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Perspectives on biomethane as a transport fuel within a circular economy, energy, and environmental system

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Perspectives on biomethane as a transport fuel within a circular economy, energy, and environmental system

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Executive Summary

The literature indicates that the life cycle costs of biomethane fueled light vehicles may be 15 to 20% higher than for similar petrol and diesel fueled vehicles, while liquid biomethane fueled heavy duty trucks may have similar life cycle costs to diesel. However, such an analysis can be two dimensional and limited in the message it conveys. On one hand the acceptance of diesel fueled trucks and buses will be limited due to the climate emergency and air pollution and after 2030 diesel may not be the competition for biomethane anymore. On the other hand, biomethane production is part of a larger circular economy, energy, and environmental system. It is very difficult to divorce the energy vector, biomethane, from the system through which it is produced. In essence biomethane can be considered as one of the products or services of a broad biogas system.

An advantage of biogas is that it can be produced from most wet organic wastes or by-products, including for food waste, animal by-products, (such as manure), agricultural residues, sewage sludge, industrial biowaste (such as from slaughterhouses and food and beverage processing industries). Biogas production is an element in the environmental management of such wastes; biogas plants can also deliver digestate, which contains most of the nutrients in the feedstock and can be an excellent *biofertilizer*. In addition, it is possible to utilize the carbon dioxide removed in upgrading biogas to biomethane as a product with added value. The resource of biomethane is very significant in considering the vast amounts of organic wastes landfilled around the world each year, that instead could be used to produce biogas, biofertilizers and food grade CO_2 while improving the environment through reduced fugitive methane emissions and improved water quality. Furthermore, the application of biogas systems in bio-industrial contexts (such as paper mills, food production facilities, or other types of biorefineries) has huge potential to decarbonize industry while significantly increasing the resource of biomethane.

Due to the multifunctionality of biomethane solutions, broad assessment methods are needed to grasp the wide spectrum of relevant factors when comparing different technologies:

- Biomethane has a competitive performance compared with fossil fuels and other biofuels on a whole life cycle analysis and is particularly suited to long distance heavy vehicles.
- Biomethane from manure, residues, waste & catch crops is estimated to have low GHG emissions as compared to other renewable fuels.
- Biomethane may contribute to reduced air pollution in comparison with diesel, petrol, and other biofuels.
- Biomethane can contribute to a substantial reduction in acidification compared with fossil fuels.
- Biomethane may contribute to significantly reduced noise levels in comparison with diesel heavy goods vehicles.
- Well-designed and applied biogas systems may be essential to transform conventional farming to more sustainable farming and to organic farming.
- Common types of biogas solutions provide essential sociotechnical systems services as components of systems for waste and (waste) water management.
- Biogas solutions may importantly contribute to improved energy supply/security and flexibility.

Natural gas systems should be a facilitator of the introduction of biomethane for transport, but the sustainability problems associated with natural gas negatively impact the view of biomethane. This is where arguments amongst the renewable sector actors can hinder progress. Biomethane and (power to methane) can utilize the existing gas grid and accelerate progress to decarbonization of the overall energy sector beyond just electricity and also to decarbonize chemical (such as ammonia and methanol) and steel production. This should be advantageous especially when realizing that more energy is procured from the natural gas grid than the electricity grid in the EU and the US; however, suggestions that biomethane is only greenwashing the natural gas industry, and in doing so extending the lifetime of natural gas, greatly impedes this progress.

This report provides exemplars of very good biomethane based transport solutions, with a high technological readiness level for all elements of the chain from production to vehicles. Transport biomethane sits well in the broad circular economy, energy, and environmental system providing services across a range of sectors including reduction in fugitive methane emissions from slurries, treatment of residues, environmental protection, provision of biofertiliser, provision of food grade CO_2 and a fuel readily available for long distance heavy haulage. What we do not have is time to postpone the sustainable implementation of such circular economy biomethane systems as the climate emergency will not wait for absolutely perfect zero emission solutions; should they exist.

Glossary

Some essential terms are explained below. It should be observed that the report focuses on *biomethane* as a transport fuel, and that there are different ways of referring to this type of fuel in different contexts and different jurisdictions.

Anaerobic digestion (AD)	Microbial degradation of organic substances in absence of oxygen. The degradation process delivers raw biogas and digestate.
Biofertilizer	Refers to a fertilizer product based on the digestate from AD process. Biofertilizer contains important plant macro- and micronutrients. The presence of living microorganisms promotes plant biomass growth by increasing the availability of nutrients.
Bio-CNG	The same as *biomethane*, 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 *liquid biomethane*, 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 c. $97\%_{vol.}$ Similar quality to natural gas. Can be injected into natural gas grids and be used to fuel methane-powered vehicles.
Compressed biomethane (CBM, CBG)	Biomethane that has been compressed to 200–300 barg to reduce the volume. Compressed biomethane is commonly used to fuel vehicles.
Compressed Natural Gas (CNG)	Natural gas that has been compressed to 200–300 barg to reduce the volume.
Digestate	The remaining material after anaerobic digestion processes: an important product in addition to biogas/biomethane (and carbon dioxide). Digestate contains most of the nutrients in the feedstock, and the AD process transforms the nutrients into a more bioavailable form.
Feedstock	The organic material that is digested. Similar to *substrate*.
Life-Cycle Assessment/ Analysis (LCA)	A methodology for assessing environmental impacts associated with all the stages of the life cycle of a product, process, or service.
Liquid biomethane (LBM) sometimes referred to as liquid biogas (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.
Multi-Criteria Analysis (MCA)	Or Multi-Criteria Decision Making (MCDM). Umbrella terms for methods used to support decision-making based on multiple criteria.
Natural gas	Methane gas of fossil origin.
Raw biogas	The gas originating from AD (biogas production plants) that typically contains 50–70% methane (CH_4), 20–45% carbon dioxide (CO_2), and some trace gases. Raw biogas needs to be upgraded to reach fuel quality standards.
Renewable natural gas	The same as *biomethane*. The term renewable natural gas is used in some countries.
Substrate	The organic material that is digested. Similar to *feedstock*, which is the term that is mainly used in this report.
Upgraded biogas	The same as *biomethane*. 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 to biogas systems

