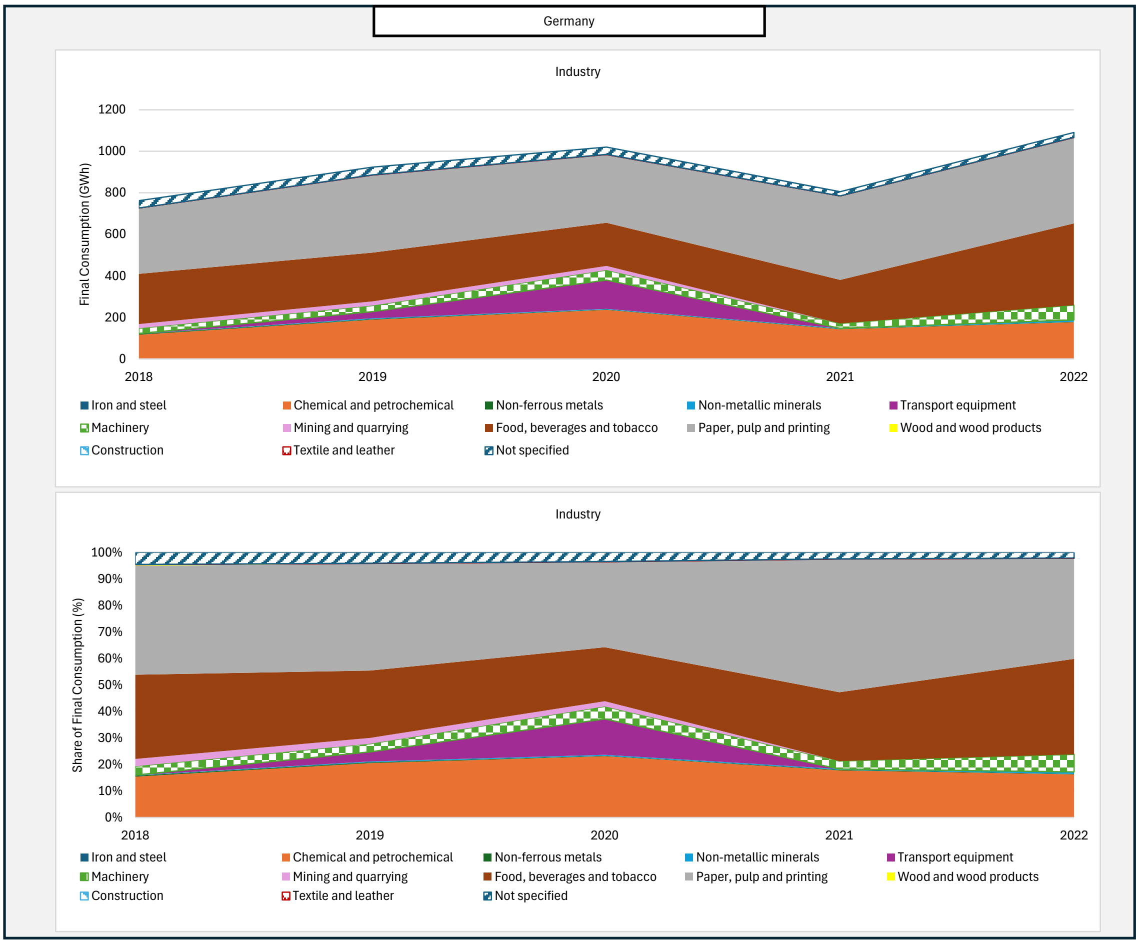

*Figure: H-3 Industry final consumption and sectoral share of biogas in Germany from 2018-2022*

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## Further Information

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