A perspective on the state of the biogas industry in 12 member countries of IEA Bioenergy Task 37

IEA Bioenergy: Task 37

September 2024

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Citation

Gustafsson, M., Meneghetti, R., Souza Marques, F., Trim, H., Dong, R., Al Saedi, T., Rasi, S., Thual, J., Kornatz, P., Wall, D., Berntsen, C., Saxegaard, S., Lyng, K.A., Nägele, H.J., Heaven, S., Bywater, A. (2024). A perspective on the state of the biogas industry from selected member countries. Gustafsson, M., Liebetrau, J. (Ed.) IEA Bioenergy Task 37, 2024:2

ISBN 979-12-80907-43-1

Published by IEA Bioenergy

Cover Photo: Nature Energy biogas plant in Korskro, Denmark. The plant takes in agricultural substrates from 70 farms within a 30 km radius, delivering biomethane to the gas grid, biofertilizers to the farmers and biogenic CO_2 to breweries.

Index

Executive Summary

INTRODUCTION

Activities within International Energy Agency (IEA) are set up under the Technology Collaboration Programs. These are independent bodies operating in a framework provided by the IEA. IEA Bioenergy, one of several active Technology Collaboration Programs, was set up in 1978 with the aim of improving cooperation and information exchange between countries that have national programs in bioenergy research, development and deployment. IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply whilst reducing greenhouse gas (GHG) emissions from energy use.

IEA Bioenergy Task 37 addresses the challenges and opportunities related to the economic and environmental sustainability of the production and utilization of biogas from anaerobic digestion (AD). In most, if not all, countries, biogas production has been dependent on investment support and/or subsidies to be financially viable, indicating the need to improve steps in the value chain to reduce both investment and operating costs, and derive more revenue or value from all of its products. Anaerobic digestion is a relatively simple and effective way of producing renewable energy and recovering nutrients from waste streams, whilst also delivering several other valuable services and benefits, including GHG mitigation. Task 37 publications include technical reports, case studies and country reports that provide important, current information intended to improve both the economic and environmental performance of biogas value chains where the gaseous end products, biogas and biomethane, can be utilized as heat, electricity, vehicle fuel or base material for chemical processes or combinations of these products. The main co-product from a biogas plant, the digestate, is a very important contributor to the overall sustainability of the biogas value chain and is also addressed in various Task 37 publications.

This current publication is the sixth annual summary of Task 37 country reports collated from the presentations made at meetings and from additional background details provided by the national representatives. It is hoped that this publication will enable widespread dissemination of up-to-date information on the state of the biogas industry in Member Countries located in the EU, North America, South America and Asia that will inspire readers to see the great potential for biogas solutions.

BIOGAS SOLUTIONS

Producing and using biogas through anaerobic digestion (AD) is a unique way of addressing multiple sustainability issues at the same time, including renewable energy production, waste management, climate change mitigation, and sustainable agriculture. Systems involving the production and/or use of AD products are often referred to as biogas solutions. Potential feedstock for biogas include most wet organic wastes and by-products, such as animal manure, crop and other agricultural residues, household, commercial and industrial food waste, sewage sludge and industrial wastewater. AD technology enables improved sustainability performance of several sectors—including agriculture, wastewater and solid waste treatment of municipalities as well as industry—by capturing fugitive methane emissions and converting the energy potential in residues and wastes into useful forms of renewable energy. In addition, the co-products of AD can provide several positive effects. Digestate, the liquid or semi-solid residue of the input feedstock, holds the undegraded carbon and almost all of the nutrients from the feedstock, and can be used a soil amendment and fertilizer. When biogas is upgraded to biomethane, it is also possible to recover biogenic CO_2 as an additional co-product. Although not widely implemented so far, CO_2 from biogas has plenty of potential areas of use where it could replace fossil-based products in, for example, the food industry, chemical production and power-to-gas, further lowering the carbon footprint of AD. Last but not least, the energy-rich biomethane can be used to replace fossil fuels in the energy and transport sectors reducing CO_2 and particulates emissions, or as a renewable feedstock for the chemical industry.

Renewable energy production from waste streams is generally considered to be the main purpose of AD, and therefore the capacity of AD plants is usually defined in terms of energy output or volume of biogas produced. Nevertheless, the co-products and other services provided by AD are key to its the overall economic and environmental sustainability performance.

ABOUT THIS REPORT

The country summary report series provides a regularly updated compilation of information about the biogas industry in the Task 37 member countries, including production of biogas and biomethane, utilization of biogas and other products from anaerobic digestion, policy and financial conditions and innovative projects. The 2024 report includes updates from 12 countries: Brazil, Canada, China, Denmark, Finland, France, Germany, Ireland, Norway, Sweden, Switzerland and United Kingdom.

The way information is gathered, recorded and reported varies from one member country to another and as a consequence comparison of country data is not always straight forward. Direct comparison is hampered by countries using different approaches to collect industry data, and, in particular, different units to compile the biogas data. One of the main differences is how the biogas production is quantified and expressed. The following three methods exist: i) the energy content in the produced biogas from different plant types independent of losses and the utilization; ii) the energy content in the produced and utilized energy (such as electricity, heat and vehicle gas); iii) installed capacity for energy production. While every attempt has been made to harmonize data in this publication, the different ways original data have been collected by member countries has made harmonization and subsequent comparison difficult.

Biogas production is presented for the following plant types:

- Wastewater treatment plants (WWTP) – digestion of municipal wastewater and sewage sludge
- Bio-waste – co-digestion or mono-digestion of food waste and other types of bio-waste, also known as source separated organics (SSO)
- Agricultural – digestion at farms (manure, energy crops and other crop and agricultural residues)
- Industrial – digestion of waste streams from various industries (e.g. food industries)
- Landfill – collection of landfill gas

Upgrading of biogas to biomethane is presented for the following technologies:

- Membrane – separation of methane and CO_2 by membrane filtration
- PSA (pressure swing adsorption)– separation of methane and CO_2 under pressure according to the gases' molecular characteristics and affinity for an adsorbent material
- Chemical scrubber – physical absorption of CO_2 by scrubbing with solvent (typically amines)
- Water scrubber – physical absorption of CO_2 by scrubbing with water
- Organic scrubber – physical absorption of CO_2 by scrubbing with organic solvent
- Cryogenic – separation by cooling to the point of condensation of CO_2 (can also be used to liquefy methane)
- Combined/other – upgrading plants implementing a combination of other or unspecified technologies

RESULTS AND CONCLUSIONS

China has the highest number of biogas plants among the reporting IEA Bioenergy Task 37-member countries, with more than 100,000 biogas plants, followed by Germany with over 10,000 and France with over 1,600 plants (Figure 1). Of the other reporting countries, Brazil has more than 800 biogas plants, UK has over 700 and the others have less than 500. With the exception of China, these are total numbers and include digesters of all sizes and technical configurations. (Note: China estimates that there are in the order of 40 million household digesters in the country, however, information on these household units is not included in this report.)

Germany has the highest annual biogas production, around 87 TWh/y. China produces around 81 TWh per year, UK 32 TWh, France 25 TWh, Brazil 12 TWh and Denmark 7 TWh. The other reporting countries produce less than 3 TWh. The actual biogas production is not reported in all countries; thus, in some cases it has been calculated, based on electricity and heat production and an assumed efficiency of 38%. These numbers do not distinguish the size of the plants, nor the technical configuration.

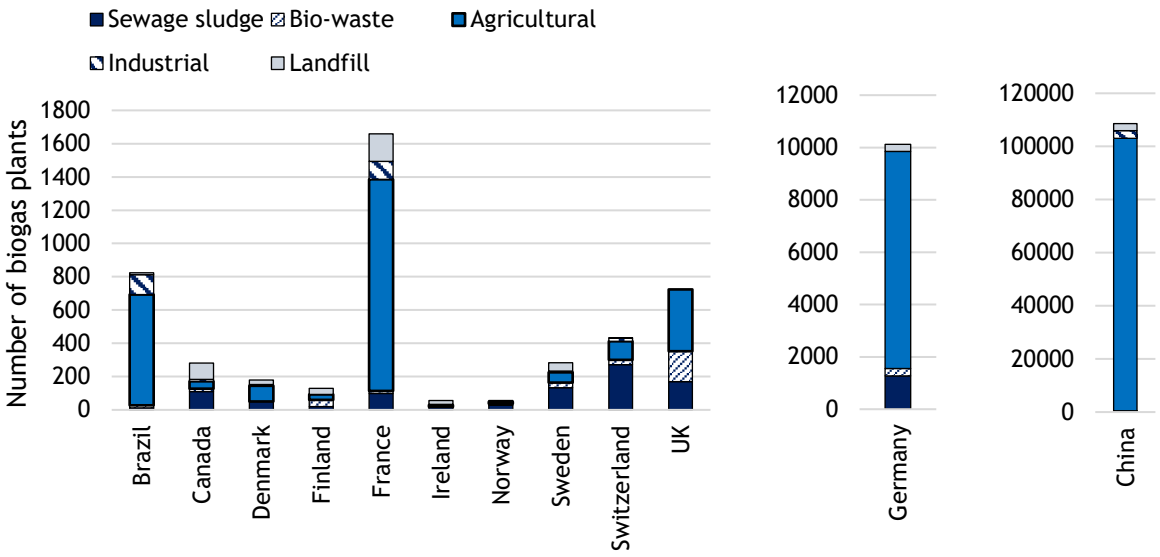

Figure 1. Number of biogas plants in operation in selected IEA Bioenergy Task 37 member countries

The production systems differ between the reporting countries, both in terms of biogas plant types (Figure 2) and upgrading plants (Figure 3). In Finland, Norway, Sweden, Switzerland and Canada, both wastewater treatment plants (WWTP) and plants based on mixed bio-waste play a more substantial role in biogas production than in other reporting countries, while agricultural plants constitute the majority of the biogas produced in China, Denmark, France and Germany. Landfilling of organic waste is being phased out in many countries, but landfill gas continues to be produced for many years and is the largest source of biogas in Brazil, Ireland and Canada.

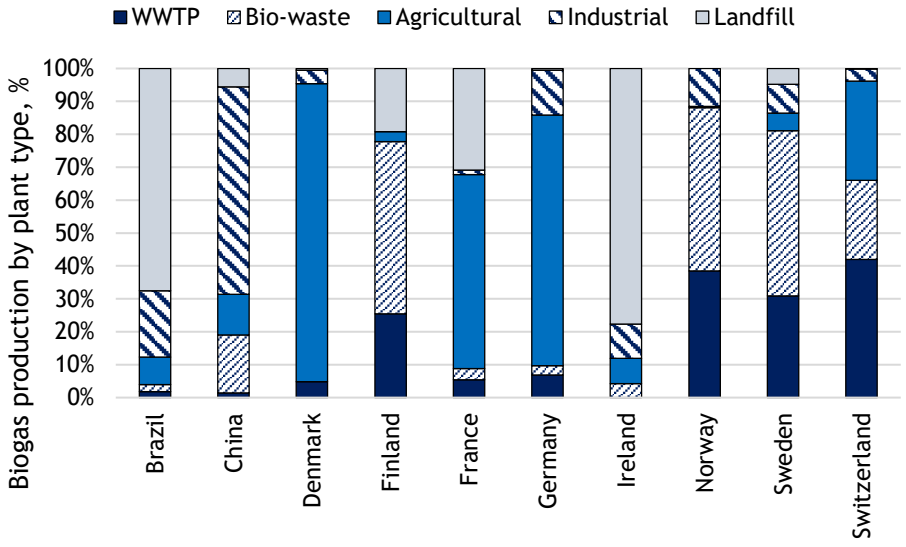

Figure 2. Production of biogas by type of plant in selected IEA Bioenergy Task 37 member countries

Regarding the upgrading of biogas to biomethane—where only half of the countries have reported recent data—membrane separation is the most common technology used in France and Switzerland. With 364 upgraders, France also has the highest number of upgrading plants among the reporting countries. Chemical scrubbers dominate biogas upgrading in Denmark, while Sweden and Germany have the highest shares of water scrubbers. Brazil has a large percentage of combined upgrading technologies. In Europe and North America, new installations are most often membrane separation units.

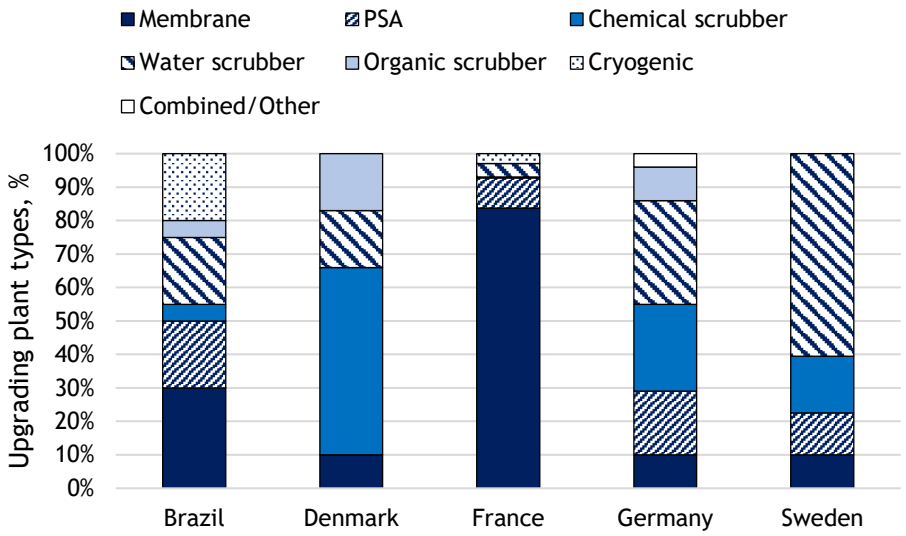

Figure 3. Upgrading plant types in selected IEA Bioenergy Task 37 member countries

Electricity and heat generation are the most common uses of biogas in Germany, Brazil, Canada, France and Finland (Figure 4). In Denmark and Switzerland, a large share of the produced biogas is upgraded into biomethane and injected into the gas grid. Sweden and Finland also have notable shares of biomethane production, but there it is mainly used as vehicle fuel, either as compressed (bio-CNG) or liquefied (bio-LNG) gas. Industrial use is relatively common in France, Norway and Brazil. Differences in how data are reported in each country make exact comparisons difficult, e.g., use as vehicle fuel can be reported as "vehicle fuel", "biomethane" or even "other". Also, once injected into the gas grid, the databases do not always distinguish the specific end uses of biomethane.

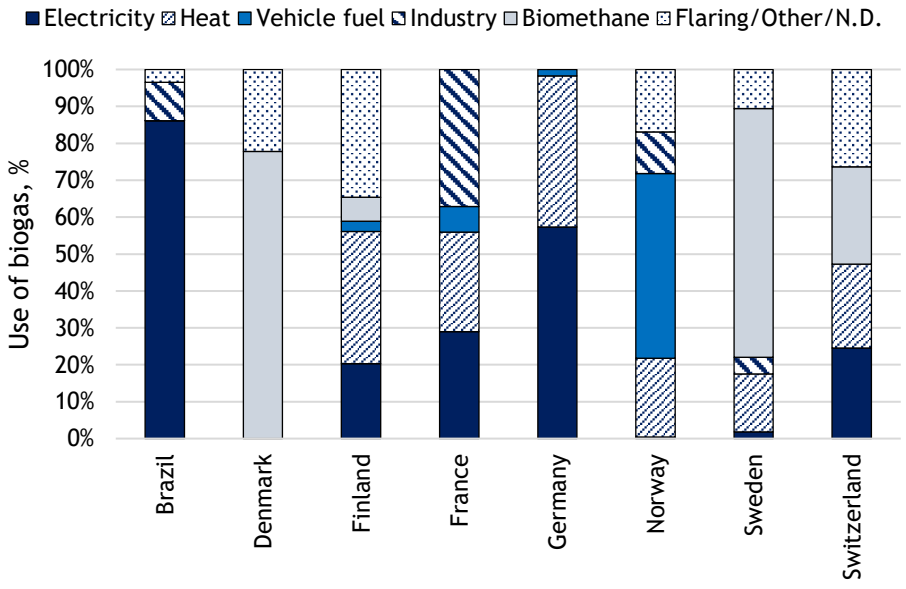

Figure 4. Use of biogas in selected IEA Bioenergy Task 37 member countries

Policy frameworks and financial conditions for biogas production have developed in various directions as they are context-specific, that is, they depend on the country's energy and industrial infrastructure and its objectives related to clean energy, climate change and waste management. Subsidizing electricity production from biogas through feed-in-tariffs has served as a common starting point in many European countries and North America, and is still the predominant support system in Brazil. Although biogas is used for heat, especially in WWTP and industrial biogas plants, only Ireland and France noted programs that support AD for heat production, and the UK has recently closed its Renewable Heat Incentive program. In recent years, in most European countries, Brazil and North America, the focus of biogas support has been shifting towards biomethane production for grid injection or for use as vehicle fuel. Sweden, Norway and Finland use tax exemptions for biogas use and investment support for new biogas plants as their main financial instruments. Moreover, many European countries have incentives for producing biogas from manure to mitigate agricultural methane emissions, and China has supported numerous AD demonstration projects for different types of manure. No programs were reported to support co-product development, other than the Nutrient Cycle Grant that is under consideration in Finland.

Finally, the IEA Bioenergy T37 member country report reveals a lot of promising technical progress and innovation in the biogas sector, with projects on everything from food grade CO_2 production to green aviation fuel. In particular, there are many examples of projects aiming to exploit the biogas potential in lignocellulosic biomass through gasification, to increase conversion of CO_2 via methanation and power-to-gas, as well as projects that are investigating greater use of straw and intermediate crops in AD. Along with innovative system integration projects, these examples reflect growing momentum in this space, and increased societal relevance for the biogas sector in the future.

1. Brazil

By: Rogério Meneghetti (Itaipu) and Felipe Souza Marques (Centro Internacional de Energias Renováveis)

The Brazilian biogas sector is becoming more solid and organized every day. A strong effort by the Brazilian Biogas Association (Associação Brasileira de Biogás – Abiogas) has encouraged the development of public policies with a focus on increasing the competitiveness of biomethane compared to fossil fuels and valuing the positive attributes of biogas. Regarding new business models and market strategies, the International Center for Renewable Energies (Centro Internacional de Energias Renováveis – CIBiogas), leads the actions in the country. Brazil is a large country of continental dimensions and of differing realities, depending on the region. Consequently biogas, an energy source with a strong regional connection, requires several different strategies to establish itself as a viable alternative in Brazil.

An important point of evolution in recent years was maturation of the understanding of state natural gas companies with respect to the role that could be played by biomethane. State natural gas companies, who control gas distribution, have adopted strategies to include biomethane in their businesses. Several public calls dedicated to the purchase of biomethane were launched. Currently, the gas company sets a renewable gas content target, however there is no legal requirement and the targets vary from state to state. Discussions are underway to establish a national law that would require the setting of a target on the minimum content of renewable gas.

With respect to biogas-generated electricity, an important milestone was implementation of the first biogas microgrid system in the country, in a rural area in the municipality of São Miguel do Iguaçu. In the event of a failure in the electricity supply, the biogas plant generates electricity and serves four nearby consumers. This plant operates in net-metering mode when it is not part of the microgrid. This project demonstrated to energy companies, who manage electricity distribution, that biogas-generated electricity can be an ally in the consistent supply of electricity. Important activities are underway to value the attributes of biogas as a dispatchable source of electricity, in a different way. The Itaipu Technology Park initiative, developed with Itaipu Binacional, has been the main driver of regional development projects with biogas and biomethane in the western part of the State of Parana for over ten years.

Regarding decarbonization, the sugarcane industry has adopted a very strong agenda, as it has organized itself to deliver ethanol for light vehicles and biomethane for heavy vehicles, including its own fleet dedicated to its operations. This industry has made significant advances in terms of technologies and processes for the production of biogas from vinasse and filter cake, for electricity and biomethane.

1.1. PRODUCTION OF BIOGAS AND BIOMETHANE

Brazil has diversified many of its biogas production strategies, incorporating both new business models and new technological routes. This has expanded the range of substrates used to produce biogas, e.g. organic processing plants that digest “bio-waste”. As shown in Table 1-1, landfills produce the most biogas, and agricultural biogas plants, especially animal protein (livestock and poultry), represent the largest number of AD plants operating in the country.

Table 1-1. Biogas production in Brazil

Plant type	Number of plants	Share (%)	Production (GWh/year)	Share (%)
WWTP	12	1.4	124	1.8
Bio-waste	15	1.7	145	2.1
Agricultural	666	75	576	8.4
Industrial	119	13.4	1,380	20.1
Landfill	76	8.6	4,630	67.5
Total	**888**		**6,855**	

There are 20 upgrading plants operating in Brazil, producing 1,245 GWh biomethane per year. As shown in Table 1-2, a variety of upgrader technologies are in operation, including member, PSA, water scrubber and combined technologies.

Table 1-2. Biogas upgrading plants in Brazil

Plant type	Number of plants	Share (%)	Production (GWh/year)	Share (%)
Membrane	6	30	30.4	2
PSA	4	20	76.9	6
Chemical scrubber	1	5	1.1	0.1
Water scrubber	4	20	284.3	23
Organic scrubber	1	5	138.9	15
Combined/Other	4	20	713.3	60
Total	**20**		**1,244.9**	

1.2. UTILIZATION OF BIOGAS

In Brazil, most biogas is converted into electricity. It is common, especially in agro-industrial boilers that are located far from the natural gas supply, to use biogas in boilers to replace wood in industrial boilers. As presented in Table 1-3, "Industry" is the largest user of thermal energy of biogas. Regarding biomethane, vehicle fuel use only considers biogas plants that are dedicated to vehicle fuel production. Therefore, the volume of biomethane injected into the natural gas grid was considered to have multiple applications including both industrial and vehicular uses. Not all biogas use was documented and some of the difference can be attributed to flaring.

Table 1-3. Utilization of biogas in Brazil

Utilization type	Utilization (GWh/year)	Share (%)
Electricity	4,914	89.1
Heat	0	-
Vehicle fuel	3.8	0.1
Industry	593	10.4
Multi-application	197	3.5
Flaring	N.D.	-
Total	**5,511**	

1.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

Brazil has not yet approved any direct subsidy for biogas and biomethane production, however several laws and policies, and financial support systems promote biogas energy use in the form of electricity and biomethane. The main ones are the following:

Distributed generation of electricity

Law 14.300/2022: This law sets ground for the distributed electricity generation from of all energy sources in Brazil. It replaces the resolution, Resolução 482/2012, from the regulatory agency (ANEEL), which was in effect until January 6, 2023. The net metering element of value generation was not changed. On one hand, new biogas plants benefit from this new set of rules, because biogas-generated electricity is considered a

dispatchable source of electricity. On the other hand, the new Law changes the way in which net metering energy credits are calculated, and they turn out to be less attractive than energy credits under the previous resolution.

Biomethane production

Law 14.134/2021 or *New Law of Gas:* This law aims at promoting competition on the mid- and downstream segments of the gas market. For example, it establishes the possibility of shared infrastructure, reduces requirements for the construction of new pipelines and sets new tariff rules that enable consumers to choose their supplier. One of the main highlights for biomethane, which benefits from the greater biogas production in the Brazil's interior, is the input-output approach. This approach enables matching of biomethane inputs in many different locations and different tariffs for gas injection with biomethane consumption (outputs).