Across the planet we are facing a wide range of sustainability challenges including: climate change; air pollution; water availability and pollution; noise; waste management; and non-cyclic practices within agriculture. Clearly, many present-day systems are unsustainable, as they consume finite resources and impact negatively on life sustaining systems. There is a great need for well-designed sociotechnical systems that are multifunctional (Lindfors et al., 2019) and can provide key products and services, such as food, energy, mobility, and other essential services, based on sustainable management of natural resources. We need a shift towards a biobased and circular economy. In this context, biogas solutions can play an essential role, which will be illustrated in this report focusing on applications of biomethane to the transport sector. Initially, this report delivers a broad and basic introduction to biogas systems, followed by chapters more specifically dealing with different aspects of biogas used for transportation.

1.1 BASICS OF BIOGAS AND BIOFERTILIZER PRODUCTION

Biogas is produced as the main product of anaerobic digestion (AD) of wet biomass in biogas plants, where microorganisms degrade the biomass (or feedstock) in an environment in the absence of free oxygen. Raw untreated biogas from AD plants typically contains 50 – 70 % methane (CH_4), 20 – 45 % carbon dioxide (CO_2), and some trace gases. Biogas in a raw form can be used to produce heat and/or electricity. To use as a transport fuel, the raw biogas needs to be cleaned and upgraded; impurities must be removed, and the level of carbon dioxide reduced to generate a gas with a methane content of at least 97 %. The cleaned and upgraded gaseous fuel is called biomethane (*bio* to emphasize the biological origin), which has qualities very similar to natural gas; in some countries biomethane is referred to as renewable natural gas (RNG). Biomethane can replace natural gas as a fuel for transport, but also in applications like space and process heating, and as a fuel for chemical reforming (Capra et al., 2019). Similar renewable gases can also be generated from gasification of woody solid biomass; a process which converts solid biomass fuel into a gaseous combustible gas through a sequence of thermo-chemical reactions. Another process is power-to-gas, where methane (CH_4) is produced in a two-step process: firstly (preferably renewable excess) electricity is used to split water (H_2O) to hydrogen gas (H_2) and oxygen (O_2) using electrolysis; secondly this hydrogen is transformed to methane through reaction with CO_2 ($4H_2 + CO_2 = CH_4 + 2H_2O$). However, the AD technology is the most mature and is thus focused on in this report.

In addition to the biogas, the AD process at biogas plants also generates another important product – digestate – which is the remaining (digested) biomass. Digestate contains most of the nutrients in the feedstock, and the AD process transforms the nutrients into a more bioavailable form. Thus, digestate can be an excellent plant fertilizer to be used in agriculture or elsewhere, rich in both organic matter and in macro- and micro-nutrients (Drosg et al., 2015). There is also a potential to make use of the carbon dioxide removed in the cleaning and upgrading steps, which can replace fossil-based CO_2-products and thus further improve the climate sustainability of the anaerobic digestion performance – see section 2.8.

1.2 FEEDSTOCK AND BIOGAS POTENTIAL

The biomass used for biogas production is commonly referred to as feedstock or substrate. A great advantage with biogas, in comparison with other biofuels, is that it can be produced from several different types of feedstock, with various shares of carbohydrates, lipids/fats and proteins, both from primary and secondary raw materials (Allen et al., 2016). Most biodegradable non-woody biomass can be used. Wood biomass has a high lignin content and as such is not amenable to anaerobic digestion. The large variety of suitable feedstocks have a wide range in biomethane potentials and all are impacted by a variety of technical, political, economic, environmental, and social opportunities and challenges (Ammenberg and Feiz, 2017). Biogas is commonly produced from wastes or by-products (secondary materials), such as food waste, animal by-products (manure and slurry), agricultural residues, sewage sludge, industrial biowaste (such as from slaughterhouses and food and beverage processing industries). For example, enormous amounts of organic wastes are landfilled around the world, that instead could be used to produce biogas and biofertilizers and/or other valuable products (Cappannelli et al., 2020). 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 (Cherubini, 2010; Hagman et al., 2017).

In addition, several primary feedstocks are used, including for different types of crops. A wide range of crops can be used for biogas production (Gissén et al., 2014; Murphy et al., 2011). From a sustainability perspective, it is wise to avoid competition with food or fodder production. For example, a well-designed sequential cropping scheme can involve cover/intermediary crops (such as ley crops), which can be used to produce biogas and biofertilizers (Brémond et al., 2020; Magnolo et al., 2021; McCabe, B. et al., 2020). Such measures can lead to long-term soil fertility improvements, reduced needs of pesticides and improved biodiversity (Feiz and Ammenberg, 2017), thus strengthening the food and fodder production system rather than the opposite (Szerencsits et al., 2016). Another strategy is to utilize marginal lands for the production of 'energy crops'. Brémond et. al (2020) have noticed a shift from 'energy crops' to more waste-based biogas systems.

Biogas plants are commonly used all year round, with continuous feeding. Availability varies for different types of feedstocks. For example, there may be relatively constant supply of food waste, while some agricultural fractions may be more seasonal. Thus, there is need for a good selection/combination of feedstock, and facilities for on-site storage may be required. However, the storage should be designed to minimize the degradation of the organic material, to avoid odor and loss of methane potential.

