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Identification and assessment of sustainability effects associated with biogas solutions

-Literature review and perspectives from five countries

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Identification and assessment of sustainability effects associated with biogas solutions

-Literature review and perspectives from five countries

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Executive summary

A societal sustainability transition is urgent, requiring the shift towards a more circular and regenerative biobased economy. Biogas solutions (based on anaerobic digestion, AD) can take many different forms, from sludge stabilization at wastewater treatment plants to stand-alone digestion of the organic material separated from municipal waste to digestion of dairy manure and intermediate crops in rural areas to landfill gas collection, and can produce a number of energy and digester/biofertilizer products, and biogenic carbon dioxide. Biogas solutions are multifunctional and can deliver key products and services to society, such as energy, mobility, nutrients, fodder, clean water, chemicals, and environmental services including sustainable management of natural resources. Across the globe, there is great potential for expanded adoption of biogas solutions.

BROAD RANGE OF SUSTAINABILITY EFFECTS

Based on a scientific literature review this report describes the roles of biogas solutions in different parts of society, identifying the sustainability effects observed through five lenses: 1) biogas solutions adopted in the waste and wastewater treatment sector; 2) biogas solutions adopted in agriculture/rural areas; 3) the use of digestate/biofertilizer; 4) the use of biogas energy, biomethane and biogenic carbon dioxide (CO₂); and 5) society at large. In total, 53 sustainability effects are presented in detail, including information on critical factors and relevant references. While greenhouse gas (GHG) emission reduction is one positive effect that is seen repeatedly, some sustainability effects are unique to a particular lens. For example, biogas solutions for wastewater treatment provide important societal services such as sanitation and improved water quality, while in the agriculture sector they can diversify farm income and encourage new production practices for more resilient agriculture. The majority of the sustainability effects are positive, reinforcing the message that biogas solutions offer multiple benefits to society - in addition to renewable energy and GHG emission reduction. However, the other effects are often not well documented and can be difficult to quantify, leading them to be undervalued or even absent from decision-making. A few effects are negative and should be avoided or mitigated, as for any operation. Also, it was noted that some effects can be positive or negative depending on the operation of the biogas plant or the context, and care should be taken to adopt good operating procedures along the entire value chain.

COMPREHENSIVE ASSESSMENTS FOR BETTER DECISIONS

Today, new development of biogas solutions is strongly based on its energy and GHG emissions reduction value while the other sustainability effects are not given very much consideration. The report includes several examples of comprehensive sustainability assessments that use systems analysis methods such as multi-criteria assessment (MCA) to evaluate multiple effects of biogas solutions and thereby carry out more complete comparisons. Two transport sector MCA studies from Sweden bring to light the strengths and weaknesses of different energy carriers, and provide insights on the best applications of biomethane in transport. In addition, the report reviews studies completed in France, Switzerland and for Europe (EU 27 and UK) that have identified key sustainability effects of biogas solutions, including the main beneficiaries, and monetized some of the effects (or externalities). They all consider biogas systems to provide several products and numerous positive effects that benefit society at large. As such the total added value makes biogas solutions highly competitive from a socio-economic perspective, when compared to both non-renewable and other renewable alternatives, and helps to justify the government support that governments provide to the sector. Such comprehensive studies provide a more complete understanding of all of the attributes of biogas solutions and point to the different types of organizations (or actors) that should be involved in value chain development and decision-making.

EXPERIENCES FROM FIVE MEMBER COUNTRIES

Experiences regarding biogas systems and associated sustainability effects are shared by experts from five Task 37 Member Countries - Canada, France, Norway, Sweden and Switzerland. In each of these countries, biogas solutions have evolved over several decades, influenced by factors such as population density, the industrial and agricultural profiles, energy resources and infrastructure, geography and climate. From the technology perspective, the solutions are very similar to one another as wet, organic wastes and residues from the municipal, industrial and agricultural sectors are converted into biogas energy (electricity, heat and biomethane) and digestate/biofertilizer meeting quality standards is applied to agricultural soils according to site specific prescriptions. As such these five countries acknowledge many of the same sustainability effects, but the relevance of the effects (or the order of importance) varies among countries depending on the types of biogas solutions and feedstocks, the energy end-uses of the biogas, and the country's goals with respect to waste management, environmental protection, climate change and its clean energy transition.

For each country, descriptions are provided of the country contexts and biogas systems, relevant sustainability effects, important drivers and barriers related to these systems and effects, and outlooks for further adoption. Some of the interesting features include Switzerland's strong adoption of biogas solutions for wastewater treatment with almost complete coverage, Canada's attention on landfill gas capture and treatment in its methane reduction strategy, France's significant use of intermediate crops as a co-substrate with manure in its many agricultural biogas plants, and Norway and Sweden starting to digest fish processing sludge to lower the risks of eutrophication. All countries have digestate standards and guidelines in place to recover the nutrients for crop production and reduce synthetic fertilizer use, while protecting their soils and water supplies. The respective contributions of biogas energy to the country's energy mix and GHG emission reduction depend to a large extent on the country's energy infrastructure, its energy and transport policies, and how biogas energy is recognized in its clean energy transition.

At a societal level, biogas solutions appear to be in good alignment with the countries' commitments to sustainable development, including goals on climate change mitigation; waste management; regenerative, circular bioeconomy; and more recently, the broader concept of supply security, including not only energy but also food/nutrients, water, and biogenic carbon. While many sustainability effects are cross-sectoral and benefit society at large, all five countries note the essential roles that public policies, legislation and financial support continue to play with respect to advancing biogas solutions. A mix of influential policy related drivers and barriers exist in the studied countries. Policy related risks and uncertainties influence the development of biogas solutions, and its competitiveness is strongly influenced by policy, including subsidies for competing and complementary alternatives. A strong focus on electrification and future hydrogen systems presents a serious challenge to new development.

GUIDANCE FOR PLANNERS, DEVELOPERS AND THE POLICY COMMUNITY

The opportunities for biogas solutions are expected to increase as populations and their associated waste generation continue to grow, and land and resources become more limited. While energy systems become more decarbonized, the value of the other sustainability effects of biogas solutions, such as resource recovery and circularity, could increase over time. However, many pieces have to fall into place to build reliable, efficient value chains, and both local communities and the broader public have to be willing to accept biogas solutions and their respective roles in supporting development.

It is of utmost importance that decision-makers, including planners, developers and policymakers, and the public develop a comprehensive understanding of the broad system effects of biogas solutions and their highly cross-sectoral nature involving waste management, energy, industry and agriculture. Unlike mono-functional systems which are easier to understand and manage, biogas solutions contribute to multiple sectors and sustainability goals, and require a great deal of cross-sectoral collaboration to create industrial-urban-rural symbiosis.

The report concludes by proposing the following recommendations:

Promote More Holistic Understanding and Perspectives

- Use science-based, multi-criteria sustainability assessments to inform decisions on technical alternatives.
- Recognize the cross-sectoral benefits of biogas solutions in waste, wastewater, agriculture, energy, transport, and various industrial sectors.
- Encourage greater cross-sector collaboration, shared decision-making and support solutions that contribute to a circular economy. Include different sized solutions and solutions that are co-created with local communities.
- Shift the focus toward integrated strategies that combine multiple renewable technologies to deliver desired functions while addressing urgent sustainability challenges.

Adopt Coherent and Effective Policy Frameworks

- Harmonize lifecycle and value chain perspectives across relevant policies.
- Enable biogas value chain actors to capture the full societal value of their contributions.
- Remove regulatory and administrative barriers, such as restrictions on sustainable crop-based biogas and lengthy approval processes for mature technologies.
- Set clear targets for the production and use of biogas, biomethane, digestate/biofertilizers, and biogenic CO₂, and ensure the development of supporting infrastructure and access to land to make these targets achievable.
- Balance top-down strategies with local adaptability to facilitate effective and implementation.

Glossary

Some essential terms are explained below.

Anaerobic digestion (AD)	Microbial degradation of organic substances under exclusion of free oxygen. The degradation process delivers raw biogas and digestate.
Biogenic carbon	Carbon derived from recent biological sources, such as plants, animals, and other living organisms. This carbon is part of the natural carbon cycle, where it is absorbed from the atmosphere by plants during photosynthesis, stored in biomass, and eventually returned to the atmosphere through processes like respiration, decomposition, or combustion. Unlike fossil carbon, biogenic carbon is part of a relatively short-term carbon cycle.
Biofertilizer	In this report the term refers to a fertilizer product based on the digestate from biogas production (AD processes), including direct digestate application as well as various valorized fertilizer products. Digestate contains most of the nutrients in the digested feedstock transformed into a more bioavailable form, organic matter, and living microorganisms, and thus when used in agriculture contribute to soil fertility and health. The term '<i>biofertilizer</i>' varies in usage across countries. Since digestate is typically highly diluted, it may not meet specific fertilizer requirements without further processing (valorization), leading to the use of alternative terms. In some countries, digestate is not officially recognized as a fertilizer <i>per se</i>, but as a soil conditioner or nutrient supplement, depending on its composition.
Bio-CNG	The same as <i>compressed biomethane</i> , the term is used in some countries and indicates that it is Compressed Natural Gas, but of biological origin (or at least associated with a green gas certificate).
Bio-LNG	The same as <i>liquid biomethane</i> , the term is used in some countries and indicates that it is Liquid Natural Gas, but of biological origin (or at least associated with a green gas certificate).
Biomethane	Purified and upgraded biogas, with a methane content of ~97% _{vol} . In North America, this is known as Renewable Natural Gas (RNG). Similar quality as natural gas. Can be injected into natural gas grids and be used to fuel methane-powered vehicles.
Biosolids	Stabilized sludges from a wastewater treatment process.
Biowaste	Organic fraction separated from municipal solid waste, largely consisting of food waste from households, commercial establishments, food production and food trade. In Canada, this material is referred to as Source Separated Organics (SSO).

Compressed biomethane (CBM, CBG)	Biomethane that has been compressed to 200- 300 barg to reduce the volume.
Compressed Natural Gas (CNG)	Natural gas that has been compressed to 200- 300 barg to reduce the volume.
Digestate	The remaining material after the anaerobic digestion (AD) process, a co-product of biogas production. Digestate contains the undigested carbon, microorganisms and most of the nutrients in the feedstock, and AD processes transform the nutrients into a more bioavailable form. See biofertilizers.
Energy crops	Agricultural or woody crops that are specifically grown for renewable energy provision.
Feedstock	The organic material that is digested. Similar to <i>substrate</i> .
Fertilizer	A natural or artificial substance containing chemical elements that improve growth and productivity of plants.
Fossil carbon	Carbon originating from fossilized organic materials. This means plants, animals, and other living organisms which have been buried and subjected to geological processes over millions of years, transformed into coal, oil, natural gas, etc.
Intermediate crops	Agricultural crops planted between two main crops. An important purpose is to cover the soil (cover crop function), to prevent weed growth and avoid nutrient leakage. There may also be other important environmental benefits, such as carbon sequestration.
Liquid biomethane (LBM, LBG)	Biomethane that has been liquefied by cooling to -162 °C, at atmospheric pressure (1.03125 bar _{abs}). The liquid form has a higher energy density, making it possible to transport the fuel over longer distances and increasing the range of LBM fueled vehicles.
Liquid Natural Gas (LNG)	Natural gas that has been liquefied.
Natural gas	Methane gas of fossil origin.
Raw biogas	The gas originating from AD (biogas production plants) that typically contains 50-75% methane (CH ₄), 20-45% carbon dioxide (CO ₂), and some trace gases. Raw biogas needs to be upgraded (to biomethane) to reach fuel quality standards.
Renewable natural gas (RNG)	The same as <i>biomethane</i> . The term renewable natural gas is used in some countries, for example, in North America.
Substrate	The organic material that is fed into the anaerobic digesters. Similar to <i>feedstock</i> , which is the term that is mainly used in this report.
Upgraded biogas	The same as <i>biomethane</i> . Most of the carbon dioxide (CO ₂) and impurities have been removed by purification and upgrading, to reach a methane content of ~97% _{vol} .

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1 Introduction, aim and scope

Across the planet we must address a wide range of environmental sustainability challenges, such as climate change; air pollution; water availability and pollution; waste management; noise; and non-cyclic practices. Many of the current anthropogenic systems have a significant negative impact on life sustaining systems and consume finite resources. There is an urgent need for a transition to more well-designed sociotechnical systems, involving a shift towards a more circular and regenerative biobased economy.

In this context, biogas solutions (or anaerobic digestion systems) already play essential roles that could be greatly expanded in most parts of the world. That biogas solutions are multifunctional is a great advantage (Lindfors et al., 2019), since they can provide, or support the provision of, key products and services, such as food, fodder, energy, mobility, water, chemicals, and environmental services, including a more sustainable management of natural resources.

However, the understanding of and views of biogas solutions usually appears to be very limited, and sometimes even wrong. That biogas solutions commonly are multifunctional is very beneficial from a societal perspective, but their cross-sectoral nature and the broad range of societal services and effects also makes it challenging for decision makers and other actors to fully account for the multiple attributes (Gustafsson and Anderberg, 2021; Lindfors et al., 2022). Lack of knowledge, significant complexity and too limited perspectives in decision-making, may lead to socio-economic sub-optimization, including prioritization of less beneficial technologies and systems, and risks of unintended problem shifting.

This report identifies and describes relevant sustainability effects and values associated with biogas solutions in various contexts, based on synthesized information from a scientific literature review. The sustainability effects are presented, including information on contextual and critical factors. In addition, the report contains expert based information from five countries, describing biogas concepts and associated sustainability effects in different parts of the world, along with key drivers, barriers, and expected future development.

1.1 Basics about biogas and biofertilizer production

Biogas is an important product of biogas plants, which utilize anaerobic digestion (AD) processes. Biogas plants have one or several digesters, where microorganisms degrade the wet biomass (or feedstock) in an environment in the absence of free oxygen. Raw untreated biogas from AD plants typically contains 50 - 75 % methane (CH_4), 25 -50 % carbon dioxide (CO_2), and some trace gases. This raw biogas can be used to produce heat and/or electricity, while cleaning and upgrading is needed to reach a quality very similar to natural gas. The cleaned and upgraded gaseous fuel is called biomethane, which can be injected into natural gas grids or used as a transport fuel (Ammenberg et al., 2021b). In some countries biomethane is referred to as renewable natural gas (RNG). Similar renewable gases can also be generated from thermal gasification of woody solid biomass or via power-to-gas systems (Hrbek, 2022; Murphy et al., 2024). However, the AD technology is the most mature and is thus focused on in this report.

Biogas plants also generate digestate, which is the remaining (digested) biomass containing most of the nutrients in the feedstock, transformed into a more bioavailable form. Containing organic matter and microbes, and being rich in macro- and micro-nutrients, digestate can be an excellent plant fertilizer to be used in agriculture or elsewhere (Drosg et al., 2015). Thus, digestate used as soil conditioner, or fertilizer material, is an important co-product from biogas plants, which can be refined to match specific contexts or demands. For consistency, the term *biofertilizer* is used in this report to refer to all digestate based products.

There is also potential to make use of the biogenic carbon dioxide (CO₂) that is removed in the cleaning and upgrading steps at biogas plants producing biomethane, which further improves the sustainability performance of anaerobic digestion. This biogenic CO₂ can replace fossil-based CO₂-products, or undergo methanation with hydrogen to produce additional biomethane (Cordova et al., 2023).

This report focuses on the described ‘traditionally designed’ biogas plants (AD processes), but it should be observed that AD processes may be configured to provide other/additional valuable products as well (Sawatdeenarunat et al., 2016).

1.2 Feedstocks and potential

Biogas plants can utilize a wide variety of feedstocks, including industrial waste. This great flexibility is beneficial. Most biodegradable non-woody biomass can be used¹, with varying shares of carbohydrates, lipids/fats and proteins, both from primary and secondary raw materials (Allen et al., 2016). Biogas is commonly produced from wastes or by-products, such as food-waste or agricultural byproducts including manure, but biogas systems may also function as essential components in more advanced bio-industrial contexts (such as paper mills or biorefineries), contributing to their resource efficiency and circularity (Cherubini, 2010a; Hagman et al., 2017). Sewage sludge, industrial waste and wastewater and landfills are sources for biogas. In addition, a wide range of crops can be used for biogas production (e.g. Gissén et al., 2014; Murphy et al., 2011), where intermediate crops in well-designed crop rotation schemes can be favorable, in comparison to ‘energy crops’ (such as maize) to avoid competition with food or fodder while achieving several environmental benefits (Brémond et al., 2020; Magnolo et al., 2021; McCabe, B. et al., 2020). Digestate return to the fields where crops have been removed, as emphasized in the biogasdoneright(TM) concept, is a key feature of sustainable feedstock supply (Magnolo et al., 2021).

Biogas plants are normally used all year round, while the availability varies for different types of feedstocks. Thus, a good combination of feedstocks to co-digest is essential, and facilities for on-site storage may be required. Of course, other aspects than seasonality influence what is a good feedstock combination. For example, feedstocks within reasonable distances are chosen to fit certain types of biogas plants/processes, and to get a good carbon nitrogen balance, etc. (Karki et al., 2021).

Significantly more biogas, biofertilizers/digestate, and biogenic CO₂, can be produced, also in countries which already have a relatively large production (Alberichi et al., 2023; e.g. Hamelin et al., 2020; Lindfors and Feiz, 2023). In a report Cappannelli et al. (IEA, 2020) state:

“The feedstocks available for sustainable production of biogas and biomethane are huge, but only a fraction of this potential is used today”

They estimated the 2018 global biogas production to potentially reach about 400 TWh, just based on AD of crop residues, animal manure, the organic fraction of municipal solid waste, and wastewater; without utilization of agricultural land that could be used for food production. The potential would be larger if other feedstocks would be included, such as aquatic feedstocks (Herrmann et al., 2016; Tabassum et al., 2016) that are commonly excluded in biogas potential studies (Tjutju et al., 2024).

¹ Wood biomass has a high lignin content which makes it challenging to digest, since lignin is not degradable in the absence of oxygen.

1.3 Biogas use

The produced biogas is mainly used for generation of heat (including cooking) and electricity in many countries (Gustafsson et al., 2024). A small but growing share is upgraded to biomethane and used for transport (Ammenberg et al., 2021b). In some countries, there is large scale upgrading of biogas to biomethane, which is injected into natural gas grids and used for power production, heating and industrial uses. It is possible to liquefy biomethane to significantly increase its energy density, which may be particularly relevant in areas lacking gas grids. Many actors and countries seem to shift focus to upgrading and see biomethane as a superior product to biogas-generated electricity, due to the greater flexibility for use (e.g. Miltner et al., 2017). Figure 1 schematically illustrates biogas solutions, where different types of feedstocks are converted in AD plants to energy carriers (biogas, biomethane and/or electricity) and biofertilizers for use in agriculture. In addition, biogenic CO₂ can be separated from the biogas and used for different purposes.

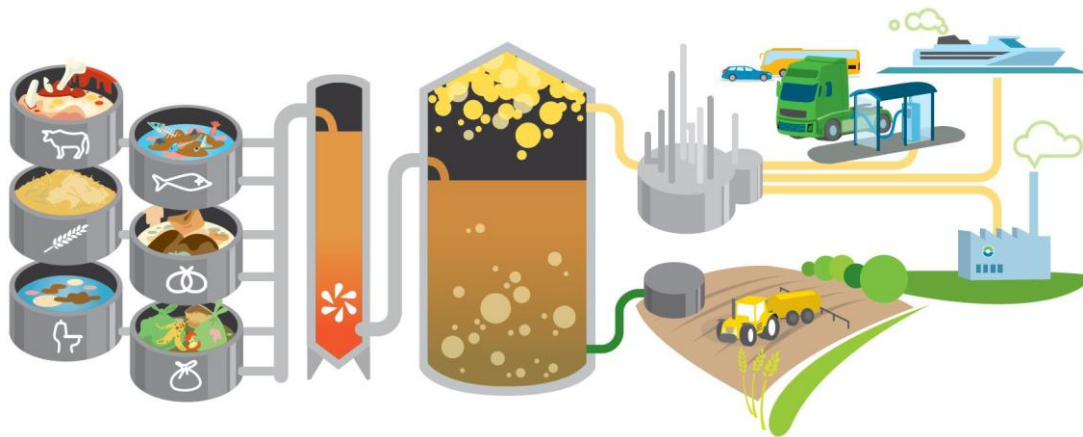


Figure 1. Schematic of biogas solutions. Illustration: Mattias Schläger.

In terms of biogas production and usage, it's worth noting that there are millions of household-scale biogas plants worldwide, many of them in countries like India and China. However, a significant number of these plants are not currently in operation. Household-scale biogas systems can be challenging to operate with sound environmental performance. This report focuses on larger biogas facilities, covering farm-scale systems and beyond.

2 Sustainability effects associated with biogas solutions

This chapter provides an overview of sustainability effects associated with biogas solutions, based on a review of scientific literature. A majority of the sustainability effects should be of general relevance, although local conditions are influential and essential to consider. For some parts, the research seems to be directed towards biogas systems in Europe and North America. For example, different agricultural systems in South America or Asia should be observed, that may influence the possibilities for digestate management, etc.

To start with it is essential to emphasize that a comprehensive understanding of the sustainability performance of biogas systems (and any other complementing or competing alternative) requires a broad systems perspective. This means considering the full lifecycle of the different products (or the complete value chains), all relevant types of sustainability impact (environmental, social and socio-economic) and both the current situation as well as the future. This is further developed in Chapter 3. Due to their multi-functionality, broad perspectives are especially important for biogas systems. While broader studies are more complex and resource demanding to carry out, they are essential for informed decision making, avoiding unintended problem shifting.

The following sections describe the roles of biogas solutions in different parts of society, including information on associated sustainability effects. Details on the sustainability effects, influencing factors, and references can be found in the tables ending each subsection (2.1-2.5).

2.1 Waste and wastewater treatment

Biogas solutions are essential components in waste treatment systems in several parts of the world, where biogas and biofertilizers/digestate are produced from organic waste or by-products, such as food waste and industrial biowaste from slaughterhouses, food and beverage processing industries, etc. Such waste management systems involve separation of the organic waste fractions, which facilitate recycling of other fractions as well, such as metals or plastics. AD technology is frequently used in urban WasteWater Treatment Plants (WWTP), where the process sanitizes the generated sludge, thereby reducing risks related to pathogens and some other problematic substances. It also converts some of the carbon into biogas and reduces the sludge volume.

Globally, huge amounts of organic waste are landfilled, releasing enormous GHG emissions (and other emissions to air, land and water bodies) over several decades. Waste-management systems involving biogas solutions may dramatically reduce the amounts of organic waste that are landfilled, thereby reducing odors, air emissions and leachates as well as landfill area demand. In addition, biogas may be collected from wells in covered landfills, which is an important strategy to reduce the GHG emissions (methane) from existing landfills. Depending on the country, landfills are often situated within, or close to, cities. When biogas systems contribute to avoided landfilling, they can also support urban land availability, flexibility and may also increase the value of surrounding land and other types of properties (like buildings).

Biogas solutions are used by different types of industries to treat industrial wastewater, where they can function as compact and cost-effective systems. In addition to energy recovery, the utilization of AD technology can improve the process efficiency and lower the pollutant loading of its effluent, thereby allowing increased production within the limits of a given environmental permit. This is the case for single industries, but also for more complex biorefinery networks. That biogas systems can handle low-grade and wet biomass is an important asset in biorefinery contexts.

When designing and managing biogas systems, it is essential to apply the best available technology and practices, to avoid system leaks and other unwanted effects. Generally, good waste management practices are essential to avoid odor related problems, littering, the spread of unwanted substances, and other negative effects, which is also the case for biogas systems.

Proactive approaches, including well-designed societal systems to avoid waste and by-products streams containing problematic substances, are critical for all circular practices.

In summary, biogas systems in many contexts can contribute to safer and more efficient waste and wastewater treatment, including recovery of energy and nutrients that are needed in agricultural production, and reduction of emissions. Biogas systems productize and valorize wastes and by-products, generating products such as biogas, biomethane, biofertilizer, and biogenic CO₂ (when the biogas is upgraded), while also contributing to water security and broader resource efficiency.

Table 1 lists the sustainability effects that are associated with biogas solutions in the waste and wastewater treatment sector, including specifications, information on important factors, and relevant scientific references.

Table 1. Sustainability effects that are associated with biogas solutions in the waste and wastewater treatment sector.

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
W1	Improved water security, availability of clean water	Waste management, broader society Waste and wastewater treatment, water management	AD plants (including the use of feedstock for improving water bodies ²) are essential components for water security and supply - circulation and to avoid pollution from municipal and industrial wastewater	Current waste and wastewater management of municipal and industrial wastes and wastewater, i.e. the extent to which AD plants exist and/or would involve essential differences Wastewaters and sludges with sufficient organic loading	(Ammenberg and Feiz, 2017; Appels et al., 2008; Belinska et al., 2023; Cheng et al., 2017; Khawer et al., 2022; Uche et al., 2020)
W2	Improved resource efficiency, valorization of waste and byproducts	Waste management Waste and wastewater treatment	Biogas systems recover value from by-products and waste and provide valuable products such as biogas, biofertilizers and/or other valuable products. The valorization can be significant, ranging from low to high value depending on the end-uses and established markets. Also, in more advanced bio-industrial contexts (such as paper mills or biorefineries), there are commonly residue streams of low value that can be suitable for AD	The value added, considering initial values and alternative treatments and uses Most biodegradable non-woody biomass can be used. Essential that the waste or biomass is non-polluted (e.g. containing heavy metals), or that 'pollutants' can be sufficiently removed	(Cherubini, 2010b; Hagman et al., 2017; Lindfors et al., 2022; Liu et al., 2022)

² For example, the utilization of aquatic feedstocks to reduce nutrient loads in water bodies.

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
W3	Reduced climate impact (GHG emissions)	Waste sector Waste management, landfills	Biogas collection at landfills leads to significantly reduced methane emissions. i.e. legacy emissions from past activities Also, organic waste diverted from landfills, sorted out and treated in a better way, prevents uncontrolled methane formation and leakages	The level of positive climate impact is influenced by the share of collected landfill gas, how the collected biogas is managed and used, involving what is replaced. Other factors: the size of the landfill, distance to pipelines and users, etc. The performance of alternative waste management in comparison to landfilling Essential to avoid methane emissions (leakage)	(Aguilar-Virgen et al., 2014; Blair and Mataraarachchi, 2021; Mohsen et al., 2019; Themelis and Ulloa, 2007; Zhang et al., 2023)
W4	Enhanced urban land availability, flexibility and value	Waste sector Waste management, recycling	Recycling (involving AD) instead of landfilling may require less land. Reduced areas with deposited waste and/or land/soil pollution gives greater land use flexibility. Avoiding urban landfilling can have positive effects on the value of surrounding areas (prices of land, buildings, etc)	The extent to which areas with landfills (existing and future) can be used for other purposes. Across the world, there are landfills in central city areas that may be attractive for other uses.	(Shukla and Khan, 2022; Feo and Gisi, 2014; Ready, 2010; cf. Moh and Abd Manaf, 2014)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
W5	Safe waste management, reduced emissions and odor, and reduced risk of spreading problematic substances	Waste and wastewater sector Waste and wastewater treatment	Improved waste handling, involving less waste to landfills, can essentially reduce emissions and odor from waste management facilities. Waste hygienization, e.g. reducing risks related to pathogens -Organic waste from households, industry, ... -Sewage sludge at WWTPs -Industrial biowaste	Properly designed 'waste' management systems, applying BAT. Since biogas systems may be sensitive to polluted feedstock, they function as waste flow quality checkpoints.	(Oikonomou et al., 2014; Orzi et al., 2015; Varel et al., 2012; Vaverková, 2019; Zhao and Liu, 2019)
W6	Facilitated and more efficient waste treatment, improved separation	Waste sector Waste and wastewater treatment	Organic waste separation making other fractions easier to treat. Ability to treat low solids waste	Properly designed 'waste' management systems, applying BAT	(Calabrò and Satira, 2020; Satchwell et al., 2018; Wainaina et al., 2020; Zhang et al., 2022)
W7	Cost efficient treatment, increased production capacity	Industrial sectors Waste and wastewater treatment	AD may be a cost-efficient technology for treatment of industrial wastewater and sludge at e.g. paper mills, that may also allow increased production within the frames of an environmental permit	Current production, treatment and permitted levels	(Ekstrand, 2019; Kong et al., 2019; Larsson, 2015; McKeown et al., 2012; Saravanan et al., 2023)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
W8	Reduced risk of odor related problems	Waste sector Waste and wastewater treatment, but also of general relevance	In general, handling of waste and wastewater involves odor related problems. Well-designed and operated biogas systems may reduce such problems, while poor management of feedstock, and inadequate design and construction of biogas plants, may contribute to such problems Storage and land application of biosolids and digestates are essential	How feedstock is transported, stored, and handled. The design of biogas plants involving share of hermetic 'parts', technology to avoid and treat odor-related problems, content of off-gases, etc. Procedures for cleaning vehicles and surfaces may also be relevant, also standards and best management practices for land application of biosolids and digestates	(Barbusiński and Kalembe, 2016; Luo et al., 2022; Rahman and Borhan, 2012; Senatore et al., 2021; Wiśniewska et al., 2020)

2.2 Agriculture, feedstock related effects

The choice of feedstocks, and how they are produced and handled, is important regarding the sustainability performance of biogas systems. While this is generally true, this section is mainly focused on agricultural feedstocks and also includes some aquatic feedstocks. Biowaste and industrial wastewater can be co-digested with agricultural feedstocks, but these effects are addressed in 2.1.

The merits of crop use for biofuels are heavily debated, where critics emphasize the “food versus fuel” issue, including land use change aspects. This topic is also partly relevant for biogas systems, mainly for countries where there has been large-scale use of maize for biogas production. This practice is being phased out with caps placed on the use of food or fodder crops for biogas production. Actually, there are great opportunities to utilize biogas systems in a way that supports the production of food and fodder, rather than the opposite.

Within agriculture a multitude of byproducts are generated at different stages of the processes. Several different types of crop residues are commonly left on the fields, that could be utilized as feedstocks in biogas plants. Globally, extensive animal husbandry generates a lot of manure, and the way manure is stored and handled in many parts of the world leads to emissions of vast amounts of greenhouse gases. Utilization for biogas purposes involves manure collection and improved storage, which can significantly lower emissions of GHG and reduce odor problems. In combination with other effects (described in 2.3 and 2.4), biogas production based on manure can be climate positive (due to the avoided emissions from manure storage and in other parts of the lifecycle).

When agricultural residues, or byproducts, are used for biogas production it is often essential to return the digestate to the fields from which crops were removed. By doing so, the nutrients are recycled, and relatively stable organic matter and microbes contribute to soil health. How much to return and in what form, should be adapted to the local conditions and the specific needs of the soil and crops. Digestate/Biofertilizers are further dealt with in 2.3.

In the category of agricultural feedstock, different types of crops are also included. Their sustainability performance largely depends on what type of land is used - both direct and indirect land use changes are of relevance (LUC, ILUC). The choice of crops is influential, including how they are integrated into agricultural systems, and agricultural practices. Of course, agricultural practices, such as fertilization, pest management, harvesting and crop rotation, always influence the sustainability performance, independent of whether a certain crop is to be used for biogas production and/or for other purposes. Precision farming and good environmental farm planning are essential to optimize the use of fertilizers and water.

A distinction should be made between ‘energy crops’ and ‘intermediate crops’, where:

- Energy crops include main crops (like maize or millet) that normally are used for food or fodder, but when referred to as energy crops are grown for energy purposes.
 - Dedicated energy crops should also be mentioned, which could be crops similar to food crops but specifically developed (to ‘non-food crops’) for utilization in energy conversion (e.g. cup-plant).
- Intermediate crops are added in crop rotations, in between main crops, commonly to cover the soil and provide various ecological services that are beneficial for agriculture as well as the environment.

To avoid competition with the production of food crops and negative land use change, intermediate crops are commonly regarded as favorable from an environmental sustainability perspective, strongly linked to their ecological services discussed below. Another commonly used (and overlapping) term is *Low ILUC crops*, which refers to a category of crops that do not contribute to direct or indirect land use change (ILUC) due to competition with food crops.

Competition with fodder may also be critical. However, in an overarching context of achieving a more sustainable use of natural resources and reducing essential environmental problems, it is not obvious that, for example, cattle/feed should be prioritized in society. For example, cattle beef is significantly more land intensive than many other types of food and associated with large climate impact as well as additional resource use and negative environmental impacts of various kinds. Indiscriminate prioritization of fodder production over mobility (based on biofuels with good sustainability performance), may cause unwanted effects on welfare and sustainability. Concerning crops, it is important whether primary agricultural land is utilized, or fallow or marginal lands (or ecological focus areas, etc.). To use fallow or marginal land for energy purposes can be beneficial and the income from the energy carriers may be essential for economic viability and agricultural resilience.