National Biofuels Law – Federal Law 13.576/2017 or *RenovaBio*: This Law is considered to be the main national instrument for the reduction of GHG emissions from the transport sector in Brazil. It benefits biomethane projects, since biomethane is regulated by the regulatory agency ANP as a biofuel and has the best environmental footprint (lowest carbon footprint score) when compared to the other biofuels. Value creation comes in the form of a decarbonization credit (CBIO), based on the biofuels' carbon footprint, that is traded on the B3 stock exchange.

Ordinance 6.759/2009 or *Repetro-Sped:* This is considered to be the main public policy that supports the importation of equipment and exploration of oil and natural gas in Brazil. It does not support biogas and biomethane as it is a direct subsidy of the oil and fossil gas industry in Brazil, that will be in force until 2040. This decree, adopted in 2021, indirectly reduces the cost of the fossil upstream production and slows down the renewable energy transition.

At COP 26 (2022), Brazil signed onto the goal to reduce methane emissions and created the National Program for Emissions Reduction called "MetanoZero" with the Ordinance 71/2022. It aims to promote the construction of new biogas and biomethane plants, renewable gas fueling stations for vehicles, international cooperation and finance products in order to accelerate the growth of the biogas sector. Although this Ordinance does not carry the weight of a law, it is an important step in public policy legitimization of the biogas sector. In addition, there are also State laws that support biogas and biomethane production through specific credit lines, tax reduction and licensing ease.

National Economic and Social Development Bank (BNDES)

The Brazilian Economic and Social Development Bank offers at least 3 credit lines that are available for biogas and biomethane projects. The most relevant credit line is called "Fundo Clima" (climate fund), which supports decarbonization and environmentally relevant projects, and can help finance biogas and biomethane projects contribute to urban mobility, renewable energy, use of solid residues and innovation. In 2022, interest rates in Brazil rose to their second highest rate in the last decade, making it important for projects to secure incentivized lines of credit to be economic feasible.

1.4. INNOVATIVE BIOGAS PROJECTS

Integrative projects for processing substrates in the protein chain (livestock and poultry industries) and producing biogas are gaining ground in Brazil. These projects adopt strategies that integrate producers who cannot find viability on their own, such as by sharing a biogas pipeline or sending their substrates to a common biogas plant, thereby enabling gains in technological robustness due to the larger scale of the biogas plant. Examples are the plants of the company Enerdimbo in Ouro Verde do Oeste-PR, and Central de Bioenergia Toledo in Toledo-PR. The Toledo plant is part of the Itaipu Binational strategy on regional sustainability and treats substrates and swine carcasses from 15 farms.

The largest producer of biomethane authorized by the National Agency of Petroleum, Natural Gas and Biofuels (ANP) is a landfill located in the City of Seropédica, in the State of Rio de Janeiro. It is operated by the company Gás Verde, belonging to the Urca Energia Group, and upgrades landfill gas into biomethane with an installed production capacity of 204,000 m^3/day.

According to the company, its current effective production is 130,000 m^3/day of biomethane, which is distributed by a bundle truck through the Neogás company. The company also issues CBIO, decarbonization credits in accordance with ANP specifications, and BIORec, biomethane traceability certificates, in addition to producing electricity, with a total power production capacity of 2.86 MW registered with the National Electric Energy Agency (Aneel). In 2024, the company will start producing 100 tons/day of green CO_2 from the same landfill and will be the first plant in the sector to produce a sustainable substitute for fossil CO_2.

The landfill in Caucaia, in the State of Ceará, has the second largest biomethane plant in the country, with a biomethane production capacity of 110,000 m^3/day. This facility is operated by the Marquise group and MDC Energia, and biomethane distribution is carried out by pipeline through the distribution grid of Cegás (gas company). Following the commissioning of this project, this gas company had one of the most renewable gas grids in the world, with a volumetric average of 13% of biomethane.

Currently, the only company in the sugar-energy industry authorized by the ANP to produce biomethane is Cocal Energia, located in Narandiba, São Paulo (SP). The biomethane production capacity is 27,113 m^3/day. In addition to sugar cane and sugar, it produces ethanol, electricity, biomethane, green CO_2 (food grade) and yeast. It has an installed electricity production capacity of 5 MW of total power, granted by Aneel for. Part of the biomethane is distributed through the first gas pipeline in Brazil that is dedicated exclusively to the transport of biomethane. Through approximately 65 km of distribution network, the biomethane from the sugar-energy plant is connected to the industrial consumer market in the City of Presidente Prudente (SP).

Another plant in the sugar-energy industry, located in the City of Guariba (SP), belongs to the company Raízen Energia, which is the largest producer of energy generated from sugarcane biomass. With a total installed power production capacity of 21 MW, it sells its power through supply contracts via the Brazilian Free Contracting Environment (ACL). Its units are self-sufficient in energy consumption and the surplus energy is sold. The group operates in the production and commercialization segments of both sugar and ethanol, and bioenergy.

The landfill in the City of Caieiras (SP) has the largest thermoelectric plant powered by biogas in the sector and one of the largest in the world, belonging to the Solví group. It has a total capacity of 29.5 MW_e. With respect to biomethane, an upgrader plant is under construction and will have a capacity of 73,920 m^3/day. The biomethane produced will be distributed through the Comgás gas pipeline.

Finally, there is development of a pilot-scale technology for the production of Sustainable Aviation Fuel (SAF) from biogas, offgas and green hydrogen (GIZ). This project is funded by the German-Brazilian Cooperation for Sustainable Development, through the German Technical Cooperation Agency GIZ (*Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH*) in partnership with Ministry of Mines and Energy (MME) and Ministry of Science, Technology and Innovations (MCTI). It is executed by the International Center for Renewable Energies (CIBiogás), the Araucaria Foundation, the Federal University of Paraná (UFPR) and also has the support of the Hydrogen Research Center of the Itaipu Technology Park (PTI) and Itaipu Binacional. The initiative aims to develop an alternative technology that is able to convert biogas into sustainable aviation fuel (SAF), which can be used by the aviation sector to reduce its climate impact. The proposed technological route integrates the reforming process with Fischer-Tropsch synthesis, and it will be implemented at the UD Itaipu, which is financially maintained by the Hydroelectric Power Plant. The project also foresees the transfer of knowledge and the design of a technical model for decentralized production of renewable fuels.

2. Canada

By: Hank Trim (Agriculture and Agri-Food Canada) and Maria Wellisch (MWA Consultants)

2.1. PRODUCTION OF BIOGAS AND BIOMETHANE

Wet anaerobic digestion systems are the most common in Canada. Approximately 193 AD plants process sludges from WWTPs, bio-waste, manure and industrial effluents with a high organic loading. They convert these organic materials into biogas that is used for heat and electricity, and, increasingly, biomethane, and a digestate slurry with typically less than 15% total solids. Landfill gas is collected from 99 sites. The breakdown by sector and biogas production, shown in Table 2-1, was provided by the Canadian Biogas Association. Co-digestion of materials results in some overlap in the plant categories, particularly in the case of agricultural AD plants that generally co-digest manure with industrial waste from nearby food processing plants and/or bio-waste.

Table 2-1. Status of biogas production in Canada (Canadian Biogas Association, 2022)

Plant type	Number of plants	Share (%)	Energy Production (PJ/year)	Comment
WWTP (sludge)	111	39%	2.9*	Increasing trend: more CH_4 recovery and use over time
Biowaste (SSO)	17	6%	1.3	Processing 1 Mtons/yr inputs; several new AD plants under development; growth in biomethane
Agricultural	43	15%	1.6**	Processing 0.9 Mtons/yr inputs; mostly electricity and heat today; future: biomethane
Industrial	12	4%		Little publicly available data; Mostly internal use as heat
Landfill	99	35%	16.6	Mostly electricity; logistical and economic barriers to use
Total	**282**		**22**	

** Value includes energy from Industrial AD plants ** Value from Agriculture and Agri-Food Canada*

Most of Canada's biogas production is derived from the management of municipal solid waste and wastewater. In 2022, approximately 111 WWTPs used anaerobic digestion to stabilize the sludge that is generated by the wastewater treatment process. According to Canada's 2024 National Inventory Report (NIR), methane recovery has increased significantly at these facilities. In 2022, 107.6 kilotons (kt) of methane were recovered, of which 36.4 kt CH_4 was used for energy and 71.2 kt CH_4 was flared (Environment and Climate Change Canada, 2024).

Close to 100 landfills are collecting landfill gas for energy use or are flaring the biogas to reduce odors and methane emissions. Modelling carried out for the NIR estimated a total production of 1,206 kt CH_4 from Canada's landfills in 2022. Of this, 210 kt CH_4 were captured and used for energy, 244 kt were captured and flared, 77 kt were oxidized via landfill covers, and 696 kt were released to atmosphere (Environment and Climate Change Canada, 2024).

With more regions banning the landfilling of organic waste, there are at least 17 AD plants treating bio-

waste, referred to as source separated organics (SSO) in Canada, and several new plants under development.

According to the Canadian Biogas Association, there were 43 operating agricultural AD systems in 2022. Due to the smaller scale of Canada's dairy operations and the large distances between farms, most agricultural AD plants process 51-60% dairy manure combined with 40-49% food waste from nearby food processing plants to achieve economy of scale. Existing systems produce electricity for sale to the grid and use part of the heat production, while all new systems include biogas upgraders to produce biomethane for injection into the gas grid. The AD plants under construction are significantly larger than existing plants, and several are adding depackaging equipment to accept more bio-waste.

Data, both on the number of AD facilities and energy production, are more difficult to retrieve for the industrial sector. The Canadian Biogas Association reported 12 operating facilities while Agriculture and Agri-Food Canada identified 25 digesters operating at food and beverage processing facilities and 2 at pulp mills. In most cases, biogas is directly used in on-site boilers to displace natural gas. Nevertheless, the NIR for 2022 reported a significant amount of flaring at industrial facilities. Of a total CH_4 production of 14.8 kt, 8.1 kt were used for energy and 6.8 kt were flared.

Biogas end-use data can only be presented as a whole, and not by plant type. Approximately 40% of the collected landfill gas and digester biogas is currently flared. This is largely attributed to location, small scale, lack of access to infrastructure and the need for energy off-take agreements to justify the investment. The Canadian Biogas Association reports the distribution of total biogas energy use as 50% electricity, 22% heat and 28% biomethane, with most new projects targeting biomethane production.

Depending on the plant type and location, whole digestate or digestate solids are applied to agricultural soils, landfilled and, in the case of biosolids, sometimes incinerated. Regulations vary between provinces, with end-use being dependent on digestate quality and the types of inputs to the AD plant. Approximately one third of agricultural AD plants separate the solids from the whole digestate and use these as animal bedding.

Economics of Agricultural and Agri-Food Anaerobic Digestion

AD systems are capital intensive. Costs range from roughly $10M up to $100M (€6.7 – 67M) depending on the size of the project. Technology costs are high due to a lack of domestically produced systems and limited design expertise which has led to a reliance on European technology and designers. The costs of connection to the electrical grid or the natural gas network are also very high, and for smaller systems can represent 20% of overall project costs. These costs can be further compounded by AD systems' reliance on economies of scale to produce biogas cost effectively.

Data on Canadian operating costs is limited. Facilities seem to have operating costs that range from 4% to 8% of capital costs. Canadian operating costs are roughly in line with European operating costs. It is important to note that, while operating costs are not prohibitive it can be a challenge for a farmer to take on the knowledge and time intensive operation of an AD system. In response, biogas developers have developed partnerships and cluster-focused business models where an AD system is centrally located and biogas is produced through revenue sharing agreement with agricultural partners in a feedstock cluster.

Agriculture and Agri-Food Canada (AAFC) economists estimate that an AD plant in the Province of Ontario, with a $30/GJ (€72/MWh) 20-year contract to produce biomethane and capital costs of $10M (€6.7M), would have a $3M (€2M) annual income, $800k (€540k) operating costs and operational income of $2.2M (€1.5M) (Canadian Biogas Association, 2021a). The investment would take 4.5 years to pay back and have a cost-to-benefit ratio of 3.3 using a standard discount rate of 3%. These estimated revenues do not include the value of digestate nor biogenic CO_2. Digestate is not normally sold by farm operators because they can use it directly as soil conditioner and fertilizer to replace a portion of synthetic fertilizer use. Analysis by the Province of Ontario suggests that NPK nutrients in digestate are worth roughly $190 (€130) per acre.

Digestate cannot completely replace the synthetic fertilizer demand for all crops, but it is well suited to

use on forage crops and can provide organic matter to enhance soil health. While the N_2O emissions of liquid digestate are similar to emissions from synthetic fertilizer, it can have lower lifecycle GHG emissions due to the avoided emissions associated with fertilizer manufacture. However, the net effect can vary depending on the system retention time, digestate storage conditions and the way in which digestate is applied to agricultural soils.

The estimated GHG abatement costs for AD systems are relatively high (Canadian Biogas Association, 2022). For comparison, the abatement cost for solid/liquid separation of manure is roughly $225 (€150) per ton CO_2-eq. However, it is important to note that manure treatment does not create a new revenue stream for farms, nor can it achieve as deep GHG reductions because solid/liquid separation addresses a smaller percentage of methane emissions. AAFC scientists are therefore investigating other types of manure treatment, such as acidification, as a way to avoid the production of methane during manure storage.

Potential of Anaerobic Digestion in Agriculture

There is significant potential for AD systems to reduce agriculture's GHG emissions and to contribute to rural economic sustainability. AAFC estimates that only about 1% of its total annual manure production is digested. Recent research supported by the Canadian Biogas Association estimates that with aggressive policy support agricultural biogas could cut Canada's total GHG emissions by 9.3 Mt CO_2-eq in 2030, and 22.2 Mt CO_2-eq in 2050. According to AAFC scientists' analysis AD systems could capture 0.429 Mt CO_2-eq annually or roughly 10% of total methane emissions from manure. Processing and different management of digestate could increase total methane abatement by an additional 30% to provide a further 0.130 Mt CO_2-eq reduction annually. This estimate does not include abatement from the disposal of food waste or reductions from displacing fossil energy and synthetic fertilizer. It only includes reductions that could take place on large livestock farms where AD systems are most financially viable.

There is significant room for growth in the biogas industry if demand for biogas energy increases. Biomethane mandates in the Provinces of British Columbia and Quebec are currently driving expansion in the biogas industry. A recent study of the Province of Ontario's biogas potential estimated that there could be 540 economically viable feedstock clusters in the Province given a biomethane price of $27/GJ (€65/MWh), which is close to the contract rate offered by the gas utility FortisBC (Canadian Biogas Association, 2021b). Companies with expertise in financing, AD management and project development are aware this potential and making investments in the sector. Énergir (gas utility) in the Province of Quebec and the Danish company Nature Energy announced a partnership in December 2022 to build up to 10 AD facilities in Province. These projects could produce roughly 200 million m^3 of biogas and abate 400,000 tons of CO_2-eq annually. The total investment if all projects are built would be roughly $1.4bn (€940M).

AD systems also provide significant co-benefits that are not usually monetized. In the context of concerns over fertilizer emissions and farm nutrients, the most important co-product of AD plants is digestate. It is a comprised of undegraded organic material rich in plant-available phosphorous, potassium, and nitrogen and other micronutrients, serving both as a soil conditioner and fertilizer. The digestate has the potential to be certified as an organic fertilizer, if it meets quality standards, and be sold commercially in pellet form, which could reduce reliance on synthetic fertilizers more broadly. However, this would require investment in digestate processing technology and a market willing to pay a sufficient price for these fertilizer products.

Depending on the digester inputs, digestate may contain contaminants such as heavy metals, polyfluoroalkyl substances (PFAS) and microplastics. This is of increasing concern to AD plants in the waste and wastewater treatment sector, but it also needs to be considered by agricultural AD plants that co-digest bio-waste and WWTP sludges. Investigations are underway to better understand how these contaminants are mobilized, and the appropriate uses of digestate.

2.2. POLICY AND FINANCIAL SUPPORT SYSTEMS

It is clear that AD can deliver significant benefits to waste management, regenerative agriculture, GHG mitigation and clean energy. In the case of agriculture, to deliver these benefits the agricultural biogas industry must overcome several barriers. The primary challenges are the closely linked issues of policy uncertainty and investment capital. AD plants, biogas upgrading and grid connection are all capital intensive, and facilities have few sources of revenue. This makes market certainty and strong policy signals fundamental to de-risking biogas projects and attracting needed investment. The recent growth in biomethane project investment and production highlight the impact of policy signals such as the renewable gas mandates.

As close to 90% of the feedstock, on a ton basis, leaves the AD plant in the form of digestate, the management of digestate is also an important emerging issue. If it does not contain noxious substances, digestate can be an important source of animal bedding, soil conditioner and fertilizer. However, it needs to be properly stored, treated and applied to avoid ground water pollution and the release of CH_4, N_2O and ammonia. Given the current size of the biogas industry in Canada, digestate is not a significant source of emissions or water pollution today, but as the biogas industry expands its potential for harmful impacts will increase. Therefore, appropriate management practices and technologies, that could effectively recover the nutrients and organic matter and/or reduce the potential emissions from digestate, need to be developed to support the growth of the biogas industry and obtain public acceptance.

There is limited support for AD at the federal level in Canada. Work is underway to develop offset protocols and carbon accounting methodologies to enable AD projects to generate carbon credits. Agriculture and Agri-Food Canada provides some financial support for AD through the Agricultural Clean Technology Program. This Program supports both farmers and food processors' adoption of technology, and research and innovation to reduce GHG emissions. It includes AD technology as an eligible technology, but this program does not prioritize AD projects.

Provincial energy market and climate change regulations have done significantly more to support the adoption of AD in Canada. Several Provinces had set up Feed-in-Tariff programs that included the production of electricity from biogas at a premium. The FIT programs have come to an end, but two Provinces have set renewable gas mandates that require a percentage of gas grid to be renewable gas. Today, this is the main driver for new investment in AD in Canada. The Provinces of Ontario, British Columbia and Quebec have also worked to amend regulations around provincial gas utilities, off-farm material being used as feedstock, digestate regulations and other areas to enable greater adoption of AD on farms. This is an important consideration because most standards and regulations applying to AD systems fall under provincial or local jurisdiction.

2.3. INNOVATIVE BIOGAS PROJECTS

The Sherbrooke Research and Development Centre at Agriculture and Agri-food Canada has been working on AD research since the late 1990s. The Centre chose to build their own biodigester to push their research further, especially in regards to low-temperature AD to tackle high-ammonia wastes including swine and chicken manure. This is where Bähler Biogas came into play: they built a biodigester able to support this scientific work.

The scientific team is testing the methods and practices of AD that will meet the needs of a medium-sized Canadian farm. The research has the following goals:

1. Reduce the environmental impact of farm activities by reducing methane emissions.
2. Increase the value of residual matters by converting manure into bioenergy (biogas) and bioproducts. For example, solid residues from the biodigester could be converted into high-quality biofertilizers or biochar, which have multiple applications.
3. Find answers to the problems that are encountered by Canadian agricultural producers when it comes to managing manure or slurry on their farm.

Meeting these goals should help Canada's agricultural and agri-food industries to benefit from the advantages of small-scale AD of agricultural waste.

Compared to other existing approaches to treat livestock effluents, the AD technology developed by AAFC has many forward-thinking, unique and promising benefits for agricultural waste, including:

- Operation at low temperature (20 – 25 °C), thereby reducing process energy consumption
- Reliable and stable process that is ideal for agricultural applications
- Possibility to use a variety of livestock effluents and other organics such as agri-food residual materials
- Purification of biogas through the removal of hydrogen sulfide
- Removal of pathogens in the digestates
- Simple process, easy to integrate into the farm's activities
- In the next years, research will allow AAFC to develop an optimal biodigester that meets the needs of Canadian livestock farms. This biodigester will help medium-sized farms to reduce their ecological footprint. It will also help using purified by-products generated by the anaerobic digestion and produce renewable energy.

This work is considered to result in innovation to fight climate change, and to demonstrate how agricultural waste can contribute to a circular economy. Bähler's technical expertise in building small-scale bioreactors combined with the scientific expertise of AAFC researchers should promote the development of AD facilities that are more profitable and advantageous for Canada's agricultural and agri-food industries.

21

3. China

By: Renjie Dong (Bioenergy and Environment Science & Technology, China Agricultural University)

China has a long history of biogas use dating back to the Song Dynasty (960-1270). The development of China's biogas industry has gone through five stages since the 1950's: initial development, technological maturity, rapid development, emphasis on construction and management, and transformation and upgrading. In the past 20 years, in order to promote the development of the rural biogas industry, the Chinese government has invested a total of more than ¥48bn (€6.2bn), and the rural biogas industry has successfully realized the transformation and upgrading from household biogas to various types of biogas projects and large-scale biomethane (bio-natural gas) projects. As of 2021, together with the existing about 40 million household biogas digesters, the total annual biogas production in mainland China was estimated to be about 60 billion cubic meters (bcm). There were 64 biomethane projects (≥ 10,000 m^3 biomethane per day per project) and 8,000 large-scale biogas projects (≥ 1,000 m^3 biogas per day per project).

3.1. PRODUCTION OF BIOGAS AND BIOMETHANE

Table 3-1 presents the types and approximate numbers of biogas plants in China, not including the 40 million household digesters. As of 2021, there were over 100,000 biogas plants in China, with small biogas plants predominantly found in rural areas. However, when it comes to actual production share, industrial-scale biogas plants, including large plants, account for more than 60% of total biogas production.

Table 3-1. Biogas plants in China

Plant type	Number of plants	Share (%)	Production (Mm^3/year)[a]	Electricity capacity (MW)[b]	Share (%)
WWTP	100	0.1	190	39	1
Bio-waste	366	0.3	2,380	489	18
Agricultural	102,637	94.6	1,660	341	12
Industrial	2,800	2.6	8,500	1,747	63
Landfill	2652	2.4	750	154	6
Total	**108,555**		**13,480**	**2,770**	

[a]China's Biogas Contribution under "Carbon Peaking and Carbon Neutrality" Target; [b]Calculated.

3.2. UTILIZATION OF BIOGAS

Apart from electricity generation and vehicle fuel, there is not much data on the utilization of biogas in China. As of 2022, the installed capacity of biogas power generation in China reached 1.22 GW, a 37% increase from 2020. Meanwhile, the biomethane market in China is just starting up with only 0.3 bcm of annual production, compared to the consumption of 331.9 bcm natural gas in 2022. There is almost no biomethane being injected to the natural gas grid so far. As is the case for the household digesters, the majority of the biogas plants are also small and located in rural areas, where the biogas is usually used by farmers for cooking and local heating.

However, the annual biomethane potential in China is estimated by the Chinese Biogas Association to be 150 – 200 bcm, with one trillion yuan (€388bn) market investment. China's Carbon Peaking and Carbon Neutrality Strategy and, in particular, its newly launched Methane Emission Reduction Action Plan, fuel a new vitality for biogas development in China that includes biogas power generation, biomethane utilization as vehicle fuel or industrial fuel, biomethane injection into gas grid, and biogas to hydrogen or biomethanol, and so on.

Table 3-2. Utilization of biogas in China

Utilization type	Utilization (GWh/year)
Electricity	3,700
Heat	N.D.
Vehicle fuel	3,000
Industry	N.D.
Flaring	N.D.
Total	**N.D.**

3.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

The 14th Five Year Plan for the Modern Energy System, National Energy Administration, 2022
The 14th Five Year Plan (2022) aims to develop renewable energy sources in accordance with local conditions and promote the diversified utilization of biomass energy. It should also create a steady development of urban waste incineration power generation, orderly development of agricultural and forestry biomass power generation and biogas power generation and development of clean biomass heating. Regarding biogas, the plan specifically addresses the agricultural sector, through coordination of the planning and construction of biogas plants in major grain-producing areas and concentrated areas of livestock and poultry farming, and promote field application of digestates.