There are many biofuel and biogas potential studies, conducted under different conditions using a range of methodologies and as such providing a wide range of results (Offermann et al., 2011; Searle and Malins, 2015). However, it can be concluded that there is a great potential to increase the biogas resource, even in countries which already have a relatively large production (Hamelin et al., 2020). 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."* This report estimated the 2018 world total biogas production to be about 400 TWh, and that the theoretical resource was almost 7 PWh (c. 16 times larger) 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 than those mentioned above would be included. In addition, one could consider aquatic feedstocks such as seaweed (Tabassum et al., 2016) and micro-algae (Herrmann et al., 2016; Wall et al., 2017) that are commonly excluded in biogas potential studies. Cover/intermediary crops could contribute significantly (Brémond et al., 2020).

1.3 BIOGAS USE

The produced biogas is mainly used for generation of heat (including cooking) and electricity in many countries (Gustafsson et al., 2020a). Of the total production globally, only a very small share is upgraded to biomethane and used for transport, however this part is growing (IRENA, 2018). In some countries, there is large scale upgrading of biogas to biomethane, which is injected to natural gas grids and mainly used for other purposes. Italy is one exception, where most of the biomethane is used for transportation (IRENA, 2018). Sweden has a relatively large-scale use for transport – about two thirds of the domestically produced raw gas is upgraded and the dominant use of this fraction is as vehicle fuel. However, there are established and emerging markets for biomethane as fuel for road transports in several other countries, such as Austria, Czech Republic, France, Switzerland, United Kingdom, and the US. Many actors and countries seem to shift focus to upgrading and see biomethane as a superior product, due to the greater flexibility for use (Miltner et al., 2017). Pöschl et al. (2010) found it more favorable in terms of primary energy savings to substitute fossil fuels in the transport sector instead of producing green electricity. Figure 1 schematically illustrates biogas solutions.

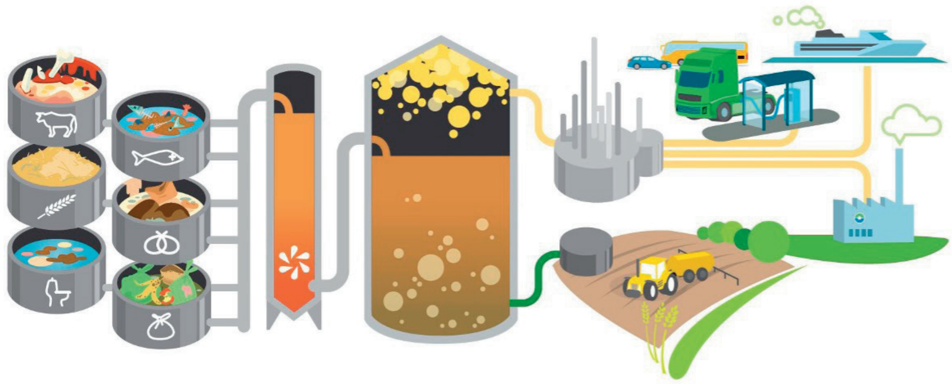


Figure 1. A schematic illustration of biogas solutions, where different types of feedstocks are converted in AD plants to biomethane fuel and biofertilizers for use in agriculture. In addition, carbon dioxide is separated and may be used for different purposes. *Illustration: Mattias Schläger.*

1.4 BIOGAS SYSTEMS AS BIOBASED AND CIRCULAR PROBLEM SOLVERS

Biogas solutions can contribute to a wide range of societal benefits, depending on the context. Well-designed biogas solutions will have many positive links to the UN Sustainable Development Goals (McCabe and Schmidt, 2018). Thus, it is commonly wise to look upon biogas systems from several different perspectives, using a broader sustainability framing, and not to assess them just as an energy or transport technology. For example, biogas solutions (in addition to energy/fuel services) may contribute to:

- Waste management functions, such as:
  - Separation, which can facilitate recycling of other waste fractions;
  - Hygienization, for example reducing risks related to pathogens;
  - Reduced volumes, meaning less waste to treat with other technologies and thus potentially reduced costs.
- Water management functions and improved water quality:
  - being an essential part in advanced Waste Water Treatment Plants (WWTPs), providing clean waste water;
  - reduced eutrophication related to the use of aquatic feedstock (removal of nutrients from water) and more sustainable agricultural practices involving reduced leakages of nutrients (Akram et al., 2019).
- More sustainable land use:
  - Closing nutrient flows, reduced need for unstainable use of mineral fertilizers;
  - Improved soil fertility and carbon sequestration;
  - More organic cultivation.
- Improved energy supply/security and regional employment:
  - For example, providing base load to complement variable renewable electricity such as from wind and solar power.
- Reduced emissions of:
  - Greenhouse gases (GHG), leading to reduced climate impact;
  - Particles and nitrogen oxides, improving air quality.
- Positive effects regarding biodiversity.
- Lowering impacts due to reduced needs of pesticides in smartly designed crop rotation systems.
- Lower noise levels from gas engines than from diesel fueled heavy goods vehicles.
- Reduced odor when for example, pig manure is treated in an AD plant.

This overarching list shows that well-designed biogas solutions play an essential role in circular economy energy, agricultural, and environmental systems already. Nevertheless, there is a great potential for expansion and a potential to valorize the biogenic carbon dioxide streams. The list suggests that biogas solutions may be among the key components in the transition towards a more biobased and circular economy (Biogas Research Center, 2019).

2 Technology for biomethane as a transport fuel

This chapter focuses on processes downstream of the anaerobic digester. Emphasis is paid to technologies for biogas cleaning, biogas upgrading, biomethane liquefaction, biomethane storage, and biomethane distribution and on applications within the transport sector such as biomethane fueling stations, and biomethane fueled vehicles.