Well-chosen and smartly integrated intermediate crops is a strategy that can lead to a win-win-win situation. The introduction of intermediate crops in sequential cropping schemes may deliver:

1. Additional crop harvests and incomes
2. Short- and long-term soil fertility and health benefits
3. More sustainable agriculture

Intermediate crops can be part of agricultural intensification, delivering additional crops for biogas systems (or other uses) while strengthening the production of food and fodder due to improved soil quality. Depending on the soil type and climate, the agricultural system, and type of intermediate crop, the sustainability effects vary somewhat, but additional commonly reported effects include carbon sequestration (beneficial for the climate and soil health, where the roots play an essential role), reduced use of pesticides, improved nutrient management, and positive effects on biodiversity. Cultivation of such crops also reduces risks of soil erosion and damage associated with flooding events.

Regarding changes and intensification of agriculture, it is necessary to have a balanced approach and to avoid or minimize unwanted effects. For example, to select suitable intermediate crops and integrate them in a way to avoid negative impacts on the main crops and to utilize good fertilization practices. Expanded use of crops such as ley crops, may require additional fertilization and use of water, which is negative from a sustainability perspective (e.g. may contribute to eutrophication, instead of reducing it). The Italian *Biogas Done Right* concept provides guidance on crop selection and digestate recirculation (Dale et al., 2016). In France, a project entitled RECITAL developed recommendations for farmers in five regions of the country on how to select the most appropriate crop systems to produce *CIVE* (French abbreviation for Energy-Producing Intermediate Crops).

Table 2 lists the sustainability effects associated with agricultural feedstocks used in biogas solutions, including specifications, information on important factors, and relevant scientific references.

Table 2. Sustainability effects that are associated with agricultural feedstocks used in biogas solutions.

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AF1	Agricultural land availability	Broader society, agricultural sector. Conservation and availability of agricultural land	Demand for feedstock to produce biogas and associated products may prevent loss of agricultural land	Relevant in contexts where significant shares of the agricultural land is not used, and there is a risk of afforestation, or that this land is used for other purposes	(Rahman et al., 2014)
AF2	Improved resource efficiency, valorization of waste and byproducts	Agricultural sector Agricultural residues	Biogas systems commonly provide valuable products such as biogas, biofertilizers (carbon, nutrients, etc) and/or other valuable products from agricultural residues such as straw, stalks/stem, leaves, stover, husk, shell, bagasse, seed pods, discarded crops, etc.	The total value for different ways of managing the residues (not harvested/collected vs alternatives). E.g. the value of leaving crop residues on the fields in comparison to the value of biogas production and spreading the digestate on the same fields	(García-López et al., 2023; Insam et al., 2015; Nkoa, 2014; Scott Bentsen et al., 2016)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AF3	Improved soil fertility/health, more sustainable land use	Agricultural sector Feedstock, intermediate crops	Introduction/Expansion of ' <i>intermediate crops</i> ' ³ in sequential cropping schemes. Soil effects related to organic carbon, organic matter content (structure). The roots are essential. Soil erosion may be reduced and there may also be important indirect effects, like increased number of earthworms, providing improved soil structure	Soil organic matter is a key indicator of soil fertility Well-designed crop rotation systems, avoiding competition with food and fodder (iLUC 'free') ⁴ . Crops should be chosen to get a good yield while also breaking disease cycles and better controlling weed populations.	(Ammenberg and Feiz, 2017; Barrios Latorre et al., 2024a, 2024b; Björnsson et al., 2013; Frøseth et al., 2014; Kätterer et al., 2011; Koblenz et al., 2015; Liang et al., 2023; Lugato et al., 2014; Nemecek et al., 2015; Nilsson, 2023; Oldfield et al., 2020; Prade et al., 2017)
AF4	Reduced use of pesticides	Agricultural sector Feedstock, intermediate crops	Introduction/Expansion of ' <i>intermediate crops</i> ' in sequential cropping schemes may break crop disease cycles and inhibit weeds, thus reducing the need for pesticides	Depends on the type of crop rotation and type of intermediate crop. Crops should be chosen to get a good yield while also breaking disease cycles and better controlling weed populations.	(Deike et al., 2008; Guinet et al., 2023; Liebman and Dyck, 1993; Prade et al., 2012; Zuk-Golaszewska et al., 2019)

³ In this report, intermediate crops mean crops grown in between main crops, encompassing terms such as cover crops, catch crops, and bottom crops. Also note the term low ILUC crops. Grasses, such as ley crops, are also relevant.

⁴ However, in the context of achieving a more sustainable use of natural resources and reducing essential environmental problems, it is not obvious that for example cattle/fodder should be prioritized (de Vries et al., 2015).

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AF5	Changes in main crop yields	Agricultural sector Feedstock, intermediate crops	Introduction/Expansion of ' <i>intermediate crops</i> ' may influence the main crop yields positively or negatively (or not at all), e.g. depending on how they are integrated in cropping schemes	The outcome may depend on the time-perspective. For example, the use of intermediate crops may be seen as long-term investments in soil fertility, but there may also be direct positive or negative effects. It is challenging to draw general conclusions. Long-term field experiments are needed, and many factors are influential	(Brooker et al., 2021; Kollas et al., 2015; Malézieux et al., 2009; Shackelford et al., 2019; Smith et al., 2008)
AF6	Reduced climate impact, carbon sequestration, more sustainable land use	Agricultural sector Feedstock, intermediate crops Feedstock, perennial species mixtures on marginal land	Introduction/Expansion of ' <i>intermediate crops</i> ' in sequential cropping schemes. Soil effects related to carbon sequestration, the roots ⁵ are essential Low-input perennial species mixtures on marginal land may contribute to soil carbon sequestration	The balance between stable carbon that is bound long term and any carbon removed/emitted. Essential to minimize any additional N ₂ O emissions Agricultural practices, the use of fossil fuels and mineral fertilizers	(Ammenberger and Feiz, 2017; Barrios Latorre et al., 2024a, 2024b; Björnsson et al., 2013; Englund et al., 2023; Höglund et al., 2013; Kätterer et al., 2011; Lugato et al., 2020, 2014; Nilsson et al., 2020; Prade et al., 2017; Styles et al., 2015; Szerencsits et al., 2016)

⁵ More accurately: roots *and* rhizodeposit (considering all belowground C inputs)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AF7	Reduced climate impact (GHG emissions), improved manure management	Agricultural sector Feedstock, manure	AD systems commonly involve improved management of liquid manure, including covered storage and shortened storage of untreated manure. This reduces emissions of methane, and nitrous oxide (N ₂ O)	Applicable to operations where sufficient quantities of manure can be easily collected Shortened manure storage times and well-designed covered storage are essential Varying emission factors (for manure and digested manure) are used in different studies and contexts, which is influential The temperature influences emissions from manure/digestate	(Berglund and Mjöfors, 2024; Eggemann et al., 2023; Esteves et al., 2019; Menichetti et al., 2024; Møller et al., 2022; Sommer et al., 2004)
AF8	Improved nutrient management, reduced need of mineral fertilizers	Agricultural sector Feedstock, catch crops, intermediate crops	Introduction/Expansion of catch crops that fix atmospheric nitrogen and thus may involve reduced need of mineral fertilizers for main crops When catch/ley crops are harvested, instead of being used as a green manure, N fixation can be increased. Harvesting above ground biomass of leguminous cover crops may significantly reduce nitrogen leaching risk	The extent to which mineral fertilizers are replaced and the environmental effects when comparing catch crop use to mineral fertilizer use Essential to harvest catch/ley crops at appropriate time, to decrease the direct residual N effect of harvesting instead of cutting	(Constantin et al., 2010; Eichler-Löbermann et al., 2008; Gunnarsson et al., 2011, 2008; Möller et al., 2008; Sieling, 2019; Zuk-Golaszewska et al., 2019)
AF9	Reduced problems of eutrophication and improved air quality	Agricultural sector Feedstock, manure	AD systems commonly involve improved management of manure, including covered storage and shortened storage of untreated manure. This reduces emissions of ammonia (NH ₃), that can contribute to both eutrophication and formation of particles (health problem)	Shortened and covered storage of manure, and coverage of digestate. Appropriate digestate application practices are essential not to counteract the benefits of improved manure management.	(Kaspersen et al., 2016; van den Oever et al., 2021; Vries et al., 2010)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AF10	Reduced problems of eutrophication	Water management, in agriculture and elsewhere Feedstock, aquatic feedstock	Use of aquatic feedstock for biogas and biofertilizer production involves removal of nutrients, which is positive for water bodies with excess of nutrients	The amount of essential nutrients in the utilized aquatic feedstock. Good fertilization practices, when the biofertilizers are used	(Ammenberg and Feiz, 2017; Bucholc et al., 2014; Czyrnek-Delêtre et al., 2017; Kaspersen et al., 2016; Pacetti et al., 2015; Singh et al., 2023)
AF11	Increased problems of eutrophication	Agricultural sector Feedstock, crops	Agricultural crop production practices commonly contribute to eutrophication, due to soil conditioning and fertilization. This can be the case for energy crops, ‘intermediate crops’, and grasses. Results vary depending on crops, agricultural practices, and local conditions.	It is essential whether the crop production involves additional fertilization The contribution to eutrophication is not related specifically to the use for biogas production, it is generic for these crops and depends on agricultural practices and local conditions	(Bužinskienė et al., 2023; Lindfors and Ammenberg, 2021; Pehme et al., 2017; Styles et al., 2015; van den Oever et al., 2021)
AF12	Increased use of water	Agricultural sector Feedstock, crops	Expanded crop production may require increased use of water	The increased water demand may be mitigated by applying water efficient irrigation systems (e.g. see the BDR™ ⁶ concept).	(González-García et al., 2013; Pacetti et al., 2015; Shackelford et al., 2019)
AF13	Reduced risk of flooding and water erosion	Agricultural sector Feedstock, crops	Inclusion of intermediate crops, specifically grass, in rotations with annual crops in sub-watersheds	Farm management and local conditions Weather conditions (more extreme events)	(Englund et al., 2023)

⁶ Biogas Done Right

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AF14	Reduced odor	Agricultural sector Feedstock, manure and seaweed	Manure used as feedstock, reduced odor when for example pig or chicken manure is collected, stored and treated in an AD plant Seaweed is also collected to reduce odor related problems	Biogas plants with good technology to avoid odors (relevant for all feedstock), not to generate odor problems nearby the production Impact depends on type of manure and seaweed Although different than the odor of manure, digestate has odor and storage should be covered. Land applying digestate using sub-surface injection and surface broadcast with incorporation can help reduce odors at the time of application	(Crolla et al., 2013; Lemes et al., 2023; Varel et al., 2012)
AF15	Competition with food or fodder, potential for land use change	Agricultural sector Feedstock, energy crops	Production of energy crops (such as maize) may compete with food and/or fodder production	Essential to have balanced agricultural production systems providing the products mostly needed and involving efficient land use ⁷ . Relevant to consider how control and support schemes are designed. The regulations are very strict within the EU on this matter, at least regarding biofuels. Intermediate crops, or <i>Low ILUC crops</i> , can be favorable	(Debnath and Das, 2022; Hellmann and Verburg, 2010; Styles et al., 2015) Alternative perspectives: (Horschig et al., 2020; Pacetti et al., 2015)

⁷ Provision of food is, of course, normally considered top priority. However, it may not necessarily be the case that all ‘food products’ (broadly interpreted) and beverages are to be prioritized over mobility or other products and services, the same goes for fodder. It may be important to separate *needs* from *demand*, and to acknowledge that some types of food (like meat) is very resource demanding.

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AF16	Diversion of materials	Agricultural sector Feedstock	Effects of diverting waste and byproducts from their existing uses or treatments	Essential to ensure that there is a good balance. For example, when agricultural residues are digested essential substances should be returned to the soil via the biofertilizers. However, it may be essential to monitor the soil organic carbon content (utilization of straw one relevant example)	(Ammenberg and Feiz, 2017; Höglund et al., 2013)
AF17	Effects on biodiversity	Agricultural sector Feedstock, crops	Crops used in biogas systems may influence biodiversity. Introduction/Expansion of 'intermediate crops' in sequential cropping schemes may be beneficial for biodiversity. A shift from natural vegetation to energy or food crops may have positive and/or negative impact	In general, shifts from monocultures toward polycultures is favorable for biodiversity. Essential to minimize negative impact related to agricultural practices. Regarding marginal land: -consider MALLIS (marginal agricultural land low-input systems'), which e.g. could involve choosing crops favorable for pollinators and to account for local values/conditions	(Burland and von Cossel, 2023; Carlsson et al., 2017; Godwin et al., 2018; Hellmann and Verburg, 2010; López-Bellido et al., 2014; Pedrolí et al., 2013; Styles et al., 2015; Von Cossel et al., 2019)

2.3 Agriculture, use of digestate/biofertilizers and other aspects

The digestate from biogas plants is recognized as a valuable source of carbon, macro- and micro-nutrients, microbes, and even some metals that are important for crop production. The share of the (stable) carbon in the feedstock that remains in the digestate, depends on the feedstocks, AD technology, and other factors. For example, an internal study conducted by the Ontario Ministry of Agriculture, Food and Agribusiness (OMAFRA) in collaboration with the University of Guelph (Ontario, Canada) found that On-farm digester systems have shown reductions of 50 to 70% in organic matter (measured as volatile solids) during the digestion process, particularly when manure is co-digested with organic rich substrates, like fats, oils and greases (FOG), inferring that 30 to 50% of the more stable carbon remains in the digestate (Crolla, 2024). Nutrients in organic matter are transformed by the AD process into their inorganic (mineral) forms; organic nitrogen is converted to ammonium-nitrogen ($\text{NH}_4^+\text{-N}$) and organic phosphorus is converted to phosphate-phosphorus ($\text{PO}_4^{3-}\text{-P}$). This conversion into the mineral forms of key macronutrients improves the plant nutrient availability, thus adding value compared to the use of manure, crops, and/or crop residues without AD. It also enables to partially substitute the use of synthetic fertilizer.

Digestate that meets quality standards for land application is commonly spread whole on agricultural land as a fertilizer and soil conditioner. Alternatively, the digestate can be further valorized, for example by utilizing liquid solid separation, and treatment such as drying, pelletization, and alkaline stabilization (Carraro et al., 2024; Feiz et al., 2022a). Digestate treatment is costly but may be cost efficient, and leads to lower emissions during storage and application, and reduces the risk of other negative sustainability effects. Spreading of whole (unseparated) digestate via tractors can involve negative effects from soil compaction as the digestate is diluted (high water content). It is similar to liquid manure application but gives greater compaction than the spreading of mineral fertilizers. The relatively high weight means that untreated digestate is costly to transport.

The net impact of digestate/biofertilizer use depends on the base case - what would have been done with the feedstock in the absence of a biogas system. Manure and agricultural residues traditionally are utilized within agriculture, meaning that the base case involves nutrient recycling while mineralization due to the digestion is positive. In the case of anaerobic digestion of food waste and other urban and industrial organic waste fractions, nutrients are recovered instead of being 'lost' in landfills or receiving water, or due to incineration. Composting also involves nutrient recycling, but in comparison to digestate, compost contains less readily available nitrogen and more organic nitrogen that is released slowly over time. However, there is no energy recovery (biogas production), in the case of composting.

The use of digestate as a biofertilizer reduces the need for synthetic/mineral fertilizers, which is important as mineral fertilizers are associated with several types of significant negative sustainability effects, including climate impact. This also contributes to nutrient security, via closing phosphorus loops (P, limited and scarce). Reducing the use of mineral fertilizers means lower net input of nutrients thereby lowering the risks of nutrient related problems (eutrophication).

In addition to the nutrients, digestate/biofertilizer contains organic matter and microorganisms. In line with the arguments above, especially biofertilizers based on urban and industrial organic waste fractions brings additional organic matter and microorganisms. Since biogas plants utilize the organic fraction that is most easily digested (becomes biogas), relatively stable carbon structures are returned via the digestate/biofertilizers, and the application of biofertilizers may slow down the carbon losses from the existing soils. However, soil chemistry is complicated - the climate, soil characteristics, and biogenic emissions (N_2O , CO_2) may be influential and difficult to estimate.

Consequently, the use of digestate/biofertilizers from biogas plants can contribute to improved soil quality (carbon content, structure and microbes), fertilization, and carbon sequestration (beneficial for the climate). There may also be important indirect effects, such as higher earthworm populations, further improving the soil structure. Some studies have found that the application of digestate/biofertilizers can lead to improved soil water retention.

Access to natural sources of nutrients is a necessity for ecological (or organic) farmers to certify their products. Digestate, if it is produced only from agricultural inputs, can be a source of these nutrients.

Finally, the feedstock quality will affect the use of digestate/biofertilizers, in particular, its use on agricultural soil that is used for food production. The presence of pathogens, heavy metals, plastics and polyfluoroalkyl substances (PFAS) needs to be regularly monitored to avoid the risk of contaminating agricultural soils. Upstream measures are crucial to prevent pollutants from entering our sociotechnical systems and hinder circular practices.

Table 3 lists the sustainability effects associated with the use of digestate/biofertilizers in agriculture, including specifications, information on important factors, and relevant scientific references.

Table 3 Sustainability effects that are associated with the use of digestate/biofertilizers in agriculture.

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AB1	Improved food security	Broader society, agricultural sector Overarching effect, management of soils and nutrients	Well-designed and operated biogas solutions can certainly contribute to improved food security, linked to more sustainable management of agricultural land, soils and nutrients, and water resources, being critical for food security long term.	Essential that positive impacting factors are strengthened and the negative avoided or minimized (see other effects on the agricultural systems) Dependent on adoption of best management practices for storage and application of digestate and biosolids.	An overarching effect, based on several of the other listed effects. (Rimhanen et al., 2023)
AB2	Nutrient security, phosphorus	Agricultural sector Digestate/Biofertilizers	Biogas solutions can contribute to more sustainable management of phosphorus (P), and function as essential components in nutrient redistribution (involving other nutrients as well). P is a limited and scarce resource that is needed for crop production. The main source is phosphate rock, of which c. 75% of the high-grade reserves are located in Morocco. P is essential for all life, including plants, animals and bacteria, and its functions cannot be performed by any other nutrient. An adequate supply of P is required for optimum growth and reproduction. Biogas systems recover and mineralize P in the feedstock.	The extent to which biofertilizers contribute to efficient P recycling, e.g. depends on a good match between nutrient content (and plant availability) and the local conditions and needs. Transport distances, and other factors, influence possibilities for redistribution of nutrients	(Hörtenhuber et al., 2019; Keuter et al., 2021; Metson et al., 2020; Roy, 2017; Valve et al., 2020)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AB3	Improved soil fertility/health, organic matter and microbial activity (relative to mineral/synthetic fertilizers)	Agricultural sector Digestate/Biofertilizers, soil conditioners	Use of digestate may contribute to improved soil fertility via the addition of organic matter. The stability of the carbon structures influences the time perspective - whether the effects are short term and/or long-term Digestate can reduce the rate at which existing organic matter is depleted from soils. Digestate also contains microorganisms and there may be important indirect effects, like enhance microbial activity - for example greater microbial activity in root zones and increased number of earthworms, providing improved soil structure Biogas digestate can be utilized to produce biostimulants.	It is essential to what extent the biogas production involves any removal of organic matter from the specific area (e.g. biofertilizers from food waste different from locally grown crops or local agricultural residues). Impact depends on the degree of soil carbon loss. However, carbon in biofertilizers (digestate) is usually considered more resistant to decomposition than carbon in the feedstocks as AD converts the more easily digestible carbon. Biofertilizers may also have negative priming effects (hindering C loss, which is positive). Impact depends on reference case, e.g. comparison with raw manure, compost or synthetic fertilizer	(Béghin-Tanneau et al., 2019; Crolla, 2024; Frøseth et al., 2014; García-López et al., 2023; Głowacka et al., 2020; Mayerová et al., 2023; Nkoa, 2014; Odlare et al., 2011; Oldfield et al., 2020; Sani et al., 2025; Smith et al., 2014; Wentzel et al., 2015)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AB4	Improved soil fertility/health, fertilization	Agricultural sector Digestate/Biofertilizers	The use of digestate/biofertilizers may positively influence crop yields due to fertilization effects - addition, or circulation, of essential macro and/or micro-nutrients (amounts) and impacts on nutrient plant availability (level of mineralization). Nutrient circulation, or preservation, is essential for low-input farming (resource efficiency) Not only the use of digestate from AD of food waste or industrial waste may be influential, but also the return of digested crops (such as catch and intermediate crops) as biofertilizers, to the same cropping system, since it provides better potential to adjust the N supply to crop demands	The level to which essential nutrients are added/circulated (amounts) and the nutrient plant availability is improved (level of mineralization). The “age” of the digestate and timing of application, e.g. application of fresh digestate to a growing crop Choice of biofertilizers and product development for such fertilizers are important to match the need, including adaption to local conditions (for example suitable NPK values). Commonly of relevance to compare with mineral fertilizers - varying results in academic literature, including clearly positive to clearly negative results. Based on a review, Nkoa (2014) regarding digestate/biofertilizer properties conclude: <i>“... their efficacies lie between those of livestock manures and mineral fertilizers, with many instances where digestates equaled mineral fertilizers”</i>	(Abubaker et al., 2012; Bartóg et al., 2020; Crolla et al., 2013; Czekala et al., 2022; Frøseth et al., 2014; García-López et al., 2023; Głowacka et al., 2020; Lošák et al., 2015; Nkoa, 2014; Odlare et al., 2011; Przygocka-Cyna and Grzebisz, 2018; Smith et al., 2014; Wentzel et al., 2015)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AB5	Reduced climate impact (GHG emissions)	Agricultural sector ...Digestate/Biofertilizers	Use of digestate/biofertilizers may involve soil carbon sequestration through the addition of more stable carbon Digestate/Biofertilizer application should reduce the use of mineral/synthetic fertilizers, and the corresponding GHG emissions associated with such fertilizers	Impact depends on the reference case. Comparison of added organic matter, long term, in relation to any removal and emissions. Carbon in biofertilizers (digestate) is usually considered more resistant to decomposition than carbon from plant materials (AD removing the share easier to digest). Biofertilizers may also have negative priming effects (hindering C loss). Carbon soil effects are challenging to study. Long term field experiments are essential. Soil characteristics and biogenic emissions (N₂O, CO₂) both may be influential and difficult to estimate. The extent to which mineral fertilizers are replaced is influential	(Aguilera et al., 2013; Andrade Díaz et al., 2023; Baldé et al., 2016; Bartóg et al., 2020; Béghin-Tanneau et al., 2019; Chen et al., 2012; Greenberg et al., 2019; Levavasseur et al., 2023; Malet et al., 2023; Menichetti et al., 2024; Møller et al., 2009; Nilsson et al., 2020; Nkoa, 2014; Timonen et al., 2019; Wei et al., 2020; Wentzel et al., 2015)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AB6	Reduced problems of eutrophication	Agricultural sector and broader society Digestate/Biofertilizers, WWTPs	Digestate/Biofertilizers from AD involving nutrient recycling may replace the use of mineral fertilizers. Reduced net input of nutrients to society and specific systems means lower risks of nutrient related problems. Not only the use of digestate from AD of food waste or industrial waste may be influential, but also the return of digested crops (such as catch and intermediate crops) as biofertilizers, to the same cropping system, since it provides better potential to adjust the N supply to crop demands.	...Essential to which extent net input of fertilizer (N and P) is reduced, but also effects on N mineralization (nutrient plant availability) Inappropriate use of biogas digestates/biofertilizers, e.g. at unfavorable times in crop rotations, may negate benefits Aspects such as time, weather and application rates are influential	(Gunnarsson et al., 2011, 2008; Hagman and Eklund, 2016; Kaspersen et al., 2016; Siegmeier et al., 2015, 2014)
AB7	Improved soil structure and workability (tilth), water retention	Agricultural sector Digestate/Biofertilizers	Application of biofertilizers/digestate can lead to improvements regarding soil water aspects. It can positively influence water retention and runoff, lead to easier root penetration, and reduce the risk of soil erosion	Type of soil and digestate influential. Increasing the organic matter content has been shown to improve the water retention of sandy soils, while it opens up clayey soils to allow better air and water movement into and through the soil. Depends on reference case. Some studies indicate that composting may be more beneficial regarding water retention	(Eich-Greatorex et al., 2018; Insam et al., 2015; Mayerová et al., 2023; Nkoa, 2014)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AB8	Facilitation of ecological/organic farming	Agricultural sector Digestate/Biofertilizers	Ecological, or organic, farming requires access to natural fertilizers	Digestate/Biofertilizers must be derived from acceptable feedstocks for organic production. The extent to which biogas plants produce approved biofertilizers made available for ecological farming Digestate typically contains less organic matter than manure or compost.	(Hagman, 2022; Siegmeier et al., 2015, 2014)
AB9	Increased spreading of pollutants	Agricultural sector Digestate/Biofertilizers	Digestate/Biofertilizers may contain pollutants, that are spread through land application. However, this largely depends on to what extent there are pollutants in the feedstock (such as heavy metals) treated at biogas plants - meaning that new pollutants seldom are added in the biogas production processes. Plastics in biofertilizers may be of particular interest, which may originate from waste packaging material. Micro-plastics from WWTPs may be relevant	Depends on the existence and fate of the pollutants upon land application. To avoid pollution the use of pure high-quality feedstock is essential, including societal measures upstream to avoid inflows/use of heavy metals, plastics, pesticides/herbicides (e.g. containing pyralids) and other problematic materials/substances. Pretreatment of feedstock and/or aftertreatment of digestate, and monitoring influential. Micro-plastics from WWTPs may be difficult to handle Digestate/biofertilizer quality assurance systems are used in several countries.	(Insam et al., 2015; Nkoa, 2014; Odlare et al., 2011; Öling-Wärnå et al., 2023; Porterfield et al., 2023)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
AB10	Soil compaction	Agricultural sector Digestate/Biofertilizers	When whole digestate is spread the soil might be compacted, resulting in lower crop yields. Digestate mainly contains water, which means that a relatively much higher mass needs to be transported compared to mineral fertilizer products, to reach the same level of fertilization	There are different measures to reduce soil compaction, e.g. better adapted machinery. The stability of the soil when the digestate is spread is important Hose systems, instead of heavy machinery, may prevent compaction. Refining digestate or biofertilizers to more concentrated products has great impact on this issue	(Jaša et al., 2019; Rodhe et al., 2006)

2.4 Use of biogas, biomethane and biogenic carbon dioxide

There are many opportunities for local production of biogas/biomethane, and biogas-generated heat and electricity, across the planet, where biogas solutions thereby can contribute to improved energy and transport security. The shift toward more renewable energy and transport systems means a higher share of intermittent (varying) energy sources such as wind and solar power. Biogas systems are dispatchable and thus can function as valuable complementing components for energy flexibility and robustness. For example, this is the case in Germany.

The sustainability impacts related to the use of biogas energy are highly influenced by what energy carriers are substituted, and somewhat by the actual use. In general, a shift from fossil fuels (also including fossil-derived electricity) to biogas/biomethane is significantly positive from a sustainability perspective.

Concerning transport, biomethane can be very beneficial from a climate perspective, for a wide range of feedstocks - when derived from manure and/or intermediate crops it is an energy carrier that can even be climate positive. This can be the case when considering the full lifecycle, and accounting for the mentioned effects associated with the feedstock and biofertilizers (2.1-2.3). Utilization of the biogenic CO₂ from biogas plants may contribute to additional benefits, depending on what products are replaced. Storage of CO₂ may also be beneficial. In the transport context, electrification is commonly emphasized as a solution to lower the climate impact. However, vehicles driven on biomethane (or vehicle gas, including a small share of natural gas) can have a better climate performance than vehicles driven on fully fossil-free electricity, which for example has been demonstrated in Sweden, despite a large share of the electricity from hydro and nuclear power (due to vehicle gas with a high share of biomethane, from various feedstocks). Electrification may be most beneficial to lower noise levels in areas with slow-moving traffic, but when the speed exceeds 50 km/h noise from the tires/road dominates and thus the type of engine is not significant. However, heavy vehicles running on biomethane may also contribute to significantly reduced noise levels (dB(A)) in comparison with heavy vehicles using diesel. Electric vehicles can be especially advantageous in areas where avoiding local exhaust emissions is important. However, a shift from diesel (including biodiesel) to biomethane is also beneficial in this regard. Today, the electric vehicle technology is best suited for lighter vehicles and shorter distances (although there is a rapid development). A strategy to combine the strength of both alternatives might be to prioritize electric vehicles in central city areas, for lighter vehicles travelling shorter distances, complemented by biomethane (and other renewable alternatives) for vehicles in the surrounding areas, for long-distances, and heavy-duty vehicles (and working machines). Such a strategy would make the expectations on expanded electrification more realistic. Biomethane could also play an essential role as a renewable energy carrier in the maritime sector, and potentially in aviation.

The use of biogas/biomethane in energy, transport, and industrial systems, may contribute to reduced eutrophication in comparison with fossil and alternative renewable energy carriers, due to relatively lower emissions of nitrogen and sulfur oxides (the latter in places/sectors using petroleum products that have not been desulfurized). However, the impact depends on the type of feedstock and agricultural practices and may range from significantly positive to negative (the latter for biomethane from energy crops).

In the literature, there are also positive sustainability effects mentioned due to extended use of existing natural gas networks.

Table 4 lists the sustainability effects associated with the use of biogas and biomethane (more in detail) and CO₂ (overarching), including specifications, information on important factors, and relevant scientific references. Since there is an emphasis on energy and transport applications, “ET” is used.

Table 4. Sustainability effects that are associated with use of biogas and biomethane (in detail) and CO₂ (overarching).

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
ET1	Improved energy and transport security	Broader society Biogas/Biomethane	Local production of AD based energy carriers is possible across the world, based on the availability of various biomass resources	The extent to which ‘biogas’ is recognized and being integrated into energy and transport systems (existing and future). How energy from biogas complements and/or competes with other renewables. Location and capacity of gas networks	(Bielski et al., 2021; D’Aquino et al., 2022; Edwards et al., 2015; Pugesgaard et al., 2014; Surroop et al., 2019; Zhao and Liu, 2014)
ET2	Improved energy system robustness, flexibility	Broader society Biogas/Biomethane	Biogas plants can be essential components in robust energy systems by complementing intermittent energy sources such as solar and wind power	The extent to which other flexible energy sub-systems exist, and the extent to which biogas solutions, and the broader energy systems, are designed for flexibility	(Hahn et al., 2014; Lauer and Thrän, 2018; Liebetrau et al., 2020; Mauky et al., 2017)
ET3	Reduced climate impact, substituting fossil energy carriers	Energy, transport & industrial sectors Biogas/Biomethane	The use of biogas/biomethane in energy, transport, and industrial systems may significantly reduce the negative climate impact due to substitution of fossil energy carriers (or ‘fuels’). Biogas/biomethane may be climate positive, when combining the effects of substituting fossil fuels with the effects related to feedstock and/or digestate/biofertilizers	What energy carriers are substituted is impactful. Essential to minimize methane emissions at biogas plants, distribution, etc. The overarching climate performance also depends on the previously listed effects linked to the choice of feedstock and the use of digestate/biofertilizers (carbon sequestration and related issues)	(Ammenberg et al., 2021b; Börjesson et al., 2016; Gustafsson et al., 2021a, 2021b; Prussi et al., 2020; Varling et al., 2023)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
ET4	Reduced air pollution, substituting other energy carriers	Energy, transport & industrial sectors Biogas/Biomethane	The use of biogas/biomethane in energy, transport, and industrial systems may contribute to significantly reduced air pollution (including particles) in comparison with fossil and alternative renewable energy carriers	What energy carriers are substituted is impactful. Emission standards (vehicle models) are influential regarding transportation	(Ammenberg et al., 2021b; Börjesson and Berglund, 2007; Brynolf et al., 2014; Camargo Pérez et al., 2015; Lindfors and Ammenberg, 2021; Lyng and Brekke, 2019)
ET5	Reduced noise levels, substituting other energy carriers	Transport sector Biogas/Biomethane, transport	Heavy vehicles driven on biomethane may contribute to significantly reduced noise levels (dB(A)) in comparison with heavy vehicles using diesel	The design of vehicles is influential, so is speed. Low frequency noise may be important to consider (dB(C)) It should be emphasized that locally biogas production can lead to increased transportation and noise nearby production sites	(Ammenberg et al., 2021b)
ET6	Reduced environmental impact (climate and other problems)	Energy, transport & industrial sectors Biogenic Carbon dioxide utilization	When raw biogas is upgraded (to biomethane) biogenic CO ₂ is separated/produced. This CO ₂ can substitute other products - biogenic carbon capture and use (BCCU) or storage (BCCS) - or be utilized to produce synthetic methane	What CO ₂ products are replaced influences the size of the benefits. End use opportunities depend on the CO ₂ purity and volume produced	(Cordova, 2023; Varling et al., 2023)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
ET7	Impact on eutrophication, substituting other systems and energy carriers (positive or negative)	Energy, transport & industrial sectors Biogas/Biomethane	The use of biogas/biomethane in energy, transport, and industrial systems may contribute to reduced eutrophication in comparison with fossil and alternative renewable energy carriers. Biogas/biomethane based on energy crops typically has a worse performance. Combustion of biogas/biomethane may result in relatively lower emissions of nitrogen and sulfur oxides (the latter in places/sectors using petroleum products that have not been desulfurized) Such positive effects may be strengthened or reduced by the effects related to feedstock and/or biofertilizers	What energy carriers are substituted will impact the size and direction of the impact Emission standards (vehicle models) are influential regarding transportation The positive and negative effects regarding eutrophication linked to feedstocks and biofertilizers depend on agricultural and fertilization practices, and some other factors	(Ammenberg et al., 2021b; Lindfors and Ammenberg, 2021; Lyng and Brekke, 2019)

2.5 Broader societal sustainability effects

In combination, many of the effects described in section 2.1-2.4 contribute to broader and more overarching societal sustainability effects.