Implementation Program for Emission Reduction and Carbon Sequestration in Agriculture and Rural Areas, 2022
This program specifies six tasks centering on energy conservation and GHG emission reduction measures in crop and animal production, emission reduction and carbon sink enhancement in the fishery industry, carbon sequestration in crop fields, energy conservation and emission reduction in agricultural machinery sector, and renewable energy production and substitution of fossil fuels. It suggests to develop rural biogas according to local conditions, and encourages the construction of large-scale biogas plants, where necessary, to treat large amounts of agricultural biowastes and replace fossil energy.

Demonstration Counties for Rural Energy Revolution, 2023
This policy encourages the development of bioenergy projects according to local conditions of the selected demonstration counties of each province, to effectively deal with biowastes and produce continuous and stable green renewable energy. The target is "by 2025, each demonstration county will have renewable energy account for over 30% of the total primary energy consumption and over 60% of the incremental primary energy consumption."

Administrative Measures for Voluntary Emissions Reduction Trading of Greenhouse Gases, 2023
The Administrative Measures clearly state that the establishment of a unified, national trading institution for the voluntary GHG emission reduction, will be developed. Four kinds of China Certified Emission Reduction (CCER) methodologies have been issued, marking the official resumption of CCER trading is approaching. The biogas sector hopes to re-enter the voluntary emission reduction trading market soon, which will bring additional benefit to biogas stakeholders.

3.4. INNOVATIVE BIOGAS PROJECTS

Jiangsu Xinyi Animal Manure Biogas Project
Jiangsu Xinyi Animal Manure Biogas Project is located in Huaying Agricultural Ecological Industrial Park of Xinyi County, Jiangsu Province. The project, designed to treat whole livestock manure and some crop residues in the park, has a total investment of about ¥65 million (approximately €8.4 million) and occupies a land area of about 47,000 m^2.

The project's daily treatment capacity is about 1,040 tons (260 t chicken manure, 160 t duck manure, 460 t pig manure and 40 t crop residues), out of which 826 tons are digested in four 5,000 m^3 vertical-stirring mesophilic CSTRs with special sand and scum separation design, and 214 tons are composted. The total solids (TS) content is 8 – 10% and the ammonia nitrogen concentration in the reactors is below 6,500 mg/L. The biogas purification system consists of two biological desulphurization units (4 m diameter, 12 m height) and one chemical desulphurization unit, with 70 – 120% processing flexibility and daily processing capacity of 22,000 m^3. The H_2S content is reduced from just under 10,000 ppm to 20 ppm. The desulfurized biogas is stored in the double-membrane gas tank and is used for heating in the park or upgraded to biomethane through membrane purification system for export to natural gas network. After solid/liquid separation of the digestate, the daily production of 737 t slurry digestate is used for crop field application in the park after certain period of storage. The daily production of 63 t fiber digestate is mixed with 40 t of crop residues (peanut shell, rice husk, straw, etc.) and treated in a flipping composting /deodorizing composting system to produce commercial fertilizer. The total annual output of commercial fertilizer, meeting China's organic fertilizer standard, is 24,000 tons.

Figure 3-1. Jiangsu Xinyi Animal Manure Biogas Project

Scale-up Biogas Project in Yicheng city, Hubei Province

Hubei Yicheng large-scale biogas project uses yellow storage rice straw as the main feedstock, and livestock and poultry manure, fruit and vegetable waste, starch residue, and food processing waste as supplementary materials for mixed fermentation. Part of the biogas is upgraded for gas grid injection, and part is cleaned for biogas power generation. All the digestates (fibre and slurry) are used for soil improvement.

There are 13,000 m^3 of feedstock storage capacity and six anaerobic tanks with 17,182 m^3 of fermentation volume. The fermentation TS reaches around 17% in the tank. This project has three independent modules: cogeneration units (800 kW and 637 kW), membrane biogas upgrading (15,000 m^3 biomethane per day), and digestate used as biological fertilizer (100 tons per day). It processes 56,000 tons of straw, manure, vegetable residues and organic waste annually, produces 12.25 million m^3 of biogas, 5 million m^3 of biomethane, 6.4 – 11.5 GWh electricity and 30,000 tons of digestates. The project adopts a multi-stage AD technology with high temperature, high loading and high fermentation TS (around 17% in the tank), which overcomes the difficulties of co-digesting different types of feedstock, such as crop residues, animal manure, rotten fruit and vegetables, organic household waste, and kitchen leftovers, and so on.

Figure 3-2. Biogas Project in Yicheng city, Hubei

Kweichow Moutai Industrial Demonstration Park Biogas Project

Kweichow Moutai Industrial Demonstration Park Biogas Project focused on the comprehensive utilization of distiller's grains, producing biogas for energy and digestates for biofertilizer. The biogas is used to generate steam for the distillery, with a portion upgraded to biomethane that is being injected into the local town gas pipeline network in Yaxi Town. The digested slurry is used as fertilizer for the production of sorghum and other grains used in brewing. This project, implemented in 2015, is one of the first group of national pilot biogas and bio-natural gas project.

The project has 16 digester tanks with a capacity of 3,000 m^3 each, one pressure swing adsorption (PSA) upgrader, two sets of steam boilers and one biofertilizer production unit to make use of the fibre digestate. The project is designed to process 100,000 tons of distiller's grains annually and treat 48,000 m^3 of brewery wastewater. It can produce approximately 21 million m^3 of biogas per year and extracts 11 million m^3 of biomethane. Additionally, it produces 50,000 tons of biofertilizer for sale and 60,000 tons of slurry digestate for local land application.

The project has resolved the technical challenges of high ammonia nitrogen, high acidity and high organic load contained in distiller's grains. It has established a technological pathway for coupling AD with the complete utilization of brewing waste, achieving the resource utilization of distiller's grains and brewery wastewater while providing green low-carbon energy such as biogas and biomethane.

Figure 3-3. Kweichow Moutai Industrial Demonstration Park Biogas Project

4. Denmark

By: Teodorita Al Saedi (BIOSANTECH Biogas consult)

Biogas from anaerobic digestion is a well-established renewable energy technology in Denmark, with significant contribution to the share of renewable energy in the Danish energy consumption, and to the overall reduction of GHG emissions. Most of the biogas produced in Denmark is upgraded to biomethane, with a quality corresponding to that of natural gas, and fed into the national gas grid, gradually superseding the fossil natural gas in the Danish energy consumption. The overall role of biogas in the Danish energy supply is to balance the wind dominated electricity production and as an important and economically advantageous tool in the "green energy transition", for the mitigation of climate change and reduction of CO_2 and other GHG emissions from the energy, transport, and the agricultural sector.

Figure 4-1. Biogas plant in Korskro, Jutland (Nature Energy Korskro A/S)

4.1. PRODUCTION OF BIOGAS AND BIOMETHANE

In 2020, there were 180 biogas plants in Denmark, producing close to 7.3 TWh/year (Table 4-1). The cornerstone in the Danish biogas production are the agricultural biogas plants, with 91% of the total biogas production. More recent data show the production of biogas and biomethane in Denmark has grown to 7.5 TWh (Figure 4-2). Most of the biogas is upgraded to biomethane (97 – 99 % of CH_4) and fed into the gas grid.

Table 4-1. Biogas production in Denmark (Biogas Danmark, 2022)

Plant type	Number of plants	Share (%)	Production (GWh/year)	Share (%)
WWTP	50	28	352.5	5
Agricultural	94	52	6,587.5	90.5
Industrial	8	4	297.5	4
Landfill	28	16	38.6	0.5
Total	**180**		**7,276.1**	

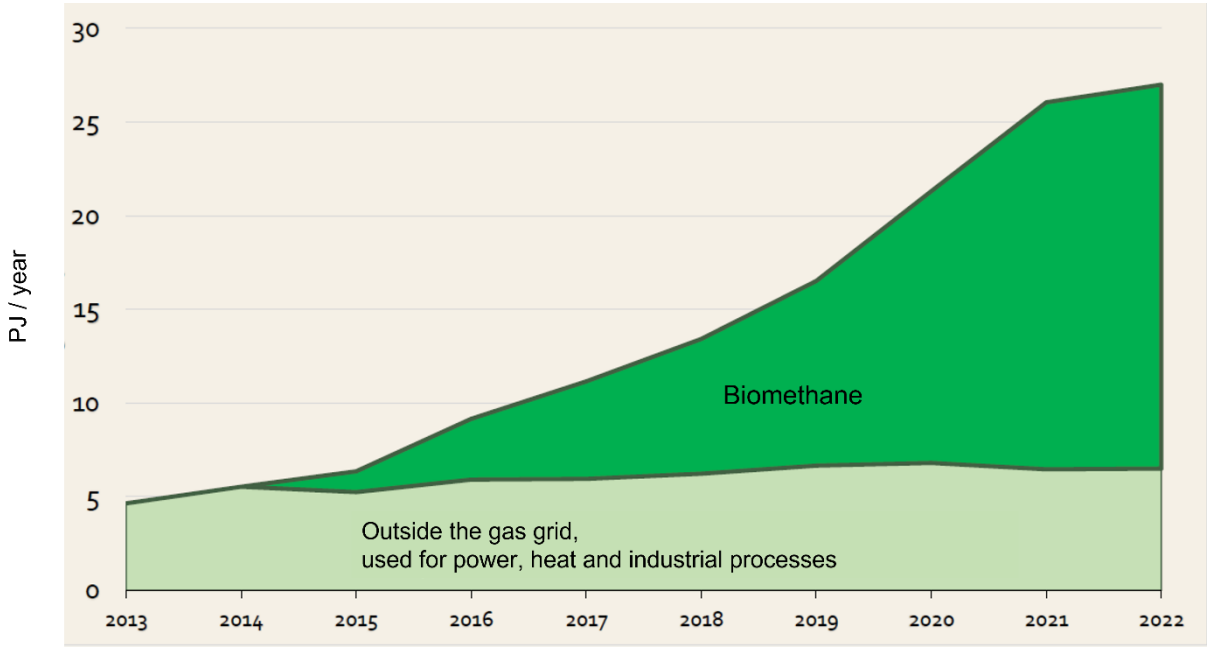

Figure 4-2. Production of biomethane to the gas grid and of biogas in Denmark, 2013-2022. Adapted from Biogas Danmark, 2022.

By the end of 2022, there were 51 biogas upgrading plants in Denmark, with a combined capacity of 77,300 m^3/h raw biogas (Table 4-2). Over half of the upgrading plants are using chemical scrubber technology (56%).

Table 4-2. Biogas upgrading plants in Denmark

Plant type	Number of plants	Share (%)	Capacity (m^3/h raw gas)	Share (%)
Membrane	11	21.5	7,850	10
Chemical scrubber	26	51	43,405	56
Water scrubber	10	19.5	13,250	17
Combined/Other	4	8	12,800	17
Total	**51**		**77,305**	

The potential of biogas production in Denmark is greater than the total gas consumption. The total bioresources in the form of livestock manure and digestible residual products from households, industry and agriculture that can be utilized for biogas production amounts to 26 TWh, according to a report prepared by the University of Southern Denmark for the Danish Energy Agency. The production forecast, based on estimates from the Danish Energy Agency and the Danish Biogas Association (Biogas Danmark), indicates a probable production of 14 – 15 TWh in 2030, and 17 TWh in 2035.

4.2. UTILIZATION OF BIOGAS

Most of the biogas produced in Denmark is upgraded to biomethane and fed into the gas grid (Figure 4-2, Figure 4-3 and Table 4-1). Biomethane plays an essential role in the green transition of the gas system and the security of energy supply. In 2022, the biomethane share was almost 40% of the total gas consumption, and the objective of the Danish Government is to achieve 100% green gas consumption by 2030 – a target that could be achieved even earlier. The current record for biomethane coverage of the total measured Danish gas consumption is 98.2% over 24 hours.

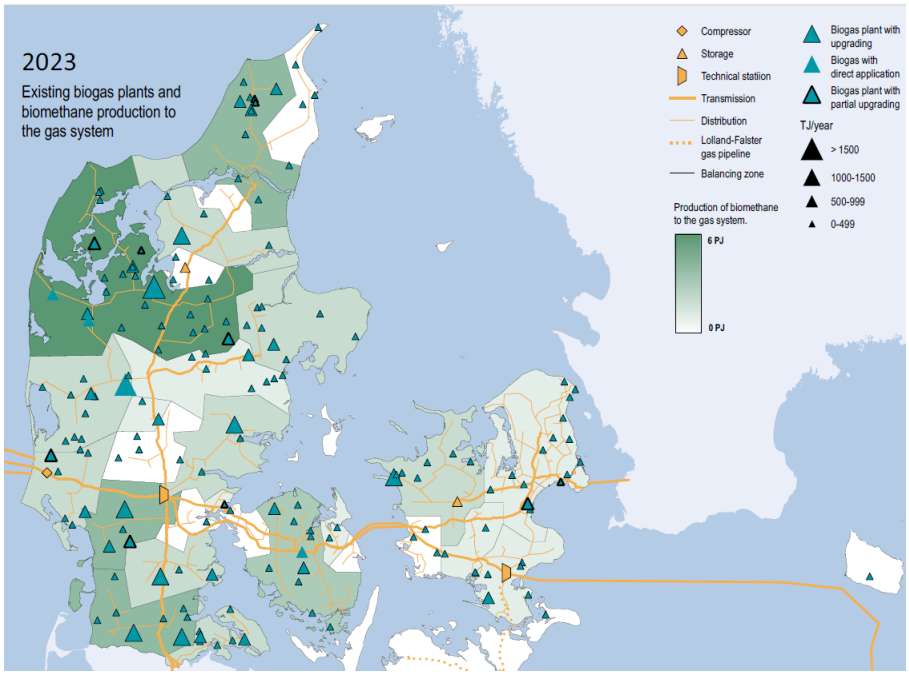

Figure 4-3. Biogas plants supplying biomethane to the national gas grid (Danish Energy Agency, 2023)

Production and utilization of digestate

Digestate from the agricultural biogas plants is used as crop fertilizer (Figure 4 4). In the biogas plants, the value of livestock manure as fertilizer is improved, and at the same time the risk of loss of nutrients to the aquatic environment is reduced. Digestate smells far less than manure when used as a fertilizer. The recirculation and recycling of the nutrients contained in organic wastes by biogas plants is important in relation to the future food supply, as some of the nutrients the crops need are scarce resources, such as phosphorus, or they involve energy intensive production, such as nitrogen fertilizers.

Apart from animal slurries, grain straw is considered to be one of the feedstock resources with a large unused potential. One ton of straw yields more than twice as much biogas as one ton of energy crops due to the low water content of the straw. Research shows that when straw and deep litter are digested in biogas plants, most of the slowly convertible carbon is returned to the agricultural soil (Thomsen et al., 2013). Consequently, when treating the straw in AD processes, the same amount of carbon is stored long-term in the soil as if the straw were crushed directly into the soil after harvest. As shown Table 4-3, the 1.22% straw (on a mass basis) provides 5.5% of the biogas production. In general, the older and smaller farm biogas plants do not use straw as feedstock, while almost all newly built plants use straw, some of them in very large amounts. The Danish Energy Agency and Biogas Danmark estimates indicate that 64% to 70% of manure and slurries and 20% of straw production will be supplied to co-digestion biogas plants by 2030. Table 4-3 shows the main feedstock types, and the respective amounts and biogas production of the agricultural biogas plants, in 2021 – 2022.

Figure 4-4. Application of digestate as fertilizer. Left: Dragging hoses (Maskinbladet/Arkivfoto: Morten Damsgaard). Right: Injection (Solrød Biogas)

Table 4-3. Feedstock supply and biogas production of agricultural biogas plants in Denmark

Feedstock types supplied to agricultural biogas plants	Supplied amount, kton	Share of supplied, %	Produced biogas, million m³	Share of produced biogas, %
Animal slurries and manure	11,701	74	335.3	30.9
Energy crops	833	5.3	127.0	11.7
Other crops, crop-residues, discarded feed	184	1.2	26.1	2.4
Grain straw and seed grass	193	1.2	60.2	5.5
Grain remover and sunflower peelers etc.	121	0.8	41.4	3.8
Olive oil press residue	36	0.2	11.0	1.0
Potato/beet pulp and the like	306	1.9	21.9	2.0
Fish waste, silage, and pond sludge	212	1.3	18.6	1.7
Slaughterhouses, etc. processing of animal	514	3.2	45.0	4.1
Soap stock etc. from oil refining	110	0.7	38.1	3.6
Molasses	247	1.6	80.3	7.4
Glycerin and the like products	240	1.5	156.3	14.4
Various other org. wastes from industries	576	3.6	62.8	5.8
MSW pulp, commercial kitchen waste etc.	544	3.4	62.3	5.7
Total	**15,817**	**100**	**1,086.8**	**100**
Methane yield, m³/t biomass			**44.66**	
Energy potential, TWh			**7.0**	

4.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

Financial support to existing biogas installations and installations put into operation by 31/12 2022
Since 2013, financial support schemes have been available to facilitate the use of biogas for electricity production, and to supply biomethane to the natural gas grid, for transport, for processing purposes in enterprises and for heating and other purposes. Subsidy rates were regulated based on electricity and gas prices, and the price development in general.

The biogas support schemes were changed in 2020. Only existing biogas installations and a few projected installations, which the Danish Energy Agency has committed to support, will be eligible for support under the new schemes. Furthermore, the amount of subsidies has been capped and the subsidy period is limited to 20 years. Support granted under the new support schemes may be reduced if there is a risk of overcompensation according to EU's State aid rules. The most recent overcompensation assessment concludes that no such overcompensation occurred in the period 2018-2020.

Tenders for support of biogas and other green gases
Green gas is a collective term used for the gases that are produced from renewable sources, and by various sustainable processes. The term includes e.g. biogas, electricity to gas and thermal gasification. The 2020 tender allocated a total pool of about DKK 13.6 billion (€1.8bn) for six tenders for support to green gas production, in the period until 2030. A follow-up political agreement of December 2021 sets out the framework governing how to design and implement the support tenders. Unlike previous biogas support schemes, only green gas produced for the gas grid will be eligible for support. In the first tender round, upgraded biogas and e-methanol are eligible for support.

The successful tenderers will be those making the lowest premium bids until the budget is exhausted. The Danish Energy Agency expects upgraded biogas to be the successful tenderer and to defeat other green gases based on PtX technology, as upgraded biogas currently has the lowest production costs, according to the Danish Energy Agency's Climate status and projections.

Framework for tenders for support to biogas and other green gas production is as follows:

- The first tender is in 2023 with an outflow from 2024 of DKK 200M/year (€27M)
- The second tender is in 2024 with an outflow from 2025 of DKK 120M/year (€16M)
- The third tender is in 2026 with an outflow from 2027 of DKK 75M/year (€10M)
- The fourth tender is in 2027 with an outflow from 2028 of DKK 75M/year (€10M)
- The fifth tender is in 2028 with an outflow from 2029 of DKK 90M/year (€12M)
- The sixth and last tender is in 2029 with outflows from 2030 is DKK 88M/year (€11.8M)

The bid price must be quoted as a fixed premium for each GJ green gas supplied to the gas grid, and gas eligible for support is subject to a maximum amount. An upper limit on bids ensures that excessive bids may be rejected. Support is granted for 20 years, corresponding to the successful tenderers' bid prices. Moreover, support is capped at a gas price of DKK 120/GJ (€58/MWh). If the gas price exceeds this upper limit, support will be reduced correspondingly. There is an obligation to meet minimum gas production quota, which is subject to a penalty for non-compliance. The subsidies provided for the production of green gases must contribute to increased competition, thereby helping to reduce production costs. It is estimated that these tender calls will reduce GHG emissions by approximately 200,000 tons of CO_2-eq in 2025 and 700,000 tons of CO_2-eq in 2030.

Climate Agreement on green electricity and heat 2022 – More green gas
The current need to ensure the energy supply security makes the production of biogas even more relevant for Denmark. The Climate Agreement (2022) aims to further develop and increase biogas production in Denmark through implementation of these specific measures:

- To limit methane losses by regulating methane loss from biogas production. The sources of methane loss at each biogas plant must be identified and remedied. The regulation is therefore introduced based on an annual, external plant review with requirements for improvements, improvements at the plants, a self-monitoring program and a point source limit of 1% from specific point sources. The regulation is enforced from January 2023.
- Tenders for support of biogas projects. As part of the Danish Climate Agreement for energy and industry from 2020, it was decided to hold tenders for support for biogas and other green gases, within a total support framework of 13.6 billion DKK (€1.8bn) up to 2050. In December 2021, an agreement was reached on the implementation of the first support tender, which is expected to be held in 2023. A second tender will be held in 2024, with a run-off from 2025.
- Promote sustainability of biomass feedstock used for biogas production. The possibility of further lowering the use of energy crops for biogas will be assessed, along with increasing the use of straw as biogas feedstock. Straw has a high biogas potential compared to other biomasses and can therefore contribute to maintaining a large biogas production, when the use of energy crops is phased out.
- Financial overcompensation assessments for biogas production are required when the annual accounts are available, and, if overcompensation is determined, the Danish government will present concrete proposals to address overcompensation.

The Climate Agreement (2022) estimates the following reductions in GHG emissions:

- Regulation of methane loss is estimated to reduce GHG emissions by 0.36 Mt CO_2-eq in 2025 and 0.45 Mt CO_2-eq in 2030.
- Overall, the Agreement is expected to result in concrete reductions in national GHG emissions of 0.44 Mt of CO_2-eq in 2025 and 0.43 Mt CO_2-eq in 2030.
- The fulfilment of the 100% green gas target in 2030 is estimated to contribute an additional 0.45 Mt CO_2-eq reduction.

Use of energy crops for biogas production
A Danish political agreement, reached in 2021, on new energy crop requirements will subject the use of energy crops in biogas production to stricter requirements. These requirements will also apply to biogas production that does not receive financial subsidies.

The agreement entails phasing out of maize as a source of energy by 2025. Moreover, a reduced energy crop threshold was gradually phased in, falling from 12% of biomass feedstock to 8% in 2022. In 2023, the energy crop threshold was to be reduced to 6%, stopping at 4% in 2024/2025. As the war in Ukraine has increased the need for biogas production, the phasing-out of energy crops has been temporarily stopped.

Stricter climate requirements for the transport sector aim reaching climate targets by 2025
The challenges of the green transition are greatest for the heavy transport and agriculture sectors. The government's announcement of additional GHG mitigation requirements in the transport sector can ensure that Denmark reaches its climate target in 2025. This is expected to include the setting of a cap on the use of food crop-based first-generation biofuels that should significantly contribute to a positive climate impact.

At the same time, it is expected that the gas in the gas network will be completely green before 2030, thus releasing additional biogas production that could be used in heavy transport. Since biogas derived from livestock manure results in the most effective GHG mitigation, a large part of the increased GHG mitigation requirement will be met by greater use of biogas from manure. This results in further GHG reductions in the agricultural sector.