2.1 CLEANING

Typically, raw biogas contains 50 – 70 $\%_{vol}$ methane (CH_4), 20 – 45 $\%_{vol}$ carbon dioxide (CO_2), and trace amounts of impurities. Examples of common impurities are water vapor (H_2O), hydrogen sulfide (H_2S), ammonia (NH_3), volatile organic compounds (VOCs), hydrogen (H_2), oxygen (O_2), nitrogen (N_2), carbon monoxide (CO) and particles (Hoyer et al., 2016; Sun et al., 2015). The existence and concentrations of impurities depend on the feedstock used (Petersson and Wellinger, 2009). Table 1 outlines the range of compound concentrations commonly found in raw biogas from AD, but also provides information on landfill gas and natural gas.

Table 1. Typical composition of biogas from anaerobic digestion (AD), landfill gas, and natural gas. Adapted from Yang et al. (2014). Natural gas composition can vary from region to region, the natural gas properties provided in this table are intended to be indicative only.

Compound	Unit	Biogas from AD	Landfill gas	Natural gas
Methane (CH_4)	%vol	53-70	30-65	81-89
Carbon dioxide (CO_2)	%vol	30-50	24-47	0.67-1
Nitrogen (N_2)	%vol	2-6	<1-17	0.28-14
Oxygen (O_2)	%vol	0-5	<1-3	0
Hydrogen (H_2)	%vol	NA	0-3	NA
Higher hydrocarbons	%vol	NA	NA	3.5-9.4
Hydrogen sulfide (H_2S)	ppm	0-2000	30-500	0-2.9
Ammonia (NH_3)	ppm	<100	0-5	NA
Chlorines	mg/Nm^3	<0.25	0.3-225	NA
Siloxane	$\mu g/g_{dry}$	<0.08-0.5	0<0.3-36	NA

Raw biogas is cleaned prior to upgrading as the impurities present may damage the upgrading technology. For example, hydrogen sulfide (H_2S) is highly corrosive, and particles may cause mechanical wear. Impurities such as siloxanes are problematic when used in combustion engines (Arrhenius et al., 2011). Where and how different impurities are removed from the raw biogas varies depending on the technologies used for digestion and upgrading, and on gas quality standards. For example, hydrogen sulfide is normally maintained below 100 ppm inside the digester by adding iron chloride (Nordell et al., 2016), and can also be separated in a raw biogas cleaning step, or as a part of the upgrading process. H_2S levels of 3000 ppm in biogas can be removed by chemical absorption down to impurity levels of < 30 ppm for further treatment within the upgrading unit. An alternative is to inject oxygen gas (O_2), or air, into the digester to enable the removal of hydrogen sulfide by biological oxidation (Petersson, 2013). The use of oxygen may be preferred over the use of air as this prevents the addition of N_2 contained in air which can be difficult to remove from biogas. If air is used and N_2 gas is introduced into the biogas, more propane would be required for grid injection to increase the calorific value of the biomethane to match natural gas. Biogas plant owners need to be aware of impurities present and limits applicable, when considering how to efficiently remove these impurities.

2.2 UPGRADING TECHNOLOGIES

The energy content of biogas is directly proportional to the methane concentration (Petersson and Wellinger, 2009). As carbon dioxide has no energy value the presence of CO_2 in raw biogas means that it has a lower energy content than natural gas which has a high methane content along with other short chain hydrocarbons. Natural gas for example may contain 5 % ethane, which raises the calorific value of natural gas. The calorific value of natural gas can be expressed in terms of gross calorific value (higher heating value) at 15°C and 1.01325 bar_{abs}. A comparison of the gross calorific value of biogas (55 $\%_{vol}$ CH_4, 15°C, 1.01325 bar_{abs}) to natural gas from several countries is shown in Figure 2. Biogas contains 48–62 % of the energy contained in an equivalent volume of natural gas.

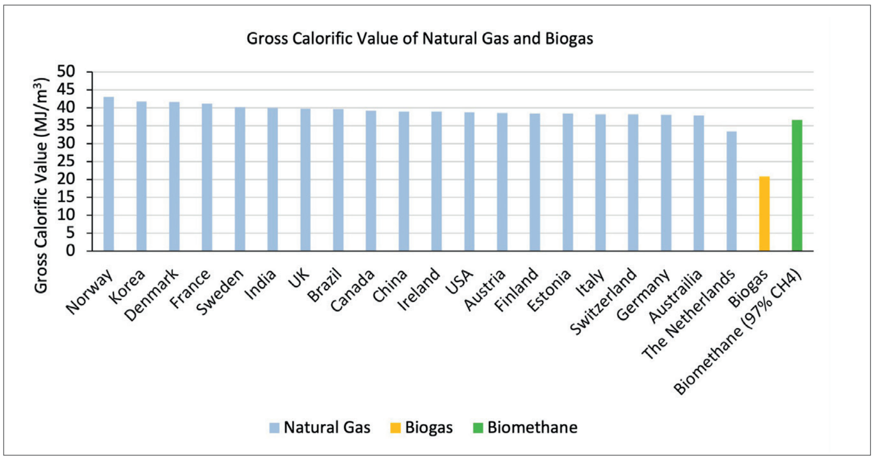


Figure 2. Gross calorific value of natural gas and biogas (55$\%_{vol}$ CH_4). Temperature: 15°C. Pressure: 1.01325 bar. Data adapted from (IEA, 2021).

In most gas fueled vehicles the combustion engines and other equipment are designed to use natural gas. Biogas must be upgraded to a corresponding quality (c. 97 $\%_{vol}$ methane) through the removal of carbon dioxide; the upgraded biogas is referred to as biomethane and has a gross calorific value c. 6 – 8 % lower than natural gas (Figure 2). There are several national standards for grid injection of biomethane and use as vehicle fuel, as shown in Table 2 adapted from Petersson and Wellinger (2009). There are four main methods of carbon dioxide removal from biogas (Miltner et al., 2017), along with methanation which can convert the carbon dioxide into additional methane (see section 2.8).