Biogas systems provide renewable energy, valuable crop nutrient recovery and biogenic carbon, and are essential components in our sociotechnical systems where they contribute to ensuring critical supplies and societal resilience (food/agriculture, water, energy, transport). There may also be additional products, for example due to varying ways of using anaerobic digestion processes. The renewable and circular character means that biogas solutions facilitate a transition to a more circular economy, and they are important for an efficient bioeconomy, for example in valorizing low value waste streams in biorefineries and via the circulation of renewable carbon and essential nutrients.

The multifunctionality of biogas solutions means that they can contribute to a broad range of societal sustainability goals, with positive links to many of the UN Agenda 2030 objectives. The typical cross-sectoral character involves services in several sectors, where biogas systems may contribute to goals directed towards increased resource efficiency; reduced climate impact, air pollution and noise (involving reduced health related costs); clean water; preserved biodiversity; etc.

The shift away from fossil resources to a larger share of renewables will likely lead to a shortage of renewable/biogenic carbon. From a resource (and climate) perspective, the commonly used term *decarbonization* is problematic since biogenic carbon sources may become very essential and thus should not be phased out. For improved efficiency, it is favorable if biogas plants that upgrade the raw biogas to biomethane can utilize/sell the separated CO₂, thus supporting biogenic carbon capture and use (BCCU). There are several options, for example, to replace fossil- CO₂ used in slaughterhouses, carbonated drinks, medica, greenhouses, laboratories, and for food purposes. Another strategy is to use the CO₂ to produce additional methane, via biological or catalytic methanation - a process where the biogenic CO₂ is combined with hydrogen to generate synthetic methane or e-fuel ($4\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$).

The strong sustainability performance of biogas systems brings opportunities for cities and companies regarding development and sustainability branding, which is already a reality. A more sustainable development and growth must involve a shift towards more sustainable products, companies, and systems. Many biogas systems have a local and decentralized character, meaning that “green jobs” are created in areas where such systems are established, including rural areas and the development of infrastructure in such areas.

Table 5 lists broader societal sustainability effects associated biogas solutions, including specifications and information on important factors. The table also contains some references. However, due to the overarching nature of these effects, the references in section 2.1-2.4 are also very relevant.

Table 5. Broad societal sustainability effects that are associated with biogas solutions.

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
S1	Facilitation of a circular economy	Biogas solutions, overarching effects Circularity	Many biogas systems utilize renewable waste and byproducts, contributing to valorization and productification, thereby having essential circular elements. Sustainable management of natural resources is a basis for a circular economy. Biogas solutions may be a critical component for that purpose, making societal systems more sustainable (less linear)	Degree of integration of biogas solutions; use for all products and co-products (biogas, digestate and biogenic CO ₂) Important that society is organized not to pollute essential feedstock streams (essential biomass flows), and to address problems regarding this matter upstream (societal/industrial inflows) rather than downstream (hindering the use of waste and byproducts: hindering circularity)	(Barros et al., 2020; Ellacuriaga et al., 2021; Fagerström et al., 2018; Kapoor et al., 2020; Kiselev et al., 2019; Sica et al., 2023)
S2	Contribution to societal sustainability objectives	Biogas solutions, overarching effects Sustainability	Biogas solutions are multifunctional and can contribute to several societal sustainability goals, like the UN Agenda 2030 objectives	Well-designed and operated biogas solutions, well adapted to and integrated into other sociotechnical systems. Essential to strengthen the knowledge about biogas solutions and that their multifunctionality is acknowledged	(Archana et al., 2024; Belinska et al., 2023; Dhungana et al., 2022; Hagman and Eklund, 2016; Lindfors and Ammenberg, 2021; Mukisa et al., 2022; Obaideen et al., 2022; Piadeh et al., 2024; Yong et al., 2021)
S3	Efficient bioeconomy, critical component in bio-refineries	Biogas solutions, overarching effects Resource efficiency, biorefineries	In a shift towards a more biobased economy, biogas solutions can essentially contribute as critical components of resource efficiency in biorefineries (e.g. internal waste treatment, nutrient recycling, energy self-sufficiency)	Well-designed biogas solutions, well adapted to and integrated into biorefineries and other industrial and sociotechnical systems	(Andersen et al., 2018; Beschkov, 2020; Hagman, 2022; Hagman et al., 2017; Kapoor et al., 2020; Khoshnevisan et al., 2021; Kougias and Angelidaki, 2018; Sarkar et al., 2018; Sawatdeenarunat et al., 2016; Surendra et al., 2015; Wainaina et al., 2020)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
S4	Improved management and use of natural resources	Biogas solutions, overarching effects Sustainability, resource management	Biogas solutions can contribute in several ways to more efficient and sustainable management and use of natural resources, partly via improved industrial and urban symbiosis. Overarching effect, more sustainable management of agricultural areas, forests, and aquatic environments, including management of stock resources (such as P)	Well-designed biogas solutions, well adapted to and integrated into other industrial and sociotechnical systems	(De Meester et al., 2012; Sutherland et al., 2021) Overarching effect, based on the references concerning impacts on soils, water, nutrients, climate, land, and stock resources.
S5	Improved health, reduced health related costs	Biogas solutions, overarching effects Sustainability	Reduced pollution (e.g. due to combustion of a cleaner fuel, i.e. gas) and noise come with important health improvements and reduced health related costs	Well-designed and operated biogas solutions, well adapted to and integrated into other sociotechnical systems. Depends on what products/systems are replaced, and on existing conditions, i.e. ambient air quality and noise levels	(Archana et al., 2024; Dhungana et al., 2022; Hagman and Eklund, 2016; Mukisa et al., 2022; Obaideen et al., 2022; Piadeh et al., 2024; Yong et al., 2021) Also supported by references on reduced air pollution.

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
S6	Contribution of biogenic carbon, supply of renewable carbon for energy and non-energy uses	Biogas solutions, overarching effects, carbon capture and use	Future scenario studies indicate that there may be a lack of renewable/biogenic carbon when fossil fuels are phased out. Biogas plants, which upgrade the biogas to biomethane, may produce biogenic CO₂ that can substitute other products (involving fossil carbon) - biogenic carbon capture and use (BCCU) or storage (BCCS) In addition, biomethane may be used as a molecule for producing different types of products such as chemicals. As many of these products are currently produced from fossil hydrocarbons, this means a shift to biogenic/renewable carbon	Sustainability ambitions of manufacturers and consumers Ability to easily differentiate between renewable and fossil carbon content What products are replaced is influential	(Cordova, 2023; Junne and Kabisch, 2017; Mortensen et al., 2020; Yentekakis and Goula, 2017)
S7	Business value creation	Biogas solutions, overarching effects Business values	Positive values for companies associated with a 'sustainable technology', and due to products and services with improved sustainability performance Development and economic resilience of rural areas	The general view of biogas solutions and the extent to which stakeholders know of and value the improved performance. There are many examples of branding related to biogas solutions sustainability performance	(Tapaninaho and Heikkinen, 2022) Based on articles above supporting the competitive sustainability performance of biogas systems in combination with those showing the business value related to strong sustainability performance (e.g. Camilleri, 2017; Eccles et al., 2014)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
S8	Improved agricultural resilience	Biogas solutions, overarching effects	Biogas solutions may contribute to additional revenue streams in agriculture - economic resilience. In addition, there can be other types of resilience improvements (energy, water, climate, soil health, nutrient, etc - see other effects)	Well-designed biogas solutions that are cost-efficient for farmers, both short and long term. Depends on affordability and profitability of biogas solutions, linked to government policies and support measures There are examples of successful and profitable, as well as problematic and costly, biogas plants in agriculture. In case of high CAPEX third party ownership (not farmers) may be required	(Belinska et al., 2024; Dale et al., 2020; Guenther-Lübbers et al., 2016; Hasan et al., 2023; Herbstritt et al., 2023; Plieninger et al., 2006; Saidmamatov et al., 2021; Siegmeier et al., 2015; Surie, 2017; Were et al., 2016; Winqvist et al., 2021)
S9	Local and regional development, employment, and 'sustainable growth'	Biogas solutions, overarching effects	Biogas solutions may be essential components in global 'sustainability transitions', involving rural development. Biogas solutions may contribute to local and regional development and 'sustainable growth'	In a 'sustainability transition' biogas solutions can be essential components to facilitate acceptable sustainability performance, and to create jobs locally and regionally, in a future more sustainable society	(D'Adamo et al., 2021; Fallde and Eklund, 2015; Guenther-Lübbers et al., 2016; Markandya et al., 2016; Nevzorova and Karakaya, 2020; Timonen et al., 2021)
S10	Sustainability city branding	Biogas solutions, overarching effects	Biogas solutions may contribute to the sustainability branding and communication of cities and regions, which may be essential to attract and keep citizens and companies	There are many examples of branding related to biogas solutions sustainability performance	Mainly based on the authors' own observations, but the topic is also dealt with in: (Andersson, 2016; Keuter et al., 2021; Lindfors et al., 2019; Wang et al., 2017)

No.	Effect	Overarching system part	Specification: system and effect	Influential factors and conditions	References
S11	Societal resilience, security of critical supplies	Biogas solutions, overarching effects	Combining other effects, overarching synthesis: essential contribution to water, food, energy and transport security, being significant component in several sociotechnical systems	See W1, AF1, AB1, ET1, and other relevant effects in this table	See W1, AF1, AB1, ET1, and other relevant effects in this table, dealing with resilience in relation to energy, water, climate, soil health, and nutrients

2.6 Overview of the sustainability effects

Many of the sustainability effects described in Chapter 2 are shown in Figure 2. This figure is an illustration of a generic biogas system, in the center. Feedstocks are supplied and the AD process delivers raw biogas and digestate, that in turn can be utilized as fuel or for electricity generation, and as biofertilizers. In addition, when the raw biogas is upgraded to biomethane, high quality biogenic CO₂ may be produced, that can substitute fossil CO₂ in several ways. Linked to these different parts of the biogas system there may be several positive sustainability effects, and some negative if the systems are not well-designed or poorly operated. Some of the effects are more direct, while others are more overarching and indirect (the boxes).

For an overarching view of sustainability effects, also refer to Figure 4 in section 3.3.2.

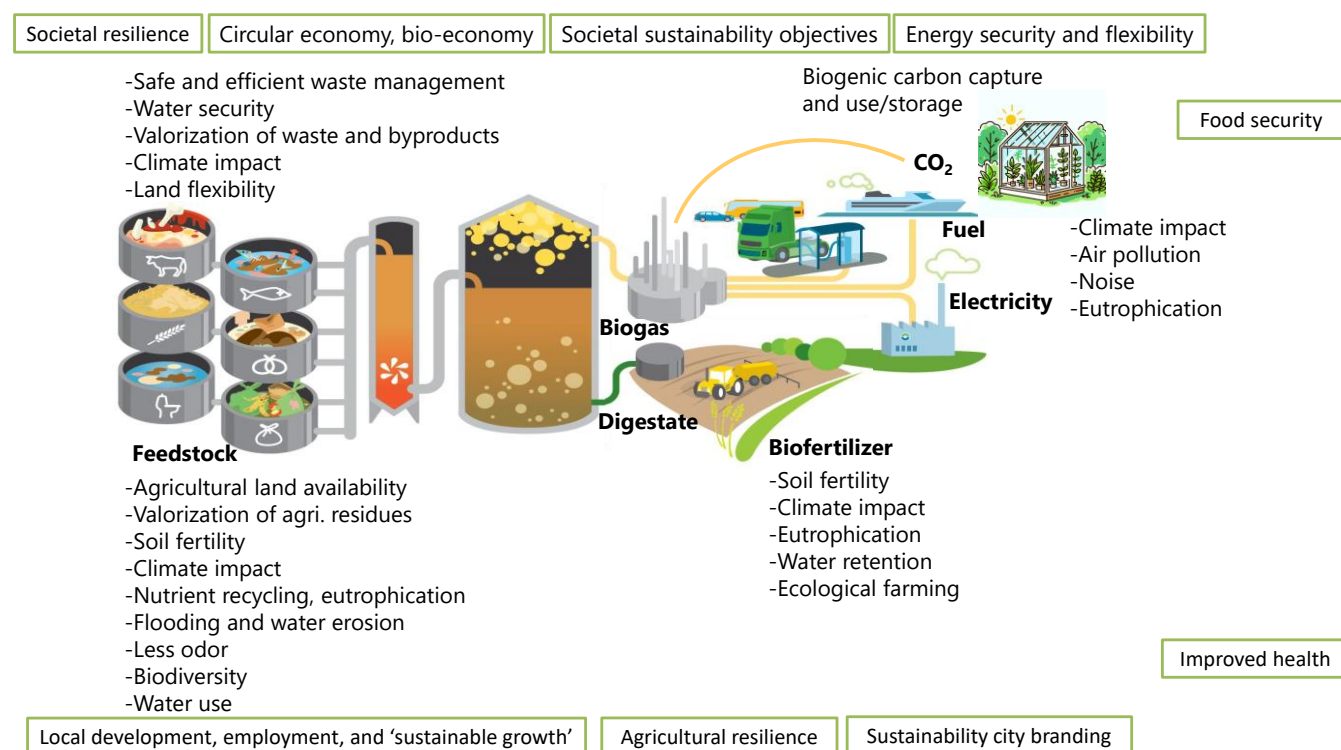


Figure 2. Illustration of a generic biogas system and associated sustainability effects. Combined illustrations from Mattias Schläger and Microsoft CoPilot.

3 Sustainability assessments of biogas solutions

While Chapter 2 shows that well-designed biogas systems provide a multitude of valuable sustainability services in our societies, Chapter 3 is oriented towards more comprehensive assessments of the sustainability effects. It starts with a short introduction to sustainability assessments, followed by a few sections synthesizing information from some selected types and examples of relevant sustainability assessments, with an emphasis on monetization.

3.1 Introduction to sustainability assessment

Sustainability assessments are commonly used to estimate and compare the sustainability performance (or impact) of different products or technical systems, with the purpose of guiding decisions makers (Bond et al., 2012; Ness et al., 2007). The process usually involves development and use of models or tools for analysis. Sustainability assessments, or environmental and sustainability systems analysis (ESSA) studies, can be conducted on both existing and hypothetical systems, involving scenarios, to gain better understanding of impacts, risks, efficiency in relation to alternatives, opportunities for improvements, etc. In addition to sustainability performance, such studies may encompass the potential and feasibility of different alternatives (Lindfors et al., 2019).

The term *systems analysis* indicates a focus on larger systems rather than on smaller parts (the components of the system). A comprehensive approach is advantageous, as it reduces the risks of sub-optimizations and unintended problem shifting, in comparison to more limited perspectives (Moberg, 2006; UNEP/SETAC, 2005). It is essential to pay attention to:

- The physical scope - for example what is included from a lifecycle, or supply chain, perspective.
- What impact is considered - what categories of environmental, social and/or economic impact a study covers.
- The time perspective - if the study concerns past, current or future situations.

For example, it should be obvious regarding transport systems that a tailpipe and climate emission-oriented study says very little about the broad sustainability performance of different transport technologies from a societal perspective - it fails to account for most of the sustainability effects presented in Chapter 2 (see Table 1-Table 5 and Figure 2). For ESSA studies, it is very essential to consider the validity of models, critical assumptions, what indicators are studied (and excluded), data quality, and uncertainty management (Brandão et al., 2021). However, even if comprehensive approaches have advantages, they also come with challenges. Wider physical, impact, and time perspectives involve additional work and complexity. ESSA studies commonly involve extensive inventories and impact assessments. While the inclusion of many sustainability indicators is good for relevance, it may also counteract the purpose to guide (or facilitate) decision making. However, **informed** decision making requires relevant frames (or system boundaries) and access to relevant information. It is a kind of balancing act - trying to cover the most essential areas on an overarching synthesis level, while avoiding getting stuck in too many details.

3.2 Comprehensive sustainability assessments including biogas systems

Many environmental systems analysis studies encompass biogas systems, commonly based on lifecycle assessments (e.g. Börjesson et al., 2016; Gustafsson et al., 2021a; Lyng and Brekke, 2019; Prussi et al., 2020). While some of them are referred to in this report (mainly in Chapter 2) they are not focused on in this section. Instead, a couple of broader sustainability assessments, based on Multi-Criteria Analysis (MCA)⁸, are briefly presented as examples of assessments that cover several sustainability impact categories (or indicators). These examples are also selected due to their

⁸ Or Multi-Criteria Decision Making (MCDM).

decision-making context - the MCA methods were developed to support the procurement of public transport services. An advantage with MCA methods is the possibility to include several different types of indicators (Hüging et al., 2014), both of a quantitative and qualitative character, making it feasible to cover a broader range of essential sustainability aspects (Dixit and McGray, 2013; Lindfors, 2021; Mendoza et al., 1999; Wedley, 1990). Thus, MCA methods are suitable for broad assessments of biogas systems, and complementary, or competing, alternatives. This is essential for fairer comparisons (i.e. with adequate systems perspectives).

The presented studies are oriented towards heavy-duty transport application and have been conducted within the Swedish Biogas Solutions Research (BSRC).

3.2.1 How the choice of energy carriers influences national environmental objectives

In section 2.5 it was concluded that the multifunctionality of biogas solutions means that they can contribute to a broad range of societal sustainability objectives, which has been investigated by Lindfors and Ammenberg (2021). An MCA method was developed based on Sweden's 16 national environmental quality objectives, which was then applied to assess to what extent a shift from fossil diesel to some alternative energy carriers would contribute to the objectives. A tool to support green public procurement was also developed.

Table 2 shows some of the results, for heavy-duty vehicles (buses and trucks) in a Swedish context driven on bioethanol, biomethane, electricity (Battery Electric Vehicles, BEV), hydrogenated vegetable oil (HVO), and rapeseed methyl ester (RME). Only the impacted objectives are included - those significantly influenced by the choice of energy carriers (6 objectives, or criteria, and 8 indicators). It is relevant to note that none of the Swedish objectives covers noise, which is very relevant regarding the sustainability performance of transport systems. Since the mentioned energy carrier types are produced in different ways and contexts, which greatly influences the environmental performance, some sub-categories were included - for example, biomethane from different feedstock and varying electricity mixes (it should be noted that Sweden has a high share of renewable electricity). Eighteen different energy carriers were assessed in total, but they are not all included in Table 6.

The results clearly show the importance of broad assessments, since the choice of energy carriers is impactful and specific energy carriers have varying strengths and weaknesses. Such assessments can be used to find the best option and (maybe more importantly) can provide guidance on how to efficiently combine several energy carriers in relation to their performance. This is further discussed in the following section.

In summary, the study by Lindfors and Ammenberg (2021) showed that there were several renewable energy carriers on the Swedish market with a substantially lower environmental impact than fossil diesel and natural gas. In general, the waste-based biofuels appeared to be well aligned with the national environmental objectives, while the crop-based did not perform as well but this depended on the type of crop and agricultural system. Electric vehicles based on renewable electricity contributed positively to several objectives, while a shift to the European electricity mix resulted in worse performance. All the electric alternatives suffered from poor recycling infrastructure for batteries.

Table 6. The impact of different energy carriers on the Swedish environmental quality objectives (or areas related to the specific objectives), when shifting from fossil diesel in the heavy-duty transport sector, based on Lindfors and Ammenberg (2021).

Area	Biomethane, food waste	Biomethane, manure	Biomethane, WWTP sludge	Biomethane, imported (waste based)	Biomethane, imported (crop based)	Ethanol	Ethanol, imported	HVO, pine oil	HVO, imported	RME	RME, imported	Electricity, BEV	Electricity, Europe BEV	Electricity, Marginal BEV
Reduced climate impact	Sign. pos. effect	Sign. pos. effect	Sign. pos. effect	Sign. pos. effect	Small pos. effect	Sign. pos. effect	Small pos. effect	Sign. pos. effect	Small pos. effect	Small pos. effect	Small pos. effect	Sign. pos. effect	Small pos. effect	Negligible effect
Improved air quality	Sign. pos. effect	Sign. pos. effect	Sign. pos. effect	Sign. pos. effect	Small pos. effect	Small pos. effect	Small pos. effect	Small pos. effect	Small pos. effect	Small pos. effect	Small pos. effect	Sign. pos. effect	Sign. pos. effect	Sign. pos. effect
Increased biodiversity and reduced eco-toxicity	Sign. pos. effect	Sign. pos. effect	Small pos. effect	Negligible effect	Negligible effect	Small neg. effect	Negligible effect	Negligible effect	Negligible effect	Small neg. effect	Negligible effect	Negligible effect	Negligible effect	Negligible effect
Improved resource recovery	Sign. pos. effect	Sign. pos. effect	Sign. pos. effect	Negligible effect	Negligible effect	Negligible effect	Negligible effect	Sign. pos. effect	Negligible effect	Negligible effect	Negligible effect	Small neg. effect	Small neg. effect	Small neg. effect
Reduced acidification	Small neg. effect	Negligible effect	Small pos. effect	Small neg. effect	Sign. neg. effect	Sign. neg. effect	Sign. neg. effect	Small pos. effect	Negligible effect	Small neg. effect	Small neg. effect	Sign. pos. effect	Negligible effect	Sign. neg. effect
Reduced eutrophication	Small pos. effect	Small pos. effect	Small pos. effect	Small pos. effect	Sign. neg. effect	Small neg. effect	Sign. neg. effect	Small pos. effect	Sign. neg. effect	Sign. neg. effect	Sign. neg. effect	Sign. pos. effect	Small pos. effect	Sign. neg. effect

3.2.2 The sustainability performance of different bus technologies

In a similar context, Ammenberg and Dahlgren (2021a) developed an MCA method to assess the sustainability performance of bus technologies for public transport in Sweden. However, the scope was broadened beyond environmental sustainability. The MCA method was based on four key areas: technical, economic, environmental and social performance. It consisted of both quantitative and qualitative indicators, 12 in total.

Seven bus technologies (or energy carriers) were assessed: biomethane, bioethanol, diesel, electricity, FAME, HVO and natural gas. The results are presented in Dahlgren and Ammenberg (2021), where each energy carrier was assessed on a scale from *Very poor* to *Very good* (divided into 5 or 3 levels) for each indicator.

The alternatives using diesel engines had the best technical scores, while gas engines also performed well. Electric vehicles had a lower technical maturity, but the ongoing development was noted. The picture was relatively scattered concerning the economic performance, and these results were more uncertain. For example, regarding Total Cost of Ownership the literature contained data ranging over 3-5 levels for most of the alternatives. Fossil diesel had the best economic results (i.e. focused on owners/operators, short term⁹).

As expected, the environmental results highlighted the many negative impacts of fossil fuels, although natural gas sometimes performs a bit less poorly than diesel. All the renewable alternatives can contribute importantly towards improved environmental sustainability, but this depends on the feedstock/sources and production systems. Among the renewable alternatives, HVO and biomethane had the highest non-renewable primary energy efficiencies. Biomethane outperformed the other energy carriers from a generic environmental perspective, and was the only alternative that could have a positive climate impact (reducing emissions). However, the strength of electric vehicles makes them favorable in central urban areas, with slow moving traffic. Dahlgren and Ammenberg (2021), in line with many other studies referred to in this report, emphasized that the environmental performance is very dependent on the underlying sociotechnical and agricultural systems.

Regarding social performance, biomethane scored best due to positive links to other sociotechnical systems and energy supply services, while electric buses could both bring positive and negative effects.

Figure 3 presents a schematic overview of some of the results, with the purpose of showing that the sustainability performance varies significantly between different specific energy carriers. A high score is positive for all the indicators. The figure indicates common generic results (based on a Swedish context), while more specific studies are needed for accurate comparisons taking local conditions into account. Nonetheless, the figure, in line with the results from Lindfors and Ammenberg (2021) and Dahlgren and Ammenberg (2021), clearly illustrates that biogas solutions (and biomethane for transport) are competitive from broad sustainability perspectives.

⁹ In contrast to the results for environmental and social indicators, of more long-term and socio-economic relevance.

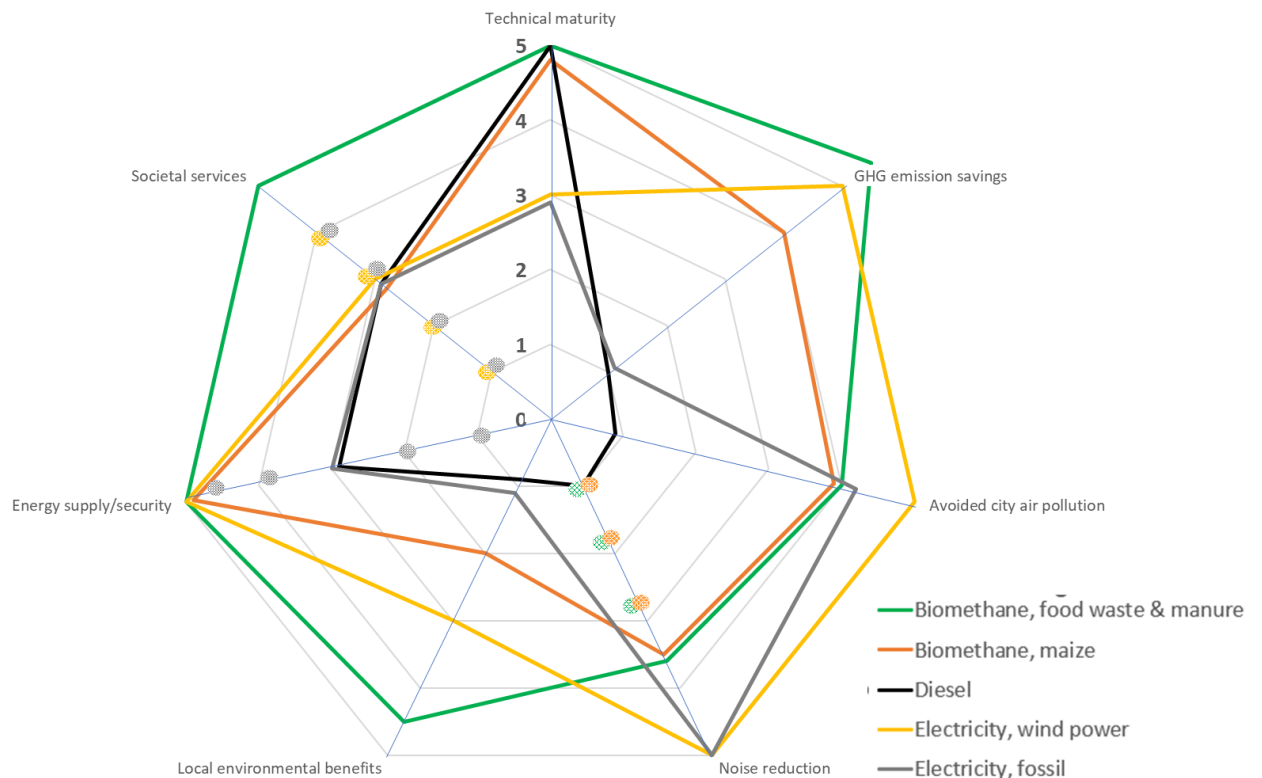


Figure 3. Schematic illustration of multi-criteria analysis results - generalization from a study of bus technologies in a Swedish context. The results include two types of biomethane, in comparison with two types of electricity and fossil diesel. Alternative results presented with pattern filled circles indicate larger uncertainties.

3.3 Monetization of sustainability effects involving biogas systems

Although pluralism¹⁰ has been emphasized as critical for good sustainability assessments, it is common practice to utilize monistic approaches (single criterion methods). For example, there are many examples of monetization, where sustainability (and other) effects are translated into economic units, using different types of methods (Arendt et al., 2020; Boardman et al., 2011). While methods such as cost benefit analysis (CBA) are commonly used they are also heavily criticized, due challenges in accounting for all relevant effects and correctly estimating their values (Ackerman and Heinzerling, 2002; Barfod and Salling, 2015; Beria et al., 2012; Hüging et al., 2014).

The main advantage of monetization (or other single criterion approaches) is the simplicity for decision-making and communication, as the results can be presented as single (or few) indicators (Browne and Ryan, 2011). Since monetization is utilized in many societal contexts, not only related to sustainability, the following sections present a few studies of international relevance focusing on biogas solutions.

3.3.1 “Beyond energy - monetising biomethane’s whole-system benefits”

In 2023 the consultancy firm Guidehouse delivered a report that describes and monetizes environmental, social and economic externalities associated with ‘biogas systems’. This report, written by Alberichi et al. (2023), is focused on Europe (EU27 and UK) and the years of 2030 and 2050. It both considers anaerobic digestion (AD) and thermal gasification, that can be used for woody or lignocellulosic biomass, as a complement to AD. Externalities are defined as effects of

¹⁰ i.e. to include several indicators, with various directions and units.

production or consumption of goods and services that impose costs or benefits on others which are not reflected in the prices charged for the goods and services being provided (OECD, 2008). Thus, externalities are effects that markets fail to account for, which can be positive (providing a benefit) or negative (representing a cost or unwanted impact). Thus, the term we have mainly used this far - “sustainability effect” - is broader than “externality”, since the latter is focused on the effects that are not accounted for on certain markets.

Twenty-one externalities (or sustainability effects) are described in the report by Alberichi et al. (2023) (9 environmental, 5 social and 7 economic). These externalities are largely covered by Chapter 2, which contains some additional sustainability effects as well (the effects/externalities are also somewhat differently formulated and/or defined).

Out of the 21 externalities, 7 were selected for quantification/monetization by Guidehouse¹¹. The following aspects were the basis for the selection:

- Feasibility of monetization.
- Inclusion of the externalities with the greatest overall impact, and of both positive and negative externalities.
- Inclusion of at least one externality per sustainability dimension (environmental, social, economic).

While impact on soil health was selected, the authors due to lack of well-established methodologies to quantify the value of soil health and soil ecosystem services decided to make a qualitative description instead. Thus, 6 externalities were quantified in the end.

The process was carried out in 5 main steps, based on a study of ‘available feedstock’ 2030 and 2050 (Alberichi et al., 2024), and what technology (AD or thermal gasification) that could be applicable for each feedstock category:

1. Externality mapping - relevance to each feedstock and technology
2. Counterfactual definition - alternative scenarios, if no ‘biogas systems’
3. Identification of quantification metrics - quantification per feedstock and technology type (impact per MWh)
4. Monetization (€ per MWh)
5. Quantification of externalities for each technology

The results were calculated for a low and high scenario.

In 2030, the benefits for Europe (EU27 and UK) were estimated to €38-78 billion per year, to a dominant extent delivered by AD (€35-73 billion) since thermal gasification was assumed to be fully commercial from 2030 onwards. In 2050 the benefits were estimated to €133-283 billion per year (AD €77-168 billion, corresponding to 60%), with a significant contribution from thermal gasification (€57-115 billion, 40%). As a frame of reference, Alberichi et al. (2023) point out that the high value for 2050 corresponds to the gross domestic product (GDP) of Finland in 2021.

The authors emphasize that the benefits were underestimated, since only a limited selection of the externalities (or sustainability effects) were monetized (6 out of 21). Furthermore, the inclusion of additional feedstock categories could also lead to higher benefits.

In conclusion, the study indicates that sustainability benefits associated with biogas solutions are significant from a socio-economic perspective. Of course, in line with 3.1, it is very challenging to carry out cost-benefit analyses, which was clearly the case. Among other things, it should be noted

¹¹ Included externalities: change in soil health (qualitative estimation), greenhouse gas impact (both positive and negative), improved energy security, organic waste processing, provision of biogenic carbon dioxide, replacement of resources, job creation.

that the results are highly influenced by assumed values for emissions, CO₂, natural gas, etc. (see Annex D in the report by Guidehouse).