Update and future development
In 2022, more than 800 Mm^3 of biogas were produced at facilities in Denmark, setting a new domestic record. Of these, 622 Mm^3 were upgraded to biomethane and supplied to the gas grid and some 180 Mm^3 biogas were delivered directly to industry, to cogeneration and to other uses. The biomethane supplied to the gas grid equates to roughly 40% of gas consumed in Denmark in 2022, according to the trade association Biogas Denmark. By displacing fossil natural gas, this volume of biomethane achieved a net reduction in GHG emissions totaling 1.5 Mt CO_2-eq. Furthermore, abatement of methane emissions stemming from utilized livestock manure amounted to 250,000 tons CO_2-eq. The value of the natural gas that the biogas has displaced is estimated at approximately DKK 7.4 billion (€1bn).

The Danish government forecasts biogas to account for 70% of the gas consumption by 2030. Estimations show that as early as 2027, the net GHG reduction from biogas production and use could reach 3.7 Mt CO_2-eq, of which almost 1 Mt is attributed to reduced methane emissions from livestock manure, which in the future will be sent more quickly to the biogas plants. In addition, there is an additional reduction potential of more than 1.5 Mt CO_2-eq that could be achieved through capturing and storing biogenic CO_2 from biogas. For these reasons, considerable political attention is directed to promoting biogas development in Denmark.

The Danish biogas market is undergoing significant changes, encompassing the establishment of new installations and the formulation of new solutions for optimizing the green transition. The process of further expanding biogas production in Denmark is highly dependent on and driven by the economic framework and, specifically, the framework conditions applicable to biogas production. It is expected that the framework conditions for biogas will be continually improved and adapted to changing market demands and requirements, helping to grow the market. This is also expected to help improve Denmark’s energy security. Thus, it is expected that an increasing number of initiatives that boost the use of biogas will be implemented.

As part of its National compromise on Danish Defense policy, Danish political leaders have resolved to phase out gas consumption to ensure Denmark's independence from imported natural gas. In a few years, Denmark will not be dependent on fossil gas anymore, according to experts, as biogas is quickly becoming one of the most produced forms of energy in Denmark. It is estimated that biogas will overtake natural gas by 2030, if not before.

The Green Gas Strategy presents the government’s nine interlinked objectives that represent the Government’s policy goals for how the Danish gas system can transition towards green gas, while remaining competitive. Collectively, the objectives lay out the future of gas consumption, sustainable production of green gases and the infrastructure of the Danish gas system. Establishing a clear direction serves to provide certainty and predictability for users as well as help ensure security of supply in the overall energy system.

Tariffs will also be kept at a competitive level, and as low as possible, to minimize their financial impact on gas consumers.

Denmark's future gas system
The Government's ambition is to bring about a green transition of the Danish gas system and for gas to supplement energy efficiency improvements and electrification as part of the overall green transition of the Danish energy system. The green transition has implications for the future of Denmark's gas system, as natural gas consumption is expected to decline and become 100% green by 2030.

Initially, the country's gas infrastructure must be able to handle a decline in gas consumption, a changing consumer landscape and an increase in biogas production. In the slightly longer term, from 2030 and onwards, there may arise a need to adjust Denmark's gas infrastructure to meet the demand for transport and storage of other green gases such as hydrogen, but also raw biogas and CO_2 for producing carbon-based fuels. As part of the expansion of biogas plants in Denmark, pipelines will be upgraded, as it is expected that large volumes of gas will be exported to Poland, Germany, and Sweden in the future.

4.4. INNOVATIVE BIOGAS PROJECTS

Research topics and focus areas
Research and focus areas are highly affected by the regulatory framework, which is changing rapidly as the biogas sector grows. The current political ambition is that biomethane should be the green energy solution for heavy industries that cannot easily switch to electricity. For this reason, subsidies for new applications for biogas-CHP production and biogas heat production have been significantly reduced, encouraging new projects to distribute the biomethane via the gas grid.

Owners of biogas plants are increasingly aware of the value of their biogenic CO_2 recovered from biogas upgrading as a future source of income. Huge efforts are being put into developing PtX technologies as the CO_2 derived from upgrading biogas and biomass-fired CHP plants can be used to produce e-fuels such as e-methane and e-methanol. According to the Danish Energy Agency, the demand for biogenic CO_2 from biogas, the least expensive individual source of CO_2, will increase in 2023 onward (Danish Energy Agency, 2023).

Pyrolysis of digested manure fibers is another focus area in Denmark, and several initiatives are underway. The produced syngas contains hydrogen, methane and carbon monoxide, which can all be further processed into methane, methanol, or other fuels. At the same time biochar is produced for carbon storage. As farmers will soon be facing CO_2 taxes on their carbon footprints, the use of biochar could enable them to obtain considerable tax reductions.

Another issue in focus is the phasing out of energy crops such as corn silage or grass silage that is produced solely for biogas production. The most abundant alternative biomass resource is straw, which is in fact an excellent biomass for biogas production but much more challenging to handle in biogas plants. It can also affect the viscosity of the digestate and thus the quality when used as a soil fertilizer. As a result, much effort is being made in finding pretreatment technologies to facilitate straw handling and increase the biogas yields or, at least, speed up the digestion process. Also, work is underway to test other forms of green biomass such at catch crops and crop residues like sugar beet tops.

Finally, lawmakers have initiated the development of pyrolysis technologies with the aim to store carbon on agricultural lands in the form of biochar. This could be important for biogas plants, as the biogas process can only convert 50 – 60% of the organic content of the feedstock, which leaves significant energy potential in the digested manure and straw. If separated, the fiber fraction may form an inexpensive substrate for pyrolysis, helping farmers to increase soil carbon through biochar application and reduce future CO_2 taxes.

5. Finland

By: Saija Rasi (LUKE, National Research Institute Finland)

5.1. PRODUCTION OF BIOGAS AND BIOMETHANE

In 2021, the total recovered energy production from biogas was about 905 GWh from 129 different biogas production plants (Table 5-1). Both the number of biogas plants and the amount of produced energy have increased in recent years.

Table 5-1. Biogas production in Finland (Statistics Finland, 2022)

Plant type	Number of plants	Share (%)	Production (GWh/year)[a]	Share (%)
WWTP	20	16	223	25
Bio-waste*	40	31	479	53
Agricultural	32	25	27	3
Industrial	-	-	-	-
Landfill	37	29	176	19
Total	**129**		**905**	

**co-digestion plants, including industrial plants*

Upgrading of biogas into biomethane was carried out at 21 plants (156 GWh), however there is lack of information on the type of upgrading equipment used at these biogas plants.

5.2. UTILIZATION OF BIOGAS

In Finland, biogas has traditionally been used in power and heat production, but in recent years vehicle fuel use has increased (Table 5-2). There are about 100 public fueling stations for biomethane/CNG and the number of gas-fueled vehicles is increasing, including heavy transport vehicles. Use as vehicle fuel, shown in Table 5-2, only covers the sales straight from the biogas plant. Meanwhile, "other use" includes use as vehicle fuel where the biogas producers sell the biomethane to other companies who distribute the vehicle fuel.

Table 5-2. Utilization of biogas in Finland (Statistics Finland, 2022)

Utilization type	Utilization (GWh/year)	Share (%)
Electricity	19	2
Heat	147	18
CHP	298	36
Vehicle fuel	23	3
Gas grid	54	7
Internal/other use	193	23
Flaring	93	11
Total	**827**	

5.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

The most important subsidies for biogas plants are three different investment support schemes. They vary according to the size of the biogas plant and the biogas use, and include:

- Investment support for large industrial plants
- Investment support for farm own energy production
- Investment support for agricultural companies

The investment support for large scale industrial plants is provided by the Ministry of Employment and Economy. A maximum of 30% of the eligible investment costs are covered in this scheme. From 2020 onwards, special attention has been given to digestate processing and use. That is, even greater financial support can be obtained if there is a higher risk to economic profitability that results from digestate handling costs.

Investment support for agricultural biogas plants is provided by the EU Rural Development Programme and is administered by the Finnish Ministry of Agriculture and Forestry. Farm-scale plants, which use most of the energy themselves are eligible for investment support of up to 50% of the eligible investment costs. It is also possible to obtain investment support when most of the energy is sold outside the farm, or the farm sells vehicle fuel. However, a separate company must be founded for this purpose. The agricultural biogas company can then receive an investment subsidy of up to 50% of the investment costs. The support for agricultural biogas plants was increased in 2021 from 40% (own energy user) and 30% (separate biogas company) to 50%. The higher level of support has led to the construction of more agricultural biogas plants. It has been estimated that 40 new agricultural biogas plants could be built between 2023 and 2025 (Finnish Biocycle and Biogas Association, 2023).

There is also a new operating grant under preparation to promote nutrient utilization. This Nutrient Cycle Grant is intended to support biogas plants that use manure or waste from aquatic vegetation as feedstock and produce processed nutrient products in addition to biogas. The proposed support model is about to be submitted to the Commission, and, consequently, its content could still change as a result of discussions with the Commission.

5.4. INNOVATIVE BIOGAS PROJECTS

Vuorenmaa dairy farm (180 cows) located in Haapavesi, Finland, has been producing biogas from dairy manure to generate electricity and heat needed at the farm. Since 2021, biogas is also converted to compressed biomethane. The annual biogas yield of the farm is around 1,200 MWh of which approximately half is upgraded to biomethane. A milk truck in Valio's (a Finnish dairy and food manufacture) logistic chain has committed to buy biomethane produced at the farm. The truck fills up its gas tank while it collects the milk. The gas fueling station is open for private passenger cars as well. The Vuorenmaa plant is the first biogas plant to sell biomethane for use in Valio's milk trucks. This is one of the methods Valio will use to achieve carbon neutral milk production by 2035. In the near future, Valio aims to significantly expand the biogas network of dairy farms, in order to efficiently convert dairy manure into biogas and reduce the GHG emissions of the company's own transport system (logistics). Valio and the Finnish energy company St1 are establishing a joint venture to produce liquefied biomethane, derived mainly from dairy manure. The company plans to build its first large scale biogas plant (460,000 t/year capacity) in Kiuruvesi, Finland. The new plant, mostly based on manure feedstock, should be in production by 2026, and the goal of the joint venture is to produce 1 TWh of biomethane by 2030. The nationwide fueling station network of St1 will be used to distribute the biomethane (St1, 2022).

6. France

By: Julien Thual (ADEME, Service Agriculture Forêt et Alimentation Direction Bioéconomie Energies Renouvelables)

The French Environment and Energy Management Agency (ADEME) conducted a foresight exercise to support public exploration of pathways that could enable France to achieve carbon neutrality by 2050. Four alternate scenarios were developed, and, in all cases, it was found essential to maximize energy efficiency, reduce energy consumption and decarbonize energy in the future society. (ADEME, 2023) Anaerobic digestion made important contributions in all scenarios, and it was estimated that 90 – 130 TWh of biomethane could be produced in 2050, equivalent to 30% of the current French gas consumption, or 70% of the country's gas consumption in 2050.

6.1. PRODUCTION OF BIOGAS AND BIOMETHANE

Over the last decade, France has experienced strong development of anaerobic digestion (AD) plants and biomethane production. In 2022, there were 1,658 AD plants, including landfills (Table 6-1). Two historically important sectors are industry and sewage/wastewater treatment. Industrial AD plants that treat their own wastewater, generally use the biogas directly for the production of hot water used in their industrial processes. The same can be seen at WWTPs; however, in the last few years, there has been a strong trend towards upgrading biogas to biomethane. Currently, 28 out of 98 WWTPs are generating 402 GWh of biomethane annually. The agriculture sector had the most AD plants in 2022. Biogas production took place in 1,271 agricultural AD plants, including 1,092 on-farm and 179 centralized plants. It is the most active sector engaged in AD, growing to 1,449 plants as of January 1, 2024.

Table 6-1. Biogas production in France (SINOE, 2023)

Plant type	Number of plants	Share (%)	Electricity (GWh/yr)	Heat (GWh/yr)	Biomethane (GWh/yr)
WWTP	98	6	240	x	402
Bio-waste	16	1	184		143
Agricultural	1,271	76.5	1,616		7,151
On-farm	*1,092*	*65.9*	*1,136*		*4,916*
Centralized	*179*	*10.6*	*480*		*2,235*
Industrial	109	6.5	56	x	108
Landfill	164	10	2,080		220
Total	**1,658**		**4,176**	**1,900**	**8,023**

In 2022, there were 364 biogas upgrading plants operating in France (Table 6-2). Most of them use membrane-type upgraders. Electricity or CHP are becoming less prominent as biogas upgrading to biomethane is a regulatory priority in France.

Table 6-2. Biogas upgrading plants in France

Plant type	Number of plants	Share (%)
Membrane	306	84
PSA	34	9
Chemical scrubber	1	0.3
Water scrubber	15	4
Cryogenic	9	3
Total	**364**	

Only the smallest new AD plants can be developed for electricity production. Ninety percent of new projects are biomethane plants. In 2022, French biomethane plants produced 8 TWh (Table 6-3), surpassing the government's multiannual energy programme (PPE) target of 7 TWh for 2023. Biomethane is the only renewable energy that is achieving the PPE target at this time.

Table 6-3. Biomethane production in France (SINOE, 2023)

Plant type	Number of plants	Share (%)	Biomethane (GWh/year)	Share (%)
WWTP	28	5	402	5
Bio-waste	5	1	143	2
Agricultural				
On-farm	*371*	*69*	*4,916*	*61*
Centralized	*111*	*21*	*2,235*	*28*
Industrial	7	1	108	1
Landfill	15	3	220	3
Total	**537**		**8,023**	

6.2. UTILIZATION OF BIOGAS

Biogas is currently used for the production of electricity, heat and biomethane (Table 6-4). Biomethane production is growing and the majority is injected into the gas grid. As it is difficult to know the specific end-use of biomethane, Table 6-4 provides an estimated breakdown of heat, vehicle fuel and industrial uses of grid biomethane. By January 1, 2024, even less biogas was converted into electricity (3 TWh) as more is being upgraded to biomethane and injected into the grid (11.8 TWh).

Table 6-4. Utilization of biogas in France

Utilization type	Utilization (GWh/year)
Electricity	4,176
Heat	1,900
Industry	350
Grid	
Heat	*2,000*
Industry	*5,000*
Vehicle fuel	*1,000*
Other/Flaring	N.D.
Total	**14,516**

6.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

In France, biogas production is supported through two tariff systems that vary depending on the biogas use, the size of the unit and the nature of the feedstocks. The feed-in-tariff for electricity production from biogas has a 20-year purchase obligation with the following rates:

- Base: 15 – 17,5 €ct/kWh
- Manure bonus of 5 €ct/kWh

The biomethane tariffs have a 15-year purchase obligation and the rates depend on the type of operation and feedstock:

- €59 – 99/MWh for biomethane from landfills (depending of volume)
- €88 – 122/MWh for upgrading the biogas to biomethane from AD plants (depending on volume and the nature of the feedstock; 2011 values that do not include 15% inflation rate)
- €0 – 10/MWh manure bonus

The French Agency for Environment and Energy Management (ADEME) provides financial support through two funds: the Circular Economy Fund and the Renewable Heat Fund. Consequently, these subsidies depend on the nature of the investment, and both the total amount and rate (%) of support are limited. Other subsidies are also available, such as funds of France's Regional Councils or the European Regional Development Fund (FEDER), for example.

In 2019, the biogas industry experienced the greatest addition of new biomethane (upgrading) plants, just before the government's announcement to decrease the tariff. Prior to the geopolitical events of 2022, France's strategy had been to reduce the production costs of AD and biogas energy. However, inflation started to accelerate in 2022 and subsequently increased both investment costs and operating costs such as electricity and biowaste/substrate costs. In 2023, the French government announced the adoption of new regulatory measures to increase biomethane production, including a re-evaluation of the biomethane tariff rates to address inflation. These measures are aimed at better accounting for the volatility of production and construction costs in the purchase price in order to continue to support the development of new projects.

More than 35,500 vehicles in France use biomethane, including 19,000 trucks (1 TWh consumption per year). There are 300 public fueling stations and around 35 private fueling stations. Most of the public stations now offer bio-CNG (compressed biomethane) and use the system of guarantees of origin. There are also 98 LNG (liquefied gas) stations. Gas grid operators are working to increase the technical capacity of the grid to introduce more biomethane. Grid reverse flow gas stations have been tested and are starting to spread in France. In 2022, 31 gas stations were operational or under construction, and collectively they would increase system capacity by 3.7 TWh. Fifteen other stations are at a planning stage.

6.4. INNOVATIVE BIOGAS PROJECTS

With the energy crisis and the rise in energy prices, in particular electricity costs, the biogas industry's efforts have focused on meeting its own energy requirements and reducing energy purchases. Examples include installing photovoltaic panels, recovering heat from the upgrader compression unit, and adding a biogas CHP to meet its own electricity and heat requirements.

As agricultural biomass is considered to be an important feedstock for agricultural AD plants (today and in the future), there are many research programs underway to identify the best practices for the sustainable production and harvest of intermediate crops. Finally, progress continues to be made on the first biological methanation and pyro-gasification pilot projects, as they could supply renewable gases in future decades.

7. Germany

By: Peter Kornatz (DBFZ, Deutsches Biomasseforschungszentrum)

The German government has set the target to increase the share of renewable energies in total energy generation to 40 – 45% by 2025, to 55 – 60% by 2035, and to 80% by 2050. The German energy transition ("Energiewende"), initiated in 2000, includes a program for coal phase-out by 2038 (introduced in 2018) and a "climate package" (introduced in 2019). Another important policy for the transition of the German energy sector is the Renewable Energy Sources Act (EEG), aiming to support competitive renewable energy technologies. As a way to encourage competition and development, an auction model was introduced within the EEG 2017. The EEG was modified by a new version in 2023. The main driver for the introduction of the limits for biomass and the auction system are the reduction of costs by means of competition, as well as the (limited) biomass potentials. These main aspects were retained in the EEG amendment, but the so-called maize cap was further tightened.

Independently of biogas, the national biomass strategy is currently being drawn up in Germany. Here, all biomasses are considered, regardless of their intended use. For the biogas sector, this is likely to have a major impact.

7.1. PRODUCTION OF BIOGAS AND BIOMETHANE

The support levels, in particular the tariffs for renewable electricity delivered, for new biogas production in Germany have been reduced through the 2014 and 2016 changes in the EEG, leading to a declining number of biogas plants. Since the introduction of the auction model and the reduction of maximum achievable tariffs in 2017, the number of new biogas plants has been very low. Most biogas plants in Germany were built between 2003 and 2012, with twenty-year energy production contracts. This means that for a large number of biogas plants, the phase of guaranteed tariffs will end between 2023 and 2032, which is expected to massively accelerate the decline in the number of plants, if economic attractive follow up conditions are missing.

In 2021, the 8,300 biogas plants in the agricultural sector made the biggest contribution to biogas production with electricity and heat supplies of 27.2 TWh/year and 16.9 TWh/year, respectively (Table 7-1). Compared to 2020, the agricultural sector lost approximately 100 biogas plants. In addition, approximately 1,200 biomethane CHP plants with electricity generation of 3.1 TWh/year and heat production of 4.8 TWh/year were registered in 2021. In total, electricity and heat generation from biogas amounted to 33.1 and 24.8 TWh, respectively.

Table 7-1. Biogas production in Germany

Plant type	Number of plants	Share (%)	Energy production (GWh/year)[a]			Share (%)
			Gross electricity	Gross heat	*Biogas[d]*	
WWTP	1,271[b]	12	1,600	2,400	*4,210*	*7*
Bio-waste	280	3	1,000	600	*2,630*	*3*
Agricultural	8,300[c]	80	27,200	16,900	*71,580*	*76*
Biomethane	239	2	3,100	4,800	*8,160*	*13.5*
Landfill	270[b]	3	200	100	*530*	*0.5*
Total	**10,360**		**33,100**	**24,800**	***87,110***	

Sources: [a](AGEE-Stat, 2023); [b](DESTATIS, 2020); [c](DBFZ, 2023)

[d]Calculated assuming 38% efficiency for electricity generation

A total number of 239 biogas-upgrading plants were in operation (Table 7-2), feeding biomethane to the gas grid, which means 7 new facilities in respect to 2020. The latest figure (2023) indicates 243 biomethane plants with a feed-in capacity of 147,810 m^3/h. A total feed-in capacity of 10.4 TWh/year was achieved which meets an amount of approximately 1 bcm/year. In relation to the natural gas consumption, the biomethane feed-in covers 1.12 % of the German demand. In respect of conditioning technology, water scrubber, chemical scrubber and PSA are the most important. Also, membrane upgrading has become more important during the last years.

Table 7-2. Biogas upgrading plants in Germany

Plant type	Number of plants	Share (%)
Membrane	24	10
PSA	45	19
Chemical scrubber	62	26
Water scrubber	74	31
Organic scrubber	24	10
Combined/Other	10	4
Total	**239**	

7.2. UTILIZATION OF BIOGAS

Compared to 2020, fuel use increased from 884 to 965 GWh/y, according to information from the Ministry of Environment (Umweltbundesamt, 2023) (Table 7-3). In contrast, electricity production has decreased from 31.7 TWh to 31.3 TWh per year compared to 2020.

Table 7-3. Utilization of biogas in Germany

Utilization type	Utilization (GWh/y)	Share (%)
Electricity	31,300	57.4
Heat	22,300	40.9
Vehicle fuel	965	1.7
Flaring	N.D.	-
Total	**54,565**	

7.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

The EEG continues to play an important role for the German biogas sector. Its latest amendment came into force on 1 January 2023 (EEG 2023). This creates a new basis for the operation and continued operation of biogas plants. The following is relevant for biogas:

- The bidding dates for biomass plants will take place on 1 March and 1 September each year from 2023 – 2025 and on 1 June each year from 2026-2028. The tender volume is 600 MW in 2023, 500 MW in 2024, 400 MW in 2025 and 300 MW from 2026-2028 (§ 28c EEG).
- The tenders for biomethane plants will take place on 1 March and 1 September from 2023 – 2028. The tender volume is 600 MW in each case (section 28d EEG).
- The maximum value for electricity from biomass plants in 2023 is 16.07 €ct/kWh, with the annual reduction of 1% from 2024 (§ 39b EEG).
- Further reduction of the permitted proportion of cereal grain or maize (§ 39i EEG).

- Section 27a EEG is repealed, which means that electricity generated in subsidized plants may also be used for self-supply in future.

Beyond the EEG, the "Guideline for the promotion of investments in emission-reducing measures in the fermentation of farm manure" is relevant. This is intended to support the implementation of the Federal Government's Climate Protection Program 2030 for the implementation of the Climate Protection Plan 2050, in particular the fermentation of manure for energy use as the second most important measure in the agricultural sector.

The coalition agreement of the current federal government includes the mandate to develop the national biogas strategy (NABIS). The need for the NABIS arises on the policy side from the challenges posed by biomass use. Here, conflicts of use, the limited biomass potential versus the rapidly growing demand, a lack of a hierarchy of use oriented towards protected assets and questions of security of supply (primarily food) are particularly decisive. The subject of the strategy is defined as biomass production and use (taking into account production, import and export) with a focus on land-based biomass including residues and waste (aquatic biomass should also be taken into account). It does not include the aspect of possible short-term mobilization of biomass use for energy to ensure energy supply security. Furthermore, the position on the bioeconomy strategy is not clearly delineated.

For the objectives and target levels of the NABIS, the following was defined:

- Overarching political goal: creating framework conditions for sustainable biomass production and use in Germany.
- Strategic objective: Steering of biomass flows, taking into account food security, climate protection, biodiversity, environmental protection, security of energy and raw material supply.
- Operational objective: Development of measures for the sustainable production and use of biomass and the elimination of existing disincentives.