Table 2. Biomethane grid injection standards.

Parameter	Unit	France		Germany		Sweden	Switzerland		Austria	Nether-lands	Ireland[1]
		L gas	H gas	L gas grid	H gas grid		Limited injection	Unlimited injection			
Gross calorific value	MJ/m³										36.9-42.3
Higher Wobbe index	MJ/Nm³	42.48-46.8	48.24-56.52	37.8-46.8	46.1-56.5				47.7-56.5	43.46-44.41	47.2-51.41
Methane	%vol					95-99	> 50	> 96		> 80	
Carbon dioxide	%vol	< 2		< 6			< 6		≤ 2		≤ 2.5
Oxygen	%vol ppmV Mol%	< 100		< 3			≤ 0.5		≤ 0.5	< 0.5	≤1
Hydrogen	%vol	< 6		≤ 5			<5		≤ 4	< 12	< 0.1
$CO_2 + O_2 + N_2$	%vol					< 5					
Water dew point	°C	<-5		< Ground temperature		< ambient temperate -5°C			≤-8	-10	
Water content	mg/m³										< 50
Relative humidity	ρ						< 60%		≤ 5		
Sulphur	mg/Nm³	< 100 < 75		< 30		< 23	< 30			< 45	< 50

[1] *Values for Ireland are at 15°C, 1.01325 bar_{abs}*

2.2.1 Chemical or physical absorption in liquids – scrubbing

Absorption takes advantage of the fact that carbon dioxide is more soluble in certain selected liquids than methane (Sun et al., 2015). There are three main types of scrubbing techniques based on absorption: water scrubbing, organic physical scrubbing, and chemical (amine) scrubbing (Petersson and Wellinger, 2009). Cleaned biogas is injected into the bottom of a column, while the liquid (solvent) is injected at the top, showering the gas in a counter flow configuration. The column is filled with packing material to increase the contact area (Bauer et al., 2013). When the liquid meets the biogas, it absorbs carbon dioxide and the gas leaves the column at the top. This upgraded biomethane is saturated with solvent vapor and must be dried before injection to a gas grid or use as a vehicle fuel (Bauer et al., 2013). The liquid is pumped into a desorption column where the carbon dioxide is desorbed from the liquid, allowing the liquid to be fully or partially reused.

Water scrubbing

A water scrubber consists of a pressurized absorption column (typically at about 10 bar) to increase the efficiency of absorption. The used water solvent passes into at flash tank at a slightly lower pressure than the absorption column where methane and some carbon dioxide are released from the water. The gas stream can be recirculated back to the biogas inlet. A desorption column (or stripper) is used to regenerate the water solvent by full depressurization allowing the carbon dioxide to be desorbed from the water (Figure 3). Methane recovery can exceed 99 % and a methane content of 97 – 98 $\%_{vol}$ is possible (Bauer et al., 2013; Ryckebosch et al., 2011). Water scrubbing technology is the most commonly used scrubbing technology among the IEA Task 37 member countries (Gustafsson et al., 2020a) and is a simple and robust system (Miltner et al., 2017). The high efficiency and good tolerance for impurities (hydrogen sulfide, ammonia, and some VOCs can dissolve in water) are strengths of water scrubbing (Hoyer et al., 2016; Ryckebosch et al., 2011). Some drawbacks include the introduction of oxygen and nitrogen to the water in the desorption step (Miltner et al., 2017), the low concentration of carbon dioxide in the off-gas may preclude the recovery of carbon dioxide, clogging due to bacterial growth, and possible foaming in the scrubbing columns (Ryckebosch et al., 2011). The latter can be minimized using lower temperatures and biocides (Hoyer et al., 2016). Methane slippage is a disadvantage of this technique as there is normally 1 – 2 % slippage to atmosphere from the desorption process.