3.3.2 Other reports on externalities associated with anaerobic digestion

Over the last decade, a number of studies have examined the externalities associated with biogas solutions in different countries.

In 2018, ENEA and ASTRADE released the report “Renforcer la compétitivité de la filière biométhane française” (Reinforcing the French bio-methane sector competitiveness) that initiated the development of a framework to evaluate and monetize all of the non-energy services and externalities provided by biomethane value chains in France (Blaissonneau et al., 2018). Figure 4 provides a concise description of externalities identified under four types of services: agricultural and agro-ecological; socio-economic; environmental and energy.

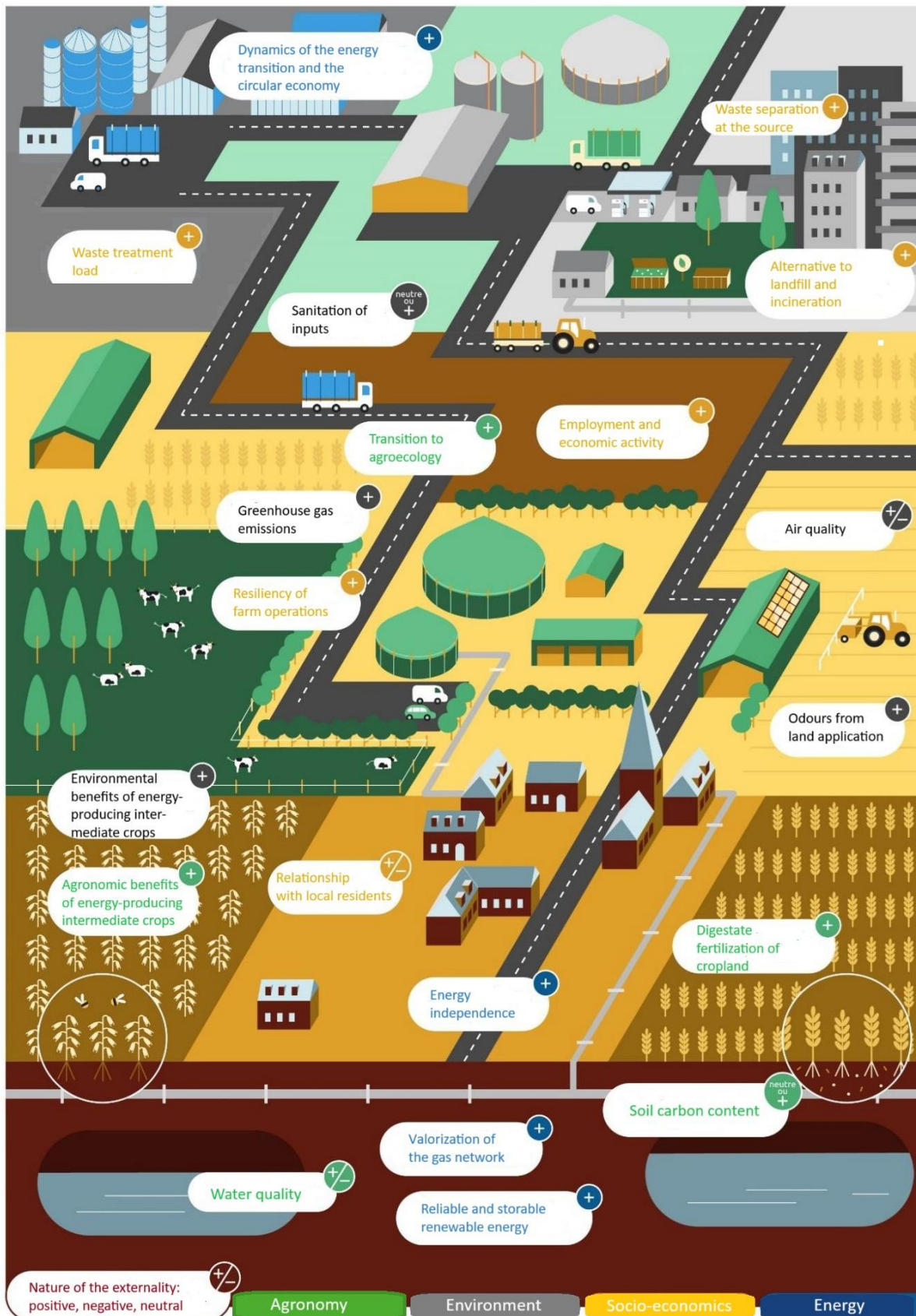


Figure 4. Illustration of externalities (or sustainability effects) associated with biogas systems in France (translated, based on Nouveaux Systèmes Énergétiques, 2021).

Most of the externalities associated with biogas solutions are considered to be positive in nature, with a few having the potential for negative impacts (indicated with “+” or “-“ below):

- **Energy:**
 - Source of stable and storable renewable energy (+)
 - Use of existing natural gas system (+)
 - Greater energy independence (+)
 - Support the clean energy transition and circular economy (+)
- **Agriculture:**
 - Reduction in the use of synthetic fertilizers by replacement with digestate (+)
 - Increase in soil organic matter content (+)
 - Impact on water quality (+/-)
 - Agronomic benefits of intermediate crops on main crops (+)
 - Transition to environmental/regenerative agriculture (+)
- **Environment:**
 - Reduction in GHG emissions (+)
 - Change in local air quality (+/-)
 - Less odour associated with manure spreading (+)
 - Environmental benefits of intermediate crops, such as biodiversity (+)
 - Sanitation of waste feedstocks (neutral/+)
- **Socio-Economic**
 - Job creation and economic activity (+)
 - More resilient agriculture sector (+)
 - Lower cost of waste disposal (+)
 - Greater waste separation (+)
 - Alternatives to landfilling and incineration (+)
 - Change in relationship with local residents (+/-)

Several of these externalities can be monetized, and the report by Blaissonneau et al. (2018) provided a first total estimate of 55-85 Euro/MWh of non-energy value. As shown in Table 7, society at large was considered to be the major beneficiary of the added values.

Table 7. Estimated value of externalities (Blaissonneau et al., 2018).

Monetized Externalities	Estimated Value of Externalities (Euro/MWh)	Beneficiaries
Reduced GHG emissions; Avoided cost to clean up groundwater; Job creation	33 - 35	Society at large
Production of renewable energy; Limited increase in cost of natural gas	21	Energy consumers
Lower cost of waste disposal	0 - 24	Waste producers/industry
Reduced use of synthetic fertilizer	3 - 4	Agricultural producers

In a report prepared for the French Government in 2021 somewhat lower numbers were estimated, i.e. 20 Euro/MWh (2021) for GHG reductions, 0-5 Euro/MWh for avoided costs for water clean-up, and 10 Euro/MWh for reduced waste disposal costs (Ayoun, P. et al., 2021). However, the report acknowledged the difficulty associated with monetization exercises as the values were very dependent on the assumptions made and there is a high degree of diversity among the value chains, even within the same country.

A similar project was carried out for Switzerland's biogas (AD) industry (Membrez et al., 2021). Here 18 externalities were identified in four categories (agriculture, environment, socio-economy, energy), and their relevance was assessed for the following eight value chains:

- Agricultural AD with (1) biogas to CHP; and (2) biogas to biomethane
- Biowaste AD with (1) biogas to CHP; and (2) biogas to biomethane
- WWTP Sludge AD with (1) biogas to CHP; and (2) biogas to biomethane
- Industrial AD with (1) biogas to CHP; and (2) biogas to biomethane

Not all externalities were found to be equally relevant for all value chains. For example, reducing the odor from agricultural activities or the use of synthetic fertilizer, are relevant externalities for agricultural biogas plants but not likely for the other types of biogas installations.

For effective environmental policy, it is essential to account for externalities to the greatest extent possible when developing new policies, standards, and/or guidelines. As this work was to inform Swiss policymakers, the externalities were prioritized according to four criteria:

- 1) Importance of the service rendered; Is the effect significant in the Swiss context?
- 2) Methodological issues related to quantification; *Does a methodology exist?*
- 3) Methodological issues related to monetization; *Does a methodology exist?*
- 4) Ability to create a monetary reward; Can we envision that the externality can create a monetary reward?

Ten externalities, with the highest priority ratings, were selected to evaluate Swiss AD value chains. Eight externalities could be monetized, and two externalities would be assessed qualitatively. As an example, the results for an agricultural AD facility with a biogas cogeneration value chain are presented in Table 8. Only six externalities were relevant to this case and could be monetized. The financial value (in thousand Swiss Franc (CHF) per year) was shown to be significant, but the total value still fell below the subsidy provided by the SRI (Swiss electricity feed-in-tariff program). The report concluded that biogas systems provide numerous positive externalities that have both financial and non-monetized value to society, thereby justifying public support of AD, and it recommended ways to internalize externalities in the Swiss Government's decision-making process.

Table 8. Monetized Externalities for an Agricultural biogas system - Biogas Cogen in Switzerland (translated, based on Membrez et al., 2021).

Externality	Relative Value (CHF/MWh - raw biogas)	Absolute Value (1,000 CHF/year)
Reduction in use of synthetic fertilizer	4.8	60
Reduction in GHG emissions	8.7	107
Impact on N pollution of water	7.8	96
Job creation and Economic activity	16.2	200
Production of renewable energy - stable and storable	0.7	9
Elimination of fossil fuel energy	11.8	146

Negative Externalities

The above-mentioned studies focus on the positive externalities of biogas solutions. However, negative externalities exist as well, in line with Chapter 2 (Table 1-Table 5). They can include greater odor emissions, more noise and disturbance from daily truck traffic/transport volume around sites, undesired land-use change for energy crops, and the presence of installations themselves (Krekel et al., 2018). The designers and developers of biogas systems will naturally work to minimize or avoid these negative externalities in order to receive the approvals needed to construct and operate the AD system. As is the case for other economic activity, a new installation would increase the risks of accidental releases to the environment, fire and accidents (Solagro 2021); but there has been no indication that biogas facilities present a higher risk than other economic activities. It is clear that operators should be adequately trained, and the facilities should be properly maintained to reduce such risks and lower operating costs.

3.3.3 Synthesis and comparison - externalities and monetization

It can be concluded that the different studies identified similar externalities associated with biogas systems. However, there are some differences regarding what sustainability effects that were included, how the externalities were defined in detail and categorized, and which externalities that were monetized (and in what way) - see Table 9. An important challenge that remains for policymakers (in all countries) is to agree upon ways to internalise global and local externalities in all sectors of the economy and thereby improve the cost-effectiveness of environmental policies (Égert, 2011). Comparison of the different studies reveals that the purpose of the study and the country context appear to be important factors (Pouliquen, M., 2020). Even within a country, not all externalities have the same importance or carry the same weight in decision-making. The relevance of an externality depends on the type of value chain, e.g. the sector using the AD technology, the end-use of the biogas, etc.

The studies all recognized that biogas systems provide several products (bioenergy, biofertilizers, biogenic carbon) and numerous positive effects, that benefit society at large, including the waste industry, agricultural producers, and energy utilities and consumers. Given that society at large reaps many of the benefits, this provides some justification for public financial support of biogas system investments and/or its products. If based solely on the cost of biogas-derived energy, biogas systems are not very competitive, depending on fossil fuel prices and as the costs of solar and wind energy continue to decline. However, biomethane stands out as a highly competitive *renewable* gas - compared to other renewable alternatives. Currently, the competitiveness, or 'biogas actors' need of support, is strongly linked to the situation for fossil fuels and mineral fertilizers. Removal of the substantial subsidies of fossil fuels and mineral fertilizers, and measures to better internalize the costs related to their negative sustainability effects (externalities), would lead to significant differences regarding competitiveness. Taking into account the total value added, including all products and sustainability effects, biogas solutions are highly competitive from a socio-economic perspective compared to both non-renewable and other renewable alternatives.

Table 9. Comparison of key externalities identified in presented reports.

Externality	Main Beneficiary	Guidehouse, Europe: Alberichi et al. (2023)	French Report: Blaisoneau et al. (2018)	Swiss Report: Membrez et al. (2021)
Environment				
GHG Impact (+/-)	Society at large	Environmental externality - monetized	Monetized (first framework)	Priority* environmental externality - monetized
Change in soil health	Agriculture & Environment	Environmental externality - monetized		Environmental externality - not top priority
Impact on N pollution of water	Society at large	Environmental externality - not monetized	Monetized (first framework)	Priority* environmental externality - monetized
Economy, society				
Improved energy security	Society at large	Economic externality - monetized		
Organic waste processing costs	Waste producers / industry	Economic externality - monetized	Monetized (first framework)	Priority* socio-economic externality - monetized
Provision of biogenic CO ₂	Industry	Economic externality - monetized		
Job Creation	Society at large	Social externality - monetized	Monetized (first framework)	Priority* socio-economic externality - monetized
Contribution to resilience of agriculture	Society at large & Agricultural Producers	Economic externality (diversification of agricultural revenues) - not monetized	Not monetized	Priority* socio-economic externality - <i>qualitative</i>

Externality	Main Beneficiary	Guidehouse, Europe: Alberichi et al. (2023)	French Report: Blaissonneau et al. (2018)	Swiss Report: Membrez et al. (2021)
Agriculture				
Reduction in use of synthetic fertilizer	Agricultural Producers	Economic externality (replacement of resources) - monetized	Monetized N use (first framework)	Priority* agronomic externality - monetized
Impact of intermediate crops	Agricultural Producers & Environment	Environmental externalities (biodiversity, soil health, water use) - not monetized	Impacts on main crop yield and biodiversity; Not monetized	
Energy				
Use of existing gas infrastructure	Energy consumers	Economic externality (gas transmission and distribution costs) - not monetized	Monetized (first framework)	Priority* energy externality - monetized
Production of renewable energy - stable and storable	Energy consumers	Economic externality (balance energy system) - not monetized	Monetized (first framework)	Priority* energy externality - monetized
Contribution to energy transition and regional circular economies	Society at large	Social externality (local energy transition) - not monetized	Not monetized	Priority* energy externality - <i>qualitative</i>
Elimination of fossil fuel energy	Society at large			Priority* energy externality - monetized

*Top 10 priorities according to 4 criteria for Swiss decision-makers

4 Biogas solutions in different countries – contexts and sustainability effects

Countries have adopted biogas solutions for different reasons. In Chapter 4, five Task 37 Member countries - Canada, France, Norway, Sweden, and Switzerland - are highlighted. For each country, there is a description of the historical context and current status, including information on drivers and barriers to development, as well as comments on the future outlook. The descriptions are structured in line with Chapter 2, including information on relevant sustainability effects for waste and wastewater treatment; agriculture as a feedstock provider and user of digestate; the use of biogas, biomethane and carbon dioxide; and broader society.

4.1 Canada

On a per capita and area bases, Canada produces a modest amount of biogas from its landfill operations and anaerobic digesters in the waste and wastewater, industry and agriculture sectors. Increasingly, biogas is being upgraded to biomethane and injected into the natural gas network to meet renewable gas targets. The recovery of nutrients (N, P and K) from the digestate and CO₂ from biogas upgraders are largely not monetized, and cost-effective technologies and markets for these co-products are needed. As in other countries, AD systems provide many co-benefits to waste producers, industry, agriculture and broader society. The sustainability effects are described below by sector.

4.1.1 Waste and wastewater treatment

Landfills are the largest source of biogas production in Canada today. As more regions are working to reduce landfilling and mandate waste separation, more opportunities are emerging for biogas systems and composting of biowaste, referred to in Canada as source separated organics (SSO). The predominant form of wastewater (WW) treatment in Canada is primary treatment followed by secondary aerobic treatment. Many of the larger WW treatment plants (WWTP) anaerobically treat the sludges from wastewater treatment process. Some industries with effluents that have a high organic loading, such as the dairy products industry, potato processing and breweries, have also installed anaerobic process to treat their effluent to produce biogas that can be used to generate process heat. With a growing population, the solid waste and wastewater treatment sectors are expected to increase their biogas and biosolids or digestate production.

There are over 3,900 WWTPs operating in Canada to treat municipal wastewater prior to discharge into receiving waters. Given the large size of the country, its population distribution and low population density in many areas, often rural areas are served by septic systems. Most WWTPs include primary and secondary (activated sludge) wastewater treatment. Many of the larger plants digest their WWTP sludges to stabilize their biological activity and reduce sludge volume. Stabilized sludges that meet quality criteria (e.g. pathogen and vector attraction reduction, trace elements limits) are referred to as “biosolids”. It is estimated that over 660,000 dry tons of biosolids and sludge are produced in Canada every year (CCME, 2012). Beneficial use and disposal options (e.g. land application, incineration, landfilling) for biosolids and sludge are regulated by provincial/territorial and federal regulations and may vary accordingly. For example, the Province of Ontario generates approximately half of the Canadian annual production of biosolids and about 50% are incinerated, 40% land applied and 10% landfilled (Lebeau, 2024). Some biosolids in Canada are also composted or further processed and sold as a commercial fertilizer or supplement under the Fertilizer Act and regulations that are administered by the Canadian Food Inspection Agency.

Sludge digestion at municipal WWTPs takes place at 109 sites, most of the largest WWTPs that serve approximately 19.75 million people. In the past, most of the biogas from WWTPs was not recovered

or flared as these facilities did not have a high energy demand and energy prices were low. It is estimated that in 1990, 31.4 kilotons (kt) of methane were produced with 42% flared and 58% used for energy. Over time, more biogas has been recovered, however there is still a significant amount of flaring taking place. In 2022, 107.6 kt CH₄ were produced with an estimated 66% being flared and the remainder used for energy (Environment and Climate Change Canada, 2024).

Depending upon its location and pollution loading, industries either discharge their effluents into municipal wastewater treatment systems or they treat or pre-treat their effluents before discharge into receiving water or the municipal system. Industries are all regulated with respect to the discharges they release to the environment. The type of industrial WW treatment depends on the effluent composition, and those with a high organic loading are usually well-suited for anaerobic treatment. Information on industrial WW treatment is difficult to find in the public domain, but it is estimated that there are at least 25 facilities that have adopted AD in Canada. These facilities typically use the biogas directly in their on-site boilers to displace natural gas and generate process heat. The solids are often separated from the liquid digestate and, depending on their composition, are applied to nearby agricultural land, incinerated or landfilled. The cleaned water is often reused in the process, otherwise it is discharged into the municipal WW collection system or directly to the receiving water, if environmental standards are met.

Regarding solid waste disposal, there are several thousand managed landfills in Canada, though the largest 260 sites accounted for 82.6% of waste landfilled in 2022. Landfill gas recovery has increased since 1990 (125 kt CH₄ recovery) and, in 2022, 113 sites had landfill gas collection. Of those, 48 had biogas utilization for energy, with the remainder flaring the collected landfill gas. In 2022, it was estimated that 1,206 kt CH₄ were produced, and 210 kt CH₄ were recovered for energy, 224 kt CH₄ were recovered and flared, 77 kt CH₄ were oxidized via the landfill cover and the 696 kt CH₄ were released to atmosphere (Environment and Climate Change Canada, 2024).

With more regions banning the landfilling of organic material, there has been growth in both composting and anaerobic digestion of biowaste. The Canadian Biogas Association reports that there are 17 stand-alone biowaste AD facilities producing 1.3 PJ of biogas, and several facilities under construction. In most cases, the biogas is upgraded to biomethane and injected into the natural gas pipeline. Some facilities are using biomethane in their vehicle fleet.

As today's government incentives promote biomethane over electricity and heat production, new agricultural AD plants need to accept biowaste or residues from nearby food processing plants in order for them to produce sufficient volume of biomethane that would interest a buyer to enter into a long-term purchase contract. Consequently, going forward, the AD of biowaste will likely take place in stand-alone plants or via co-digestion in agricultural AD plants.

All of the sustainability effects listed in Section 2.1 (specified in Table 1: W1-W8) are relevant for the adoption of AD for wastewater and biowaste treatment, and landfill gas capture in Canada. The biogas solutions reduce pollution and eutrophication of surface and groundwaters (W1) by degrading organic matter and recovering nitrogen and phosphorus from the wastewater. They also require less land (W4) for landfilling as well as for secondary treatment as AD systems have a smaller land footprint than aerobic lagoons or activated sludge treatment systems. Separation of organic waste from the overall waste stream increases the opportunities to recover and better treat all of the components of waste streams (W6).

Biogas solutions are designed to provide waste sanitation services (W5), reducing the pathogen content and degrading organic materials that could cause harm to the environment and/or human health. However, attention must be paid to the composition of the final biosolids and digestates, especially if they are land applied. For example, the pathogen concentrations in biosolids are significantly reduced, but not completely eliminated, making it important to follow best practices to reduce any pathogen-associated risk when land applying biosolids. Also, the waste and

wastewater sector is subject to the presence of new constituents and/or constituents that have been newly identified as having the potential to cause harm to the environment and/or human health. As such the AD technology and the treatment system as a whole must be regularly evaluated regarding their effectiveness to address new concerns.

The more prominent sustainability effects, in the Canadian context, were identified to be W2 (resource efficiency, valorization of waste), W3 (lower GHG emissions), and W7 (economic enabler). In addition to the effects mentioned above, the advantages of biogas solutions, over other treatment options, are their abilities to recover carbon, nutrients (especially nitrogen and phosphorus) and energy from waste, to reduce GHG emissions from waste disposal and treatment, to add financial value, and to contribute to a circular economy. In the case of industries with effluents of high organic loading, biogas solutions can serve as an important feature of their development strategies (W7) in that AD provides internal treatment of their waste, lower their environmental impact and carbon taxes, and reduce their fossil fuel consumption. Two Canadian examples include: 1) pulp and paper mill production where the biogas (from AD treatment of its effluent) is used to generate power for the mills; and 2) AD incorporated into the construction of new brewery in an urban area where the municipal WWTP could not take on additional treatment load.

Key drivers and enablers regarding biogas solutions in the waste and wastewater sector

Reducing the environmental impacts of waste disposal and wastewater discharge serve as the principal drivers. Examples of key drivers include:

- Regulatory drivers related to solid waste
 - Landfill regulations - biogas recovery
 - Landfill regulations - bans on landfilling of organic waste
 - Waste separation - separate collection and treatment of organic waste.
- Increasing waste disposal fees for landfilling.
- Municipal and regional planning objectives, including GHG reduction and circular economy.
- Greater adoption of biosolids master planning by municipalities.
- Approval processes for land application of biosolids and digestates (+/-?).
- Best management practices for application of biosolids and digestates to agricultural land.
- Ongoing testing and research to investigate the fate of pathogens, regulated metals and other contaminants in biosolids and digestates.
- Regulatory framework for certification of biosolids and digestates as fertilizers.
- Environmental permitting of industrial development.
- Water quality standards.
- GHG emission reduction requirements.
- Renewable gas mandates and incentives.
- Landfill capacity limitations in some parts of the country (e.g. Greater Toronto Area).

Key barriers and enablers for the adoption of AD in the waste and wastewater sector

- Long distances between landfills and industrial users of biogas or natural gas pipeline injection ports.
- Wastewater treatment plants not designed to, or not able to directly use the biogas produced.
- Composting of biowaste has significantly lower CAPEX than an AD system.
- Lack of public acceptance of land application of biosolids and/or digestates.
- Unknown fate of “new pollutants” in AD systems (scientific challenge).
- Competition for new infrastructure funding and multi-year decision making process.
- Low energy prices even with carbon tax, and the high cost of treatment technologies.

Outlook

With an ever-growing population, the generation of solid waste and wastewater will increase and, consequently, there should be more opportunities for biogas solutions. New federal landfill

regulations are under development, and it is expected that they will further encourage landfill gas recovery for energy use and reduce flaring. Organic waste separation of solid is expected to continue, and municipalities will have to decide whether to set up composting sites or to invest in a new AD facility.

Similarly, the municipal WWT sector will continue to experience growth with rising populations, especially in cities. As such sludge and biosolids production are projected to increase. Sludge digestion and beneficial use of sludge and biosolids, such as land application, should continue to increase overtime but the types of sludge treatment will always be subject to capital and operational costs of current and new processes to manage sludge and biosolids, jurisdictional policies and regulations.

Public acceptance of the options to manage solid waste, sludge and biosolids is also key to their success, which can rely on the level of public outreach during the planning of strategies, the development of best management practices to demonstrate exemplary programs, including timely communication with stakeholders when potential issues may arise (e.g., nuisance, concerns over emerging contaminants in feedstock or byproducts).

Within industry, AD technology remains an option to treat or pre-treat effluents with a high organic loading that are amenable to AD. Here, the heavy focus on electrification and hydrogen, and the lack of support for biogas production could influence industry's treatment choices.

There is a substantial amount of flaring taking place at landfills and municipal WWTPs, indicating that there are untapped waste-to-energy opportunities. As this sector follows population growth and the banning of organics in landfills is expected to continue, opportunities for the adoption of AD are also increasing for biowaste. However, composting is a less expensive, competing technology to AD of biowaste.

Currently, sludges from many of the largest WWTP are turned into biosolids and land applied. Regulatory frameworks exist in most provinces and territories to ensure that biosolids can be beneficially used or properly disposed of to minimize potential risks to human health and the environment. AD becomes a more attractive choice when its multiple benefits are recognized and valued, e.g. organic content/carbon and nutrient reuse, GHG (CH₄) reduction and clean energy development.

4.1.2 Agriculture, feedstock related effects

There are 50 AD systems operating in Canada's primary agriculture sector today. Thirty-eight of these systems process less than 50,000 tons/year of feedstock, with most of them treating 10,000 - 20,000 tons/year (CBA, 2023a). Almost all agricultural AD systems co-digest manure with off-farm organic residues from nearby food processing plants or biowaste, with provincial regulations typically requiring a minimum of 51% manure or maximum of 49% off-farm inputs. The reasons for co-digestion with organic rich, off-farm substrates are three-fold: 1) to supplement manure due to the predominance of small-sized farms and large distances between farms yielding small concentrations of manure; 2) to increase biogas yield of manure-only AD; and 3) to achieve 500 kW-sized AD systems that were favored by the Feed-in-Tariff (FIT) programs, and even larger systems required for minimum biomethane production.

Today, most agricultural AD systems are built on dairy farms, and co-digest liquid dairy manure with off-farm substrates. A few systems take in manure from nearby poultry and swine operations, and a few take in small amounts (<10%) of straw and bedding pack. Realistically, 7 million dry tons of manure are considered to be recoverable from dairy, poultry, swine operations and beef feedlots, and less than 5% of this recoverable manure is treated via AD. This suggests that there exists a large untapped potential on a national basis, however the challenge faced by the sector is that there are relatively few large farms or regions with high manure concentrations. That is, manure and other

feedstocks need to be sufficiently concentrated in a given area in order to consider building a new agricultural AD system.

Neither energy crops (e.g., silage corn) nor intermediate crops are used as primary substrates for agricultural AD in Canada today. Here again, biomass inventories indicate that there are substantial supplies of straw available in various regions of the country (Jamie et al., 2020). However, no silage and very little straw is used currently in agricultural AD. Some straw has a market in the livestock sector, but most straw is left in the field to reduce soil erosion, retain soil moisture and regulate soil temperature. For many years, federal and provincial agriculture ministries have encouraged agricultural producers to retain straw for the reasons mentioned. Small amounts of straw removal could likely be carried out to supplement manure without environmental impact (positive and/or negative), but it would increase the operating costs of the AD system and require straw storage to provide a year-round supply.

More farms are using cover crops as intermediate crops that are grown between the main crops. The opportunity depends strongly on climate and therefore varies across the country. To date, most cover crops are incorporated into the soil to maximize their agronomic benefit. However, there are opportunities to harvest cover crops, such as oats in the fall and cereal rye in the spring in southern Ontario. This could provide an excellent opportunity to use fresh digestate, extracting maximum value from the nutrients. Clearly, weather and timing would be another consideration, especially in the spring when there is a very small window for seeding the main crop. In theory, the harvest of perennial grasses could also serve as an AD feedstock, but there is little production of perennials on agricultural land.

Only one of the sustainability effects listed in Section 2.2 (specified in Table 2: AF7) is relevant for the adoption of agricultural AD because neither energy crops nor intermediate crops are grown currently for use in AD in Canada, and there is no land use change associated with agricultural AD. Both sustainability effects are benefits associated with the use of manure for biogas and digestate production. The reduction in GHG, more specifically CH₄, emissions from manure management (AF7) is recognized as a positive externality of AD. Local air quality should be improved with fewer emissions from manure, and some have indicated that better manure management leads to fewer flies in animal barns. With respect to odors associated with manure storage and subsequent field application (AF14), a change in odor is observed. That is, the manure odor is replaced with digestate odor that may be more acceptable for some people but not for others.

As almost all agricultural AD systems in Canada co-digest manure with industrial waste from food processing plants and/or biowaste, the related sustainability effects mentioned in Section 4.2.1 also apply here.

Key drivers and enablers regarding agricultural feedstock to biogas systems:

- Government GHG reduction goals and plans - in particular, reducing GHG emissions associated with natural gas use.
- Renewable gas mandates of 2 Provinces that have programs that provide premiums for biomethane that is produced in any part of the country (driver for large agricultural AD facilities).
- Net zero by 2050 goal of Canadian dairy industry (GHG emissions target).
- Sustainability goals of vertically integrated agri-food processors (e.g. processors that own or control swine operations).
- Biomass inventories and feedstock cluster studies that identify local and regional feedstock concentrations and location of natural gas network.
- Access to expertise and equipment from other countries with more mature biogas industries e.g. Denmark, Germany, France.
- Quebec Government funding for AD project feasibility studies.

Key barriers regarding agricultural feedstock to biogas systems:

There is a bit of a ‘chicken or egg’ scenario, in that the small size of the biogas industry presents barriers to development and, if these barriers are not addressed, then the industry is likely to remain small.

- No national goals nor pathways outlined for biogas production; often not included in clean energy discussions.
- Many areas of the country have insufficient concentrations of feedstock for financially viable operation (i.e., size of dairy, poultry, swine operations and beef feedlots; long distances to feedstock supplies).
- Public opposition to the construction of new gas pipelines.
- Little natural gas fueling infrastructure and use of gas vehicles.
- Agriculture and energy fall under the jurisdictions of different government ministries, and the agriculture sector is not traditionally viewed as a player in the energy system.
- Relative to other countries, little research is conducted on affordable agricultural AD systems for Canadian context, lignocellulose supply and pretreatment, CO₂ uses at small scale, alternative biogas energy storage and use, etc..
- Ending of electricity Feed-in-Tariff programs has removed the financial support for biogas cogeneration systems in agriculture
- Wind and solar power production on farms outcompete biogas power production, and use the capacity of rural electricity lines.
- No dedicated policies or support for biogas from manure.
- No dedicated policies or support for small scale biogas production.
- High CAPEX of large agricultural AD systems that produce sufficient biomethane for grid injection.
- No investment tax credits for biogas projects (all types).
- Different ownership structures needed to finance, develop and operate larger systems (farm operation is no longer sole owner).
- More buildings and equipment needed for feedstock receiving, depackaging food, odor control, etc.
- Harvesting and storing straw for AD? Needs to be demonstrated and to have “best practices for removal for AD”.
- Harvesting of cover crops? Needs to be demonstrated and to have “best practices for removal for AD”.
- Perennial for AD? Needs to be demonstrated and to have “best practices for removal for AD”.
- AD pretreatment technologies for lignocellulose feedstock need to be demonstrated and costed along with net impact on GHG emissions.
- Small size of biogas industry doesn’t justify having the necessary technical support, domestic equipment manufacturers, etc.

Outlook

In the absence of a clear commitment to biogas production (generally) and agricultural AD (specifically), growth in agricultural AD is expected to be modest. Opportunities appear to exist for large livestock farms and centralized AD concepts, farms that have access to lignocellulose feedstocks, and integrated operations, such as farms with nearby greenhouses that can make effective use of all of the co-products (digestate, CO₂, etc.) One of the large processors within the agri-food industry has been exploring AD for the swine operations it owns and buys meat from, in order to meet its corporate sustainability commitments. There are several large swine operations in the Province of Manitoba that could be included in such a project.

In areas with sufficient feedstock concentrations, the renewable gas policies create opportunities for larger and centralized AD systems that are located near an injection port, and developers that are able to raise significant amounts of capital and secure a long-term contract for sale of its biomethane at a significant premium (> \$Cdn25/GJ). Even with all of these pieces in place, all projects would not be expected to advance to completion due to the lengthy approval processes and, in some places, community opposition to AD projects.

Unless new policies and programs are introduced to support smaller systems that do not target biomethane as the end-use, existing agricultural AD facilities with cogeneration that cannot expand their digester production and/or are not located near a natural gas pipeline will likely close.

Work would need to be undertaken to unlock the lignocellulose feedstock potential from crop residues, cover crops and perennials. This would need to include appropriate harvesting procedures (by site), demonstration of pretreatment technologies, supply logistics as well as financial and lifecycle GHG assessments.