From this, the NABIS guidelines are derived, which reflect a clear prioritization of biomass use pathways in order to establish and promote a cascaded circular economy. The prioritization puts the focus on food security and material use (especially durable industrial goods and building materials as carbon sinks), while energy use represents end-of-life recovery and should tend to be reduced. Above all, residual and waste materials are to be used for energy use. Accordingly, cultivated biomass for energy use will play a subordinate role in the NABIS and result in a phase-out path by 2035.

For biogas plants, the NABIS accordingly focuses on residual and waste materials. The extent to which agricultural by-products (e.g. straw), which can also be used as base material for other processes, are handled is not entirely clear and differentiated depending on how the term "residual and waste material" is interpreted. What is clear is that biogas plants that want to be sustainable according to NABIS must change their current substrate composition. With regard to biogas production, opportunities could certainly arise with regard to the use of manure, provided that the final version of NABIS addresses a pronounced circular economy.

Since the war in Ukraine and the subsequent energy crisis in Germany due to the previously high natural gas imports from Russia, security of supply has been an important topic of public discussion. The situation on the gas market has meanwhile eased further. The gas prices decreased on the level before the Ukraine crisis. This concerns at least the EU trading prices on the Dutch TTF. It can be assumed that the lower trading prices will also have an impact on end consumer prices. Electricity prices in European wholesale have also been falling significantly since the beginning of 2023. In the end consumer segment for new customers, prices have almost reached the pre-crisis level. There is thus a likelihood that the financial pressure on end customers will be reduced in perspective and that the public discussion about security of supply aspects will subside. With regard to gas supply, however, the geostrategic dependency continues to exist. Biogas and biomethane thus remain interesting, especially because the REPowerEU plan sets out a significant increase in biomethane production by 2030 in the EU (35 bcm). This makes it necessary for Germany to maintain and even significantly increase its biomethane production. It is possible that Germany will develop a biomethane strategy for this purpose in the future.

7.4. INNOVATIVE BIOGAS PROJECTS

Biomethaverse
The overall purpose of the BIOMETHAVERSE project is to diversify the technology basis for biomethane production in Europe, to increase its cost-effectiveness and to contribute to the uptake of biomethane technologies.

To this aim, five innovative biomethane production pathways will be demonstrated in five different European countries: France, Greece, Italy, Sweden, and Ukraine. The demonstrated production routes will cover one or a combination of the following production pathways of biomethane: thermochemical, biochemical, electrochemical, and biological. As a starting point, four demonstration plants use conventional anaerobic digestion (AD), and one uses conventional gasification. In the BIOMETHAVERSE demonstrators, CO_2 effluents from AD or gasification and other intermediate products are combined with renewable hydrogen or renewable electricity directly to increase the overall biomethane yield. All demonstrated production routes go beyond conventional technologies, with a circular approach for energy and material, while aiming at reducing the overall biomethane production costs and increasing the biomethane production.

All demonstrated production routes go beyond conventional technologies with a circular approach. The technologies tested in the BIOMETAHVERSE project have the potential to increase the biomethane production in Europe by 60% within the 2030 and 2050 timeframes, enabling 287 Mt CO_2eq of additional GHG savings, creating >800,000 jobs and reducing biomethane production costs by 13 – 44%.

The aim of the Ukrainian-German sub-consortium is to develop and demonstrate a technology for direct injection of hydrogen into anaerobic digesters in order to increase the methane concentration in the biogas from 55% to 85% (in-situ methanation). Partners of the sub-consortium are MHP Eco Energy (UA), UABIO (UA), Ellmann Engineering (EE) and DBFZ (Deutsches Biomasseforschungszentrum gemeinnützige GmbH). BIOMETHAVERSE is coordinated by ISINNOVA in Italy.

PaplGas
Poplar wood from short rotation plantations can be used as a renewable raw material for the production of renewable energies, e.g. for decentralized heat supply. However, the use of wood heating systems in urban areas faces many challenges, such as the space required for heating systems and fuel storage.

The use of poplar wood for biomethane production via the biogas process within the framework of this project is an innovative approach to the energetic use. The degree of innovation is further increased by the combination with the material use of the wood fiber fraction as a peat substitute after separation of the fermentation residues. The biogas process can be understood as an upstream conditioning step for the material use, which provides energy and exploits (with appropriate substrate conservation) the wood's potential of volatile substances too. The project PaplGas2 is based on the feasibility study of PaplGas.

The following tasks are addressed in the project: (1) double-function disintegration treatment and conservation of poplar wood for biogas and peat substitute production, (2) development of digestion processes for poplar wood fibers to biogas (biomethane) on a semi-technical scale and analysis of the microbial communities, (3) development and testing of crop cultivation utilization concepts for the solid wood-fibrous fraction of the digestate (tests as peat substitute) on a practical scale as well as theoretical considerations on the utilization options of the liquid phase of the digestate, (4) economic and ecological evaluation of the overall concept and (5) development of an exemplary heat supply concept for an urban residential area. At the DBFZ the sub-project 1 Implementation and assessment of the digestion tests is processed.

BioLube
Starting from low-cost nutrient substrates, the company Hermetia Baruth GmbH produces high-quality insect proteins that are successfully marketed as animal feed. Insect fats are a by-product of the production process for which there is currently no economically viable application. The aim of the BioLube project is to develop bio-based and biodegradable high-performance lubricants based on insect grease for broad technical use as hydraulic oil, lubricating oil and special lubricating grease. Areas of application for the target products can be found in almost all technical fields, but especially in environmentally sensitive areas, e.g. in forestry and construction, shipping and wastewater management.

For the production of biolubricants, additivated fatty acid esters based on vegetable oil are currently used almost exclusively. Despite their comparatively poor environmental impact, palm oil, palm kernel oil and coconut oil are important base oils. The environmental impact of biolubricants made from insect fat, for the production of which residual and waste materials are used, would be comparatively much better. Moreover, biolubricants made from insect fat could represent a higher-quality alternative to fossil lubricants, with better environmental compatibility.

Pülpegas
Energy-intensive industry can achieve great depths of value creation and efficiency gains through synergies in chemical parks. Bioenergy plants could achieve particularly large effects for the energy transition and resource efficiency here. In the industrial environment, however, biogas plants have rarely been directly integrated into continuous processes. The Pülpegas project addresses this problem by:

- Developing and demonstrating digestate-free monosubstrate fermentation in an industrial biogas plant
- Utilization of the residual pulp at the site of production, avoidance of transport and corresponding GHG emissions, and avoidance of use as low-value animal feed
- System integration, integration into continuous production processes and efficient plant dimensioning. Treatment and disposal of fermentation residues are not required.
- Provision of energy for the operation of central supply infrastructure
- Complete material utilization of the raw material wheat
- Creation of a reference plant for the complete and high-quality utilization of starch-containing products, research into the applicability of further components (here: biomolecules)

The overall objective of the project includes the step-by-step implementation, testing and scientific monitoring of the energetic biomass utilization (TRL 5 – 8) as well as additional material utilization.

8. Ireland

By: David Wall (MaREI Centre for Energy, Climate and Marine, Environmental Research Institute, University College Cork)

Many studies have highlighted the potential for the development of anaerobic digestion (AD) systems based on the large quantities of biomass available from the Irish agricultural sector. However, legacy issues such as feedstock supply logistics, unavailability of local heat loads for biogas-CHP systems, increased capital and operating costs, increased parasitic heat demand to pasteurize slurry imports, and high investment risk have meant relatively low deployment of the technology to date. The Irish Government's Climate Action Plan (CAP), released in 2021, provided a development plan for the country's climate action initiatives. Biogas and biomethane are intended to play a role across all modes of energy – electricity, heating, and transport. The Irish CAP projects 1 TWh of biomethane production by 2025 with construction of up to 20 AD plants of scale. This is to increase to 5.7 TWh of biomethane production by 2030 with 200 AD plants in operation. A National Biomethane Strategy was released by the Irish Government in 2023 to identify all of the necessary actions to deliver on this ambition. Improving the evidence base for sustainability and providing a holistic assessment of the benefits of biogas and biomethane will be a key building block for any large AD-based industry in Ireland.

8.1. PRODUCTION OF BIOGAS AND BIOMETHANE

The exact number of biogas plants operating in the Republic of Ireland is hard to quantify. That is, many wastewater treatment facilities have digesters but as they are privately owned, there is no official inventory of these facilities. The main use of biogas produced in wastewater treatment plants is the production of heat and electricity in onsite CHP units, and the thermal drying of dewatered digestate to produce a high grade biofertilizer. The Irish Bioenergy Association (IrBEA) states that there are numerous biogas plants at an advanced state of desktop development. A range of sources, including IRBEA, Renewable Gas Forum Ireland (RGFI), NVPenergy and Cre (Composting and Anaerobic Digestion Association of Ireland), provided the data on the landfills, and wastewater and other biogas plants presented in Table 8-1.

Table 8-1. Biogas production in the Republic of Ireland

Plant type	Number of plants	Share (%)	Production (GWh/year)	Share (%)
WWTP	15[a]	25.5	N.D.	
Bio-waste	3	5	30.7	4.1
Agricultural	12	20	56	7.4
Industrial	4	7	76.2	10.1
Biomethane	3	5	22.8	3.0
Landfill	22	37.5	566.8	75.3
Total	**59**		**752.4**	

N.D. = no data; [a] Data difficult to obtain

Most existing AD facilities produce electricity and/or heat. This is reflective of the previous financial supports available, namely, the renewable energy feed-in-tariff (REFIT) scheme, and the current updated renewable electricity support scheme (RESS).

Biomethane is viewed as having a significant role to play in reducing the GHG emissions of Ireland's agriculture sector, both in improving existing slurry management practices, and offering alternative opportunities for farmers away from livestock production. The development of a biogas industry will be "agri-centric" and provide diversification of farm activities that open additional revenue streams. Furthermore, it is intended that suitable industry clusters for biomethane supply will be identified nationally by 2025.

Investors have signaled increased interest in the development of biomethane facilities in Ireland, as demand

for sustainable, secure energy supplies increases. The war in Ukraine saw gas prices soar in Ireland and raised energy security concerns.

Ireland's gas grid operator Gas Networks Ireland (GNI) released a strategy document in collaboration with KPMG in 2021 (Gas Networks Ireland, 2021). This report showed that, given correct planning and development, a sustainable biomethane industry could be developed in Ireland. The report states that up to 9.5 TWh of biomethane could be sourced from agricultural feedstock. GNI has announced a €30M investment into a large-scale renewable gas injection facility in Mitchelstown, Co.Cork, as part of GRAZE (Green Renewable Agricultural Zero Emissions) gas project. More than 20 AD plants are planned for the region, from which the biomethane produced will be transported via truck to a central grid injection facility. The GRAZE project will have AD plants digesting agricultural biomass and food waste. The biogas will be upgraded to biomethane, and transported via virtual pipeline to the Mitchelstown injection facility, and from there into the natural gas grid. When operating at full capacity, this facility will be able to inject up to 700 GWh of renewable gas into the gas network – the equivalent to fulfilling the gas requirements of up to 64,000 homes.

8.2. UTILIZATION OF BIOGAS

The National Heat Study undertaken by the Sustainable Energy Authority of Ireland (SEAI) recommended that optimal application for biomethane was in the decarbonization of high direct heat demands where electrification is challenging. The Irish government has recently introduced a support scheme for renewable heat (SSRH) that provides financial support (an ongoing payment for up to 15 years) for anaerobic digestion (biogas) heating systems. The viewpoint of Ireland's gas network operator - Gas Networks Ireland (GNI) – is that if the biogas industry is to take off in the country it is likely to require gas grid injection to facilitate better returns on the biogas produced.

The Renewable Transport Fuel Obligation (RTFO), administered by the National Oil Reserve Agency (NORA), allows for payment of three certificates to producers of gaseous biofuel with an energy value in excess of 35 MJ/Nm^3 if the fuel is derived from residues or from second or third generation substrates and is used as transport fuel. The certificates trade at a price that reflects the difference between 1L of diesel and 1L of biodiesel. It is very likely that the return on biogas as a transport fuel is superior to the return on electricity from biogas. Freight is viewed as a prime use for biomethane, as transport sustainability requirements are less stringent for transport-use of biomethane than for heat or electricity, as per EU RED II. Public fueling stations have been constructed at the Circle K Service Station in Dublin Port, Circle K Cashel on the M8 motorway, Circle K Ballysimon Road and Circle K Clonshaugh. The stations are fully operational and have been integrated with Circle K's systems, and as such CNG is now sold through the forecourt in a similar fashion to diesel and petrol. A further nine publicly accessible fueling stations are contracted with Forecourt Operators. In addition, private fast-fill CNG stations are fully operational at the Clean Ireland Recycling premises in Shannon, at Gasworks Road in Cork, and at Ballycoolin in Dublin. Clean Ireland Recycling has replaced a portion of its diesel-powered fleet with dedicated CNG waste collection vehicles, the first of their kind to be operated in Ireland. The company plans to transition the rest of its fleet to these lower-emission CNG trucks in the coming years.

8.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

The Department of Agriculture, Food and the Marine and the Department of the Environment, Climate and Communications (DECC) has established a Biomethane Working Group to develop a National Biomethane Strategy in 2023. The Irish Climate Action Plan (CAP) projects 1 TWh of biomethane production by 2025 increasing to 5.7 TWh of biomethane production by 2030. Further, the CAP seeks to identify suitable industry clusters for biomethane supply nationally by 2025.

In 2020, a Renewable Electricity Support Scheme (RESS) was introduced, providing support to renewable electricity projects in Ireland. The scheme provides financial support to renewable energy projects through an auction process.

In 2021, the second phase of the Support Scheme for Renewable Heat (SSRH) was opened to provide operational support for biomass boilers and anaerobic digestion systems to produce heat. The scheme will support businesses and farms for up to 15 years for the installation and on-going use of biomass and biogas heating systems, and is designed to support up to 1,300 GWh of renewable heat per annum.

A landfill levy of €75/ton is in place as of July 2013. Also, as of July 2013 there is a requirement to provide collection of source segregated food waste for population centers in excess of 25,000 persons. As of July 2015, collection of segregated food waste was required for populations greater than 500 persons. These regulations provide an incentive to digest the organic fraction of municipal solid waste.

The Ireland Strategic Investment Fund (ISIF) aims to play a central role in the development of the Irish AD sector, where it will invest up to €1 billion in climate and sustainable energy initiatives. ISIF will collaborate with industry and investors, and has signaled a willingness to work with the co-operative sector to collate funding.

8.4. INNOVATIVE BIOGAS PROJECTS

SEAI Research Development and Demonstration fund (RD&D)
The SEAI RD&D Funding Programme invests in innovative energy Research, Development and Demonstration (RD&D) projects, which contribute to Ireland's transition to a clean and secure energy future. It focuses on technologies at higher levels of readiness and on other policy and market relevant research. SEAI have funded several recent projects in the area of biogas and biomethane including:

- Developing Cascading Biomethane Biochemicals and Biofertilizer Systems for a Circular Bioeconomy in Ireland (CABBBIE). The aim of the CABBBIE project is to provide a comprehensive pathway to commercialize photosynthetic biogas upgrading technology for an adaptive, flexible and secure Irish bioeconomy by 2050.
- Developing pathways for a sustainable shipping and maritime fuel value chain in Ireland (ShipFuel-IE). The ShipFuel-IE project will assess a range of potential energy carriers (hydrogen, ammonia, methane, methanol, renewable diesels) produced either from biomass or renewable electricity as fuels for the shipping sector coupled with the infrastructural requirements of Irish ports needed to deliver such low-carbon fuels and vessel technologies (internal combustion engine or fuel cell).
- The FLEET (Farm Level Economic, Environmental and Transport modelling) project will identify farm scale, landscape level and national level economic and environmental implications of farm supplied alternative feedstock for AD) at a regional level. This research will be the first of its kind in Ireland to evaluate the potential for Anaerobic Digestion (AD) to address economic and environmental outcomes at an individual farm level using Teagasc National Farm Survey data. The willingness to adopt land use change will provide useful policy insights and will be at the forefront of knowledge generation relevant to the energy sector.
- The EcoAD project (Developing Economic Solutions for on-farm Anaerobic Digestion Systems in Ireland) is approaching completion. The project investigates on-farm AD logistics, techno-economics, and also the potential use of advanced microbial electrolysis cell (MEC) systems. Finding the most efficient biomethane production scenarios, most importantly that are cost-effective, is of relevance in transitioning to a low carbon economy. Ultimately this project will deliver future best practices and assess the economic viability of on-farm biomethane production from novel integrated anaerobic digestion systems.

Teagasc
Teagasc are the state agency for research and education in agriculture, horticulture, food and rural development in Ireland. A demonstration-scale anaerobic digestion plant and biogas upgrading facility is being commissioned at Teagasc Grange in County Meath. The plant will produce biogas from grass silage and cattle slurry which will be upgraded to biomethane. When fully operational, the expected nominal gas production will be 70 m^3 per hour. The biomethane produced will be pressurized for transport by road tanker to the national gas grid at the injection point in Nurney, County Kildare.

Teagasc are also leading another project titled “Expanding the alternative use and circularity potential of crops (EXPECT)”. The EXPECT project investigates the use of crops in a cascading, biorefinery approach, and ultimately intends to co-design a framework for the development of green biorefineries in Ireland. This will achieve by holistic consideration and analysis of the socio-political, technical and economic factors involved. Part of this project explores the potential for biogas production from grass to provide positive and negative balancing of the electrical grid and support high shares of intermittent renewable electricity in Ireland (80% renewable electricity expected by 2030).

Farm Zero C

Farm Zero C is a collaboration between BiOrbic, Carbery and others to address the challenge of carbon neutral farming. It presents a holistic view of the farm to reduce GHG emissions and increase the health and resilience of the farm. Some of the initiatives of the project include: sourcing energy through renewable means, reduced fertilizer use through the planting of multi-species swards, increased on-farm biodiversity, reduced animal belching through animal diet changes, and a thorough life-cycle analysis of plant and animal life-cycles on the farm. The project recently received a €3M investment for an integrated anaerobic digestion and green biorefining development from the Department of Agriculture, Food and the Marine.

Science Foundation Ireland (SFI) MaREI Centre for Marine and Renewable Energy

The SFI MaREI Centre is a cluster of key university and industrial partners dedicated to solving the main scientific, technological and socio-economic challenges related to energy, climate and marine (MaREI, 2021). The center has amassed cumulative funding of ca. €65M and includes for 220 researchers from 13 universities or research centers, and 75 industrial partners including start-ups, SMEs, and large enterprises. 36 collaborating countries contribute to MaREI, across industry, academia, and government. MaREI includes for a number of research themes including for Bioenergy. The Circular Economy Energy and Environmental Systems (CEEES) is a research group in MaREI that focuses on renewable molecules, biorefineries, circular economy, advanced fuels and industrial ecology. The research of CEEES has been very progressive in terms of developing a platform for biogas in Ireland and the group has been involved in a number of projects, three of which are mentioned below:

- **BioWILL:** BioWILL focuses on Integrated "zero waste" biorefinery utilizing all fractions of willow feedstock for the production of high to medium based bio-chemicals/materials and renewable energy. BioWILL will deliver a biorefinery model for Northwest Europe using willow, by producing high value salicylates from willow bark for medical applications. The bark residue and bark-free willow pulp will be converted into safe food quality packaging material to replace fossil derived plastics. The end-of-life packaging will be hydrolyzed and used as a feedstock in an innovative bioenergy anaerobic digestion system producing biogas suitable for gas grid injection.
- **How to Achieve a Carbon Neutral Distillery:** The industry collaborative research project with Irish Distillers Ltd. aims to identify potential pathways to decarbonize the Irish Distillers’ production facility located in Midleton, County Cork. The focus of this research project is to identify alternative uses of by-products generated during the distillation process and the potential to convert these into renewable energy. A key technology to achieve this is anaerobic digestion to produce biogas which can then replace natural gas used onsite. Irish Distillers plan to invest €50M in its Midleton distillery to deliver a carbon-neutral operation by 2026. A series of innovative projects will see the distillery phase out fossil fuel use. Biogas could reduce direct emissions (scope 1) by 14 – 66%, and AD could reduce fossil fuel demand by 13 – 66%.
- **Irish Environmental Protection Agency (EPA) Advanced Gaseous Methane:** Integrating power-to-gas (PtoG) with AD offers an innovative means to upgrade biogas to green gas whilst supporting intermittent renewable electricity and producing advanced renewable transport fuel. This Irish EPA funded project evaluated future integrated bioenergy systems, including the concepts of cascading bioenergy and circular bioeconomy. This project aimed to achieve (1) systems integration and optimization for biogas production and upgrading to green gas, and (2) sustainability validation of green gas production.

9. Norway

By: Charlotte Berntsen, Simon Saxegaard and Kari-Anne Lyng (NORSUS, Norwegian Institute for Sustainability Research)

In Norway, 739 GWh of biogas was produced in 2022, representing a marginal increase of 4% since 2021. Seven new plants were built in this period, of which most of them are still in start-up phase. Biogas is mainly produced from sewage sludge and food waste. Feedstock from industry, including fish sludge and fish silage from the marine sector, is the third largest feedstock category. Farm scale biogas provides a relatively small share of the total biogas production, but is the dominant plant type amongst the newly established biogas plants. The biogas sector currently employs the equivalent of 215 full time jobs.

The policy and financial support system for biogas in Norway consists of investment support for biogas plants, economic support to farmers per ton of livestock manure treated by anaerobic digestion, as well as tax exemptions when biogas is used as transport fuel.

The numbers in this section are primarily drawn from the national biogas statistics, Norwegian Environment Agency and Statistics Norway.

9.1. PRODUCTION OF BIOGAS AND BIOMETHANE

Sewage sludge constituted the largest share of the feedstock used for biogas production in 2022 (on a dry matter basis), followed by separated food waste, as shown in Figure 9-1.

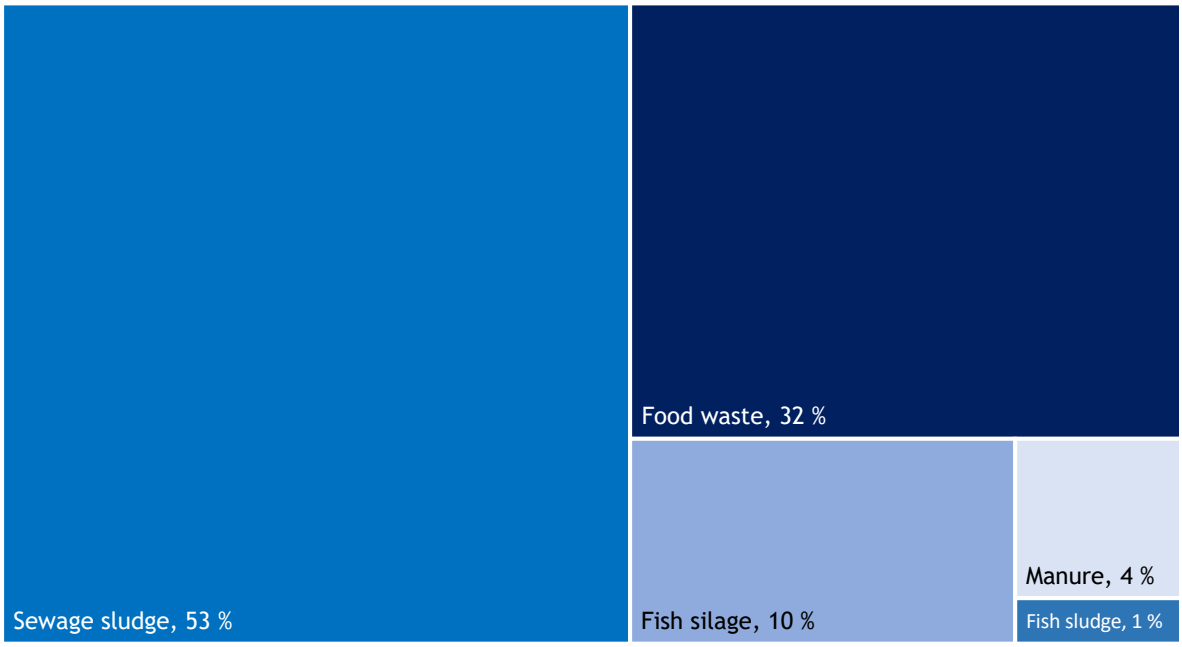

Figure 9-1. Relative shares of feedstock used for biogas production in Norway (per ton of dry matter) in 2022 (Norwaste, 2023)

The total amounts treated via AD remained relatively unchanged, with small changes in the feedstock composition: the amount of food waste, fish silage and manure increased, while the tonnage of sewage sludge decreased.