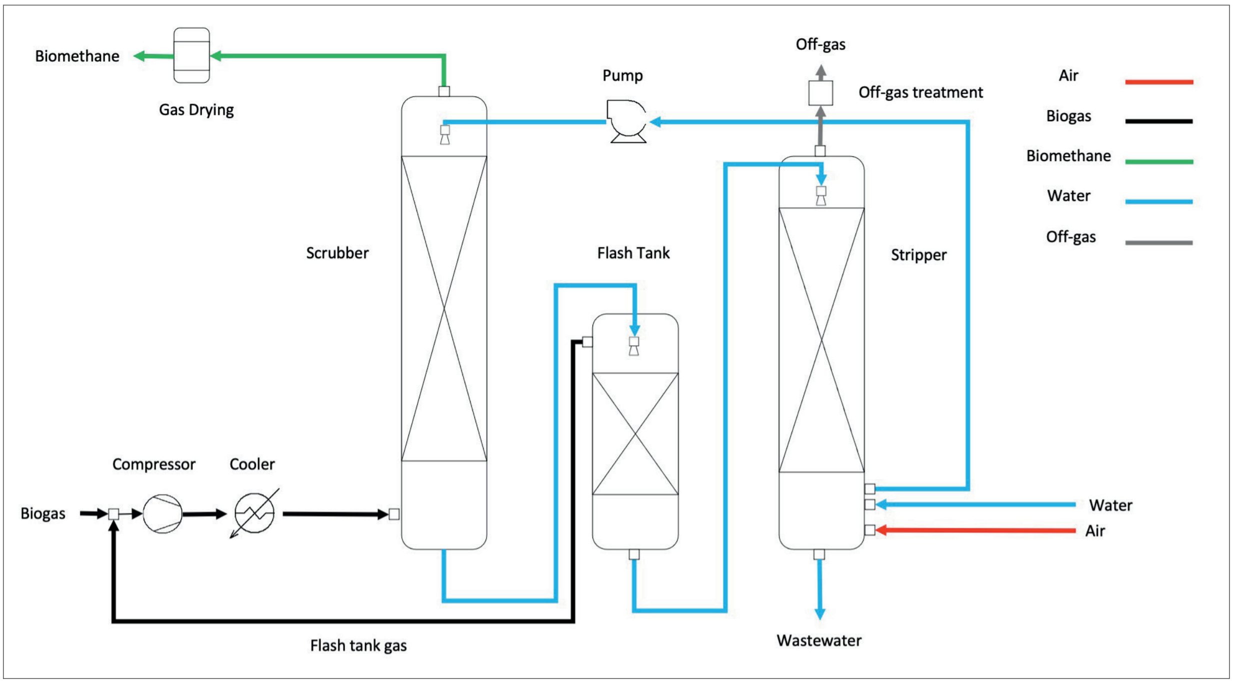


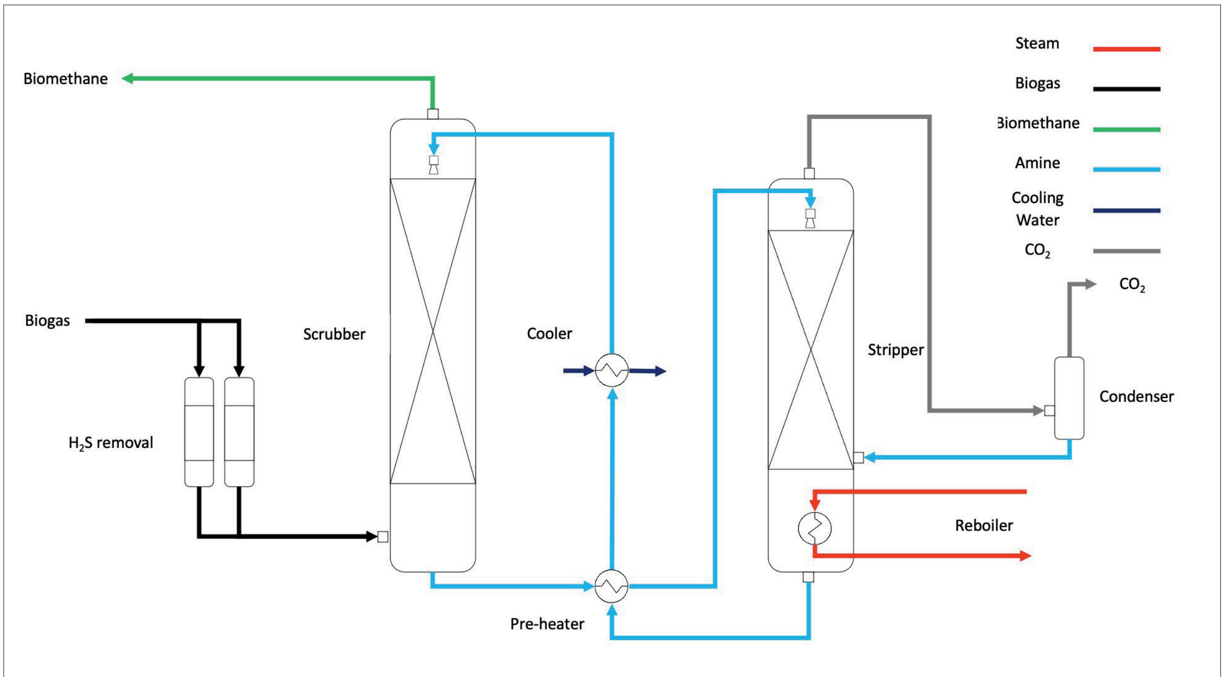
Figure 3. Water scrubbing system topology.

Organic physical scrubbing

The organic physical scrubbing process is similar to water scrubbing but is improved by using an organic solvent (such as methanol and dimethyl ethers of polyethylene glycol) with a significantly higher solubility for carbon dioxide than water (Bauer et al., 2013). A smaller upgrading plant is required for the same upgrading capacity (Petersson and Wellinger, 2009). Similar to a water scrubber, there is a flash tank and desorption column. Organic physical scrubbers are not as common as water scrubbers (Gustafsson et al., 2020a). The benefits of organic physical scrubbing are similar to those of water scrubbing with the added ability to remove additional compounds (hydrogen sulfide, ammonia, and water vapor, Ryckebosch et al., 2011).

Chemical (amine) scrubbing

In a chemical scrubber a reagent (commonly a mixture of water and amines) is used to bind to the carbon dioxide (Bauer et al., 2013). Chemical scrubbers are relatively common (Gustafsson et al., 2020a). Amine scrubbing has a higher separation efficiency than water scrubbing. Carbon dioxide is removed from biogas in a scrubber column where it binds to the amine, a desorption (stripper column) is used to separate the carbon dioxide from the amine solution, enabling solvent reuse (Figure 4). Heat is required to produce steam used to release carbon dioxide from the amine at a temperature of 120 – 150 °C in the stripper (Bauer et al., 2013). The gas stream exiting the stripper has a high carbon dioxide purity, up to 99 $\%_{vol}$ carbon dioxide (Miltner et al., 2017). Chemical (amine) scrubbers usually work at, or slightly above, atmospheric pressure (IRENA, 2018). Methane concentration can exceed 99 % in the upgraded biomethane (Olgemar and Partoft, 2017) with methane recovery greater than 99.95 % and minimal methane slip (Miltner et al., 2017). Chemical scrubbers are relatively cheap to operate but have a high heat demand and can face challenges related to corrosion, negative effects on the amines caused by oxygen or chemicals, precipitation of salts and foaming (Ryckebosch et al., 2011). Access to cheap renewable heat or heat recovered from industry can be advantageous (Viklund Broberg and Lindkvist, 2015).