It should also be noted that agricultural scientists are exploring less expensive ways to avoid or reduce GHG emissions from manure, such as solid/liquid separation and acidification of manure. Given the size distribution of dairy, swine and poultry operations, these simpler solutions may end up being more appropriate options for small and medium-sized farms where there is not sufficient feedstock for a financially viable AD system.

Provincial renewable gas policies have created new opportunities for larger AD facilities located at very large dairy or swine farms or beef feedlots, or in locations where a centralized facility can be set up (CBA, 2021). In some regions of the country, there are sufficient concentrations of manure and off-farm feedstocks, such as biowaste and residues from the food industry, to enable new AD development. Opening the door to the use of lignocellulosic feedstock, including pretreatment technologies that would complement AD, could significantly expand biogas production in the agriculture sector.

4.1.3 Agriculture, use of digestate/biofertilizers and other aspects

This section discusses the use of digestate and biosolids (digested sludge from WWTPs) when they are applied to agricultural land in Canada. Digestate production, treatment and its application to agricultural land depend on the sector and the feedstock from which it was produced, the composition of the digestate and its proximity to suitable land. Approximately 40% of biosolids, from municipal WWTPs, are land applied in Canada today. Most biosolids are directly land applied, but they can also be dried, composted or lime treated to become a higher quality biosolid. In some jurisdictions, these are referred to as “Class A” biosolids that are considered to be commercial fertilizers that can be applied with fewer restrictions. At industrial WWTPs, digestate is typically dewatered and solid streams are disposed of using land application. The liquid is either reused as process water or discharged to a nearby receiving water or municipal sewer system. In the case of biowaste AD systems, digestate can be used whole (e.g. application on nearby agricultural land, if available) or it could undergo solid/liquid separation with solids being either dried, composted or stored and applied to land. Increasingly, biowaste AD facilities are registering their digestate product and taking the steps to certify it as a fertilizer through the Canadian Food Inspection Agency.

In the case of agricultural AD systems, approximately one third of the AD systems separate the solids in the digestate for reuse as animal bedding. In Canada, two farms have advanced nutrient recovery systems that extract the nutrients from the liquid fraction and produce concentrated organic fertilizer products. Digestate, in whole form, and the liquid fraction are typically stored in permanent nutrient storage facilities, which are often concrete tanks or earthen lagoons, and are applied to agricultural land to replace raw manure and synthetic fertilizer.

Dewatering is the simplest treatment that facilitates digestate storage, and enables digestate carbon and nutrients to be applied where they are most needed. The solid and liquid fractions of the digestate contain different shares of carbon and nutrients. In the case of nitrogen, the Canadian Biogas Association (CBA)’s Canadian Digestate Management Guide notes that the $\text{NH}_4^+\text{-N}$ proportion of total nitrogen (TN) in separated liquid digestate ranged from 50 to 80 % (w/w) and in separated solid digestate the proportion ranged from 20 to 35 % (w/w). More mineral nitrogen is found in the liquid (soluble) fraction of digestate, while the opposite is true for phosphorus. Total phosphorus

content of whole digestate was reported to range from 0.02 to 0.15 % (wet weight) and from 0.2 to 1.2 % (wet weight) for solid separated digestate (CBA, 2023b). The Crolla et al. (2013) study identified the PO_4^{3-} - P proportion of total phosphorus to be 80% in whole digestate.

While digestate and biosolids provide significant quantities of carbon, nitrogen and phosphorus to replenish some of the soil carbon that is lost during agricultural production, and provide important macronutrients for the next crop, they have to be stored, handled and applied appropriately in order to avoid potential negative effects on the environment and/or human health. These effects can include nutrient overloading and the risk of eutrophication, as also is the case for manure and synthetic fertilizer; and the presence of entrained contaminants; greater volatilization of ammonia due to higher pH; and potentially greater GHG emissions (CH_4 and N_2O) released during storage and field application of digestate and biosolids. Just as is done with manure and synthetic fertilizer, farms must adhere to a farm specific nutrient management strategy/plan that specifies application rates, setback distances and timing of digestate application to avoid potential negative environmental impacts. In Canada, Provinces have regulatory frameworks in place that specify the limits on constituents of off-farm feedstocks fed to a digester system, the types of land use and soils digestate can be applied on, the rates and timing of application, the set-back distances, etc. Broadly speaking there are two different pathways - one that applies to digestates derived from on-farm materials and another that applies to digestates and biosolids derived from non-agricultural source materials (NASM) that could include biosolids, pulp mill sludge, digestate from biowaste AD, etc. Most provinces require a farm to have an approved nutrient management or NASM plan that dictates what can be applied where and when. These frameworks are accompanied by best management practices (BMPs) that are prepared by provincial agriculture and environment ministries to provide guidance on how to extract the most value from digestate and biosolids application while avoiding potential harm. The Canadian Digestate Management Guide describes the best practices for using digestate so that it aligns with nutrient stewardship principles (CBA, 2023b).

Most of the sustainability effects mentioned in Section 2.3 (specified in Table 3: AB1-AB10) are relevant for the Canadian context, including positive effects such as carbon and nutrient recycling and substitution of synthetic fertilizers (AB1, AB2), improved soil fertility through the addition of organic matter and mineral form of nutrients (AB3, AB4), and improved soil structure and tilth (AB7). The impacts vary depending on the quality of the digestate, whether it is whole or the solid or liquid fraction, and what product digestate is substituting, e.g. raw manure, or synthetic fertilizer. Digestate, if derived using no off-farm feedstocks, is becoming a growing interest for use by ecological/organic farming (AB8) as it can provide a higher proportion of mineralized nutrients. However, there is a trade-off as it contains less organic matter than raw manure.

Digestion has been shown to increase the availability of N and P for crops relative to undigested feedstocks, including raw dairy manure, keeping in mind that N and P availability to crops is highly influenced by factors like the timing and method of land application. A digestate characterization study conducted at four Ontario on-farm AD facilities demonstrated that the NH_4^+ -N and PO_4^{3-} - P concentrations in whole digestate can increase by 36% and 33% (on a wet weight basis), respectively, when compared to the feedstock (dairy manure and waste grease) concentration values (Crolla et al., 2013). The Canadian Digestate Management Guide reports the NH_4^+ -N to total nitrogen (TN) proportion in whole digestate ranged from 40 to 75 % (w/w) for a series of full-scale biogas facilities processing a broad array of feedstock materials, including manures, agricultural and biomass crops, commercial and industrial food waste and source-separated organics (CBA, 2023b). In order to benefit from the more available form of nitrogen, digestate and biosolids need to be properly stored to avoid ammonia losses and should be applied to the field using appropriate techniques to a growing crop.

Another effect is greater microbial activity in the root zone, as microorganisms utilize the carbon in exchange for nutrients to plant roots. Increasing the organic matter content via biosolids application has been shown to improve the water retention of sandy soils, while it opens up clayey soils to allow

better air and water movement into and through the soil. It has been shown that poor soil conditions can be improved with regular applications of biosolids (OMAFRA, 2010). These effects are not unique to digestate, and would also be observed with the application of compost or raw manure.

With respect to impacts on crop yields, the results are not as definitive as yield depends on numerous factors. Digestate application has the potential to increase crop yields but it depends on how and for how long the digestate has been stored, when it is applied and the type of crop that receives the application. Some studies have shown no significant increases while others have demonstrated higher crop yields that could be attributed to digestate application. The Crolla et al. (2013) study corroborates increased corn crop yields when using whole digestate compared with raw dairy manure. Digestate application just before planting or on actively growing cover crops (e.g. oats, tillage radish, cereal rye) has shown biomass increases in the order of 30-40%, relative to no addition of nutrients. These increases were obtained under good growing conditions with good moisture.

Application of digestate to a growing cover crop (or any crop taking up nutrients during the growing season) helps maximize nutrient use ($\text{NH}_4^+\text{-N}$ portion of the digestate and NO_3^- once it is converted from $\text{NH}_4^+\text{-N}$), as well as the use of other nutrients and micronutrients. Also, phosphorus applied to a growing crop will be less likely to move with water and provides significant increase in cover crop biomass. Finding ways to quickly use whole digestate would appear to be a sensible strategy to benefit crop production, avoid ammonia and nutrient losses, and optimize storage and transport of digestate and biosolids.

As digestate and biosolids application reduce the use of synthetic fertilizers, it follows that GHG emissions related to the production of synthetic fertilizers are also reduced or avoided. However, the net impact of the land application of digestate on GHG emissions (AB5) cannot be generalized and should be evaluated on a case-by-case basis. That is, on the positive side of the ledger one might find increased carbon sequestration and avoided GHG emissions resulting from the substitution of synthetic fertilizer with digestate or biosolids. However, depending on how digestate is stored and applied to soils, CH_4 and N_2O emissions could be equal to or greater than those of raw manure. In Canada, digestate storages are typically uncovered so CH_4 emissions can represent a measurable proportion of direct GHG emissions from the AD system, as can be the case for uncovered storages containing raw manure. In the Province of Ontario, Baldé et al. (2016) measured CH_4 emissions over two years at an uncovered earthen storage lagoon containing digestate and found that although a significant proportion of volatile solids (VS) were destroyed during the digestion process the annual average cumulative CH_4 emissions from digestate corresponded to 12% of the CH_4 produced within the digester. As CH_4 emissions are influenced by many factors, including the reduction of VS in the digester, the digestate characteristics and the temperature of digestate storage, this value should not be taken as an absolute but instead serve as a reminder that storage emissions are part of the GHG footprint of AD systems. The authors emphasized the benefits of AD systems, that the significant VS destruction in these systems leads to large reductions in CH_4 emissions but point to the importance of digestate management to further enhance the benefits of AD systems and minimize CH_4 emissions, including considerations like adding storage covers or solid-liquid separation.

Research studies have also been directed around N_2O emissions from fields treated with digestate. Crolla et al. (2013) reported a slight elevation in N_2O emissions, a 1.2 times higher N_2O emission factor ($\text{kg N}_2\text{O-N/kg N}$ applied) from a field surface broadcast with digestate compared to a field that received raw dairy manure. Schwager et al. (2016) reported annual N_2O emissions were significantly higher from plots at a University of Guelph research facility treated with digestate compared to raw dairy manure in sandy-loam soils overall; however, there was no significant difference observed with N_2O emissions in the clay soil plots. The high ammonium-nitrogen ($\text{NH}_4^+\text{-N}$) and degradable organic carbon in substrates like manure and digestate can enhance denitrification

in soils and increase N₂O emissions. N₂O emissions can be higher than pre-digested manure when applied after corn harvest where fall losses are low due to cool soil conditions, but nitrate (NO₃⁻) in the spring combined with cold wet soils could have higher N₂O emissions. Fall application after corn harvest (or late season soybeans) can result in high NO₃⁻ in the soil in the spring when soil conditions are most prone to N₂O emissions. The timing of digestate or biosolids application, soil type and crop type all appear to influence N₂O emissions.

With respect to the spreading of contaminants (AB9), digestate and biosolids likely contain some pathogens, regulated metals, plastics and possibly trace organic compounds. The digestate characteristics are heavily influenced by the feedstock materials used in the AD system and these other digestate constituents need to be taken into account prior to land application. Depending on the type and annual loading rate of feedstocks, applicable provincial and federal regulations, and end-use guidelines for digestate, other requirements for the safe handling of digestate may include limits for pathogen indicators (typically Faecal Coliforms/E.coli and Salmonella), toxic elements (e.g., heavy metals), physical contaminants (e.g., plastics) and trace organic contaminants. These limits may be applicable to the individual digester feedstocks, the digestate product, or both, and can vary by Canadian jurisdiction. If limits are exceeded, the digestate or biosolids cannot be applied on land that will be used for food production. The regulatory frameworks require regular analysis of the composition of digestate and biosolids, and at this point in time, the risk management measures appear to be sufficient so the thresholds of these potential contaminants are not exceeded.

Increased soil compaction (AB10) resulting from whole digestate spreading is a possibility if digestate is applied on wet soils for example. Raw digestate is a very dilute product. According to Application of Municipal Sewage Biosolids to Cropland, one ton of dewatered biosolids contains approximately the same amount of nutrients found in 35 kg of mono-ammonium phosphate (11-52-0), inferring that it would take many passes to achieve the same level of fertilization (OMAFRA, 2010). Nutrient management planning with the adoption of best management practices should help to avoid situations of soil compaction. Further digestate or biosolids treatment, such as dewatering, drying and pelletization, would further reduce this risk but would increase operating costs.

Digestate storage and application can result in greater ammonia and odor. The elevated pH of digestate, often above a pH of 8, can result in elevated NH₃ emissions from digestate storage and from the field at the time of application. Baldé et al. (2018) conducted a study at four dairy farms in Canada and found average annual NH₃ emissions (per surface area) were 3.7 times higher in a digestate storage (10.0 g/m² day) facility when compared with raw dairy manure (2.7 g/m² day). The researchers noted that the lower NH₃ emissions from the raw manure storage were partly due to the 30 cm thick surface crust which formed on the manure surface from the wood shavings used as bedding. Another study conducted in Ontario showed that a field receiving digestate showed 1.7 times higher NH₃ emissions at the time of land application when compared to a field receiving raw dairy manure (Crolla et al., 2013). Incorporation of the digestate into the soil was shown to be effective at reducing the NH₃ emissions, and subsurface injection of digestate can also contribute to lower NH₃ emissions during land application.

Regarding odors, both digestate and biosolids have an associated odor. These odors differ from that of manure, but nevertheless it cannot be said that there is no odor associated with storage and land application. Best management practices, including using injection or rapid soil incorporation, adhering to set backs, and informing neighbors when applying digestate, should help to reduce odor issues (OMAFRA, 2010).

Improved agricultural resilience is another potential sustainability effect as more AD systems are adopted and more carbon, nitrogen and phosphorus are recovered from municipal and industrial waste and wastewater treatment operations and are used to substitute for synthetic fertilizer in agriculture. Although the primary driver for the integration of an AD system in an agricultural

operation today is the financial return from the sale of biogas energy, the soil amendment and fertilizer values of digestates and WWTP biosolids have a significant financial value that is expected to increase in the future.

Key Drivers and Enablers for the Agricultural Land Application of Digestate

- Circular economy goals, plans and programs; i.e., recovery of C, N and P from wastes and residues for use on agricultural land to substitute synthetic fertilizers
- Higher value of macro and micro nutrients in digestate; i.e., greater mineralized nutrient content than in raw manure
- Increased costs and price volatility of synthetic fertilizers, more attention paid to security of nutrient supply and broader agricultural resilience.
- Increased awareness and demand for more sustainable agriculture, long term investments for enhanced soil health and water quality protection.
- Potential increase in crop yields (depends on crops and conditions).
- Digestion of food waste and agricultural residues prior to land application results in fewer pathogens and greater nutrient availability, when compared with undigested residues
- Some types of digestate are acceptable for use as fertilizer and soil amendment for ecological/organic farming (provided federal guidelines are followed).
- Provincial government regulations are defined for land application of digestate and biosolids
- Federal legislation (Canadian Fertilizers Act and Regulations) sets out the requirements for registration and certification of biosolids and digestate as fertilizer product through the Canadian Food Inspection Agency (CFIA).
- Environmental Farm Plans and Nutrient Management Strategies and Plans help farmers implement sustainable strategies for managing and using digestate
- Approved plans for the application of non-source agricultural materials (NASM) ensure that non-farm materials are safely applied to agricultural land.
- Availability of guidelines and best management practices for the appropriate management of digestate and biosolids (storage and land application).
- Ongoing research to identify potential contaminants and their impact on agricultural production.

Key Barriers to the Agricultural Land Application of Digestate

- Agricultural tradition and hesitation to move away from conventional practices of using undigested manure and inorganic/synthetic fertilizers.
- Easier storage of synthetic fertilizers and their ability to be formulated to provide the “right nutrient mix” for a specific crop at a given point in time.
- Digestate is not accessible in all regions; i.e., there are only a limited number of AD facilities in Canada and transportation costs may be cost prohibitive.
- Digestate is fairly dilute (e.g., 3 to 7% solids) and dewatering technologies can be costly, which limits the opportunities of transferring digestate to farther sites (high transportation costs).
- Potential loss of nitrogen through NH_3 emissions from digestate storage and at land application.
- Potential N_2O emission increases in the spring when digestate is land applied in the previous fall on fields with no growing crops.
- Concern over the fate of potential contaminants in digestate and biosolids and impact on agricultural soils, given that some feedstocks used in AD are viewed as wastes.
- Regulations in some provinces limit or prohibit land application of digestate and biosolids depending on feedstocks used in AD.
- Digestate post-treatment can have a high CAPEX and OPEX; and implementation is limited, particularly at on-farm anaerobic digester systems.
- There is a great variability in digestate composition and limited established markets for digestate products.

Outlook

Given the size of the AD industry, Canada is relatively limited in its use of digestate and biosolids as a nutrient and soil amendment in agriculture. As more digestate and biosolids are generated,

inventories will be needed of different digestate products, biosolids and compost, as well as strategies and systems that can best extract the value of these materials while minimizing harm to the environment and/or human health.

The dilute nature of whole digestate, often less than 5% dry matter, makes it prohibitive to use digestate beyond a radius of a few kilometers from an AD facility, and problematic for AD facilities that don't have land available close by that will accept digestate. Therefore, further digestate treatment is considered to be an area of opportunity for enhancing digestate products. Technologies such as composting, drying, evaporation, pelletization, hydrothermal liquefaction and other thermal/chemical treatment, etc. can address achieving a higher quality product with less land application restrictions, a dewatered product that facilitates transportation, nutrient recovery for targeted fertilization, and treatment of contaminants. As treatment systems require energy to operate, the energy production of AD systems will also need re-examination.

Digestate characteristics are heavily influenced by the feedstock materials used in the AD system and the operating parameters of the system. Further studies are needed to help characterize digestate products for contaminant levels and assess the variability of contaminants related to feedstocks and AD processes in order to help inform end-use guidelines and safe handling requirements, and assure agriculture producers and the public of their safety. Contaminants of interest typically include pathogen indicators (e.g., Faecal Coliforms, E.coli and Salmonella), toxic elements (e.g., heavy metals), physical contaminants (e.g., plastics) as well as emerging contaminants, such as microplastics, perfluoroalkyl and polyfluoroalkyl substances (PFAS) and, pharmaceuticals and personal care products (PPCPs). A digestate characterization study was conducted in 2023/2024 by the Ontario Ministry of Environment, Conservation and Parks (MECP) and the Ontario Ministry of Agriculture, Food and Agribusiness (OMAFRA) to investigate the concentrations of these parameters in digestate from nine full-scale anaerobic digester systems (five on-farm systems and four commercial/ off-farm systems). The data is currently being aggregated and analyzed. Understanding the fate of these contaminants in full scale AD processes is important in assessing digestate quality, and making necessary changes to the system, if required. It will be important to track the fates of these contaminants, especially if there is greater adoption of AD with digestate application to agricultural land.

Canadian provincial and federal governments are supporting projects to better understand the GHG and NH₃ emissions from the management of digestate and biosolids. The results of these research and monitoring projects should help refine best management practices. Better understanding storage practices to reduce CH₄ and NH₃ emissions (e.g., storage covers, smaller surface area, acidification, etc.) and addressing land application rates, timing, and method of application to help reduce N₂O and NH₃ emissions are some of the options being investigated. Further demonstration and validation of new practices is needed at different sites across the country for a wide range of weather conditions that can be experienced.

4.1.4 Use of biogas, biomethane and/or carbon dioxide

The Canadian Biogas Association estimates that 22 PJ (6.1 TWh) of energy were produced from biogas in Canada in 2022. Most of this energy (73%) was from landfills.

The use of biogas varies by sector as follows:

- Landfill gas: mostly converted to electricity that is sent to the grid or used onsite; some direct biogas use by nearby industry; some upgrading to methane for injection into gas grid.
- Biogas from WWTP AD: biogas is used for heat and some electricity; starting to see upgrading to biomethane for injection or fleet vehicle use.
- Biogas from Biowaste AD: some electricity and heat use of biogas; new systems are upgrading biogas to biomethane for injection into gas grid or fleet vehicle use.
- Biogas from Agricultural AD: today most is converted to electricity that is sold to the grid with some use of heat from cogeneration systems on farms; new systems are upgrading biogas to biomethane for injection into gas grid.
- Biogas from Industrial AD: biogas is mostly used internally for process heat, generally displacing natural gas.

With the exception of industrial facilities that are larger energy users and fossil fuel energy purchasers, all of the other biogas and landfill gas producers are low energy users and need to find a buyer for their biogas energy. As such, their location relative to an energy user or a natural gas injection port plays a key role in determining the end use of the biogas.

The GHG reduction potential is greatest when biomethane replaces diesel fuel, however, relative to countries such as Sweden, for example, there is little natural (or vehicle) gas fueling infrastructure in Canada, and very limited use of biomethane in vehicles. A few municipalities have started fueling their truck fleet with biomethane, but there is little adoption by light duty vehicles where electric vehicles are being strongly promoted.

Interest in selling biogenic CO₂ from larger biogas upgrading facilities, such as biowaste AD systems, is growing. Some capture and sale of biogenic CO₂ is happening at ethanol plants as they have purer streams of CO₂. Several markets exist for the use of biogenic CO₂ in the agri-food sector, including carbonation in the beverage industry and dry ice production, and improving yields in greenhouse operations, but no projects have yet been developed in Canada that use CO₂ separated from biogas upgraders.

Most of the sustainability effects presented in section 2.4 (specified in Table 4: ET1-ET7) are relevant or potentially relevant in the Canadian context. The reduction in GHG emissions (ET3) resulting from the substitution of fossil-based energy with biogas-generated energy (electricity, heat or biomethane) is the clearest positive externality. Closely associated are the positive impacts on air pollution (ET4) and eutrophication (ET7), but the size of these impacts depends on what types of fossil fuels are displaced. The other effects (ET1 & ET2) of improved security of energy supply and more robust and flexible systems could become relevant if biogas production was to significantly grow in Canada. At its current level, it would be difficult to make this argument. However, one could say that biomethane production supports the use of existing natural gas infrastructure, buildings and equipment that currently use natural gas, and the transition to a renewable gas network.

Effects (ET5 & ET6) are not considered relevant because of the very small vehicle application, and the absence of any recovery and use of biogenic CO₂ from biogas upgraders.

Key drivers and enablers regarding the use of biogas, biomethane and biogenic CO₂

- Renewable gas mandates of two Provinces, with programs that provide premiums for biomethane that is produced in any part of the country.
- Government GHG reduction goals and plans - in particular, reducing the GHG emissions of the natural gas use.
- Carbon tax applied to industries with emissions above a certain threshold; i.e. encourages replacement of fossil fuels.
- Interest of private industry to lower the environmental footprint of its operations and products; i.e. CO₂ neutrality, sustainability goals.
- Regional ambitions for circular economy, waste reduction and local energy production.
- Local and regional air quality standards.

Key Barriers regarding the use of biogas, biomethane and biogenic CO₂

- Mismatch between production and use of biogas energy (i.e. with the exception of the industrial sector, biogas producers cannot use all of the energy they produce and must find an energy user or sell to the grid).
- Biogas energy has a much higher production cost compared with natural gas and other types of renewable electricity; i.e. necessity for government support, increasing cost to rate payers requires approval.
- High cost of new pipeline injection ports, and disagreements on who should pay for this cost
- Lack of natural gas fueling infrastructure and very little use of natural gas vehicles.
- Wide variability between AD systems and no single carbon intensity value that applies to biogas energy.
- No national biogas/biomethane/renewable gas targets, plans or identified pathways
- Ending of provincial electricity FIT programs; no financial support for electricity and heat production from biogas.
- Little recognition of biogas as a renewable energy carrier that could play a role in Canada's clean energy future; i.e. too small of an impact on the national scale.
- Federal carbon management framework (Natural Resources Canada, 2023) makes no mention of renewable or biogenic carbon.
- No incentives for use of biogenic CO₂.
- No technological solutions for small scale biogenic CO₂ from biogas plants (that are demonstrated and cost-effective).

Outlook

New federal landfill regulations are expected to encourage more recovery and energy use of landfill gas. Similarly, it is expected that WWTPs will be converting more of their biogas into energy, flaring less. As mentioned in Section 4.2.1, growing quantities of biowaste could either be composted or converted into biogas via AD, depending on the planning decisions of a region or municipality. Energy from agricultural AD is expected to grow at a modest rate. It is unclear what will happen to existing AD cogeneration systems after the electricity feed-in-tariff programs have sent out their last payments. Finally, little is known about industry's plans for new AD investment, but AD appears to remain a viable option to treat or pre-treat their effluents with a high organic loading, replace some of their fossil fuel energy and reduce their carbon taxes.

Excluding internal use of biogas for process heat, biogas upgrading and biomethane injection into the natural gas network is the only biogas energy pathway that is being supported going forward. Two Provinces (British Columbia and Quebec) with 2030 renewable gas targets are incentivizing new biomethane development across Canada, favoring large scale production projects. The Canadian Biogas Association has proposed a Clean Gas Standard for Canada that would include biomethane, bio-SNG and hydrogen (CBA, 2023c). Projections for the clean gas demand are 92 PJ in 2030 (with 42 PJ from biomethane) and 294 PJ in 2040 (with 188 PJ from biomethane).

Canada's clean energy focus on electrification and hydrogen, in terms of both policies and investment support, and the absence of a national vision for the role of renewable carbon in future energy systems presents uncertainty for developers and investors in Canada. An understanding of

what energy and material pathways make most sense for biogas, biomethane, e-fuels, biogenic CO₂ - at different scales of production - in lacking for the Canadian context.

4.1.5 Broader societal effects

Biogas solutions have effects that extend beyond the physical boundaries of the AD system or landfill gas collection system. As mentioned in the previous sections, many of the effects are regional in nature such as improvements in air quality, surface and groundwater quality, employment, and waste management, for example. There are also broader effects of sustainable development such as the transition away from fossil fuels to cleaner energy systems, the building of more circular economies (e.g. recovery of soil nutrients from wastes) and GHG emission reduction that has a global impact.

Given Canada's relatively small biogas industry, the broader societal effects that can be attributed to AD are not easy to identify. In countries with much higher population densities, the value of biogas solutions was recognized earlier and, consequently, led to a larger biogas industry and larger and more recognizable impacts. Nevertheless, the AD systems that are operating in Canada today are serving as concrete examples of how energy, nutrients and water can be recovered from waste streams using relatively simple technologies, and move the country towards achieving its sustainable development goals.

Canada's biogas solutions contribute to most of the overarching sustainability effects presented in Section 2.5 (specified in Table 5: S1-S11). Given the modest level of adoption of AD in Canada, the impact is small today but it would be expected to grow with more landfill gas energy recovery and AD system development. One of the most important societal contributions that biogas solutions are making in Canada is to increase the integration of distinct sectors of society, such as energy supply and waste management. That is, Canada's rich endowment of land and energy resources, combined with its low population density, have made sector integration less of a necessity, more costly and sometimes even impractical. Where AD systems have been adopted, new linkages have been established between traditionally separate sectors, such as:

- Agriculture and industrial and municipal waste management (carbon and nutrient cycling);
- Waste management and energy (electricity and natural gas) production; and
- Agriculture and energy (electricity and natural gas) production.

These connections are a prerequisite for building a more resource-efficient and circular economy, and are more challenging to create in large countries with a dispersed population.

The only sustainability effect that might not apply currently in the Canadian context is "improved agricultural resilience" (S8). While there exist biogas solutions that are profitable and contribute additional revenue streams and employment in the agriculture sector, today there is very little adoption of AD. Given the geography of the country, its farm-size distribution, the location of the natural gas network and current policy support, the adoption of AD by the agriculture sector is not expected to grow significantly.

Key drivers and enablers for contributing to broader societal sustainability effects

- Sustainable development legislation, goals and action plans.
- GHG reduction goals and action plans.
- Carbon taxation on fossil fuels.
- Circular economy goals and action plans.
- Renewable and clean energy transition.
- Use of existing natural gas infrastructure.
- New energy technologies, including energy storage.
- Rural economic development strategies and plans.

Key barriers to contributing to broader societal sustainability effects

- Land availability, good air and water quality in most parts of the country resulting in fewer “environmental hot spots”.
- Low population density in many parts of the country, i.e. few large cities.
- Abundance of energy resources – both fossil fuel and renewable resources – and relatively low cost.
- Importance of fossil fuel industry to Canada’s economy, placing attention on technologies to clean fossil fuels (e.g. carbon capture and storage).
- Policy and investment focus on electrification and hydrogen future, with very little mention of biogas solutions.
- Opportunities for biogas solutions are region-specific, making it challenging to justify national programs or policies.
- Division of jurisdictional powers over specific sectors, e.g. energy, environment, waste management and agriculture.
- Timing of infrastructure replacement, i.e. opportunities arising every few decades.
- Increased complexity of AD projects that requires active commitment from numerous other sectors.
- GHG emission reduction associated with biogas solutions are not a “single, standard number” but calculated on a case-by-case basis, making it more difficult to understand if there is a benefit, and how large the benefit might be.
- Uncertainty related to the presence of contaminants in biosolids and digestate, and suitability of land application.
- Undeveloped markets for AD co-products (digestate, CO₂).
- Public opposition to industrial development, including the powerful role that social media can play regarding new project development.
- Lack of public discussion of renewable carbon and nutrient recycling, as they relate to waste management and regional development.

Outlook

At a high level, the frameworks are in place to support further development of AD in Canada. Collectively, the Federal Sustainable Development Strategy; numerous environmental and climate change commitments, policies and funding programs; and Canada’s clean energy transition plans lay the foundation for inclusion of biogas solutions. However, today, biogas solutions do not figure prominently in government policies and programs, with the exception of the two Provinces that have adopted renewable gas mandates and support measures.

The opportunities for AD are regional, and they are about more than energy from biogas. Good examples exist that can demonstrate different sustainability effects, sector integration and important contributions of AD systems to the circular economy of a region. What is perhaps missing are robust sustainability assessments of AD systems in different regional contexts that can tell the story and expand understanding of how carbon, nutrients and water can be recovered and cleaned, how all of the products and co-products can be monetized and valued, and address common questions such as net GHG benefits, impact on odors and the fate of contaminants in land application of biosolids and digestate.

Biogas solutions should perhaps more accurately be referred to as AD solutions that are technically, relatively simple, proven technologies that can recover carbon, nutrients and water from waste streams and residues that can be used for energy and chemicals, regenerative agriculture and environmental services such as clean air and water.

4.1.6 Sustainability assessments

Although it is recognized that harmonized methods and evaluations would be very useful to assess the contribution of biogas solutions towards sustainable development in Canada, there are no known sustainability assessments that have examined the environmental, economic and social effects of the biogas industry as a whole. However, two case studies on AD systems are worth noting. One is a

study by Ncube et al. (2021) that used LCIA methodology to compare the environmental impacts of biowaste AD systems incorporating biogas cogeneration with those who were upgrading biogas to biomethane (via chemical amine scrubbing). The lifecycle of a medium-sized biowaste facility in the Province of Ontario was studied, and the following impact categories were evaluated: ozone depletion, global warming, smog, acidification, eutrophication, carcinogenic effects, respiratory effects, ecotoxicity and fossil fuel depletion. It was found that the AD-CHP configuration had better environmental performance in all impact categories compared to the AD-biomethane configuration. The substitution of fossil energy and fertilizer flows with renewable sources resulted in negative values for many categories. However, there were minor positive values for ecotoxicity, eutrophication and global warming impact when biomethane was compared to natural gas, pointing to areas that should be looked at more closely. Using renewable electricity that is produced onsite is better than using electricity from the grid, but the energy contracts don't allow for this. Also, the presence of plastics in biowaste and their subsequent disposal can significantly impact the overall sustainability of the value chain, and should not be ignored in assessments.

Wang et al (2021) studied the financial and environmental impacts of an AD system at a hypothetical large dairy farm (600 cattle) in the Province of British Columbia. Four scenarios were compared: 1) upgrading to biomethane; 2) cogeneration; 3) biogas combustion and local heat use; and 4) integration of AD co-products and heat by nearby agricultural operations. From both financial and environmental perspectives, the system which integrated agricultural AD with the operation of a nearby greenhouse and mushroom farm provided the best results. Here, all of the products of AD were utilized, i.e. heat and CO₂ were directly used in the greenhouse displacing natural gas, the liquid digestate reduced synthetic fertilizer use in the greenhouse and the dried solid digestate was used as mushroom growing media replacing 25% of rock wool consumption. As opportunities for such integration do not always exist, the next best option with respect to GHG emissions and cost (i.e. least amount of subsidies) was to combust the biogas and use the heat directly (e.g. district heating).