In 2021, about 66.2% of the separated organic waste was utilized for biogas production while 33.8% was composted (SSB, 2023). Of separated organic wastes, food waste from households and industry was the predominant waste type. The waste treatment data for 2022 were not available at the time this report was developed.

Political instruments have been introduced to increase biogas production from livestock manure, and contribute to the reduction of GHG emissions from agriculture. Figure 9-2 shows that the amounts of manure treated in biogas plants has increased the last five years. The data were collected from the Norwegian Agriculture Agency (2023), managing the economic support system for farm scale biogas plants and farmers supplying manure to centralized plants. Also, Figure 9-2 shows that the largest volumes are treated in The Magic Factory (Den Magiske Fabrikken), which until now has been the only centralized plant in Norway co-digesting food waste and manure.

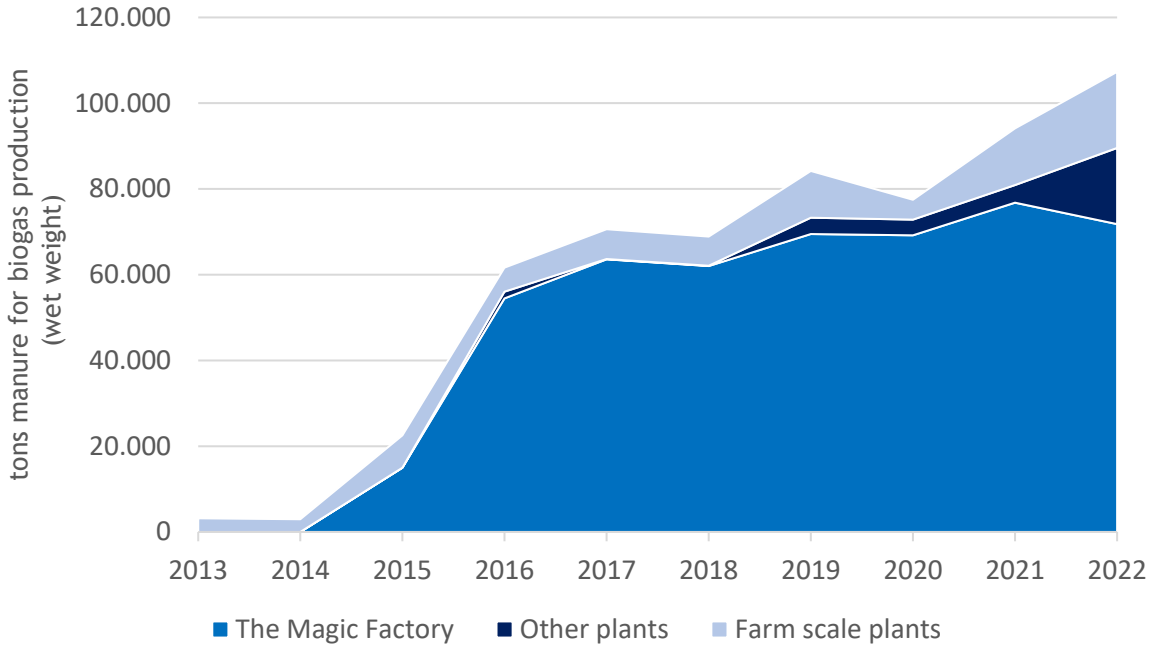

Figure 9-2. Use of livestock manure for biogas production in Norway (Norwegian Agriculture Agency, 2023)

There were 56 biogas plants in Norway in 2022 (Table 9-1), which is seven more than in 2021. Of the new biogas plants, five are agricultural and two are industrial (Norwaste, 2023). The number of wastewater treatment plants (WWTP) and bio-waste plants remains the same as in 2021.

Table 9-1. Biogas production in Norway (Norwaste, 2023)

Plant type	Number of plants	Share (%)	Production (GWh/year)	Share (%)
WWTP	27	48	285	39
Bio-waste	10	18	367	50
Agricultural	12	21	3	0.4
Industrial	7	3	85	11
Total	**56**		**782**	

Despite the growth in number of plants, the increase in biogas production was only marginal (about 4%) from 2021 to 2022. Since 2009, biogas production has increased by 84% (Norwaste, 2023). Employment in the biogas industry corresponds to 215 full time jobs, which is a 21.5% increase from 2021 (Norwaste, 2023).

Landfill gas data were not collected for this report, as the utilization of landfill gas has seen little attention in Norway. This is due to the ban on landfilling of organic waste, which will reduce the potential for collection and utilization of landfill gas (Lyng and Berntsen, 2023). In the 2020 IEA Bioenergy Task 37 country report, it was reported that landfill gas was collected at 78 landfills in Norway, corresponding to 119 GWh (Gustafsson et al., 2020).

According to the biogas statistics there are four biogas plants that are currently being built, which would represent an addition of 70 GWh to annual biogas production when the plants are operational. 22 plants are under planning, representing an increase of potentially 809 GWh. Existing plants have plans of expansion representing a possible additional production of 684 GWh (Norwaste, 2023). This indicates that biogas production in Norway has the potential to double in the coming years.

9.2. UTILIZATION OF BIOGAS

The utilization of biogas (excluding landfill gas) in Norway in 2022 is presented in Table 9-2. As the categories reported in the Norwegian biogas statistics are different from the categories used in this country report, some assumptions were made when splitting into utilization type. More than 60% of the produced biogas was upgraded to either compressed biomethane (bio-CNG) (275 GWh) or liquid biomethane (bio-LNG) (178 GWh in 2022) (Norwaste, 2023). According to the national statistics, 370 GWh biomethane was utilized for transport in 2022, of which 366 was used for road transport and 4 GWh was used for maritime transport (Statistics Norway, 2023). It was assumed that the remaining bio-CNG and bio-LNG was used in industry. Of the 158 GWh used for heat, 148 GWh was used internally at the plants, while 10 GWh was used for district heating (Norwaste, 2023). About 10% was flared, and the uses of the remaining biogas production, about 7%, are not known.

Table 9-2. Utilization of biogas in Norway (Norwaste, 2023)

Utilization type	Utilization (GWh/year)	Share (%)
Electricity	3	0
Heat	158	21
Vehicle fuel	370	50
Industry	83	11
Flaring	73	10
Not specified	52	7
Total	**739**	

Fueling stations

The number of fueling stations in Norway has increased rapidly the last few years. The distribution of fueling stations is primarily in the eastern part of Norway, with some biogas fueling hubs in and around some of the larger cities such as Trondheim, Ålesund and Stavanger. Most of the fueling stations provide bio-CNG (23 stations), while three provided bio-LNG, and four provided both bio-CNG and bio-LNG. In the next couple of years approximately 20 new fueling stations are planned to be built. The new fueling stations are spread more evenly across the country. Figure 9-3 is a map from Biogas Norway's overview of fueling stations that is regularly updated by Biogas Oslofjord (Biogass Norge, 2022).

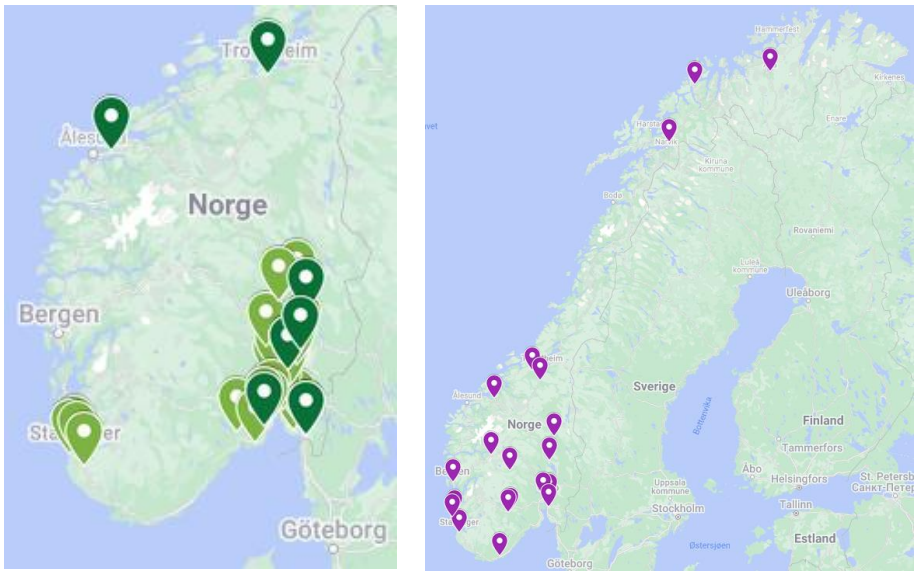

Figure 9-3. Left: Existing fueling stations in Norway. CBG fueling stations are light green, and LBG or combined CBG&LBG fueling stations are dark green. Right: Planned new fueling stations (in purple) in 2023 to 2025. Maps are from Biogass Norge (2022).

Utilization of digestate

Digestate is a co-product from biogas production which can be used as biofertilizer. The quality of the biofertilizer is dependent on the feedstock to the AD plant and, it is regulated by the fertilizer ordinance. In 2022, Norwegian biogas plants produced 370,000 tons (wet weight) liquid digestate and 218,000 tons (wet weight) dewatered/dry digestate (Norwaste, 2023). According to Norwaste (2023) this corresponds to about 3,075 tons of nitrogen, 1,867 tons of phosphorus and 23,583 tons of carbon. As shown in Figure 9-4, 84% of the digestate was used as fertilizer in agricultural production, 14% was used in gardens and parks, and about 2% was used as landfill cover.

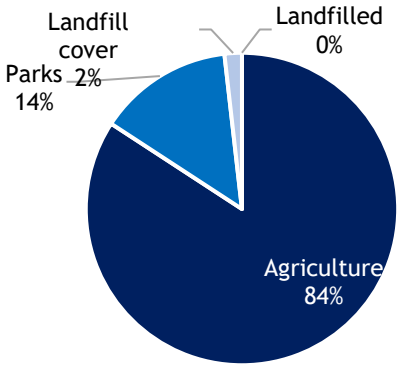

Figure 9-4. Utilization of biofertilizers in Norway (Norwaste, 2023)

Utilization of biogenic CO_2

There is a growing interest in utilizing the biogenic CO_2 that is separated during biogas upgrading. Currently there are no data on the production and utilization of bio-CO_2 from biogas plants in Norway. At The Magic Factory biogas plant, CO_2 from upgrading of biogas is transported in pipes to a greenhouse located nearby, where it is used in tomato production (Lyng, 2020). The largest wastewater biogas plant in Norway, VEAS, recently announced that they have established a subsidiary for capturing, refining and selling CO_2 to the food and beverage industry. Several new biogas plants are also looking at different opportunities for utilizing the CO_2, to reduce emissions and to improve the profitability of the value chain.

9.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

The financial support system comprises three main components, namely investment support (administered by Enova and Bionova), support per ton of manure treated by anaerobic digestion (administered by the Norwegian Agriculture Agency), and tax exemption for biogas used as transport fuel. Descriptions of each of these programs are provided below.

Enova's biogas program provides support for establishing or developing industrial biogas production with innovative technologies that have a high dissemination potential. The amount of support depends on each individual project. In 2022, the support on eligible costs was up to 45% for large companies and up to 50% for small and medium-sized companies. However, as of 2022, Enova no longer provides support for biogas fueling stations and the purchase of new biogas vehicles.

Bionova, established by Innovation Norway, is a program designed to support the development of bioeconomy and GHG reduction in the agricultural, forestry, and aquaculture sectors, with the goal of achieving a low-emission society. Starting from 1st of January 2023, Bionova can provide funding for investments in biogas facilities. The financing is primarily intended for farmers and forest owners. Applicants can receive up to 45% support and a maximum of 8 million NOK. The program also provides funds for feasibility studies and preliminary projects for establishing biogas and biochar facilities. Individuals or agricultural enterprises that intend to establish facilities are eligible to apply. External costs for feasibility studies and preliminary projects can receive up to 50% support, with a maximum of 50,000 NOK (≈ €4,300) for feasibility studies and 150,000 NOK (≈ €12,900) for preliminary projects.

In 2013, a scheme was introduced to provide financial support to farmers per ton of manure treated in anaerobic digestion plants. This support has increased annually and currently (2023) stands at 833 NOK/ton of dry matter. The support is calculated based on the number of animals, for farm scale biogas plants, and per ton of dry matter when manure is supplied to centralized AD plants.

While there is no financial support or feed-in tariff based on the amount of biogas produced, biogas and other renewable fuels used for transport are exempt from road fees and CO_2 taxes. This creates a market advantage over fossil fuels. From 1st of September 2022 heavy duty biogas vehicles are exempted from toll-on-toll roads in the Oslo region. The Norwegian national transport plan of 2021 states that all new city buses are to be zero-emission vehicles or use biogas by 2025.

9.4. INNOVATIVE BIOGAS PROJECTS

A new report on the overall potential of biogas production in Norway was published in 2023 (Lyng and Berntsen, 2023). The report has gained attention both in the biogas industry and in the political debate. The report was divided in three main parts: 1) calculation of the theoretical biogas potential from the current and future feedstock base, based on current technology; 2) theoretical biogas potential related to possible future technology development; and 3) climate benefits related to higher utilization of the biogas potential. The report estimated the potential future feedstock base for biogas production for the current technology by looking at the ambitions and development trends of the sectors where the waste is generated. In total, it was estimated that the possible future feedstock base can provide a theoretical biogas potential of 11.3 TWh. The theoretical biogas potential for the current feedstock base for the current technology for biogas production (anaerobic digestion), was estimated to be 5.5 TWh. The results showed that the greatest potential for increased biogas production comes from agriculture feedstocks (livestock manure and straw), residues from fish farming (fish sludge), and food waste from households and industry. The theoretical biogas potentials for the different cases are summarized in Figure 9-5.

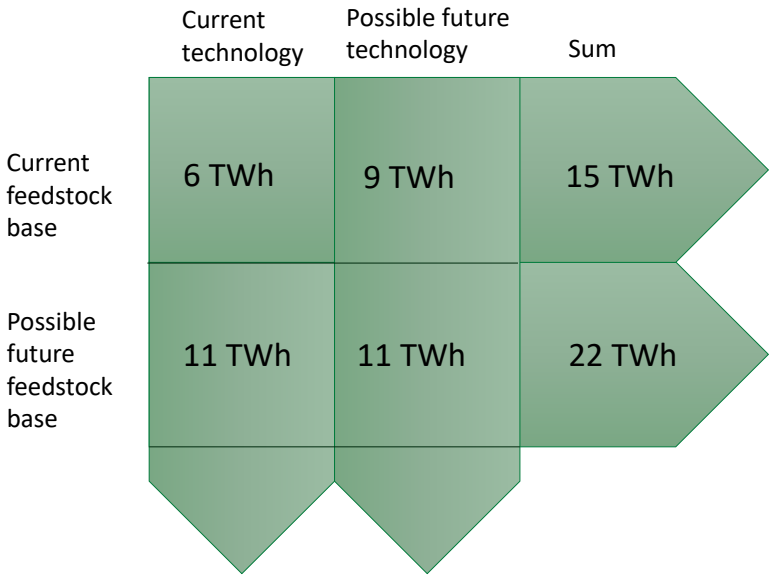

Figure 9-5. The theoretical biogas potential for current and possible future raw material base and for current and possible future technology (Lyng and Berntsen, 2023)

The theoretical potential for capturing biogenic CO_2 from biogas upgrading was estimated to be approximately 298,000 tons of CO_2 with the current feedstock base and approximately 611,000 tons of CO_2 for the possible future feedstock base. The latter is significantly higher than the amount of CO_2 consumed in Norway.

The study also shows that possible future technology development can increase the theoretical biogas potential in Norway in two main ways: The first is using pyrolysis and gasification to produce biogas from feedstock that are not suitable for anaerobic digestion. By including the potential from woody demolition waste, garden waste, and extraction of some forest residues (branches, tops, stumps, and roots) through gasification, a theoretical potential of 7.6 TWh can be achieved. The second is to use biomethanation, where the production of biogas is increased by converting the CO2 in biogas to methane. This represents a biogas potential of 1.4 TWh when based on the current raw material base, and 2.9 TWh based on a possible future raw material base. Additional theoretical biogas potential related to possible technology development is thus 9.0 TWh and 10.5 TWh for current and possible future raw material bases, respectively. Considerable research and technology development effort will be required for this potential can be realized. While 100% of the theoretical potential never can be achieved, the results show that currently just a small proportion of the national biogas potential is being exploited, which indicates good opportunities to produce significantly more biogas in Norway.

10. Sweden

By: Marcus Gustafsson (BSRC, Biogas Solutions Research Center, Linköping University)

The Swedish Gas Association has a vision of "Green gas 2050", including goals of 50 TWh renewable gas production by 2050 and that green gas should contribute to a climate neutral industry sector, fossil free land transportation, cleaner shipping and fossil free heat and electricity generation (Swedish Gas Association, 2013). They have also, together with other important actors in the biogas industry, formulated a proposal for a National Biogas Strategy with a specific target of 15 TWh biomethane/ biogas use in 2030, of which 12 TWh is proposed in the transport sector and 3 TWh in industry (Swedish Gas Association, 2018). Most of this biomethane should be produced in Sweden. An inquiry to update the biogas strategy was conducted during 2018-2019, with the aim that the government will implement an official National Biogas Strategy. As a part of this, an official goal of 10 TWh biogas is proposed for 2030, out of which 7 TWh should come from anaerobic digestion (Westlund et al., 2019). However, no goal or strategy have been officially adopted at this time.

10.1. PRODUCTION OF BIOGAS AND BIOMETHANE

There were 284 biogas plants operating in Sweden in 2022, producing in total 2.279 TWh of biogas (Table 10-1). Most of the biogas was produced from different types of bio-waste and residues in co-digestion plants (50%) and from sewage sludge in wastewater treatment plants (31%).

Table 10-1. Biogas plants and biogas production in Sweden (Klackenberg, 2023)

Plant type	Number of plants	Share (%)	Production (GWh/year)	Share (%)
WWTP	133	47	704	31
Bio-waste	32	11	1,145	50
Agricultural	61	21	121	5
Industrial	8	3	200	9
Landfill	50	18	109	5
Total	**284**		**2,265**	

There were 71 biomethane upgrading plants in Sweden in 2022 (Table 10-2) producing 1.47 TWh biomethane. About 546 GWh of this biomethane was injected to the south-western gas network (364 GWh) and in the Stockholm gas grid (182 GWh) via 14 injection sites, the rest was used locally or distributed further by truck to fueling stations. There were also four biomethane liquefaction plants, producing 156 GWh.

Table 10-2. Biogas upgrading plants in Sweden (Klackenberg, 2023)

Plant type	Number of plants	Share (%)
Membrane	7	10
PSA	10	14
Chemical scrubber	12	17
Water scrubber	42	59
Total	**71**	

Biomethane potential until 2030

A study from 2013 on Sweden's biomethane potential (coming from both digestion and gasification, including energy crops and forest residues) showed that when keeping current policies and implementing currently discussed ones, the realizable potential is 9 – 12 TWh until 2030 (Dahlgren et al., 2013). With improved policies, the potential increases to 11 – 22 TWh. However, with poor policies and a weak economy, (e.g. by introducing energy taxation on biomethane and only a slow increase in oil price), the potential is not higher than the current production level (1.2 – 2.5 TWh). Another study from 2008 showed a technical biomethane potential of 15 TWh from anaerobic digestion of available domestic waste and residues (Linné et al., 2008), and about 10 TWh with restrictions. When thermal gasification of forestry residues was included, the total biomethane potential could rise up to 74 TWh. Note that energy crops are not included in this potential, but may of course be significant, since there exists plenty of fallow or underused agricultural land in Sweden. So far, the use of energy crops for biomethane production is very limited due to economic constraints. In a study on the Nordic countries from 2023, the Swedish biogas potential was estimated to 13 TWh with current technologies and practices (Lindfors and Feiz, 2023). The increase from the present level was estimated to be made possible through and increased use of agricultural substrates, including manure (34%), straw (25%) and low-ILUC crops (25%). The biogas inquiry of 2019 found a technical potential of 14 – 15 TWh biogas from AD and 16 – 22 TWh biomethane from thermal gasification by year 2030 (Westlund et al., 2019). Aquatic substrates were usually omitted in these studies or estimated to have a very low potential.

10.2. UTILIZATION OF BIOGAS

The use of biogas for transportation has increased rapidly over the last 10 years, whereas biogas use for heating has declined. In 2022, 67% of the produced biogas was upgraded and used mainly as transportation fuel, due to a favorable support system. Table 10-3 shows the utilization of domestically produced biogas in Sweden (i.e. not including imported gas). Currently, the market for methane as a transportation fuel is developed in Sweden but it is highly dependent on greater policy incentives and long-term support systems to take the next step. The use of methane as vehicle fuel increased rapidly up until 2014 and has stabilized at around 1,500 GWh for the last few years (Figure 10-1). Biomethane accounted for more than 95% of the vehicle gas use in 2019 – 2022.