There are combined chemical absorption scrubbers on the market that remove both H_2S and CO_2 from biogas, that are designed a bit differently to reduce OPEX (mainly developed for the Danish market, where the raw biogas may contain 2000-3000 ppm H_2S).

Figure 4. Chemical amine scrubbing system topology.

2.2.2 Adsorption

Adsorption technology makes use of materials to which carbon dioxide bonds and can be separated from (Olgemar and Partoft, 2017). Adsorbers are highly porous solids with high specific surface areas such as activated carbon, zeolites, titano-silicates, silica gels and carbon molecular sieves (Alonso-Vicario et al., 2010). Pressure Swing Adsorption (PSA) technology uses a column with adsorbents and sequential pressure swings (Figure 5) (Petersson and Wellinger, 2009) and is commonly used for biomethane production (Gustafsson et al., 2020a). A four-step pressure cycle is employed (Olgemar and Partoft, 2017): 1) Biogas is fed into the column and the pressure is increased 2) Carbon dioxide is adsorbed on the adsorber surface while the methane gas can flow through. When the adsorbent is saturated with carbon dioxide, the flow of input biogas to the column is stopped and diverted to a parallel column. 3) The column pressure is lowered. 4) Carbon dioxide is desorbed and removed in an off-gas stream and the adsorbents are regenerated for use in the next pressurization cycle (Hoyer et al., 2016). Several columns are needed, each operating in a different phase of the cycle, to enable continuous biogas upgrading. Desorbed gas should be recycled to make use of residual methane (Augelletti et al., 2017). PSA requires dried gas, free from hydrogen sulfide (Bauer et al., 2013). Methane concentrations may reach 95–98 % (Ryckebosch et al., 2011) and the methane recovery can reach 98–99 % (Augelletti et al., 2017). Gases like hydrogen sulfide or ammonia can block the adsorbents and must be removed upstream of the PSA system (Yang et al., 2014). PSA upgrading is a compact technology suitable for smaller biogas plants but can be expensive and requires more advanced control systems than other technologies (Ryckebosch et al., 2011).

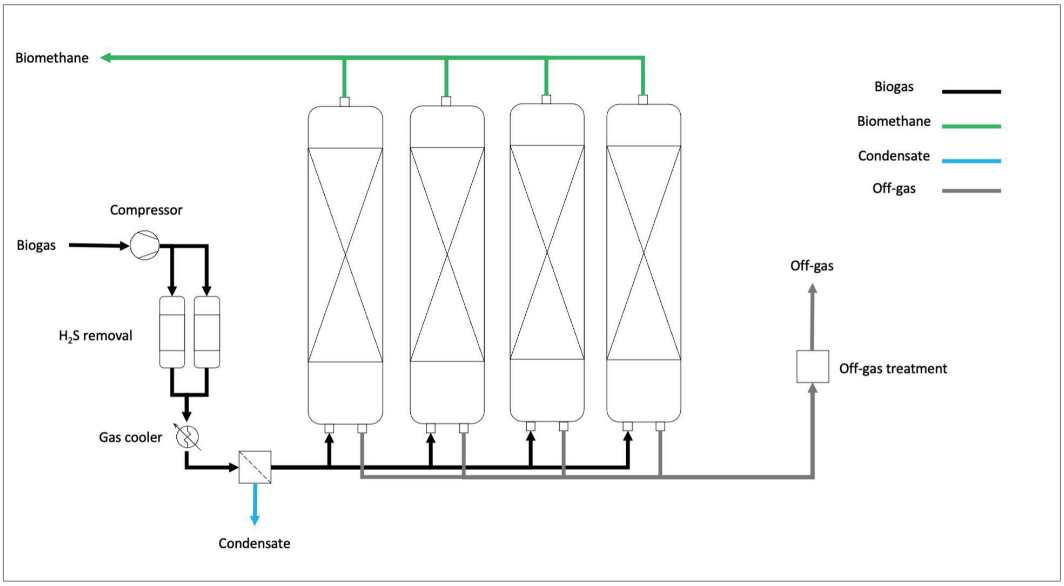


Figure 5. Pressure swing adsorption system topology.

2.2.3 Membrane separation

Membrane upgrading technology uses filters to physically separate carbon dioxide from methane. Pressurized and purified biogas is injected into a filter module (commonly using hollow fiber membranes) designed to be permeable to carbon dioxide and water but non-permeable to methane molecules (Hoyer et al., 2016). Gases with higher permeability pass through the membrane to the low-pressure side (these gasses are dubbed permeate), while gases with lower permeability accumulate on the high-pressure side (dubbed retentate) (Miltner et al., 2017), see Figure 6. The separation is not perfect, and it is common to combine several filters and recirculate the permeate flow. Methane purity can exceed 98 $\%_{vol}$ and methane recovery ranges from 98–99.5 % (Olgemar and Partoft, 2017). The ability to remove hydrogen sulfide and water in the process is advantageous along with the simple construction and operation, high reliability, and possibility to treat small gas flows, however the need for multiple sequential steps can be seen as a drawback (Ryckebosch et al., 2011). The consumption of consumables to run a membrane upgrading unit is low compared to other upgrading technologies (Bauer et al., 2013). Membrane technology is one of the newest upgrading technologies (Miltner et al., 2017) but is already widely used (Gustafsson et al., 2020a).