These sustainability studies demonstrate that the lifecycle impacts of AD systems depend on the specifics of the value chain and the environmental effects extend beyond GHG reduction. Their financial and environmental impacts will depend on the end-uses of both the biogas and the digestate, and there are important advantages provided by symbiotic integration of AD. Policies that focus exclusively on large scale production and biomethane injection into the grid to achieve GHG reduction are not capturing many benefits that could be provided at smaller scales in multiple locations across the country.

In conclusion, sustainability assessments carried out on existing AD systems could provide valuable evidence to demonstrate the potential of different AD systems located in different regional contexts to provide a variety of sustainability effects. Such information would increase the knowledge base for both policy makers and the public, enabling them to make development decisions with greater confidence.

4.2 France

France's Multi-Annual Energy Programming Policy (PPE¹²), aims to reach 24-32 TWh of biogas production by 2030, of which 14-22 TWh are expected to be biomethane that will be injected into the gas grid. The goal also includes the generation of 340-410 MW of electricity, based on biogas cogeneration plants.

Over the last three years, biomethane production has increased by 30% in France, representing almost half of the total production. However, the lower subsidies resulting from the 2020 policies on new feed-in-tariff biomethane contracts, the European gas and electricity 2022-2023 crisis and the subsequent anti-inflation readjustment policies, led to 'stop and go' conditions for the sector. As a positive outcome, French policymakers better understand the sector dynamics, its weaknesses and opportunities.

Currently, there is a slight lack of skilled workforce to design and operate biogas plants. This workforce requires combined industrial and agronomical competencies that can apply restricted schedules and responses to security alarms (in case of AD plant malfunctions at any time) and comply strictly with risk management instructions (e.g. to avoid gas-caused risks of fire, explosion or suffocation).

4.2.1 Broader history and waste and wastewater treatment

Biogas production in France mainly began in the wastewater sector, while there were also some early activities related to biogas from manure. In 1884, Ulysse Gayon, Bordeaux Agronomic station director, observed and proved energetic power of biogas and its use for heating and lighting. In 1930, two teachers at the Alger National Agricultural School received a patent on a digester. At that time, thousands of systems were set up as the manure gas cooker "Gazelle". During the second world war and subsequent oil crises, biogas plants helped to alleviate the high cost of fossil fuel energy. But as fossil fuels became cheaper, interest in biogas was declined.

Around 1980, there was a wave of new projects and almost 200 biogas plants were built (Thual, 2020). These plants were established at landfill centres (ISDND¹³), urban wastewater treatment plants, and agri-food industrial wastewater facilities.

Contemporary biogas politics

In 2002, a feed-in-tariff was introduced for landfill gas which incentivized the development of biogas plants designed to produce heat and power. In 2008, French gas operators built the first upgrading plant, transforming the raw biogas into biomethane, which led to a regulatory framework to be put in place in 2011. Consequently, there was a rapid expansion of biomethane facilities, as they became most profitable and up-to-date. In 2018, a "Releasing renewable energies" State project was launched¹⁴. In 2020 the feed-in-tariff was reduced to drive the costs of energy from biogas towards the lower costs of other types of renewable energy (Cadiou, 2023).

The start of the war in Ukraine, in 2022, and the subsequent diplomatic turbulences effected Europe's energy supply. As a result, French biogas systems were both negatively and positively impacted. Negatively, as costs for construction and operation of biogas plants sharply increased, and positively, as the costs for production of electricity and biomethane were more stable for some months, making these renewable options more beneficial for the State compared to fossil electricity and natural gas.

¹² Programmation Pluriannuelle de l'Energie (PPE), Ministry of Ecology, 2024.

¹³ Installation de Stockage de Déchets Non-Dangereux = « non-hazardous waste storage centres »

¹⁴ [Releasing Renewable Energy Plan. Ministry of Ecology, 2018](#)

As of January 1, 2024, there were 1,724 active biogas plants in France, and 161 facilities extracting landfill gas. Figure 5 summarizes the types of biogas plants and how the biogas is used.

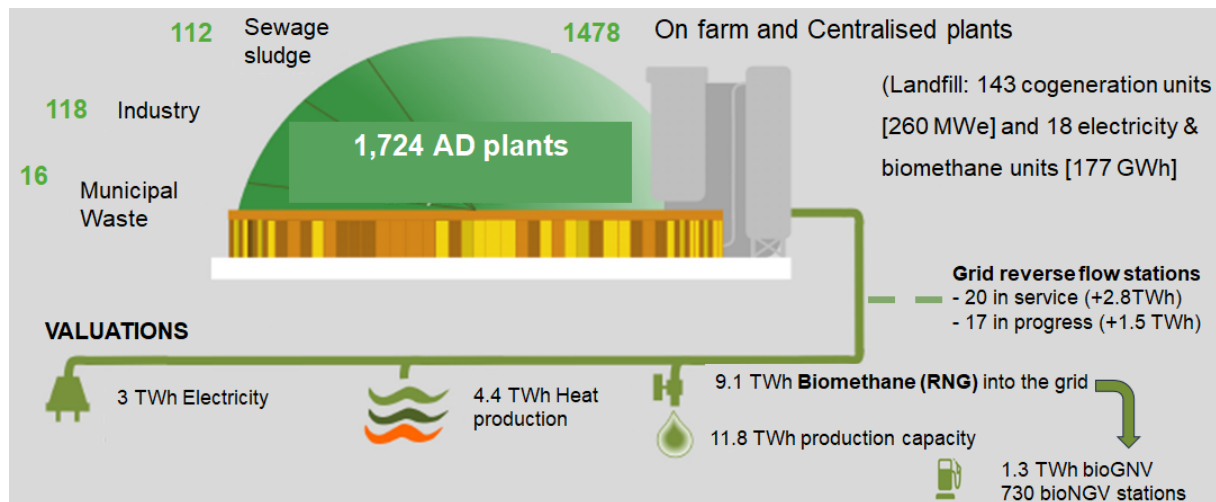


Figure 5. Biogas (AD) plant typology and energy provision in France on the 1st of January 2024 (ADEME, 2024).

The majority of French biogas plants (1,478) are “on farm and centralised”. “On farm” refers to a biogas plant which is owned by one or a few farmers. Smaller units, below 70 kWe, are classified as “micro -AD”. “Centralised plant” refers to a joint venture between an extended group of farmers but can also include an industry or a municipality. Sewage sludge is treated at 112 urban/municipal wastewater facilities. There are 118 industrial biogas plants, treating industrial effluents.

The most obvious positive externalities of biogas plants include:

- Treatment of wastewater with high organic loading, while producing energy
- Supply of energy and fertilizers from renewable bioresources (slurry, biowaste, etc)
- Energy security and flexibility - possibility to supply a mix of energy products such as electricity, biomethane and bioNGV (vehicle gas).
- Agricultural resilience - providing new incomes to farmers, allowing them to keep livestock farming on the land

Examples of essential drivers regarding biogas solutions in the waste and wastewater sector:

- French law obliges municipalities to offer a solution for sorting food waste, mainly with composter distribution or collective biowaste bin that is sent to biogas plants.
- The ADEME incentive approach “Territories in Transition” which drives communities to voluntarily comply with a holistic and updated transition action plan (e.g. to use biomethane in public transport, increase the percentage of renewable energy in their region, etc.)
- Waste premium and prices. Some waste going to biogas plants can earn an extra premium that is added to the feed-in-tariff (e.g. extra premium for a 60% livestock manure input). Some municipal or agro-industrial co-products have switched from negative prices to positive prices (costs) as co-products have become more energetically valuable and therefore more sought after by local biogas producers.
- Professionalization schemes with quality standards such as the “Qualiméthas” certified company list. This label certifies verified skills and liability of biogas plant manufacturers.
- Biogas plant cost-efficiency CAPEX and OPEX to be continuously improved by progressively lowering the feed-in-tariff, the adoption of extra-budgetary financial tools (such as BPAs - Biogas Purchase Agreements) and limiting investment subsidies to rare cases.

Examples of barriers regarding biogas solutions in the waste and wastewater sector (ADEME, 2014):

- Biogas production at WWTPs can be highly irregular, making it challenging for heat and power production. Storage and upgrading to biomethane can be feasible.
- The size of WWTPs is technically critical: that is, below 30,000 person equivalents economic viability is challenging. There is a need for off-the-shelf biogas solutions.

Outlook

There are some signs of positive development regarding micro-AD plants that could be suitable for smaller WWTP applications.

4.2.2 Agriculture, feedstock related effects

Agricultural biogas solutions comprise a major part of the French biogas system. There are many small plants and a few large, centralized biogas plants. Figure 6 presents the types of feedstocks used in these plants and their respective shares (%).

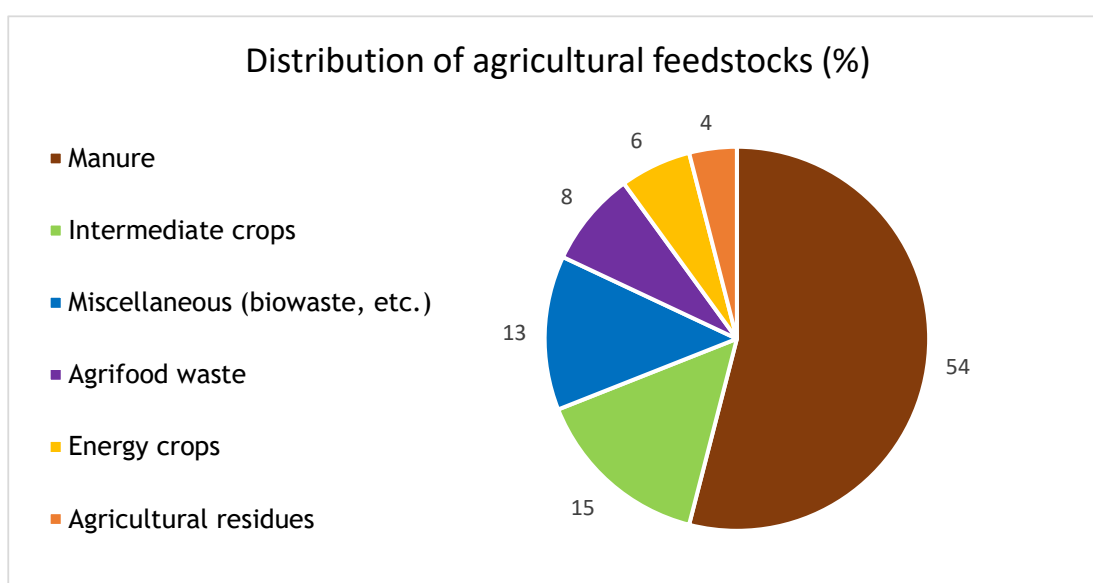


Figure 6. Biogas energy production shares for various agricultural feedstocks. In total, about 33,7 million tons wet weight (ww) is used per year (ADEME, 2024, estimates based on AD unit database SEAMETHA for 2020-2023 and 2022 ONRB tonnage).

Feedstock potential and sustainability effects

For all agricultural feedstock types only a limited share of the potential is utilized (Monod, 2022):

- Agricultural residues (cereal straw, oilseed straw, silo residues): 0.9 million tons (ww) used out of 4-7 million tons (12-23%). Sustainability effects include: enhanced resource efficiency and improved resilience for farmers.
- Agrifood byproducts/waste (middlings from starch, milling, semolina, malting, beet pulp, vegetable processing residues from tomato, pea, bean, potato processing, grape marc, lees, grape vinasses, apple marc, beet vinasses, whey powder, skimmed milk powder, co-products from slaughterhouses and from other meat industries): 7.4 mt used out of 7.4-16.8 mt ww (44-58%). Sustainability effect: enhanced resource efficiency.
- Cover crops (intermediate crops): 6 million tons (ww) harvested on 3% (300 kha) of France's agricultural land (11,337 kha). These cover crops are not intended to compete with, replace or negatively impact the yields of the main crop that will grow on the same fields. These cover crops are associated with positive sustainability effects and when well-managed, avoid several negative effects such as competition with human food or fodder.
- Energy crops: 2.5 million tons (ww) are mobilized out of 50 million tons (5%). French legislation impedes energy crops to exceed 15% of annual tonnage used in biogas plants.

Examples of essential drivers regarding agricultural feedstock for biogas systems:

- There is significant untapped potential for more biogas production from manure and agriculture residues. Research and innovation can largen the potential, for example, in relation to materials that are in limited use today because of incorporation and degradability issues (such as lignocellulose).

Examples of essential barriers regarding agricultural feedstock for biogas systems:

- In drier years, market stresses can be experienced for agricultural byproducts, such as sugar beet pulp that has historically been used as fodder. How such products are used (e.g. as fodder or for biogas) is influenced by the economic viability, which is linked to the income, treatment costs, transport costs, etc. To have greater control and avoid transport costs, it has become more common for agro-industries to build their own biogas plants.

Outlook

- About 70,000 open slurry pits exist in France, and about 570 000 more in Europe as a whole, that continuously release methane into atmosphere. There are companies supplying biogas customized pit covers, and there are huge opportunities to expand this business. For a typical French farm, such a pit cover with biogas utilization can provide its yearly energy needs, in addition to reduced climate impact, making it possible to avoid expenses related to fossil fuels. New small-scale upgrading technology may allow for biomethane production at smaller farms, thereby making it possible to produce their own fuel for agricultural tractors or other equipment.

4.2.3 Agriculture, use of digestate/biofertilizers and other aspects

In France, Digestate is commonly passed through a phase separator, delivering a solid (containing most of the phosphorus¹⁵) and liquid fraction (containing most of the nitrogen) to be spread on fields. For some biogas plants with special conditions, such as too little agricultural land nearby available for digestate spreading, the digestate can be composted to obtain a standard compost (NFU 44051) which can then be sold by retailers and spread without constraints.

Examples of essential drivers regarding use of digestate/biofertilizers:

- Relatively high cost of mineral fertilizers
- Further development of digestate/biofertilizers can make them more competitive.

Examples of barriers regarding use of digestate/biofertilizers:

- Nearby agricultural land, within a reasonable distance for spreading, can be subject to stringent nitrate directive restrictions. This requires lengthy storage of digestate and/or transportation to areas further away, which effect both the financial and environmental performance.

Outlook

New technologies and practices are being tested to improve the fertilization efficiency while preventing nitrogen losses, and they can further strengthen the case for digestate (or biofertilizers produced from digestate).

4.2.4 Use of biogas, biomethane and/or carbon dioxide

An overview of the biogas-related energy flows in 2023 is presented in Figure 7. In this year, 3 TWh of electricity and 9.1 TWh of biomethane were injected into the national electricity and gas grids. Biomethane was made accessible to distant consumers thanks to the installation of reverse flow/recompression stations on the gas network. A significant portion, 1.3 TWh of biomethane, was directed to 730 vehicle gas stations (CNG stations) for fueling trucks or buses. Given that French

¹⁵ The separation technology can significantly influence where the P ends up.

electricity consumption in 2023 was 445 TWh, electricity from biogas powered 0.6% of this demand. Biomethane supplied 2.4% of total natural gas consumption of 381 TWh (GRTgaz, 2023).

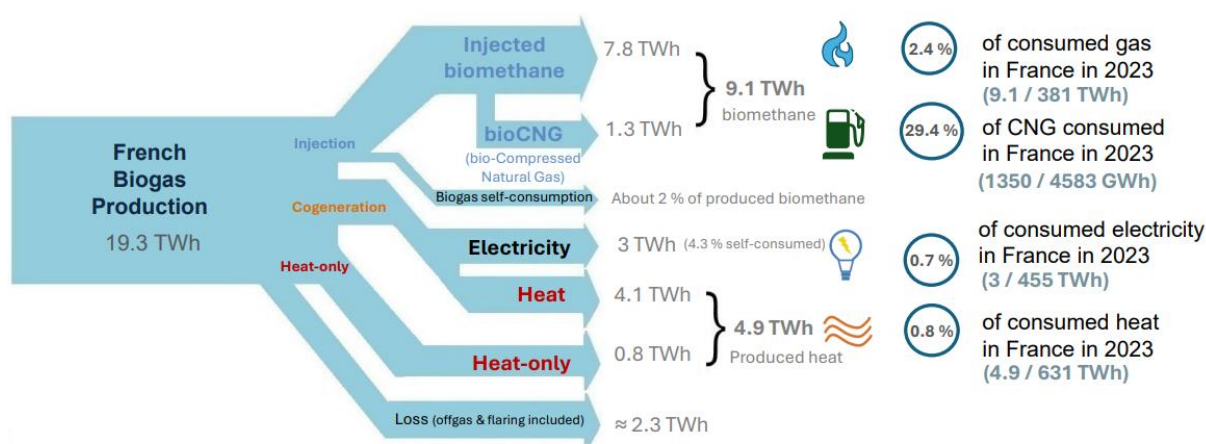


Figure 7. Biogas sector energy flows 2023 (ADEME, 2024).

The 2023 updated French Energy-Climate Strategy includes the goal to reach 50 TWh of biogas energy in 2030. By 2050, 100% of the gas in the grid is to be renewable.

Examples of key drivers regarding use of biogas/biomethane:

- Long awaited recent CPB regulations¹⁶ represent an important extra-budgetary tool for further expansion of the sector as they provide clearer financial framework for the updated PPE-SNBC¹⁷ climate strategy.

Examples of barriers regarding use of carbon dioxide:

- The relatively small volumes of CO₂ from biogas plants limit the possibilities for industrial valorization. Local valorization such as use in greenhouse seems preferable.
 - More needs to be understood regarding economic viability and sustainability performance of different options for CCU or CCS. Further studies are essential.

Outlook for renewable gases

Pyrogasification, hydrothermal gasification and other innovative green gas technologies may provide opportunities to valorize feedstocks that today are difficult to treat in biogas plants. These other technologies are expected to complement biogas energy to meet the 100% renewable gas in the grid target in 2050.

4.2.5 Broader societal effects

On the one hand French biogas policy promotes biogas and especially biomethane production, while on the other, biogas plant profitability is monitored closely to reduce the State's financial commitments while increasing private law contracts - with Power Purchase Agreements (PPA) and Biogas Purchase Agreements (BPA), and the "Certificat de Production de Biogaz" (CPB¹⁸) mechanism. This new mechanism¹⁹, from January 1, 2025, requires suppliers above the 400 GWh PCS threshold, and gradually lowered by 100 GWh/year until all suppliers are included in the system, to return the CPB to the State by "directly" producing biomethane injected into a gas network or by acquiring certificates from new producers who will inject into a gas network. With

¹⁶ Décret n° 2024-718 du 6/7/24 relatif à l'obligation de restitution de CPB [\[en ligne\]](#)

¹⁷ Stratégie Nationale Bas-Carbone (National low-carbon strategy)

¹⁸ Biogas Production Certificate

¹⁹ [Décret n° 2024-718 du 6 juillet 2024 relatif à l'obligation de restitution de certificats de production de biogaz](#)

this extra-budgetary mechanism, the final gas consumer will pay more of the production cost. Today, the French biogas system is a key part of the National energy grid, and its relative importance is gradually growing in the management of supply and demand, especially during this period of crisis.

Among different types of renewable energy, it should be noted that biogas energy offers the greatest flexibility as biomethane can be stored and consumed during energy peaks, or even be used in different seasons.

The multifunctionality and societal relevance of biogas systems are acknowledged in the French context, as further elaborated in the following section and in 3.3.2.

4.2.6 Sustainability assessments

Sustainability assessments have been used in France to help justify government financial support and other government actions that have been taken to advance the development of the biogas industry. As shown in Figure 4, in 3.3.2, key externalities (sustainability effects) associated with France's biogas systems have been identified for services in four areas: agricultural and agro-ecological; socio-economic; environmental and energy. In 2018, ENEA developed a framework to evaluate and monetize the externalities produced by biomethane value chains in an effort to improve the competitiveness of these value chains. This work helped bring to the forefront the multiple services that biogas plants can provide, and influences how policymakers make decisions around AD.

France has the ambition to balance environmental compliance (performance) and a market-based approach (including reasonable types and levels of subsidies) and aims to pave a resilient path for a 'carbon-negative' and competitive French biogas (AD) sector. As such the French government regularly reviews sector challenges and revises its approach, as required.

For example, biogas plants are regulated by the French Environmental Code, Section 2781. Depending on the annual tonnage (of feedstock) the requirements differ with respect to authorization, registration or declaration, with associated constraints and periodic checks. For instance, plants in the authorization category must, at all times, utilize best available technologies (BAT).

In 2021, the French government called for a national government inquiry to better understand the role of AD in the energy mix, including its impacts and challenges. A Mission of Information (MI) on AD was requested by the French Senate (MI Sénat, 2021). The Mission heard from 106 persons in plenary sessions, 28 others in private auditions and visited 3 units. The report noted:

- If AD is useful for the energy transition, then its support framework is ambiguous, with a "French AD model" still struggling to assert itself.
- As a source of both positive and negative externalities, AD is the subject of growing debates regarding its risks

As an outcome, 61 proposals were prepared to support a "French AD model", along these five themes:

1. Clarify public policies to ensure the balance of the energy mix by renewing the strategic and support framework.
2. Structure and strengthen governance to improve practices by diversifying the sources and uses.
3. Improve regional projects by mobilizing local authorities and strengthening project quality.
4. Improve practices to increase their positive externalities by using non-agricultural substrates, acquiring more knowledge on AD environmental impacts.
5. Prevent risks.

4.3 Norway

Norway's current biogas production amounts to c. 0.7 TWh per year (Norwaste, 2023). The Norwegian biogas platform from 2024, which is the industry's action plan for increased production and use of biogas, proposes a goal of producing 5 TWh in 2030 and 10 TWh in 2035. The development of the biogas industry in Norway from 1990 onwards is illustrated in Figure 8. The amount of biogas produced is given in the y-axis based on country's official statistics (Statistics Norway, 2024). The colours illustrate that the Norwegian biogas production can be divided into separate phases, based on the main drivers within each period. The drivers also reflect the most important co-benefits and potential sustainability effects.

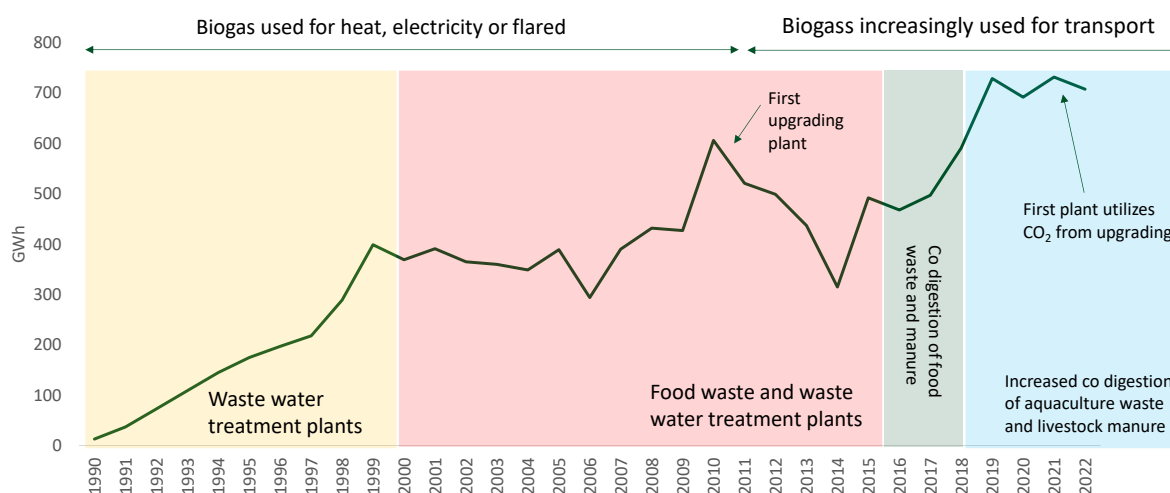


Figure 8. The development of the biogas industry in Norway, where the colors indicate different phases with varying main drivers.

4.3.1 Waste and wastewater treatment

Between 1990 and 2000 the first biogas plants were built in Norway (illustrated with yellow color in Figure 8). These were wastewater treatment plants with a primary purpose to treat sewage sludge, ensuring safe processing and preventing emissions.

From around year 2000 (illustrated with pink color in Figure 8) more wastewater treatment plants were built, in addition to several municipal biogas plants aimed at treating food waste from households and industry. Similar to the previous time period, biogas production was primarily regarded as a waste management technology. With relatively low energy prices, less attention was directed towards optimal utilization of the biogas. A large share of the biogas plants produced heat for internal purposes, or for surrounding buildings. The share of flared biogas was considerable in this period.

In these two time periods (yellow and pink color in Figure 8) the sustainability effects related to waste and wastewater treatment (W1-W8) were most relevant, especially W1 improved water security due to the wastewater treatment plants, W2 Improved resource efficiency when separating and valorizing organic waste from household and industry and W3 Reduced climate impacts.

4.3.2 Agriculture, feedstock related effects

The use of feedstock from agriculture for biogas production was less widespread in Norway until 2016, when the first large, centralized biogas plant for livestock manure was built. In this plant, manure is co-digested with food waste. The main driver behind the use of manure for biogas production in Norway is related to reducing GHG emissions from storage of manure. Economic costs are among the most important barriers to increasing the use of manure as feedstock. Due to small farm sizes and relatively low energy prices in the past, in general, there has been a lack of

economic viability for farm scale biogas production. For centralized biogas plants manure is viewed as a less attractive feedstock due to high transport costs.

To reduce these barriers, an economic support system was introduced in 2012 for farmers supplying manure to a centralized biogas plant or using manure as feedstock in a farm scale biogas plant. The amount of manure used for biogas production is increasing each year, but the share of manure treated by anaerobic digestion is still around 1%. As the majority of biogas plants currently being developed and constructed are designed to use manure as feedstock, the prospects for increased use of agricultural feedstocks are promising.

The most important co benefits (positive sustainability effects) are AF7 Reduced climate impact, improved manure management as well as AF9 Reduced problems of eutrophication, as centralized biogas plants can enable a better nutrient distribution between different geographical areas.

Co-digestion of food waste with manure is also seen as a way to reduce water use in the pretreatment process for food waste. Liquid manure has high water content, while water needs to be added to food waste in the pretreatment stage to obtain the desired dry matter content. Additionally, manure is regarded as a stabilizing feedstock that reduces the risk of unplanned production stoppages in the case of variable feedstock flows.

Co-digestion of manure with fish sludge and fish silage from aquaculture has gained increased attention and seems to be a desirable combination for most of the new biogas plants in Norway (illustrated with blue colour in Figure 8). Biogas production of wastes from land-based fish farming is relatively common, while the collection of sludge from offshore fish farming is currently being explored. Collection of sludge will reduce release of nutrients into the ocean and can potentially lead to reduced problems of eutrophication (sustainability effect AF10).

4.3.3 Agriculture, use of digestate/biofertilizers and other aspects

Although utilization of nutrients in the digestate is seen as a crucial part of a circular bioeconomy, digestate has currently little economic value as a product, and can even represent a cost for the biogas plant owners. Nevertheless, the Norwegian biogas statistics show that the majority of the digestate is used in agriculture (88% of the total dry matter of digestate produced), followed by utilization on green areas such as gardens and parks (11%) (Norwaste, 2023).

Digestate can be an attractive product among farmers, as it can be used as soil improvement to increase organic matter and microbial activity (AB3). It can also be used as fertilizer and substitute mineral fertilizer, which can reduce climate impact by avoiding GHG emissions from reduced production and use of mineral fertilizer (sustainability effect AB5).

Some farmers are concerned about spreading of pollutants when applying digestate to agricultural soil (sustainability effect AB9). For example, there may be plastics in digestate due to mis-sorting and failure to remove all plastic when the food waste is collected in plastics bags. The biogas industry has addressed this challenge by encouraging the collection of food waste in degradable bags and by developing improved technologies to remove plastic material.

The increased interest in using fish sludge and fish silage from fish farming for biogas production raises new concerns among some farmers regarding the quality of the digestate. The concerns are related to heavy metal and salt content (sustainability effect AB9), as well as the balance between nitrogen and phosphorus. Several research projects are now in place to address some of these issues and to document the quality and environmental burdens and benefits related to the use of marine substrates for biogas production.

4.3.4 Use of biogas, biomethane and/or carbon dioxide

Despite being a significant exporter of natural gas, Norway has limited gas distribution infrastructure, and domestic consumption levels remain low. When the first biogas upgrading plant was opened in 2010, it enabled the use of biogas as a fuel for transport. Since then, the share of biogas used for transport has increased steadily. Relevant sustainability effects are ET3 Reduced climate impact, substituting fossil energy carriers; ET4 reduced air pollution, substituting other energy carriers; and ET5 Reduced noise levels, substituting other energy carriers.

There is also increased interest in capturing biogenic CO₂ from the upgrading of biogas, to be utilized for different purposes, for example in greenhouse food production. The possibility of carbon capture and storage (CCS) is also being explored by several Norwegian biogas plants. This shows the relevance of the sustainability effect ET6 Reduced environmental impact.

4.3.5 Broader societal effects

With the ambition to increase food waste separation to 55% in 2025, 60% in 2030 and 70% in 2035, biogas production and recycling of the nutrients in the digestate represent an important facilitator of obtaining a more circular economy (sustainability effect S1). Biogas can also play an important part in larger biorefineries, to ensure that bioresources are utilized in the best possible way (sustainability effect S3). An example of this is the Norwegian biorefinery Borregaard, which produces advanced biochemicals capable of replacing oil-based products, where anaerobic digestion is one of many treatment steps.

Due to the country's dispersed population and long distances between settlements, value creation across the entire country is an important political principle in Norway. In this context, biogas production is seen as an enabler for local and regional development, which allows for local waste handling sources and energy provision (sustainability effect S9). According to the national biogas statistics, Norway's annual biogas production contributes to 1,255 full-time equivalent jobs and a value creation of 1,476 million Norwegian kroner (Norwaste, 2023), illustrating sustainability effect S7 Business value creation.

Finally, in a world marked by war and conflicts, there is an increased awareness in Norway that biogas production also can help to diversify its energy supply, decreasing energy dependency and vulnerability. Furthermore, recycling of nutrients in the digestate can give access to local phosphorus resources and reduce dependency on imports (S11 Societal resilience, security of critical supplies).

4.4 Sweden

The Nordic Biogas Model dominates in Sweden, where different types of wastes and byproducts are greatly valorized in biogas plants to biomethane and biofertilizers (Lindfors et al., 2022). This model is also important in Denmark, Finland, and Norway. These systems deliver renewable energy carriers, fertilizers (and/or soil conditioners), and waste management services, with several associated positive sustainability effects.

Before going into specific context and effects, some aspects of general importance should be mentioned. Firstly, a national, governmental inquiry (see 4.4.6) recommended a national target for biogas production, but such a target has not yet been officially adopted. Secondly, being part of the EU there are some strong policy drivers and barriers that are common for several other Task 37 member countries. The biogas related policy landscape is complex and has been very dynamic and uncertain for decades (Gustafsson and Anderberg, 2023, 2021, 2021; Shan et al., n.d.). It is important to note that for a long time Sweden has supported the use of biomethane as transport fuel via a tax exemption, instead of supporting biogas production as done in many other EU countries. Due to objections and EU legal processes this exemption was stopped for more than a year, which created uncertainty and slowed down development. However, the exemption was (again) approved in October 2025. Thirdly, a national climate related investment support program (Swedish: *Klimatklivet*) has significantly supported the establishment of biogas plants, filling stations, investments in gas fueled vehicles, etc. Fourthly, there are often some challenges related to finding suitable locations and in getting environmental permits for new biogas plants (cf. Feiz et al., 2022b). There are many examples of long permitting processes. Finally, a significantly expanded biogas sector will require a skilled workforce of sufficient size. This could be challenging to address.

Important sources of quantitative information (in 4.4.1-4.4.4) are Gustafsson et al. (2024) and yearly statistics from the Swedish Gas Association, published in cooperation with the Swedish Energy Agency and other organizations.

4.4.1 Waste and wastewater treatment

The history of biogas production in Sweden mainly started in the wastewater sector, where AD technology was introduced for treating sewage sludge in the 1930s. For a long time, emphasis at these plants was placed on the hygienization (sanitation) role and the biogas production was not optimized, and the gas was often flared. Nowadays, it is common practice for wastewater treatment plants (WWTPs) to utilize biogas technology, although there is still room for more efficient biogas production. Publicly owned WWTPs are an important backbone of the Swedish biogas sector, representing about 30% of the domestically produced biogas. This is a stable city centered source of biogas, produced year around.

About half of the digestate, from WWTPs utilizing AD, is used as biofertilizer. The REVAQ (SPCR 167) quality standard has been essential for this. It is a broad certification system, involving systematic efforts to limit upstream pollution, and to standardize the digestate/biofertilizer quality, traceability and transparency.