Table 10-3. Utilization of domestically produced biogas in Sweden (Klackenberg, 2023)

Utilization type	Utilization (GWh/year)	Share (%)
Electricity	42	2
Heat	358	16
Biomethane	1,535	67
Industry	101	4
Other	3	0.1
Flaring	224	10
Losses/n.d.	15	0.7
Total	**2,265**	

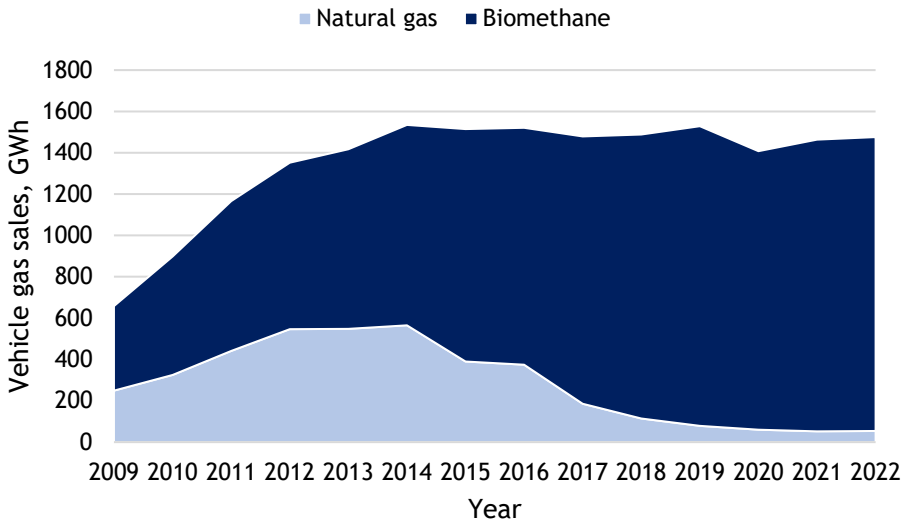

Figure 10-1. Sales of vehicle gas in Sweden 2009-2022 (Statistics Sweden, 2023)

In addition to domestically produced biogas and biomethane, Sweden also used around 1.9 TWh of imported biomethane in 2022, 22% less than in the previous year. In 2021, biomethane imports exceeded domestic production for the first time, and the total consumption of biogas and biomethane amounted to 4.8 TWh. In 2022, Sweden's total consumption was 4.4 TWh. Most of the imported biogas and biomethane was used in industry and for heating, with a smaller share used by vehicles (Klackenberg, 2023).

The Swedish biomethane market is to a large extent off-grid with small local or regional grids or stand-alone biogas gas plants and fueling stations. Today, a large part of the biomethane in Sweden is transported on the road as compressed gas (200/260 bar) and to a small but increasing extent as liquefied gas (LNG and bio-LNG). The gas grid infrastructure is limited to the south-western part of Sweden where the transmission grid is connected to the European gas grid (i.e. connection with Denmark). There is also a gas grid in Stockholm, fueled with locally injected biogas and shipped LNG.

The number of gas fueling stations has increased from less than 20 in 2000 to over 200 stations in 2021, plus 60 non-public stations (Swedish Gas Association, 2022). New fueling stations for LNG are being built in several locations in Sweden. At the end of 2021 there were 26 fueling stations for LNG (Swedish Gas Association, 2022). The number of gas vehicles has during the same period increased from just a few hundred to 52,635 vehicles at the end of 2021; 2,766 of these were buses (about 15% of all buses) and 1,426 trucks, and the rest were passenger cars and other light vehicles. The number of buses and trucks running on CNG or LNG (with a high share of biomethane) is increasing, while the number of passenger cars and light vehicles running on gas have declined since 2016, partly due to export of gas vehicles to other countries.

Liquefied biomethane for industry and heavy transport

There is an increasing interest in liquefied biomethane in Sweden. Its higher energy density compared to compressed biomethane means that liquefied biomethane can be distributed over longer distances despite the absence of a national gas grid network. Moreover, it opens up new possibilities for utilization, such as by industries, shipping and heavy road transport, which require fuels with a high volumetric energy content. At the end of 2021 there were three bio-LNG plants in operation in Sweden. The Swedish truck manufacturers Volvo and Scania have both developed new engines for LNG, and two ferries on the lines Stockholm-Turku and Nynäshamn-Visby are running on LNG.

In 2018 – 2021, the Swedish Energy Agency was commissioned to set up an innovation cluster for bio-LNG, or LBG (liquefied biogas) as it is called in Sweden. This innovation cluster, Drive LBG, was hosted by the Swedish Gas Association, and was assigned to "collect, demonstrate and increase the knowledge, innovation and development opportunities in sustainable solutions for LBG in national as well as international level" (Swedish Gas Association, 2021).

As a part of this work, the cluster provided financial support to companies and organizations who chose to invest in heavy vehicles with LNG propulsion rather than diesel. New fueling stations and bio-LNG production plants were also supported with money from Drive LBG.

Utilization of digestate
Digestate from Swedish biogas plants is to a large extent used as biofertilizer. In 2022, nearly 100% of the digestate from agricultural and co-digestion plants was used as biofertilizer, as well as 47% of the digestate from wastewater treatment plants and 88% of the digestate from industrial biogas plants, resulting in an average of 90% for all biogas plants (2,800 out of 3,130 kt wet weight) (Klackenberg, 2023). Of the 32 co-digestion plants, 28 produced certified biofertilizer according to the certification SPCR 120. Similarly, 37 WWTPs, including all of the largest plants, were certified according to Revaq. Digestate from WWTPs is usually dewatered to increase its solids content (average TS = 25%), while digestate from other plants (despite a low TS; on average 5%) is often used without dewatering.

Increased import puts pressure on Swedish biomethane producers but increases market
Most of the biogas produced in Sweden is upgraded and used for transport. Industry use has however increased over the last few years and is expected to continue to climb. The recent growing imports of biomethane, mainly from Denmark, have pushed down the price of biomethane and thus made it more competitive with natural gas in sectors where the tax exemption is not effective, such as in industry. However, the Swedish biomethane producers are having a difficult time competing with natural gas and imported biomethane due to different support regimes in Sweden compared to other countries. In Sweden, incentives are focused on the use of biomethane, with the most important incentive being the tax exemption; while in other Member States, support is often directed towards production or injection of biogas and biomethane. This means that imported biomethane can benefit from two subsidies, i.e. be subsidized both in Sweden and in the exporting country. Biomethane imports from Denmark have increased from 155 GWh in 2016 to 1.9 TWh in 2022, with 99% being produced in Denmark and 1% in other countries (Klackenberg, 2023).

10.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

The Swedish energy and climate goals push for increased use of renewable energy, especially in transport. The national 2020 goals for renewable energy were reached a few years ago, namely 50% of the total energy utilization and 10% of the energy used in transport. The following long-term climate and energy goals were adopted by the Swedish Parliament in 2017:

- 63% GHG emission reduction in EU non-ETS sector in 2030 and 75% by 2040 compared to 1990
- 70% GHG emission reduction in domestic transport (excl. aviation) by 2030 compared to 2010
- Vision to have a fossil free transportation sector by 2030
- 100% renewable electricity production by 2040 (agreement between 5 of 8 parties in Parliament)
- Climate neutral energy sector by 2045 with at least 85% GHG emission reduction; negative GHG emissions from 2045 onwards.

There is yet no overall government strategy for meeting these goals, but a number of important steps and policies have been implemented or are being investigated, in addition to the existing high CO_2 tax on fossil fuels and the green electricity certificate system as important drivers.

The biogas support system in Sweden has mainly focused on the use of biomethane as vehicle fuel. High CO_2 tax and energy tax on fossil energy and tax exemption for renewables have been the main drivers, together with local and regional investments for biomethane within public transport accompanied with previous investment support programs. During 2018 – 2019, an inquiry was conducted to explore the most suitable long-term policies for biogas and biomethane after 2020, i.e. after the expiry of the EC state aid approval of the tax exemption.

The proposals, which were presented to the government on December 17, 2019, included a maintained tax exemption for biogas as well as new incentives for production of biogas and biomethane (Westlund et al., 2019). The suggestions were met with broad political consensus, and the national budget for 2022 includes a new production support package for biogas of €43M (500 MSEK), which will be increased to €61M/year from 2023. There have also been indications that this support could be extended to 2040. In addition, a national biogas/biomethane register (guarantees of origin or certificates, etc.) to facilitate off-grid distribution, is still under investigation.

Existing policies include:

- Up to 0.40 SEK/kWh (≈ €35/MWh) production support for biogas derived from manure to reduce methane emissions from manure. Total budget 390 MSEK (2015-2023), and support given to each producer is dependent on the total domestic production of biogas from manure.
- Production support for biogas upgraded to biomethane (up to 0.30 SEK/kWh, ≈ €26/MWh) and for liquefaction (up to 0.15 SEK/kWh, ≈ €13/MWh).
- A joint electricity certificate market between Norway and Sweden. The producer gets one certificate for every MWh electricity produced from renewable resources and electricity consumers must buy certificates in relation to their total use. Price span 2014 – 2015: 140 – 190 SEK/MWh (≈ €12 – 16/MWh).
- Klimatklivet ("Climate step") – local climate investment programme 2015-2023. Investment support (up to approx. 45%) for all types of investments or measures that lead to high GHG emission reductions. The budget for 2018 was 800 million SEK/year (≈ €70M). A large part of the investment support that has been granted since 2015 has been allocated to biomethane investments and charging infrastructure for electric vehicles.
- "Bonus-Malus" taxation system for light vehicles from July 1, 2018. Bonus of up to 70,000 SEK (≈ €6,000) for new low emission cars, and gas vehicles get a bonus of 10,000 SEK (≈ €880). Malus is a higher, CO2-based tax for the first three years on higher emission cars (gasoline and diesel cars). From November 2022, only the "Malus" part of the system remains, and no bonus is given to low emission vehicles ordered after this date.
- Quota obligation for biofuels in gasoline and diesel from July 1, 2018. The obligation is expressed as a minimum GHG reduction that each fuel supplier must reach for all sold gasoline and diesel respectively by blending of sustainable biofuels. Reduction levels for 2023 were 7.8% for gasoline (normally blended with ethanol) and 30.5% for diesel (normally blended with HVO), but from January 2024 the government reduced both biofuel quota obligations to 6%. High biofuel blends such as E85 or HVO100 and biomethane are not part of the obligation and are still eligible for tax exemption.
- Environmental zones in cities from January 1, 2020. Cities are able to put up vehicle restriction zones for polluting (noise and emissions) vehicles in three different restriction levels. Only new gas engine, fuel cell and electric vehicles are allowed to travel in all three zones.

Uncertainties for the future biogas/biomethane market development

- The green gas concept is not accepted or applicable for off-grid bio-LNG by important support systems such as EU ETS, green electricity certificate system and climate investment programme (Klimatklivet). This poses a barrier for large biomethane expansion in industry and long-distance transportation modes. A future biogas register or Guarantees of Origin system might be one of the solutions that is currently being discussed by industry and the authorities.

- The CO_2 tax and energy tax exemption for biogas, biomethane and biopropane, which had previously been the cornerstone in the Swedish support system and was approved by the European Commission to continue from 2021 to 2030, was annulled by the EU tribunal in December 2022 due to a formality. This brings a great uncertainty for future development, as

well as financial risk for the current production as the decision goes back to January 2021 when the approval went into force.
The annulment is the result of an appeal by the German biogas company Landwärme, and the EU tribunal decided in their favor because the Commission had followed a simplified investigation procedure—as they normally do in cases of state aid renewal—rather than the more extensive procedure. A new round of investigation has begun, and is expected to be completed in 2024. In the meantime, the Swedish tax authority has decided to wait for the final decision before asking actors on the biogas market to pay back any money given through the tax exemption in 2021 – 2022. A long-term solution may materialize in the form of a change in the General Block Exemption Regulation, which would allow Member States to give financial support to biofuels without asking permission from the Commission.

- The strong focus on electrification in the road transport sector leads to uncertainty for the future use of biogas in Sweden. The government has considered banning all new vehicles with internal combustion engines from 2030. However, the bonus for new low emissions cars (gas, electricity and hybrid) was removed by the new, conservative government in November 2022, and the biofuel quota obligation for gasoline and diesel has been reduced to 6% from January 2024. The situation with the CO_2 and energy tax exemptions has led to increased prices on biogas and biomethane, with a strong, negative influence on the demand for new gas vehicles. In the long run, biogas may be facing a transition from use in vehicles to industrial applications.

10.4. INNOVATIVE BIOGAS PROJECTS

Biogas Solutions Research Center
Biogas Solutions Research Center (BSRC) is a national competence center, funded by the Swedish Energy Agency, that is working to develop resource-efficient systems involving anaerobic digestion. The center is managed by Linköping University and the Swedish University for Agricultural Studies, and includes partners from private and public organizations, representing different parts of the biogas value chain. The research is to a large extent cross-disciplinary and is divided into five areas: 1) the conditions and strategies for biogas solutions; 2) the production system; 3) digestion processes; 4) market and use; and 5) sustainability effects of biogas solutions. BSRC has also given rise to several spin-off projects on, for example, biofertilizers and utilization of CO_2 from biogas.

Carbon capture at Tekniska verken in Linköping
The municipal energy, waste and water company, Tekniska verken, in Linköping has decided to start capturing and liquefying CO_2 from their biogas upgrading plant (Tekniska verken, 2022). Tekniska verken's upgrading plant is one of the largest in Sweden, and they estimate that around 13 000 tons of CO_2 per year can be captured and distributed for utilization or storage. The investment cost will be around €5M, of which €2M is funded by an investment support program (Klimatklivet). In addition, Tekniska verken is investigating the feasibility of capturing CO_2 from their waste incineration plant, and the possibility of storing CO_2 in concrete or bottom ashes from incineration through carbonation.

Small-scale biomethane liquefaction at Vafab Miljö, Västerås
Another municipal biogas producer, Vafab Miljö in Västerås, put a new, small-scale biomethane liquefaction plant into operation in 2022 (Vafab Miljö, 2022). The capacity of the liquefaction plant is around 2 tons per day, or nearly 10 GWh/year, and the plant is intended to facilitate storage and internal use of biomethane. This makes it the smallest biomethane liquefaction plant in Sweden, with around one tenth the capacity of other plants.

11. Switzerland

By: Hans-Joachim Nägele (ZHAW, Zürcher Hochschule für Angewandte Wissenschaften)

The Swiss energy strategy 2050 envisages significantly increasing the production of renewable electricity (not including hydropower) from the 2018 reference value of 3,800 GWh/yr to 4,400 GWh/yr in 2020 and 11,400 GWh/yr in 2035. In 2021, the renewable energy supply had already reached 4,988 GWh/yr. Since January 1st, 2018, a total revision of the Swiss Energy Act is being in force as part of the Energy Strategy 2050. In January 2023, the Federal Council adopted the revised Energy Subsidies Ordinance, replacing the previous feed-in tariff system (EVS) that will remain in place until 2030. Domestically produced biogas contributes 1,636 GWh/yr to the energy supply. Accordingly, the Swiss Gas Industry is aiming to reach 30% renewable gas content in the grid by 2030, which would correspond to 12,000 GWh/yr (HHV) compared with 1,936 GWh/yr (HHV) in 2021. It is interesting to note that despite Switzerland's large biomass resources, only 17.5% of renewable gas consumption is derived from domestic production, with most of the renewable gas being imported to meet the high demand.

Switzerland's domestic biomass supply offers considerable potential for biogas and biomethane production. Compared to the biomass, including wood, that is already used to produce 14,720 GWh/yr of bioenergy, an additional sustainable biomass potential of 12,200 GWh/yr bioenergy remains unexploited. The non-woody biomass potential of 8,300 GWh/yr will mostly be suited for biogas production. Of this, manure has been identified as having the largest additional biogas potential at 6,750 GWh/yr. Agricultural by-products, industrial wastewater, the organic fraction in municipal waste and separately collected green waste are each offering additional potentials of 600 - 900 GWh/yr. Despite this very large biomass potential, the adoption of biogas technology is very slow, especially for manure, the largest potential supply. This is attributed to the small farm size that dominates the structure of Swiss agriculture. The AD plant sizes on the market are oversized for small farms, and the financial incentives for smaller plants are not yet sufficient.

11.1. PRODUCTION OF BIOGAS AND BIOMETHANE

The production of biogas, by sector, is presented in Table 11-1 for 2021. Anaerobic digestion of sewage sludge in domestic WWTPs has been established for decades and most middle and large size WWTPs are equipped with liquid type digesters. AD plants in this sector numbered 477 in 2021. A few installations accept industrial co-substrates that have a high energy potential. In 2021, biogas use included electricity (124 GWh/yr) and heat production (214 GWh/yr, including parasitic heat) with a large share in the form of biomethane grid injection (176 GWh/yr, 29 installations). One installation sells biomethane directly as vehicle fuel. One plant was reported to use biowaste as a co-substrate. Due to the general ban on the application of sewage sludge to agricultural land, digested sludge is dewatered, dried and incinerated, mostly in MSW incineration plants with the remainder in sludge incinerators or cement kilns. Phosphorus recovery will be incorporated into all large sludge incineration plants by 2026.

Most biowaste AD treatment plants are of larger size, in the range of 500 to 2,000 kW_{el}, with a reported total of 28 plants in 2021. Semi-solid plug-flow digesters are common with some dry AD installations in operation. As most separated green waste is already treated, there is little new development. Biogas is partially use through electricity (81 GWh/yr) and heat production (31 GWh/yr, without parasitic heat) with strong growth in biogas upgrading and biomethane grid feeding (163 GWh/yr, 11 installations). Digestate from plug-flow digesters is separated into a liquid fraction, which is directly used in agriculture, and a solid fraction, which is frequently post-composted for agricultural or horticultural use.

Most agricultural AD plants are small to mid-sized in the range of 100 - 800 kWh_{el}. A total of 121 plants are reported in the statistics. Liquid type digesters are common with few dry AD installations in operation. Many installations accept industrial co-substrates that have a high energy potential. However, dedicated manure (manure-only) plants are slightly on the rise, as manure offers the largest untapped sustainable biogas potential (160 GWh/yr).

Biogas use is mainly in the form of electricity (191.6 GWh/yr), with heat only partly used (60 GWh/yr). A small fraction (11.3 GWh/yr) is upgraded to biomethane and fed to the gas grid (3 installations) or sold directly as vehicle fuel (2 installations). Liquid and solid digestates are mainly used directly as an organic fertilizer in agriculture. A few installations upgrade solid digestate through post-composting.

Anaerobic treatment of industrial wastewater is mostly carried out in the food and beverage industry with only few installations in other sectors. In 2021, 22 installations were documented. Liquid type digesters, mainly UASB reactors, are common. Compared to today's production of 56 GWh/yr of biogas, there still remains a domestic potential of 660 GWh/yr for small to mid-sized industrial wastewater installations. Biogas is mostly used for in-house heat production (35.9 GWh/yr), increasingly being upgraded for grid injection (24.5 GWh/yr, 3 installations) and, only to a small extent, used for electricity production (7 GWh/yr). Typically, treated digester effluent is sent to domestic WWTP for final treatment and discharge.

Since 2000, landfill biogas has strongly decreased in importance, and today municipal solid waste is no longer landfilled in Switzerland. One remaining landfill continues to release very low amounts of biogas that is not converted into electricity nor converted into gas for the grid.

Table 11-1. Biogas production in Switzerland

Plant type	Number of plants	Production* (GWh/year)	Share (%)
WWTP	477*	636	39
Bio-waste	28	377	23
Agricultural	121	542	33
Industrial	22	82	5
Landfill	1	1	<1
Total		**1,638**	

** The energy statistics report a total number of 477 WWTPs with biogas production. However, the detailed renewable statistics only report 269 WWTPs with biogas production as only plants producing electricity are counted. Note that in previous country reports, only data from the detailed renewable statistics were used.*

11.2. UTILIZATION OF BIOGAS

A total amount of 1,636 GWh/yr of biogas energy was produced in Switzerland in 2021 (Table 11-2). Traditional use of biogas is mainly in the form of electricity (405 GWh/yr) and heat (341 GWh/yr) production. Today, about one quarter of biogas is used for electricity (25%) and heat (21%), respectively. Grid injection (370 GWh/yr) represents around 23% of biogas energy production. As shown in Table 11-3, most biogas upgrading is carried out using a chemical scrubber or membrane-type upgrader. With respect to the domestic production of new renewable energy, biogas accounts for 8% of renewable electricity while heat from biogas amounts to 1.6% of domestic renewable heat production. The heat production value does not include parasitic (process) heat consumed for digester heating at agricultural and industrial biogas installations. If parasitic heat is included, the total biogas use for heat rises to 36%.

Table 11-2. Utilization of biogas produced in Switzerland

Utilization type	Utilization (GWh/year)	Share (%)
Electricity	405	25
Heat	341	21
Gas grid[1]	370	23
Vehicle fuel	*39*	
Domestic heat	*289*	
Electricity	*42*	
Parasitic heat*	260	15.5
Flaring and unused* heat	260	15.5
Total	**1,636**	

[1]*The statistics of VSG provide energy data according to higher heating value (HHV) (*Swiss Gas Industry Association, 2022). *As all other statistics in Switzerland calculate energy according to its LHV, the numbers were converted into LHV equivalents.*

** Estimated values*

Table 11-3. Biogas upgrading plants in Switzerland

Plant type	Number of plants	Capacity* (Nm^3/h)	Share (%)
Membrane	27	4,816	37
PSA	6	1,430	11
Chemical scrubber	8	5,440	42
Catalytic methanation	1	1	0
Biological methanation	1	230	2
Direct Injection	3	1,090	8
Unknown	3	0	8
Total		**13,007**	**100**

** The capacity, in Nm^3/h, is provided as detailed production data were not available by upgrading technology.*

Grid feeding of raw biogas and of upgraded biomethane produced in Switzerland has undergone considerable growth since 2009, attaining 370 GWh/yr (LHV) in 2021, or 1.09% of the country's total natural gas consumption. An additional 1,742 GWh/yr (LHV) of biomethane was imported in 2021, of which 1,463.7 GWh/yr (LHV) was used for heating purposes. In 2021, Switzerland purchased biomethane from the following countries: Denmark (34.1%), United Kingdom (21%), various European countries (20.1%), Germany (13.9%) and the Netherlands (10.8%). The share of biomethane produced in Switzerland to total biomethane consumption was 17.5% while the share of total biomethane (import and domestic) use represented 6.2% of the country's total gas consumption.

Of the domestic biomethane share, 39 GWh/yr are used as vehicle fuel, equating to 17.2% of total gas consumed in transport (226 GWh/yr). Biomethane used in transport is fairly constant while the overall contribution of natural gas to road transport is rather low. Local upgrading of biogas to biomethane and direct use as a vehicle fuel is still rare with 3 installations in operation so far. At 289 GWh/yr, the main use of Swiss biomethane from the gas grid is for domestic and industrial heating.

Only biogas installations treating agricultural manure and residues, and bio-waste return their digestate back to the natural cycle as soil amendment and organic fertilizer. The agricultural application of sludge from wastewater treatment plants is prohibited in Switzerland. From a total of 722,548 t/yr of manure and 1,305,505 t/yr of organic wastes from separate collection and industry, 1,026,510 t/yr of liquid digestates and 567,867 t/yr of solid digestates and composts were used in agriculture. An additional amount of 154,456 t/yr of compost was used in private gardening, mainly in commercial gardening and horticulture.

11.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

Over the last decades, renewable electricity and, to a lesser extent, renewable heat production were promoted through cost-oriented feed-in-tariffs (KEV) under the feed-in-tariff system (EVS). This support system expired at the end of 2022. The development of the energy promotion ordinance (EnFV) involved intense discussions, as fundamental support structures were changed. The KEV provided a fixed compensation per GWh of energy produced, while the EVS promoted demand-driven production by requiring producers to sell their electricity directly on the market (i.e. direct marketing). That is, the KEV compensation minus the quarterly average power price would be paid to the supplier, in addition to the market price for the power. Thus, if energy was provided during periods when the price was higher than the quarter average, the total earnings would be higher than the KEV compensation. Both KEV and EVS compensations were limited to a certain period of time and include compensation for investment costs.

With respect to biomethane, there is no government subsidy for feeding biomethane into the gas grid in Switzerland. The financing of biomethane feed-in to the natural gas network is regulated by the Swiss gas industry.