The municipal (public) waste sector is also central to the Swedish biogas system, where source-separated organic waste, such as food waste from households and restaurants, is an important feedstock for biogas solutions. As food waste is relatively rich in energy, it is transported between different municipalities, and from Norway to Sweden. The relatively well-organized and widespread organic waste collection (involving households) is essential for biogas production and other types of waste treatment. While some municipalities send the collected organic wastes to other municipalities (involving private biogas plants owners), others treat the food waste to make a slurry suitable for biogas plants, which sometimes is done collectively (several municipalities in cooperation). Some municipalities have publicly-owned companies running biogas plants, where food waste is co-digested with other types of feedstocks supplied from the industrial and agricultural sectors, for example.

About two decades ago (from 2001 and onwards), the legislation on landfilling was revised, with much stricter regulations on landfilling of organic waste. About 5% of the domestic biogas originate from landfill extraction, but with very limited landfilling of organic material, this source is declining.

Clearly, all the sustainability effects mentioned in section 2.1 (specified in Table 1: W1-W8) are relevant for biogas solutions in the context of the Swedish waste and wastewater treatment sector. The biogas systems contribute to water security (clean water), and safer and more resource efficient (and circular) waste management both in the public and private (industrial) sectors. In comparison to some other countries, the effects related to landfills may be somewhat less important due to the limited use of landfilling mentioned. The low population density means relatively good access to land, implying that landfills may have a smaller impact on urban land availability, flexibility, and value. However, such impacts are still important in Sweden.

Examples of essential drivers regarding biogas solutions in the waste and wastewater sector:

- Regulations/Bans on landfilling of organic waste.
- Waste fees.
- Regulations on organic source separation, demands on municipalities/cities. In general, relatively well-organized waste management systems, and a culture supporting source separation.
- Public interest and investments, public sector organizations taking the role as system builders to combine residue treatment and the use of biogas in the public transport sector (for buses and vehicles owned by the public organizations) (Fallde and Eklund, 2015; Ottosson et al., 2020).
- Certification schemes and quality standards, for digestate/biofertilizers.
- Industrial cost-efficiency improvements and constraints to expand production within a certain environmental permit (AD may lower emissions per unit of production).

Examples of key barriers regarding biogas solutions in the waste and wastewater sector:

- Upstream pollution (e.g. presence of heavy metals) could hinder the use of the digestate.
- Biogas plants at WWTPs were not originally optimized for biogas production.
- Some industrial actors/sectors being conservative.
- Shift in focus from biomethane to electrification, for example, in the public transport sector (Mutter, 2020, 2019).

Outlook

The waste and wastewater sector is an important, stable and slightly growing source of biogas and digestate/biofertilizers. However, there is a potential for growth, mainly from further collection of organic waste, and implementation of AD technologies within more industries (such as the pulp and paper sector). A growing population results in more organic waste and wastewater.

4.4.2 Agriculture, feedstock related effects

The agricultural sector is importantly involved in the Swedish biogas systems (also explained in other sections in 4.4). In this sector the biogas plants take the form of both large centralized plants and several smaller farm-scale plants, but the relative contribution of the agricultural sector is small in comparison with some other countries with an active biogas sector. There is a large potential for growth.

Regarding agricultural feedstock, the use of manure has significantly expanded in the last decade, although the untapped potential is still significant. There are large amounts of agricultural residues in some parts of Sweden that could be utilized for biogas solutions (only a small share is used). Energy crops (like maize) have never been a popular feedstock, although there are examples of intermediate crops (such as ley crops and oil seed radish) that have been used.

One relatively large biogas plant was originally designed for a substantial share of intermediate crops, but it was redesigned for other feedstocks, several reasons (mainly EU policy).

Most of the sustainability effects mentioned in section 2.2 (specified in Table 2: AF1-AF17) are of some relevance. As energy crops are not used several of the negative effects are avoided, such as competition with food or fodder. Regarding the positive effects, biogas from manure can have a very strong climate performance (climate positive) and reduce odor related problems. Further on, some agricultural residues are valorized through biogas systems, bringing additional income to farmers.

Also, there are examples in Sweden of aquatic feedstock being used for biogas production, both within the agricultural sector and elsewhere, with the objective of reducing nutrient related problems (eutrophication). Intermediate crops are associated with several positive sustainability effects. However, there is currently very little use of aquatic feedstocks and intermediate crops in biogas systems. Harvesting intermediate crops in late autumn can be challenging due to wet and muddy conditions. Additionally, regulations play a significant role in determining what is allowed and what provides economic compensation.

Examples of essential drivers regarding agricultural feedstock to biogas systems:

- Manure based production is strongly supported, including financial support.
- Several private initiatives to build large, centralized biogas plants, demanding manure and other types of agricultural feedstock.
- Increased attention on the security of supply at the EU and national level. Potential for agricultural intensification involving intermediate crops that can be used in biogas systems.
- Good alignment with Swedish environmental objectives (but not supported correspondingly), including a more sustainable agricultural sector.
- Technological development and standardized production concepts, including the potential increased use of straw.

Examples of key barriers regarding agricultural feedstock to biogas systems:

- EU restrictions on the use of crops for biogas production, involving ambiguities and changes/uncertainty - pose a significant barrier to the use of intermediate crops.
- Agricultural culture and traditions.
- Lack of competency and capabilities to support farmers interested in biogas solutions.
- Partly small-scale agriculture, meaning that cooperation between farmers might be required to reach sufficient scale (also challenges related to distributed feedstock). Cooperative solutions may provide opportunities but can also be more challenging to establish.
- A large share of crop residues consists of straw, which is challenging to degrade/digest.
- In some cases, environmental legislation developed for more traditional polluting industries has hindered projects involving agricultural or aquatic feedstock to biogas production.
- In general, several early and especially small-scale agricultural biogas initiatives faced a multitude of technical and economic barriers.

Future outlook

There is a large untapped potential in Sweden for the agriculture sector to produce biogas, biofertilizers and other products, while contributing to a more resilient and sustainable agricultural sector.

The policy landscape appears most stable for the use of manure and agricultural residues, where the economic subsidy likely will expand biogas and biofertilizer production from manure. There are signs of a more nuanced view on the use of intermediate (or sequential, low iLUC) crops within EU. Support for the use of such 'sustainable agricultural feedstock' would provide a platform for expanded production, involving agricultural intensification, while also contributing to several positive sustainability effects.

There is significant interest in new biogas plants with important shares of agricultural feedstock, both from large actors and developers of farm-scale units. A technical breakthrough regarding straw digestion could make a major difference, making use of this largely untapped potential.

4.4.3 Agriculture, use of digestate/biofertilizers and other aspects

About 90% of the digestate from Swedish biogas plants is used as biofertilizer in the agricultural sector. The percentage applied to land is pulled down by the lower level of application (c. 50%) of digestate from WWTPs. Most of the large producers (including WWTPs) produce certified biofertilizers, where the standards SPCR 120 and Revaq, involving independent third-party auditing, are followed. Digestate from WWTPs is usually dewatered, while digestate from other biogas plants is typically not.

The majority of the sustainability effects mentioned in section 1.1 (specified in Table 3: AB1-AB10) are highly relevant, including effects such as nutrient recycling, soil fertility improvements, and reduced climate impact due to carbon sequestration. Biofertilizers from biogas plants are essential for ecological/organic farming.

Examples of essential drivers regarding use of digestate/biofertilizers:

- Increased costs for mineral fertilizers, more attention being paid to security of nutrient supply and broader agricultural resilience.
- Demand from ecological/organic farmers.
- Increased awareness and demand for more sustainable agriculture, long-term investment in soil health, etc.
- Valorization of digestate as better fertilizer products.

Examples of key barriers regarding use of digestate/biofertilizers:

- Agricultural culture and traditions. Different views of efficient agriculture (short term production versus long term sustainability).
 - Focusing on short term production efficiency, the use of mineral fertilizers can be attractive despite the long-term negative effects.
- Dilute, bulky product, i.e. whole digestate that is not further processed, is relatively costly to transport.
- Issues related to potential pollutants in biofertilizers, and a general skepticism regarding application also seen for high quality digestate.

Future outlook

If the techno-economic biogas potential was realized in Sweden, biofertilizers could provide a significant portion of the agricultural nitrogen and phosphorus needs (Metson et al., 2020), while also providing several other important positive sustainability effects. This would drastically lower the need to use mined phosphorus, a scarce and critical resource.

There are interesting possibilities to valorize the digestate into more concentrated fertilizer products, that potentially could also be adapted to the needs of different farmers (areas and crops). Such a development would make it possible to transport the fertilizers further and thereby redistribute nutrients between regions to balance nutrient surpluses and deficits - between areas with animal husbandry and crop production.

4.4.4 Use of biogas, biomethane and/or carbon dioxide

Domestic Swedish biogas production was around 2.3 TWh 2022, while the total use was about 4.4 TWh (including imports). The country has a history of upgrading a large share of raw biogas to biomethane and using biomethane for transport purposes. A significant amount of the biomethane is liquified to increase the volumetric energy density and expand the market geographically. Initially emphasis was placed on the use of biomethane in public transport (buses) and cars, while today there is a shift towards heavy duty trucks (freight transport) with some use within the marine sector

(ferries). Important reasons behind the described transport orientation, and interest in liquefaction, are a high willingness to pay (high valorization), Sweden's very limited gas grid, and the transport sector's slower transition away from fossil fuels. Recently, interest has grown in utilizing the biogenic CO₂ from biogas upgrading facilities (ongoing projects at biogas plants).

A few large industrial companies have indicated potential demands for large amounts of biomethane, both as an energy carrier and raw material.

All the sustainability effects mentioned in section 2.4 (specified in Table 4: ET1-ET7) are highly relevant in the Swedish context. The use of biogas in the transport and energy systems contributes to improved security of supply, more robust and flexible systems, reduced negative climate impact, less air pollution, and lower noise levels. According to data (for 2023) from the Swedish Energy Agency, vehicle gas has the best climate performance due to the large share of biomethane in Sweden's gas supply. It is noteworthy that, despite Sweden's mostly non-fossil electricity production, vehicle gas has a better climate performance than electricity.

There might be both positive and negative impacts on eutrophication, for example, depending on feedstocks and agricultural practices (Lindfors and Ammenberg, 2021).

Examples of essential drivers regarding use of biogas/biomethane and carbon dioxide:

- Ambitious national targets regarding renewable energy and climate change mitigation, a push for a transition away from fossil fuels.
 - Good alignment with Swedish environmental objectives.
- Relatively newly introduced financial production support for upgrading and liquefaction.
- Increased focus on energy and transport security, due to war in the Ukraine and other conflicts.
- Limited gas grid, driver for existing transport sector solutions and barrier for alternative uses.
- Tax exemptions on use of biomethane as a transport fuel are important.
- Climate change related subsidy program, involving investment support for vehicles and fueling stations.
- Companies undertaking initiatives towards sustainability, involving shifts to more sustainable energy and transport solutions.
- Public procurement and use in public transport, although somewhat declining importance.

Examples of key barriers regarding use of biogas/biomethane and carbon dioxide:

- Dynamic and uncertain policy landscape, both at the national and EU levels.
 - EU policy regarding internal combustion engines has made many actors hesitant to adopt biomethane for transport purposes, despite its very competitive sustainability performance. There exists a mindset where all gas is regarded as non-renewable and electricity as renewable, although the reality can be very different. This thinking appears to be influencing car producers, for example.
- The temporarily stopped tax exemption in Sweden, due to EU process
- Focus on electrification and hydrogen, with narrow mindsets looking for future silver bullets and failing to foster the good existing systems that could expand and be smartly combined with 'new' systems.
 - Reduced interest in biomethane use in public transport.
- Limited gas grid, barrier for alternative uses and driver for existing solutions.

Future outlook

There will likely be a continued shift towards the use of biomethane for heavy duty transport, both in compressed and liquid forms, complemented by expanded use for of biomethane for industrial and marine purposes. This means that biogas systems are expected to provide multiple positive sustainability effects in these sectors, going into the future.

As the use of intermittent renewable energy systems grows (wind, solar) the need for energy balancing services increases and biogas systems could play an important role here.

Interest in deriving value from the biogenic CO₂ separated in biogas upgrading will likely continue to grow, potentially resulting in various initiatives on biogenic carbon capture and use (BCCU).

4.4.5 Broader societal effects

Combined, the described Swedish biogas systems contribute to all the overarching sustainability effects mentioned in section 2.5 (specified in Table 5: S1-S11). This is relevant on the national, regional (county) and local (municipal) levels and means that biogas systems are essential components in the transition to a more sustainable society.

4.4.6 Sustainability assessments

National, governmental inquiry

During 2018 and 2019, a comprehensive governmental inquiry was conducted in Sweden that focused on the conditions for biogas systems (Westlund et al., 2019). This inquiry considered many of the sustainability effects presented in this report, which were described for the production and the use of biogas and biofertilizers, respectively. However, it was acknowledged that several of the effects are challenging to quantify/monetize. Consequently, the inquiry provided quantitative information on some categories of emissions, regarding climate change impact, particulates, acidification and eutrophication. Furthermore, the effects in terms of a change in emissions were monetized. While the climate impact related effects were found to be significantly positive, some of the other quantified impacts were judged to be redundant due to a forward-looking perspective where modern vehicles would fulfil tougher Euro-classes than the current vehicle fleet. This illustrates the importance of what assumptions are made regarding what is substituted (energy carriers, vehicles, electricity, etc) by the products from biogas systems.

In conclusion, considering both the quantitative and qualitative assessments, the inquiry found the climate impact related benefits to be of utmost importance. The qualitative assessment pointed out the significant contribution to security of supply and circularity, acknowledging that the Nordic Biogas Model (Lindfors et al., 2022) importantly involves valorization of waste and nutrient recirculation. The greatest benefits of biogas use were linked to the transport sector, followed by industrial and marine utilization, and large-scale power production where natural gas was replaced. Farm-scale use for electricity and heat was judged to be less beneficial, except when replacing fossil fuels.

Based on the situation for biogas systems, and the described and assessed sustainability effects, continued, and enlarged, support for biogas solutions were suggested. Since the ‘biogas actors’ were not compensated for many of the benefits (existing externalities), measures were recommended regarding internalization of these benefits. The inquiry proposed to introduce financial production support oriented towards upgraded and liquefied biomethane and found that the climate benefits alone could by far exceed the level of support needed. The suggested production support has been implemented in Sweden. The inquiry also suggested an overarching biogas production goal, which has not yet been officially adopted.

Regional assessments

In Sweden there are 21 *regions*, self-governing authorities on the ‘county level’, with important responsibilities related to health care, public transport and regional development. Several regions have been very active regarding biogas solutions (Brett, 2024), and these are generally centered around public transport where public procurements are essential (Aldenius and Khan, 2017; Ammenberg et al., 2021a).

A study of three regions, who are members of the Biogas Solutions Research Center (BSRC), was conducted around 2020. It involved interviews and workshops with a few employees working with biogas-related tasks, as well as interviews with representatives from the biogas industry, a consultancy firm, a politician, and a few others. The study revealed that the regional respondents had a high level of awareness of biogas systems multifunctionality and considered that valuations of sustainability effects were essential (Brett and Lindfors, 2021). However, none of these regions conducted a systematic socio-economic analysis before initially committing to supporting biogas solutions in their region. Instead, they employed discursive strategies with strong local narratives, that varied somewhat between the three regions, partly due to varying conditions (ibid.).

After several years of biogas-related activities, these regions did commission more formal socio-economic analyses. Cost-benefit analysis was conducted for the regions of Kalmar and Jönköping, supported by consultancy firms. Region Gotland organized a workshop based on multi-criteria analysis, where different fuels were studied in relation to sustainability criteria (cf. Kügemann and Polatidis, 2024). These socio-economic analyses were performed to motivate additional biogas related initiatives, such as biogas strategy work and specific public procurement requirements.

The analyses conducted for Kalmar and Jönköping Regions resulted in both quantitative and qualitative valuations of several sustainability effects, which seem to have supported additional biogas related initiatives in these regions. However, it is interesting to note that the monetized benefits were not internalized into the respective budgets of the regions (Brett, 2023; Brett and Lindfors, 2021).

4.5 Switzerland

Biogas production has a long tradition in Switzerland. Biogas plants are widely used for the treatment of municipal sewage sludge, industrial wastewater, organic waste and farmyard manure. Only the production of biogas from landfills has never been widespread in Switzerland due to the high pressure on land and progressive waste legislation. While for many years the focus was on the use of biogas for the production of electricity and heat, and this was supported financially, there has been a clear trend in recent years towards upgrading biogas to biomethane and grid feeding. Despite Switzerland's large biomass resources, only 17.5% of renewable gas consumption is derived from domestic production, with most of its renewable gas being imported to meet the high demand (Gustafsson et al., 2024). Co-benefits such as nutrient recovery, CO₂ utilisation and carbon recycling are not or only marginally monetised.

4.5.1 Waste and wastewater treatment

The progressive and very strict water protection legislation in Switzerland, established in the 1960s and 1970s led to the almost nationwide connection of residential areas and industry to efficient mechanical-biological wastewater treatment plants (W1). Three-stage treatment with primary sedimentation followed by activated sludge processes with integrated tertiary phosphorus precipitation are widespread. The combined primary and secondary sludge is usually anaerobically digested in mesophilic digesters (477 plants). In smaller plants, biogas is used exclusively for the plant's parasitic heat and electricity demand. Medium and large sludge digestion plants produce heat (214 GWh/y), electricity (124 GWh/y) and biomethane (176 GWh/y) and feed these energy carriers into the respective grids (Gustafsson et al., 2024).

Until the end of the last century, the agricultural use of biosolids was widespread (W2). In addition to ensuring local reuse, particular attention was paid to phosphorus recycling. Over the past three decades, increasingly stringent legal requirements have been introduced for the recycling of biosolids, which have placed much greater emphasis on soil protection. The spread of pathogenic vectors was successfully brought under control by the introduction of thermal and thermophilic hygienization processes during sludge treatment. The locally high contamination of sludges with heavy metals was reduced by measures at the source, both for industrial and commercial wastewater and for household products in municipal wastewater. However, the potentially high level of organic trace contamination in biosolids remains unresolved. For more than 20 years, the agricultural use of biosolids has been prohibited in Switzerland. As an alternative, the sludge is dewatered, dried and incinerated in an energy-intensive process, with the resulting ash being landfilled. The infrastructure for the recovery of phosphorus from these ashes is still under construction and has high financial, technical and energy costs.

In-house anaerobic treatment of highly concentrated industrial wastewater, mainly from the food and beverage industry, is also widespread (22 plants) (W7). Mesophilic UASB digesters predominate. Most of the biogas is used to cover the plant's parasitic heat demand and to produce high-temperature industrial heat (36 GWh/y). In some cases, biomethane is processed and fed into the grid (25 GWh/y) (Gustafsson et al., 2024).

The production of biogas from separately collected organic municipal waste (OFMSW) and from organic residues from the catering industry (HORECA) and retailers has been established in Switzerland for over 30 years. The main drivers for this recycling are the ban on landfilling organic materials (W5), which has been in place for over 20 years, and the increasing demand for renewable energy sources. Despite the 28 large-scale digestion plants currently in operation (mostly horizontal thermophilic plug-flow digesters, some garage digesters), this waste fraction has not yet been fully exploited for biogas production. Some of the fermentable MSW is recycled through industrial composting. More significant is the fraction of organic MSW that is mistakenly mixed with garbage and disposed of in incinerators, either due to a lack of logistics and infrastructure for separate collection, or due to a lack of discipline on the part of the population to separate at source. Biogas

is also used here for the production of heat (31 GWh/year) and electricity (81 GWh/year), as well as a rapidly growing amount (11 plants) of biomethane (163 GWh/year) (Gustafsson et al., 2024). Digestate is mainly used for agricultural purposes in both liquid and solid forms (W2). An increasing amount of digestate from the fermentation of organic waste is being post-composted for higher value use in agriculture and horticulture (W2).

Key drivers and enablers regarding biogas solutions in the waste and wastewater sector

- Stringent water protection regulations and water quality standards (W1)
- Increasing discharge fees for industrial wastewater (W7)
- Increased sanitation and hygiene awareness (W1, W5)
- Importance of nutrient recovery within a circular economy context (W2)
- Landfill ban for organic wastes and biosolids (W3, W4)
- Feed-in tariff for bioenergy from OFMSW
- Renewable gas incentives (W2)
- Increasing awareness of soil quality

Key barriers for the adoption of AD in the waste and wastewater sector

- Limited subsidies for renewable energy carriers
- Lack of collection and separation discipline among the population
- Limited logistics and infrastructure for the separate collection of OFMSW
- Lack of financial compensation for co-benefits
- High land pressure due to high population density
- Complex spatial planning procedures
- Discrepancy between the importance of renewable energies and lack of local acceptance (NIMBY)
- Lengthy approval procedures and a lot of high degree of bureaucracy

Outlook

The potential for anaerobic digestion of sludge from municipal wastewater treatment is almost exhausted in Switzerland. An increase in biogas production can only be achieved by increasing the degree of anaerobic digestion, e.g. by sludge pre-treatment. However, the use of biosolids faces challenges in terms of nutrient recycling, especially phosphorus, due to the ban on agricultural application. The use of phosphorus from ashes is technically and energetically complex and difficult to finance. In Switzerland, it is planned to equip all major wastewater and biosolids treatment plants with P recycling by 2026 (W2). Reestablishing permission for agricultural use of biosolids is not under discussion. The use of biogas will continue to shift towards upgrading to biomethane and grid injection.

For treatment of highly contaminated industrial wastewater, especially from the food industry, it is expected that the continued rise in discharge fees will lead to a slight increase in in-house biogas plants for industrial wastewater from small and medium-sized companies. The use of biogas will focus on the production of industrial high-temperature heat and its supply to the grid. The latter will increasingly include the option of CO₂ capture and use (W2).

Growth in biogas production is expected for the treatment of organic waste from households. The synergies between digestion and composting will be increasingly exploited by passing previously composted fractions through digestion and post-composting without significantly affecting the quality and quantity of the compost (W6). On the other hand, and more importantly in terms of quantity, the efficiency of separate collection of organic waste from households will be increased. In the coming years, new legal requirements under waste legislation are expected to lead to almost nationwide logistics and infrastructure for the separate collection of municipal organic waste (W6). It will be more difficult to improve the separation and collection discipline of the general public and to reduce the proportion of fermentable waste in household waste which is incinerated.

Regarding biogas use, there should be more upgrading to biomethane and grid feeding of biomethane, as well as greater use of biogenic CO₂ (W2, W3).

4.5.2 Agriculture, feedstock related effects

Swiss agriculture is characterised by its small-scale nature, with many small family-run farms with <40 livestock units, and by its strong seasonality, with growing seasons of 8-9 months in the Central Plateau and 4-6 months in the sub-alpine and alpine regions. Due to these short growing seasons, long storage periods of several months and correspondingly large storage volumes are required for both farmyard manure and digestate from biogas plants. On the one hand, this is a significant cost factor, but on the other hand it often offers opportunities for a massive reduction in greenhouse gas emissions through optimised storage management (AF6, AF7). The majority of agricultural production areas are located in hilly areas, often at altitudes exceeding 700 metres above sea level. Much of the production area is used as pastureland, with few alternative uses for food crops. The livestock sector is dominated by cattle farming. Larger livestock farms (cattle, pigs, poultry) are common in the flatter central plateau. Large-scale industrial production with more than 1,000 livestock units is rare. In addition to pasture, crop production includes mainly corn, cereals, fruit and vegetables. Pressure on land for food and feed production is high, and the use of agricultural land for energy crops is prohibited by law (AF15).

Although farmyard manure has the largest potential for biogas production in Switzerland with 6,750 GWh/year (Thees et al., 2017), only a small fraction is used for energy purposes. A total of 121 agricultural biogas plants, mostly 2-stage mesophilic digesters, produce 542 GWh/year of biogas, which is used to provide heat (60 GWh/year), electricity (192 GWh/year) and biomethane (11 GWh/year) and fed into the grid (Gustafsson et al., 2024). Purely agricultural biogas plants, which only digest manure and agricultural by-products, are rare. Most agricultural biogas plants co-digest manure with other feedstocks using significant amounts (20-50 %) of organic waste from the food industry and HORECA sector. There is strong feedstock competition with commercial biogas plants for the fermentation of organic waste, as these co-substrates have a significantly higher specific biogas yield and are financially attractive due to the high gate fees.

Key feedstock related drivers and enablers regarding biogas solutions in the agricultural sector

- Financial income from co-digestion through gate fees (AF2)
- Feed-in-tariff for bioenergy from manure and agricultural by-products
- Financial compensation for emission reduction measures (AF7, AF9)
- Improved fertilizer efficacy for application of digestates compared to farmyard manure
- Odor reduction during storage of liquid products (AF14)
- Regulatory framework for storage and application of manure (AF7, AF9)
- Local and national policies that promote sustainable agriculture (AF3)

Key feedstock related barriers for the adoption of AD in the agricultural sector

- Small farm sizes, decentralized structures, small herd sizes
- High investment costs, high CAPEX
- Limited availability of land for production of energy crops and intercrops
- Family farm structures and lack of cooperation between farms
- Feedstock competition for energy rich co-substrates
- Transportation costs in subalpine and alpine terrain
- Seasonal availability of manure (alpine pastures)
- Manure cannot be collected from free-range systems
- Lengthy approval procedures and a lot of bureaucracy

Outlook

Farmyard manure has been shown to have the relatively largest additional potential for biogas production in Switzerland compared to other substrates. Swiss farmers are very interested in biogas technologies and are willing to start new projects. If reliable technologies for manure-only

fermentation become available in Switzerland in the near future at significantly lower investment costs, and if financial support for the energy products heat, electricity and biomethane is secured for the long term, a significant increase in the number of plants and the corresponding amount of biogas production can be expected.

Given the small-scale nature of Swiss agriculture and the family-own and decentralised farm structures, operational concepts for inter-farm facilities are required in addition to financially viable small-scale digesters. Challenges to be overcome include the transport of manure and digestate in sub-alpine and alpine regions, specific treatment and storage options for liquid and solid digestate products, and options for small-scale grid integration or local energy self-sufficiency (AF2, AF8).

4.5.3 Agriculture, use of digestate/biofertilizers and other aspects

All aspects of small scale, geographical distribution and seasonality mentioned for the analysis of feedstocks in agriculture are also relevant for the management of digestates. Due to the small size of farms and the resulting small amounts of manure, less than 10% of manure is currently used for energy production in biogas plants. The remainder is used directly as organic fertiliser on agricultural land after short or long periods of intermediate storage. This sometimes results in high gaseous and liquid nutrient losses, especially for nitrogen (AB6). Due to the long seasonal storage periods required and the easier and more targeted application of mineral fertilisers, farmyard manure is often only applied to pasture. There are few crop-specific applications for manure and digestate. A nationwide control system for nutrient flows into and out of agriculture enables a balanced nutrient budget at the farm gate (AB2).

In Swiss agriculture, 1,735,000 m³ of solid and liquid organic fertilisers are recycled annually from biogas plants (1,370,000 m³/year) and composting (365,000 m³/year). Sixty percent of digestate originates from farmyard manure and agricultural by-products, and 40% from industrial and commercial co-substrates (Schleiss, 2024). Separation of solid and liquid fractions of digestate is common in biogas plants. Nutrient separation and the production of concentrated nitrogen or phosphorus fertilisers are still in their infancy.

Key digestate related drivers and enablers regarding biogas solutions in the agricultural sector

- Reduced odor emissions during storage and spreading (AF14).
- Reduction of GHG emissions during storage and application (AB5).
- Improved animal welfare, reduced emissions in stables (AB8).
- Increased soil fertility and humus formation, carbon sink (AB3, AB4).
- Financial support for renewable energy production.
- Reliable on-farm nutrient balances (AB1, AB2).
- Demand for organic fertilisers in organic farming (AB8).
- Rising costs of mineral fertilisers and associated negative sustainability factors.
- Nitrogen surplus in Swiss agriculture (AB2).

Key digestate related barriers for the adoption of AD in the agricultural sector

- Insufficient financial support for small-scale biogas plants.
- Traditional use of mineral fertilisers.
- High proportion of imported animal feed.
- Restrictive quality requirements for organic farming.
- Inflexible application structures (mandatory drag hose).
- National efforts to reduce livestock production.
- Limited nutrient storage capacity, high volume requirements.
- Unwillingness of farmers to pay for digestate.

Outlook

Irrespective of the development outlined for the feedstock-based approach, there are clear trends in the management and application of organic fertilisers in agriculture. Technologies for nutrient concentration and the production of finished N, P or K fertilisers allow targeted and minimised transport, crop-specific applications and inter-regional nutrient balancing. Here too, there is a need for operational concepts for multi-user biogas installations and cross-farm fertiliser and nutrient management. Linked to this is the need for adequate financial support for decentralised and small-scale systems, as well as targeted marketing of organic fertilisers in agriculture according to their monetary nutrient and soil quality enhancement values.

4.5.4 Use of biogas, biomethane and/or carbon dioxide

In Switzerland, biogas has traditionally been a valuable energy carrier, mainly used for generating renewable electricity and heat. However, in recent years, there has been a growing trend towards injecting biomethane into the grid, a development that is increasingly supported by both the government and industry. In 2022, Switzerland produced 1,638 GWh of biogas, with wastewater treatment plants (WWTP) contributing 39%, agricultural plants 33%, biowaste plants 23%, and industrial plants 5 % of the total production (ET1). The traditional use of biogas remains primarily in the form of electricity (405 GWh/year) and heat (341 GWh/year). Currently, approximately 25 % of biogas is used for electricity generation, 21% for heat production, and around 23 % is injected into the grid (370 GWh/year). The majority of biomethane injected into the grid is used for heating (289 GWh/y), with 39 allocated for vehicle fuel and 42 GWh/y utilized for electricity generation. Although these figures may appear impressive, the biogas produced in Switzerland meets only one percent of the country's natural gas consumption. It is important to highlight that the demand for biomethane in Switzerland is exceptionally high, significantly surpassing domestic production. In 2022, the share of biomethane produced within Switzerland accounted for just 17.5 % of the total biomethane consumed, leading to large imports from Europe. Domestic production and imports together covered only 6.2 % of the total demand. Gas for transport/mobility remains at a low level of development, primarily due to the limited number of fuelling stations for private vehicles and the scarce availability of gas-powered vehicles on the market. This also applies to gas-powered heavy trucks, which face similar challenges. The state's focus on promoting battery-powered vehicles further marginalizes gas-powered heavy trucks that are not exempt from the LSVA (performance-related heavy vehicle charge). This creates a market distortion, hindering the growth of both gas-powered private vehicles and heavy trucks although the industry is willing to invest after successful tests (ET3-5, 7). In Switzerland, system integration of biogas is demonstrated through the first P₂G (Power-to-Gas) plant at a practical scale, along with a company that facilitates straightforward participation in the ancillary services market by intelligently aggregating plants into a virtual power plant. For the first time, a plant for the production of food-grade CO₂ (ET6) was put into operation at a biomethane processing facility, enabling the reuse of CO₂ produced in the process. While many of the listed effects are relevant in principle, the development of markets and technologies is largely driven by economic efficiency in practice.

Key energy drivers and enablers regarding biogas solutions

- Organic waste is directed towards material and energy recovery through waste legislation.
- The support systems for renewable electricity (KEV and EnFV) play a key role in the development of the sector.
- The gas industry promotes biomethane production independently of the government.
- Demand for renewable heat in district heating systems is growing (ET2, ET3).
- Biogas and Biomethane are recognized as key players for grid flexibility, grid stabilization and energy security (ET1, ET2).

Key energy barriers for the adoption of AD

- The small-scale nature of Switzerland hinders the rapid expansion of renewable biogas due to the distribution of feedstocks and the limited availability of land for plant construction.
- Vehicle taxation policies impede the development of certain technologies.
- Legislation has predominantly advanced support for renewable electricity from biogas. Support for renewable gases for grid injection came later and was driven by the industry.
- Larger plants often face a lack of acceptance and are difficult to permit, leading to lengthy construction processes.
- Very low demand for gas-driven private transport.
- Lack of subsidies for district heating from biogas with more support for use of gas for high-temperature industrial heat.

Outlook

In the future, Switzerland is expected to increasingly rely on the production of renewable energy from photovoltaics and environmental heat, as these sources offer low-cost energy generation. Meanwhile, existing gas distribution networks in some urban areas are being partially decommissioned or dismantled, which may limit the potential applications of biogas for residential use. However, it is anticipated that the existing gas infrastructure will continue to be heavily utilized for energy supply to high-temperature processes and heavy transportation in industrial sectors. The Energy Promotion Ordinance (EnFV) now increasingly supports small-scale biogas plants, with capacities up to approximately 50 kW_{el}, primarily using pure farmyard manure. For existing plants, however, this regulation does not provide sufficient support to maintain cost-effective operations, and it is expected that some of these plants may cease operations. The new legislation, like the gas industry, focuses on increasing the injection of biomethane into the gas grid. Due to the high demand for biomethane, efforts are underway to harmonize the import of biogas. Imports will continue to play a central role, though the potential for biogas production from Swiss biomass remains significant, especially from underutilized farmyard manure. To fully unlock this potential, new utilization concepts are required, which are necessary not only from an energy perspective but also from an environmental policy standpoint.

4.5.5 Broader societal effects

The utilization of green waste has been established in Switzerland for decades, and the population is accustomed to and values the convenience of handling these waste streams. The established recycling pathways ensure effective management of these waste streams and serve as a longstanding role model for circular economy practices in Switzerland. Furthermore, the use of the products generated, particularly in the form of compost, is well known to customers as they recognize the high quality and diversity of the products, and are familiar with their application (S4). The utilization of biomass streams leads to a reduction in emissions (S5) within the biomass and agricultural sectors. The integration of biogas plants into the green waste and agricultural sectors has led to a shift from traditional composting to initial energy utilization, followed by material utilization (digestate and compost products) as a secondary focus. This shift has created new jobs within the sector, and plant operators have been able to secure new sources of income through the integration of this new technology (S9). Nevertheless, there continues to be a lack in recognition of monetary values for nutrients in organic fertilizers, not to mention for positive effects on soil quality. The trading of CO₂ certificates has become established, providing an additional source of income for some companies. The minimization of odors (from waste) is widely perceived as a positive outcome. Many of the mentioned effects (S1-S11), which were not explicitly stated in the text, are also applicable to Switzerland. However, these additional benefits are not monetized. A trend towards a bioeconomy and biorefinery has not yet fully established itself in Switzerland, partly due to mostly small to medium-size applications which are not to scale for modern biorefinery concepts, partly due to high initial costs for these applications.

Drivers (in relation to the relevant types of biogas systems and associated effects)

- New jobs.
- Emission reduction.
- Utilization of biogenic carbon (S1, S6) e.g. CCS from Biomass.
- Business case for operators - source of income (S7).
- By-products are utilized as regional and high-quality fertilizer (S4).
- Positive image for companies (e.g., “We run on biogas”) (S7).
- Regional gas suppliers support biomethane in the grid (30% by 2030).
- Recognition of biogas solutions to improve agricultural resilience (S8).

Barriers (in relation to the relevant types of biogas systems and associated effects)

- Transparency of the true costs of fossil energy sources.
- Absence of market prices and willingness-to-pay mechanisms for the identified co-benefits.
- Ignorance towards monetary value of nutrients and soil carbon in organic fertilizers.

Outlook

Biogas holds a generally positive reputation in Switzerland, supported by a well-developed industry offering mature products for diverse applications, including exports. However, local acceptance can vary depending on production locations, and the limited availability of suitable construction sites restricts new biogas plant establishment. While there is a recognized willingness among the population to pay a premium for sustainably produced energy, the idea of financially compensating for co-benefits, such as environmental and social advantages, is not yet widely ingrained in public consciousness. This underscores the need for greater awareness and strategic initiatives to enhance both acceptance and the perceived value of biogas and its broader benefits.

4.5.6 Sustainability assessments

In Switzerland, comprehensive sustainability assessments for biogas and green waste are not regularly carried out at the national level. A project that was carried out to evaluate and compare the sustainability effects of eight biomethane value chains concluded that AD provides numerous positive externalities that have both financial and non-monetized value to Swiss society, thereby justifying public support of AD - see 3.3.2 (Membrez et al., 2021).

Statistics focusing primarily on production metrics are available, and sector sustainability is being addressed in other ways by authorities, industry and researchers. For example:

The Swiss Composting and Biogas Industry Inspectorate, operating on behalf of the Swiss cantons, conducts an annual evaluation of compliance with legal regulations governing the operation of waste recycling facilities. The review primarily focuses on ensuring that facilities adhere to legal requirements related to operational processes, such as anaerobic digestion and composting, across both commercial and agricultural sectors. Additionally, it examines the compliance with regulations concerning material flows, procedural standards, analytical protocols and operational documentation. This systematic evaluation ensures that relevant legal frameworks, encompassing environmental and sustainability standards, are properly implemented and followed.

Ökostrom Schweiz, the industry association of agricultural biogas producers, collects data from its members' plants as part of its annual benchmarking. This enables plants to compare their respective efficiencies and, consequently, sustainability aspects, such as emissions. The collected data are made available exclusively to its members.

In addition, the topic of sustainability is addressed in various publications and strategy papers, such as through lifecycle assessments or simulations of environmental impacts.

An assessment of the Swiss municipal solid waste management system revealed significant environmental benefits, compensating for 1% of climate change impacts and 4% of the cumulative

energy demand. However, due to the already advanced waste stage of management systems, further improvements can be made by focusing on utilizing secondary materials to replace high-impact primary production and enhancing energy recovery in waste-to-energy plants. One dissertation developed a modular LCA model for analysing large-scale waste management systems, providing a foundation for new indicators and future applications, including the integration of Circular Economy strategies and mathematical optimization (Haupt, 2018).

Biomass is a key renewable energy source, and anaerobic digestion (AD) offers a promising method for treating organic waste while recovering energy and nutrients. A material flow model developed for Switzerland assesses the current utilization of wet biomass in industrial AD installations, showing that nutrient transfer efficiencies exceed 74%, potentially replacing up to 14,000 t/a of chemical fertilizers and reducing CO₂ emissions by 40,000 t/a. However, challenges remain, such as the 70 t/a of plastic waste generated by AD, which needs to be addressed to support its future expansion and a more circular economy (Bowman et al., 2022).

A comprehensive white paper evaluating promising technologies and concepts for accessing the untapped potential of farmyard manure was prepared in 2021 (Burg et al., 2021). It provides specific information on the opportunities and risks of implementing such measures. The paper shows that biogas technologies are indispensable for the future use of manure and that it is essential to integrate the monetization of additional co-benefits in addition to the added value of renewable energy production.

The research program SCCER BIOSWEET was established to advance the role of sustainable biomass in achieving the Swiss Energy Strategy 2050, aiming for a significant increase in biomass energy consumption to 100 PJ. It was designed to develop and implement technologies for biomass valorisation to support Switzerland's energy transition. As part of this research project, various publications addressed future scenarios, including sustainability assessments, were conducted, with a primary focus on reducing CO₂ emissions (eg. Panos et al., 2021).

To conclude, in Switzerland, the sustainability assessment of the biogas and green waste sector remains fragmented, with efforts focusing on legal compliance, benchmarking, and targeted studies rather than a unified national approach. Research highlights the environmental benefits of advanced waste management systems and anaerobic digestion, emphasizing the potential for GHG emission reduction and nutrient recovery. However, this has not led to the sector's achievements being recognized with additional financial compensation.

5 Conclusions and guidance for policy makers

A societal sustainability transition is urgent, requiring the shift towards a more circular and regenerative biobased economy. Biogas solutions (or anaerobic digestion systems, AD) are already significantly contributing to this transition but their role could greatly expand in most parts of the world. Biogas solutions are multifunctional and can deliver key products and services, such as renewable energy, mobility, nutrients (indirectly food), fodder, clean water, chemicals, and environmental services including more sustainable management of natural resources.

This report begins by presenting the results of a literature review that identified many potential sustainability effects that can arise from the adoption of biogas solutions including collection of landfill gas. Representatives for five IEA Bioenergy Task 37 countries, Canada, France, Norway, Sweden and Switzerland, reviewed these effects and identified the key ones based on the particular country context, i.e. the history and rationale for biogas development, the types of biogas applications, the end-uses of energy and digestate/biofertilizer products, the societal goals related to energy supply and environmental protection, and the actions that governments have taken to advance development of the biogas industry. Albeit climate change mitigation is the main driver for new development today, the report shows that biogas solutions can have many other positive sustainability effects for society at large, and suggests that future planning and decision-making around waste management, environmental protection, clean energy transition and circular economies should take into account the collective sustainability effects of biogas solutions.

The chapters contain a lot of information, and the main findings are summarized here. All five countries have the potential to increase biogas and digestate/biofertilizer production and some of the main barriers to expansion were noted. This chapter concludes with insights into further development of biogas solutions directed at planners, developers, and policymakers.

5.1 Broad range of sustainability effects

Biogas solutions can take many different forms, from sludge stabilization at WWTPs to stand alone digestion of the organic material separated from municipal waste to on-farm digestion of dairy manure with straw to landfill gas collection, and can produce a number of energy and digestate/biofertilizer products, and biogenic CO₂²⁰. Based on an extensive scientific literature review, this report describes the roles of biogas solutions in different parts of society, including information on associated sustainability effects (2.1-2.5):

- within the waste and wastewater treatment sectors (2.1),
- within agriculture, as a feedstock supplier (2.2),
- within agriculture, as a user of biofertilizers/digestate (2.3),
- related to the use of biogas, and biomethane, for energy and transport purposes, and the use of biogenic CO₂ (2.4), and
- on a more overarching societal level (2.5).

In total, 53 sustainability effects have been identified, and they are presented in detail in Table 1 through Table 5 (Chapter 2), including information on critical factors and relevant references. Not all sustainability effects apply to all biogas solutions, and their relevance is context dependent.

²⁰ AD processes are advanced biochemical processes that can be bioengineered to produce other types of products as well, such as hydrogen and volatile fatty acids (VFAs).

Most of the sustainability effects are unique to the perspective that is taken to examine a biogas solution. For example:

- Biogas solutions for wastewater treatment can provide important societal benefits of sanitation, reducing health risks and negative impacts on water quality.
- Biogas solutions applied in agriculture can diversify the sources of farm income and help justify new production practices that increase the resilience of agriculture.
- The application of digestates on agricultural land can effectively recirculate stable carbon and bioavailable nutrients from waste streams to agricultural soils.
- The use of biogas energy can reduce GHG emissions and other problematic emissions of the energy supply, particularly when it directly replaces fossil fuels use.

The majority of the sustainability effects are positive, and they influence different dimensions of society in a variety of ways. A few effects are negative, and these should be avoided or minimized as much as possible.

Also, it should be noted that several points on biogas value chains can contribute to meeting the same environmental objective. For example, reduced climate impact can result from the type of feedstock, such as manure, biowaste or intermediate crops, and from the uses of biogas/biomethane (replacing fossil energy), biofertilizers (replacing mineral fertilizers and increasing soil carbon sequestration) and biogenic CO₂ (replacing CO₂ of fossil origin). In addition, it should be pointed out that essential sustainability effects are linked to all of the products of biogas systems (biogas, biofertilizers, biogenic CO₂).

The wide range of sustainability effects reinforces the message that biogas solutions offer more to society than renewable energy and GHG reductions. These other effects are often not well documented and can be difficult to quantify, leading them to be undervalued or even absent when making the case for a biogas solution. Consequently, it is of utmost importance that decision makers and other actors have a good understanding of the broader implications and societal relevance of biogas solutions and recognize that the societal relevance of biogas solutions extends much further. Assessing the systems solely as an alternative energy or transport technology is only part of the story, and it is important to distinguish biogas solutions from more mono-functional systems.

5.2 Guidance for excellent sustainability performance

The information on sustainability effects presented in this report can be utilized when designing biogas solutions (and larger societal systems) to maximize the positive effects and avoid/minimize negative effects. At an overarching level, the following points can be considered as general ways that biogas solutions can contribute to sustainable development of different sectors:

- Biogas solutions in waste and wastewater treatment (e.g. in line with the Nordic Biogas model, Lindfors et al., 2022)
 - The biogas solutions adopted to treat sewage sludge and biowaste have a very competitive sustainability performance, delivering essential positive societal services such as protecting the quality of water, air and soil.
 - The solutions encourage greater waste recovery and systems for better waste separation that in turn increase the options for waste treatment and valorization.
 - Industries with residues or waste streams with a high organic loading can recover energy and nutrient values of these streams and, for example, use the energy for their plant operation or vehicle fleet.
 - In areas where landfill gas production is significant, collection and treatment of landfill gas can contribute to important methane emission reduction.

- Biogas solutions in agriculture;
 - The integration of biogas solutions brings great opportunities for strengthening food and fuel production (in contrast to the fuel versus food debate).
 - Well-designed biogas systems and good practices offer significant opportunities for improved manure management, including reduced climate impact and other positive effects.
 - Co-digestion of manure with locally available food waste or biowaste increases the profitability of biogas solutions while providing waste management services in rural areas.
 - Intermediate crop production (including grasses, cover crops, etc.) with digestate recirculation can contribute significantly to good sustainability performance of agricultural systems, associated with several benefits, while 'energy crops' grown on prime agricultural land should be avoided as feedstock for biogas plants.
 - Smart integration of intermediate crops and/or utilization of marginal land can contribute to 'sustainable agricultural intensification', deriving more value from agricultural land, and various sustainability benefits.
 - Generally (not specifically for biogas systems) the sustainability effects of agricultural crop systems depend on the type of land and eventual land use changes, specific crops, crop systems, soil types and agricultural practices (e.g. nutrient management).
- Use of digestate as biofertilizer and/or soil conditioner for agricultural production;
 - Biogas solutions can contribute to more sustainable nutrient management, including redistributing nutrients to balance deficits and excesses.
 - Biogas solutions offer opportunities to recover stable carbon and bioavailable nutrients (N, P) from waste streams and to supply these valuable materials to the agriculture sector.
 - Digestate application on agricultural soil reduces the requirement for synthetic fertilizer and avoids the associated GHG emissions. Good digestate storage and management practices are essential.
 - Digestate processing enables the production of concentrated digestate products that can be transported greater distances, thereby avoiding nutrient overloading of soils in a given region and eutrophication risks. Products need to be developed and field tested for various digestate products. This should include environmental impact assessments and market development.
 - Digestate characterization work should continue to identify new properties such as biostimulant effects, the presence of potential soil contaminants and their fate in soils, etc.
- Use of biogas and biomethane; within a foreseeable future, no single technology or energy carrier can replace all the fossil fuels used in our energy, industrial and transport systems;
 - Biogas and biomethane can replace natural gas use in industry thereby reducing GHG emissions (and other negative impact) with relatively few equipment changes.
 - Biomethane can be injected, without blending limits, into existing natural gas networks and be used as a renewable energy carrier in energy systems, industrial applications and transport. In areas with few gas pipelines, biomethane can be compressed or liquefied and be easily stored or transported by truck.
 - Biomethane can importantly contribute as one significant renewable energy carrier in the transport sector, particularly for heavy-duty transport and marine applications. Biomethane has a very competitive climate performance and, compared to fossil fuels (and liquid biofuels), can reduce air pollution and vehicle noise.
 - Affordable biogas and upgrading concepts and technologies are needed to facilitate small-scale biogas production at farms and wastewater treatment plants (WWTPs), along with cooperative solutions at larger scales.

- Society; well designed and operated biogas solutions have a broad and strong sustainability performance, meaning that they contribute to several sustainability goals from global to local levels, such as the UN Agenda 2030 Sustainable Development Goals, Global Methane Pledge, and green and rural jobs. Biogas systems are also essential for sustainable regional development, waste management, security of critical supplies (food, water, energy), and are central components in the transition towards more circular and regenerative biobased economies.
- When designing, permitting and operating biogas systems, it is essential to apply the best available technology and practices, to avoid negative effects on the surrounding community, human health and the environment. Fugitive emissions from biogas plants or elsewhere in the life cycle should be identified and minimized to reduce odors and methane losses to the atmosphere.

This high-level guidance on sustainability performance should be further refined and adapted to specific biogas concepts and contexts. That is, biogas solutions should be tailored to local and regional conditions, as these conditions influence both opportunities and system performance.

5.3 Comprehensive sustainability assessments for better decisions

At present, new development of biogas solutions is strongly influenced by a country's climate change commitments and clean energy transition pathways, and therefore emphasis is placed on the energy and GHG reduction value of biogas solutions. The other sustainability effects are not given the same weight and sometimes are not even recognized in decision-making. Systems analysis methods, such as multi-criteria assessment (MCA), enable a number of effects to be assessed and can include both qualitative and quantitative descriptors, thereby contributing to more informed evaluations of technology options and supporting sound policy decisions.

Chapter 3 provided several examples of comprehensive assessments of sustainability effects of biogas solutions. Two examples were included of transport-oriented MCAs carried out in Sweden - one MCA in which electricity and various bio-based fuels (including biomethane) and fossil fuels were compared with respect to their contribution to meeting Sweden's environmental objectives, and another MCA that examined the technical, economic, environmental and social performance of different energy carriers that could be used in public buses. The results brought to light the strengths and weaknesses of the different energy carriers, including biomethane, and provided insights on their best applications. The examples emphasized the importance of adopting a broad systems perspective to include the relevant sustainability effects of biogas systems and different alternatives, and enable more complete comparisons. MCA methods are essential to structure relevant information for several areas of interest (indicators) as a basis for more informed decision making.

As many decision makers are considering future road transport systems, and the role of electric vehicles and other technologies. Some advice may be formulated based on the studies mentioned and other parts of this report: as electric vehicles do not produce harmful local exhaust emissions and generate little noise in slow-moving traffic²¹, they may be most beneficial for use in polluted urban areas. Biomethane, with a high technological readiness level, can be more competitive from an economic perspective. When combined with electric vehicles, it may be rational to use biomethane for transportation outside urban centers and for heavy-duty transportation, especially long-distance transportation.

There have been several attempts to monetize the sustainability effects, or externalities, associated with biogas systems to help justify the public support that is provided to the biogas industry. Studies completed in France, Switzerland and for Europe (EU 27 and UK) identified

²¹ Vehicles using biomethane can also significantly contribute to lower noise levels compared to vehicles using diesel, but electric vehicles are the best in this regard, in slow moving traffic.

common externalities, some which could be monetized and others which could only be described qualitatively. The studies all recognized that biogas systems provide several products (bioenergy, biofertilizers, biogenic CO₂) and numerous positive effects that benefit society at large. When considering the total value added, including all sustainability effects, biogas solutions can be highly competitive from a socio-economic perspective compared to both non-renewable and other renewable alternatives.

Although MCAs can be data intensive and monetization is challenging, such assessments carried out at different levels (e.g. national levels) can help to better understand and define the various roles of biogas solutions in society at a particular point in time, and decide on the need for supportive policies, regulations and standards, and/or programs.

5.4 Experiences with biogas solutions from five countries

Representatives from five IEA Bioenergy Task 37 member countries - Canada, France, Norway, Sweden and Switzerland - participated in the writing of this report. Chapter 4 provides information on the context and experiences of 'biogas development' on two continents: Europe and North America. Two of the countries are EU members: France and Sweden, while Norway and Switzerland are closely connected to EU and specific member countries.

The biogas solutions in these five countries have both similarities and differences, and they have evolved over several decades, influenced by factors such as population density, the use of natural gas and existing gas infrastructure, the industrial and agricultural profile, geography and climate, and policy instruments. As illustrated for Norway in Figure 8, biogas development can be broken down into several phases beginning with sanitation and clean water concerns moving to renewable energy production and shifting to climate change mitigation and circular economy goals. Although the phases have not taken place at exactly the same point in time in all five countries, they share the same pattern of development.

The relevant sustainability effects for each country depend on the types of biogas solutions that have been adopted, the types of feedstocks used, the end-uses of the biogas, the availability of agricultural land to receive digestate products, and the societal goals with respect to climate change, waste management, and environmental protection. As many of these aspects are shared in common, most of the sustainability effects identified in Chapter 2 apply in all five countries. Nevertheless, a few differences were noted.

The municipal waste and wastewater sector has been the first to adopt biogas solutions in all five countries, and is expected to remain an important adopter. Switzerland stands out as the country with the greatest level of adoption, initiated by its strong waste management policies implemented several decades ago. Across the countries, it is common practice to integrate AD of sewage sludge into larger WWTPs for the purposes of stabilization, pathogen destruction and to reduce sludge volumes and disposal costs. Here biogas plant efficiency and gas utilization could be improved. There appears to be significant potential to increase the separation of food waste and other organic fractions, and to expand biogas production from biowaste in all countries, thereby avoiding GHG emissions, and other negative effects, from landfilling and deriving value from waste. Well-developed waste management systems, including infrastructure, are a prerequisite for biogas systems based on source separated organic waste. Each of the five countries has examples of industrial AD applications, involving treatment of residual streams with a high organic loading from several industries. Canada was the only country to report on the significant role that landfill gas collection and treatment plays in its methane reduction strategy. The other countries have low rates of landfill gas production due to the organic waste bans implemented decades ago. Environmental protection is the main driver for the adoption of biogas solutions in this sector.

Agricultural biogas systems, of different types and scales, exist in all five countries. However, they play more central roles in France and Switzerland, compared to the other countries. In all countries

there are challenges of adoption by small farms because of the relatively higher cost of smaller biogas plants, and trends towards centralized plants. Also, all it was pointed out that biogas plants co-digest manure generally with food waste to produce more biogas and benefit from economies of scale. This results in numerous positive sustainability effects, including less climate impact (avoided GHG emissions from manure and landfills), better manure management, less odor, and alternative sources of revenue for the farm. In Norway and Sweden, biogas plant operators have started adding fish processing sludge, thereby adding sustainability effects of protecting aquatic systems and reducing eutrophication. France is the only country of the five where the use of intermediate crops is promoted as a feedstock, consuming 6 million tons annually in biogas systems. The production of intermediate crops has numerous positive sustainability effects, such as reducing soil erosion, improving carbon sequestration in agricultural soils, managing nutrients more sustainably, lowering feedstock supply risks and improving economic efficiencies. The biogas solutions in this sector provide a wide variety of positive sustainability effects for the environment, improve the resiliency of the agriculture sector and provide solutions for management of locally available municipal and industrial wastes.

Digestate is an important co-product, produced alongside biogas, that contains the undigested carbon and nutrients contained in the feedstock. Digestate composition, processing, storage, and how and when it is applied, all influence the roles digestate can play with respect to sustainability. In all five countries, most of the digestate from biogas plants is applied to agricultural soils where it replaces lost soil carbon and supplies nutrients (and other essential 'compounds') needed for crop growth. If stored and applied in the right ways in the right amounts at the right time, digestate application can provide numerous positive sustainability effects including nutrient recycling, reduced dependence on mineral fertilizers, avoided GHG emissions (associated with mineral fertilizers), and facilitation of ecological/organic farming. As mentioned in Chapter 2 (and Table 3), many site-specific factors are influential regarding fertilization, soil health and climate effects, including agricultural practices and reference systems. This is well explained in the text from Canada (4.1.2-4.1.3), that includes results from field studies that show how the effects of digestate application can be very site-specific. In some countries, digestate is further processed into fractions with specific properties. For example in France, solid/liquid separation of digestate is routinely carried out to concentrate the carbon fibres and phosphorus in a solid form, while the liquid fraction contains a good portion of the nitrogen. Although processing increases costs, it enlarges both the markets and potential positive sustainability effects of digestate products by enabling digestate solids to be sold outside of regions with high nutrient loadings, thereby reducing eutrophication risks.

While greater resource efficiency and environmental protection are the dominant positive sustainability effects of digestate application on agricultural soils, the authors noted that today digestate production generates very limited income and can even represent a cost for biogas plant owners. Also, negative effects could result if the digestate contains high levels of contaminants or if it is not correctly stored and applied. Each country has quality standards and science-based guidelines in place to ensure that digestate meets the standards and that the procedures for safe application to agricultural land or alternative disposal are known. Switzerland bans the use of digested sewage sludge (biosolids) on agricultural land and limits the spreading of digestate from other biogas plants to pastureland. Other countries use threshold limits for pathogens, heavy metals, plastics and other compounds that could accumulate in soils or cause damage to the environment or human health, and have established certification systems. With the proper framework in place, digestate application can deliver positive sustainability effects to the agriculture sector and the environment at large.

The use of biogas energy to substitute fossil fuel energy and reduce climate impact is a very important, if not the main, driver for the development of new biogas solutions today. As climate change mitigation is of high priority in this phase of industry development, the preferred end-uses of biogas are applications that incur the deepest GHG emission reductions, i.e. replacing diesel fuel

use versus electricity. Across the five countries, there seems to be a shift towards upgrading biogas into high quality biomethane for grid injection and/or use in the transport sector as this provides greater GHG reductions. France and Switzerland have extensive gas grids and long-term experience with the use of natural gas, which in many ways facilitates the use of biomethane. In Canada, biomethane is also injected into the gas network but many existing biogas plants are either too small or located too far away from the gas pipelines. Norway and Sweden have very limited grids and natural gas usage, and therefore either compress or liquefy the biomethane and truck it to fueling stations to be used in the transport sector to substitute for diesel fuel, incurring the largest GHG reductions.

Even with this significant benefit, there are challenges to match biomethane production and use, expressed as a “chicken-egg-problem” (cf. Ammenberg et al., 2021b) with questions such as:

- How to get customers to invest in methane driven vehicles, if there are too few refueling stations?
- How to influence vehicle manufacturers to provide attractive vehicle model programs, if the demand seems low or uncertain?
- How to get well-established distribution, including networks of fueling stations, if the vehicle models and customers are scarce?

The use of biogenic CO₂, a co-product from biogas upgrading, is at an early stage of development. All countries mentioned growing interest in exploring CCU and CCS technologies which could further reduce the climate impact; however only one country, Switzerland, has built a CO₂ upgrading and liquefaction plant²². Arguably, CCU should be prioritized over CCS - if fossil fuels are phased out, there may be a shortage of renewable carbon.

At an overarching societal level, biogas solutions appear to be a good alignment with the countries' sustainable development goals, including goals on climate change mitigation, waste management, circular (/bio) economy and, more recently, security of supply. Many of the positive sustainability effects, especially those related to environmental protection, benefit society at large. The effects are cross-sectoral, for example, with biogas solutions in the waste sector benefiting agriculture and energy used in industry and transport. For all five countries the authors noted the importance of this alignment with broader societal objectives, and the essential role that policies and regulations play with respect to advancing and, sometimes, impeding new development. Biogas solutions' competitiveness is strongly influenced by various types of policy, including economic incentives for competing and complementary alternatives. Each country has developed different support mechanisms that influence biogas production and use, including expansions, slowdowns, shifts of feedstock and use, etc. The current focus on electrification and future hydrogen systems presents a challenge to the development of biogas solutions in all five countries, while greater interest in the circular economy appears to hold promise for explicitly recognizing the broad range of sustainability effects that can be provided by biogas solutions.

5.5 Guidance for Planners, Developers and Policy Community

Biogas solutions already play a valuable role in delivering sustainability effects in many countries, but their role could significantly expand. With growing populations, food waste, biowaste and industrial waste are expected to rise, opening up more opportunities for biogas solutions. This will require efficient waste separation systems to avoid inhibitory compounds and the entrainment of contaminants into the digestate. Landfill gas collection and treatment can be very beneficial in many countries, while the relevance is declining in some countries as less organic material is landfilled and gas production drops off. There exists untapped potential at smaller facilities, e.g. smaller farms and WWTPs, and in rural areas that often have less infrastructure.

²² Although there are similar projects ongoing in Sweden, for example.

Chapter 4 lists country-specific barriers to development that have a general relevance. Policy conflicts and uncertainty, gaps in technology and infrastructure, weak market development, the lack of awareness and misinformation, and inadequate community acceptance are some of the main hurdles. Given the strong cross-sectoral nature of biogas solutions, actors from several different sectors need to “be on the same page” to bring these new opportunities to life. Policy and regulation have very influential roles in the development of biogas solutions, and are continuing to be adjusted and revised as societal priorities shift and other technology solutions may outcompete biogas systems. For biogas solutions to effectively deliver the broad range of positive sustainability effects, many pieces have to fall into place to have reliable, functioning value chains. While different countries share many of the same components, biogas systems look somewhat different in various countries.

For planners, developers, policy makers and other influential actors, it is of utmost importance to understand and account for the broad benefits of biogas systems, that go far beyond energy carriers. The cross-sectoral nature of most biogas systems links sectors of society (e.g., energy, industry, agriculture, waste management, and fertilizer production) that have not traditionally worked together. This collaboration is a prerequisite for building a more resource-efficient and resilient economy. However, efforts may be required to support and facilitate cross-sectoral collaboration, for enhancing industrial and urban symbiosis. Lack of knowledge and overly narrow perspectives in decision-making, may lead to socio-economic sub-optimization. This includes the prioritization of less beneficial technologies and systems, and greater risk of unintended problem shifting.

The expanded use of biogas systems depends on many societal conditions that may be influenced by policy. For example, the points below should be considered:

- Decisions should be determined from science based, comprehensive and transparent, multi-criteria methods - sufficiently broad sustainability assessments to cover essential effects/values of biogas solutions and complementing or competing alternatives. Regarding systems perspectives the assessments should;
 - Cover the most essential physical parts of lifecycles and/or value chains.
 - Address the most influenced and significant sustainability impact categories.
 - Consider relevant time perspectives, e.g. via scenarios for future development.

Efforts for a harmonized common knowledge base on lifecycle, or value chain, perspectives and lifecycle methods are essential, to avoid conflicting perspectives and regulations in different policy areas.

- It appears essential to shift focus towards a strategy on how to efficiently combine different renewable technologies to simultaneously provide the functions wanted while addressing urgent sustainability challenges, that should allow for adaptation to essential local and regional conditions and opportunities. It is important to;
 - Have reasonable expectations on the development of new technologies (development and efficient implementation may require decades).
 - Recognize the importance of gaseous energy carriers, that can play an important role parallel to electric solutions, and other alternatives.
 - Prioritize multi-functional solutions that may simultaneously address several essential needs and challenges.
 - Establish clear production and use targets for biogas/biomethane, biofertilizers/digestate and biogenic CO₂.
 - Plan for new establishments in line with the goals, including setting aside land areas for production and distribution.

- Coherent and well-coordinated policy is critical for the development of biogas solutions and reduced policy related risks for all affected actors, not least for essential investments in new plants and infrastructure for distribution.
 - There needs to be a mechanism whereby ‘biogas actors’ can internalize the values generated by biogas systems. This may be based on penalties for pollution, higher carbon taxes and payments for systems that reduce pollution.
 - Removal of unnecessary policy barriers, and harmonization of policy (for example, regarding what feedstocks are acceptable to use, related to the point below).
 - More nuanced and fair policy concerning the ‘food versus fuel issue’, for example, paying attention to the fact that biogas solutions simultaneously can deliver energy carriers and contribute to food security
 - Avoidance/removal of policy barriers that hinder ‘sustainable’ crop-based biogas systems.
 - More equal conditions regarding the use of land and biomass for different sectors and purposes (e.g., it can be seen as unjustified and unfair to hinder certain uses of agricultural feedstock for bioenergy purposes while allowing combustion of the same feedstock or the installation of solar panels on agricultural land)
 - Develop policy and practices that well balances top-down and bottom-up perspectives. Local and regional conditions influence what systems are most reasonable and efficient.

Based on the country descriptions in Chapter 4 it can, for example, be noted that:

- Biogas solutions should be integrated into societal water and waste management systems, in line with the best practice exemplified in this report. For such a development, it is essential to:
 - Prevent landfilling and incineration of organic waste and support the most circular and value creating alternatives.
 - Enforce and support mandatory separation of organic waste.
 - Pay attention upstream, to avoid pollution of our societal material flows, to avoid problems downstream where pollutants hinder circular practices.
- Products and strategies need to be developed for the use of biogenic CO₂ from biogas plants, considering its purity and volumetric output. Local use in greenhouses, and various CCU and CCS options, should be explored.
 - When fossil fuels are phased out and replaced by biofuels and e-fuels, alongside the general shift towards a bioeconomy, there may be a deficit of biogenic carbon. Therefore, prioritizing carbon capture and utilization (CCU) may be reasonable.
- There is a need for expanded and improved infrastructure for the production and distribution of biogas/biomethane, biofertilizers, and bio-CO₂.

Even when the technologies exist and effective policy frameworks appear to be in place, a community may not be willing to accept a biogas solution. Reality often falls short of meeting expectations of supporting small operations that are not heard nor smelled. While the report does not delve into this topic, the country specific texts acknowledge that the public needs to accept biogas solutions for development to take place. As such, it would be helpful for the public, and especially the people living in the region where biogas development could occur, to understand biogas solutions as value chains, and be involved in their development.

Types of information that might be useful include:

- The components of biogas value chains (from feedstock sourcing to the use of biogas energy and digestate products).
- The description of competing value chains, e.g. industrial composting of food waste;
- Mass balance concept, i.e. the carbon, nutrient and water in waste all need to go “somewhere”, where should this be.
- Economies of scale and financial trade-offs of smaller facilities.
- All of the potential sustainability effects (positive and negative), and the most relevant ones in a particular region.
- How biogas value chains contribute to societal goals, and development in a region.
- Where biogas fits in the clean energy transition, including the future of natural gas.

While not the only option, biogas solutions can hopefully be viewed from a broader context as potential deliverers of many positive sustainability effects to society as a whole.

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