The revision of the Swiss Act for the promotion of renewable energy (EnFV) shall ensure continuation of the subsidies for biogas plants. This transitional solution will remain in effect until 2030. Contrary to the previous system, investment compensation is separated from compensation per GWh of energy. However, compensation of operating costs is no longer limited to a time period but continues as long as the biogas plant delivers power and fulfills the stipulated requirements. Continuation of compensation of operating costs is particularly important for biogas plants as investment costs are relatively low when compared to total costs over a plant's lifespan - unlike for other renewable energy sources such as photovoltaics. In fact, the compensation of operational costs is as large as under the KEV/EVS system, enabling biogas plants to continue operating even after the KEV subsidies have expired.

The investment cost compensation for biogas plants is 50% of the costs that are directly related to the production of energy. The operational cost compensation depends on the type of biogas plant and power supply of the plant, with bonus compensation given for plants with no or lower addition of co-substrate to relieve the pressure on the tight co-substrate market. Operational cost compensation follows the same rules as EVS compensation for direct marketing to promote demand-driven energy production. Under EVS, smaller biogas plants were not forced to enter direct marketing, however now every plant must do so.

Existing biogas plants will continue to obtain KEV/EVS support or, until 2025, receive additional cost financing through MKF, the system that was established in 1998 before KEV. These plants can also apply for operational cost compensation when the programs come to an end. Plants which are not registered in the KEV, EVS or MKF program can apply for operational cost support as well as investment cost support if they undertake significant expansion or renovation.

The main criticism received from biogas industry associations relates to the 2030-time limit that is set out in the Law. As biogas plant financing is usually based on a 20-year repayment period, the associations argue that banks will find it difficult to offer funding for new projects due to the low investment security. Also, the industry believes that there should be more financial support of biogas plants operating without co-substrates in order for these plants to be economically feasible. Finally, it is noted that there still exists an imbalance in the support provided to power producing biogas plants when compared to heat producing plants and biogas plants with gas grid injection. This lies outside of the scope of this Law, however it could have been addressed by the proposed CO_2 Law in 2021, which was unfortunately rejected by popular vote.

11.4. INNOVATIVE BIOGAS PROJECTS

CO_2 liquefaction plant at a biomethane upgrading plant

The biogas plant of Recycling Energie AG in Nesselnbach has been successfully producing renewable biogas for years. With the commissioning of the gas upgrading plant for biomethane production, it was decided to pursue CO_2 capture and utilisation. In cooperation with the local energy provider (Stadtwerke Baden), the first CO_2 liquefaction plant in Switzerland was commissioned in 2023. The plant converts organic waste from industry and agriculture into biogas which is upgraded to biomethane and biogenic CO_2. The target is to sell up to 3,500 tons of biogenic CO_2 to the food processing industry each year (Figure 11-1).

Figure 11-1. CO_2 liquefaction at a biogas upgrading plant in Nesselnbach

Limeco – Power-to-Gas Installation

A consortium of eight Swiss energy suppliers and a municipal utility alliance enabled the commissioning of the first industrial biological power-to-gas plant in Dietikon, Switzerland (Limeco, 2022). The goal is to produce 18 GWh of E-gas (synthetic methane) annually from CO_2 and hydrogen. The plant was realised at a wastewater treatment plant, which supplies the CO_2, and uses electricity from the waste incineration plant to operate the electrolyser and generate hydrogen. The facility, shown in Figure 11-2, has been promoted by Swiss authorities and serves as a flagship project.

Figure 11-2. Industrial Biological Power-to-Gas Installation in Dietikon

Agricultural Biogas Plant and Biomethane Fueling Station

The agricultural entrepreneurial family of Christian and Andrea Müller commissioned a biomethane fuelling station at its agricultural biogas plant in 2023 (Unterbuck, 2022). The feedstock consists of liquid and solid manure from the farm that is supplemented with organic residues from the region. The upgrading process is done using membrane technology. The fuel (biomethane) produced is mainly used to power a gas-tractor on the farm, allowing the fields to be cultivated in a climate-neutral way. Customers from outside the farm can also fuel their gas vehicles at the fuelling station, shown in Figure 11-3. The biogas plant with fuelling station replaces about 200,000 litres of diesel fuel per year.

Figure 11-3. First agricultural biomethane fueling station in Thayingen

12. United Kingdom

By: Sonia Heaven and Angela Bywater (Environmental Biotechnology Network, University of Southampton)

Since the early 1990's, the UK has had a range of policies designed to increase the number of AD plants. The Feed-In-Tariff (FiT) for electricity production and the non-domestic Renewable Heat Incentive (RHI), which supported both heat use and biomethane production for the gas grid. Together they created the conditions for the greatest growth in AD plants which took place between 2011 and 2018. Currently, the only two incentives available to AD developers are the Renewable Transport Fuel Incentive, which is a market-based system using certificates, and the Green Gas Support Scheme for biomethane injection More details on these are given below.

12.1. PRODUCTION OF BIOGAS AND BIOMETHANE

Table 12-1 presents the number of AD plants in UK at the end of 2022, based on data compiled in 2023. The original data were provided by the Anaerobic Digestion & Bioresources Association (ADBA) which has a slightly different classification system from that used in the IEA Bioenergy table, namely 'WWTP' equates to their 'sewage' category; and ADBA's classification of 'All three sectors', 'On-site industrial' and 'Other' are shown as 'Industrial/bio-waste' digesters in the table. Biogas production is only shown as a total value, due to the lack of detailed data.

AD in the wastewater sector has not grown significantly, with only one new plant added in the past five years. With an estimated 80 – 90% of UK's sewage already being treated through AD, this figure is not expected to change greatly. The sector is currently focusing on minimizing process emissions and on developing its bioresource market.

Table 12-1. Biogas production in the UK (ADBA, 2023)

Plant type	Number of plants	Share (%)	Production (GWh/year)
WWTP	170	24	N.D.
Agricultural	370	51	N.D.
Industrial/bio-waste	183	25	N.D.
Total	**723**		**32,000[a]**

[a]*Data from 2019 (Eurostat, 2021)*

Overall growth in the AD sector has been modest in the past year, with 11 plants being commissioned since 2021. These are split relatively equally between the agricultural sector and the industrial/bio-waste sectors, at five and six new plants, respectively. This is in contrast to the 2014 to 2017 period, for example, where the average yearly number of agricultural plants built was 70, the number of new industrial/bio-waste plants was averaging 20 and sewage AD plants averaging three per year. Figure 12-1 shows the cumulative growth in the number of plants commissioned on a yearly basis and illustrates the decline in number of plants built in recent years.

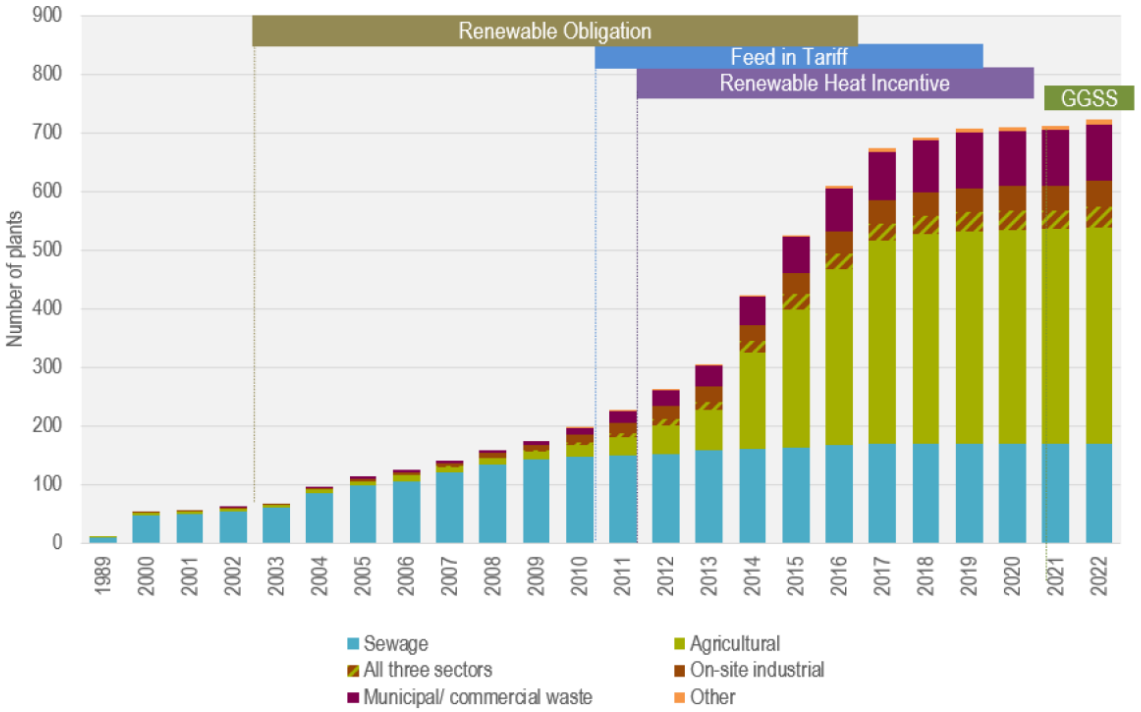

Figure 12-1. Cumulative number of biogas plants in the UK by feedstock sector (ADBA, 2023)

Several factors, most notably the conflict in Ukraine, combined to increase worldwide energy prices in 2022. This resulted in a sharp rise in fertilizer costs (Figure 12-2), which generated interest in both AD and digestate utilization.

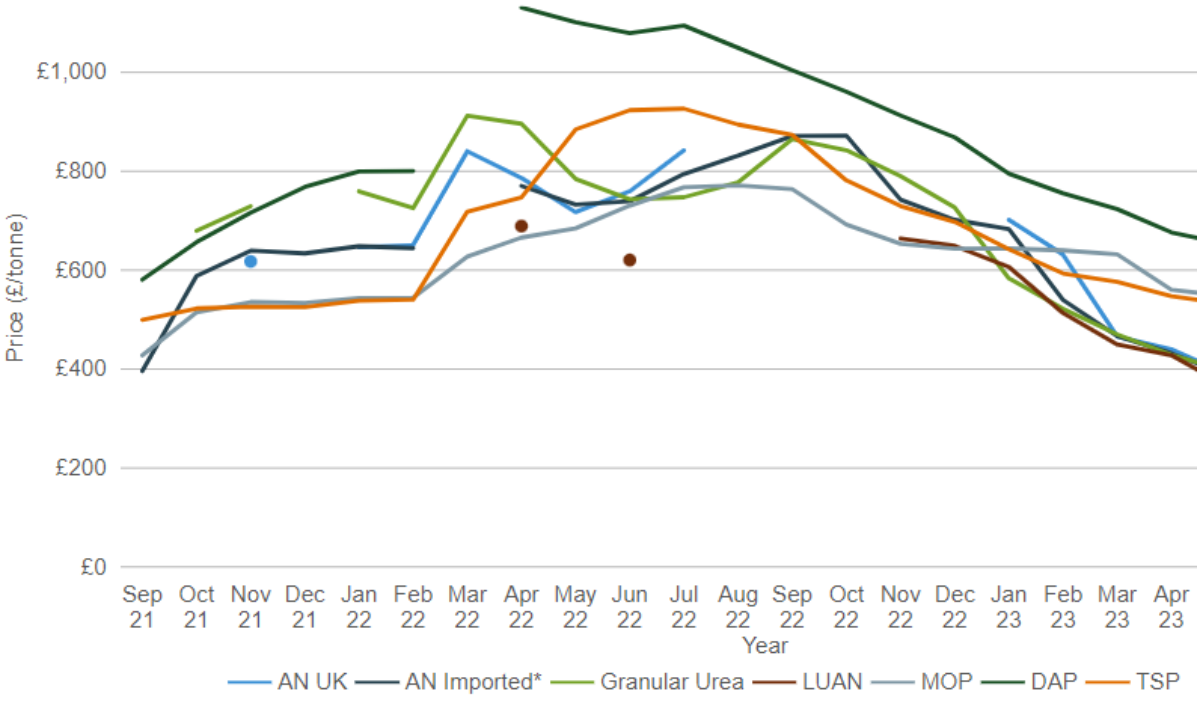

Figure 12-2. Fertilizer prices in the UK Sep 21 – Apr 23. AN = ammonium nitrate, LUAN = liquid urea and ammonium nitrate, MOP = muriate of potash, DAP = diammonium phosphate, TSP = triple super phosphate. (Agriculture and Horticulture Development Board, 2023)

12.2. UTILIZATION OF BIOGAS

Following the closure of the electricity FiT scheme in 2019, the biogas electrical capacity has remained steady at around 700 MWe with a combined installed capacity of 1.8 GWe. Since 2015 – 2016, annual biomethane output in MWe has exceeded electrical output from CHP plants (Figure 12-3). If the electrical efficiencies of CHP engines are taken into account, however, more biogas is still being produced at AD-CHP plants than at AD-biomethane plants.

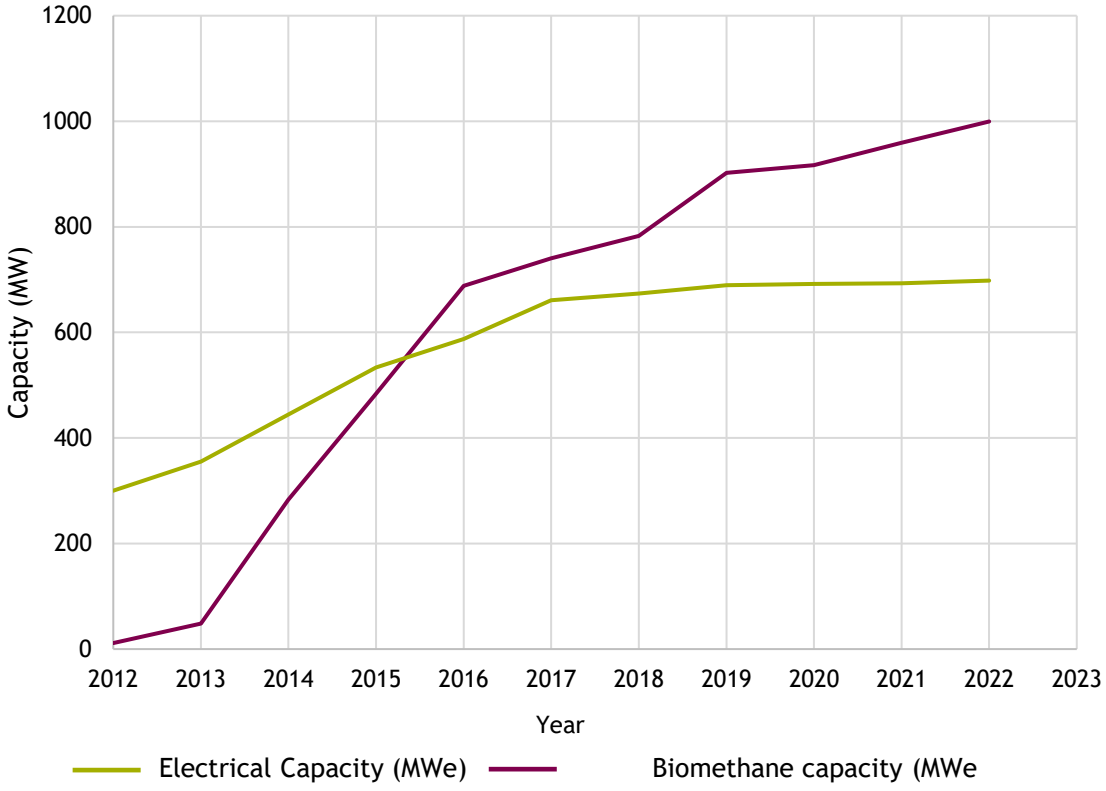

Figure 12-3. Electricity and biomethane capacity in the UK (ADBA, 2023)

Table 12-2 shows a breakdown of operational plants by biogas use. Biomethane capacity has grown much faster than other uses over the last ten years, reaching its current level of 103,174 m^3/h. In particular, the years 2014 – 2016 saw the most rapid deployment of new biomethane plants, with an average of 24 constructed per year with an average production capacity of ≈ 800 m^3/h. Deployment of new plants subsequently slowed in the period before the closure of the RHI to new applications, in March 2021. Through 2014 – 2015, when the AD electricity sector was at its peak, around 7 MWe of capacity was commissioned per month via the FiT scheme (81 MWe per year). By 2018, new electricity production had dropped significantly, and in 2020 no new CHP plants were commissioned.

Table 12-2. Biogas plants in the UK divided by electricity/CHP, heat-only and biomethane (ADBA, 2023)

Type of plant	Number of operational plants	Capacity of operational plants	
Excluding sewage plants			
Electricity/ CHP	427	497	MW_e
Heat-only	6	0.4	MW_{th}
Biomethane	120	91,175	m^3/h
Total	553	2,156	MW_{biogas}
Sewage sludge plants			
Sewage sludge CHP plants (does not include CHPs on biomethane sites)	157	215	MW_e
Biomethane sewage	13	11,999	m^3/h
Total	170	659	MW_{biogas}
Total (all sectors)			
Electricity/ CHP	584	713	MW_e
Heat-only	6	0.4	MW_{th}
Biomethane	133	103,174	m^3/h
Total	723	2,814	MW_{biogas}

12.3. POLICY AND FINANCIAL SUPPORT SYSTEMS

Over the past three decades, UK policies relating directly to anaerobic digestion have included:

- Pollution Control Grants – these were designed to help farmers minimize the pollution associated with slurry production. They included a 50% grant for farmers to install measures such as slurry storage tanks, weeping walls or anaerobic digesters. The scheme ran from 1989 to 1995.
- Renewables Obligation Scheme – this included AD, and obliged electricity suppliers to buy from renewable sources. It started in Great Britain in 2002 (and in Northern Ireland in 2005) and closed to new capacity on 1 April 2017.
- Feed-In Tariff (FiT) – a 20-year index-linked tariff for electricity production in Great Britain only (for AD < 5 MW_e capacity), began on 1 April 2010 and ended in March 2019.
- Renewable Heat Incentive (RHI) – a 20-year tariff for biomethane production. It began in November 2011 and closed to new applications on 31 March 2021. Degression (a budgetary control measure) was introduced in April 2013. Sustainability reporting became mandatory from October 2015.

In 2022, there was some political turmoil in the UK with three different Prime ministers (Boris Johnson, Liz Truss and Rishi Sunak), resulting in a period of policy uncertainty. Current policies that affect the biogas sector include:

- **Green Gas Support Scheme (GGSS) -** a 15-year index-linked tariff for biomethane injection originally open for 4 years from 30 November 2021 with a commissioning deadline of 30 November 2025. Part of the application process includes a tariff guarantee so that developers can approach funders with a guaranteed income stream. Ten tariff guarantees had been granted as of October 2022, but only one plant was receiving payments by the end of the first quarter of 2023. AD plants can opt to receive a mix of GGSS and RTFO payments on a quarterly basis. Sustainability criteria are required (GHG and land use criteria). As of the end of 2022, the tiered payments were:
    - Tier 1: First 60 GWh injected – 5.51 p/kWh (≈ €62/MWh)
    - Tier 2: Next 40 GWh injected – 3.53 p/kWh (≈ € 40/MWh)
    - Tier 3: Any further gas injected – 1.56 p/kWh (≈ €18/MWh)

- **Renewable Transport Fuel Obligation (RTFO)** - an obligation on fossil fuel suppliers to provide a proportion of renewable fuel. Changes to the RTFO design have resulted in a strong market for Renewable Transport Fuel Certificates (RTFC), with the pricing largely remaining over £0.30 per certificate over the last year (one certificate corresponds to one liter of liquid biofuel). Producers of biomethane derived from waste (which attracts double certificates) are increasingly opting to gain support via the RTFO scheme, because the income potential can exceed their RHI tier. Figure 12-4 shows RTFC prices for the past 4 years; however, these are modelled RTFC prices. As RTFC price data are not publicly available, the UK Government models these RTFC prices using market price data for fuels.

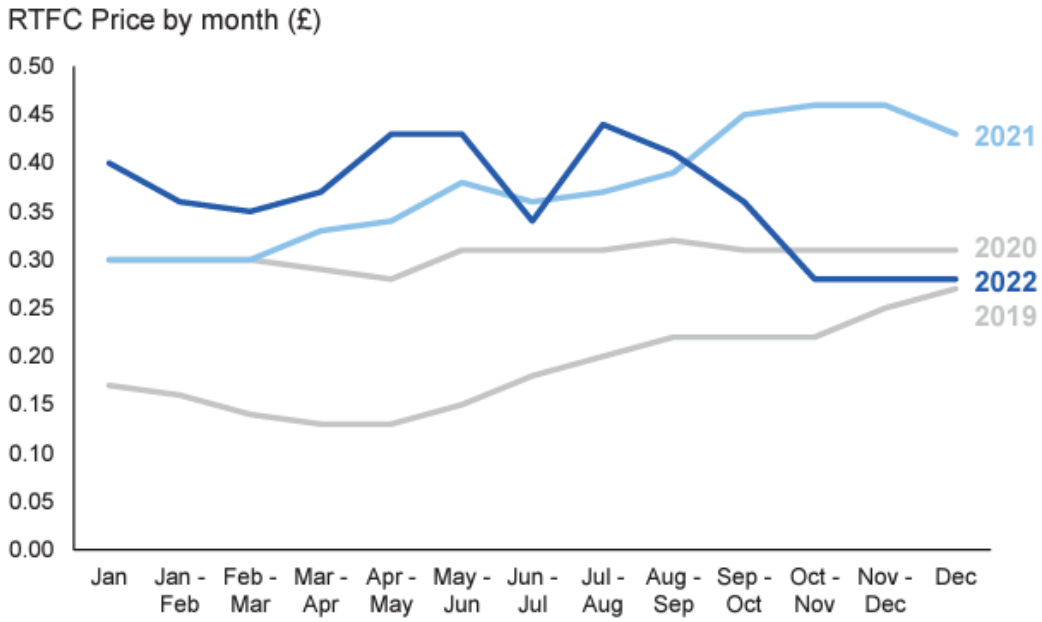

Figure 12-4. Renewable transport fuel certificate (RTFC) prices by month, 2019 – 2021 (UK Department of Transport, 2021)

- British Energy Security Strategy (7 April 2022) published in part because of rising energy prices and issues with natural gas supplies due to the conflict in the Ukraine; offshore wind, nuclear and hydrogen production were highly visible, however there was no mention of AD.
- Biomass Strategy commissioned in 2020 and due in 2022, but publication was delayed, causing uncertainty for the sector.
- In November 2021, the UK government confirmed that by 2040, all new vehicles in the UK must have zero tailpipe emissions. This will be problematic for heavy goods vehicles, where increasing numbers are running on biomethane.
- Separate food waste collection. It is almost certain that separate collection from households will be required from March 2025 as opposed to the originally anticipated 2023 date. Wales has had a long-term recycling policy for food waste, and Scotland is only slightly behind. Funding separate collection of food waste in England remains problematic; thus, delays in implementation have occurred.
- Agricultural policy – post-Brexit agricultural policy is the responsibility of the devolved nations, all of whom are at different stages of policy formulation. How this impacts AD remains to be seen; for example, England's slurry infrastructure grants specifically exclude AD, i.e. utilization of storage off-gases.

12.4. INNOVATIVE BIOGAS PROJECTS

A number of novel projects are currently being carried out in the UK. Systems of note include those which automatically remove grit without stopping the digester, a fast-rate small-scale modular containerized system, a small-scale bio-electrochemical system and novel digestate covers with mobile off-grid biomethane upgrading. There are also several projects utilizing various technologies to extract nitrogen and phosphorus from digestate as products.

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