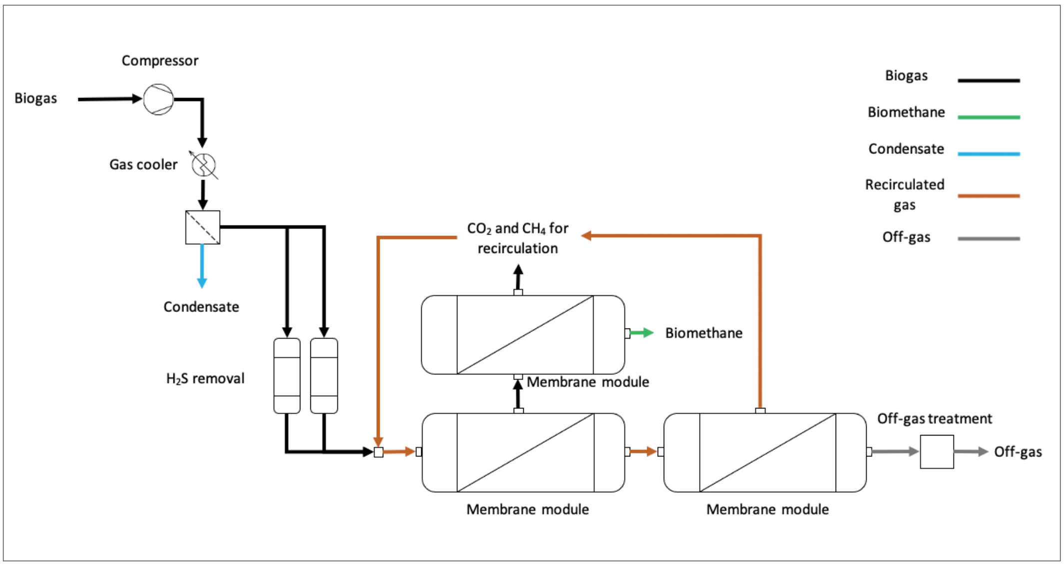


Figure 6. Membrane separation system topology.

2.2.4 Cryogenic separation

Cryogenic upgrading uses the different condensation and sublimation temperatures of the components in biogas to separate them (Sun et al., 2015). When biogas is cooled below the condensation point of carbon dioxide, the carbon dioxide liquifies and can be separated from the remaining gaseous methane (Figure 7). At atmospheric pressure the process would yield solid carbon dioxide which can damage process equipment (Olgemar and Partoft, 2017). Higher pressure is used to produce liquid carbon dioxide, a potentially valuable byproduct. For pure carbon dioxide the sublimation point is -78.5°C at 1 bar_{abs}; in a mixture containing methane and other compounds a lower temperature is required (Petersson and Wellinger, 2009). A sequence of cooling and compression is commonly used, making it possible to separate different compounds from the biogas in a step wise manner (Miltner et al., 2017). It is recommended to purify the raw biogas before cryogenic upgrading to remove hydrogen sulfide and water to avoid freezing, corrosion (Sun et al., 2015), and damage of heat exchangers (Hoyer et al., 2016). Cryogenic upgrading is relatively new and is under ongoing development (Hoyer et al., 2016; Sun et al., 2015). The process can achieve 97–98$\%_{vol}$ methane purity with low methane slip (Miltner et al., 2017; Sun et al., 2015). The process requires substantial energy input but is advantageous when the ambition is to produce liquid biomethane (Miltner et al., 2017).

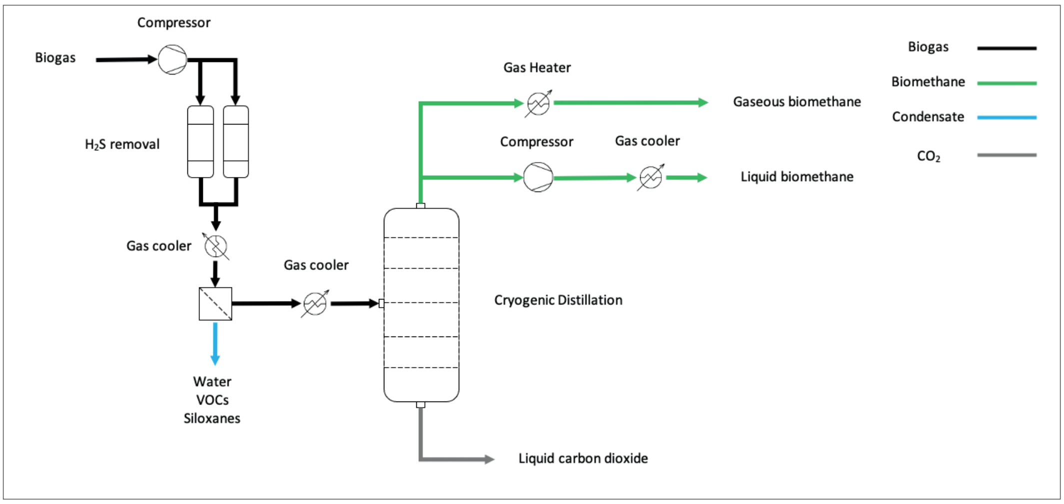


Figure 7. Cryogenic separation system topology.

2.2.5 Drying

Biomethane from all the described technologies must be dried prior to use. Two main methods are used for water removal: physical separation of condensed water (freezing) and chemical drying (adsorption or absorption), further information can be found in Ryckebosch et al. (2011).

2.2.6 Selection of upgrading technology

Upgrading technology involves a significant investment and can vary substantially depending on the scale of the facility and the region where the biogas plant is located (IEA, 2020). The cleaning and upgrading processes commonly represent approximately 20 – 40 % of the total investment costs for a new biogas plant. Economies of scale are present with larger upgrading plants (in terms of biogas upgrading capacity) having a lower specific upgrading cost (cost per cubic meter of biomethane) than smaller plants (Miltner et al., 2017), making small cleaning and upgrading plants relatively expensive. There are examples of small-scale upgrading systems, however upgrading is commonly applied to biogas plants with a gas output greater than 200 m^3/h of raw biogas. As technologies develop, smaller upgrading plants may become profitable in the future. This would significantly aid owners of smaller biogas plants who currently produce electricity and heat in shifting to the production of biomethane. Collaborative solutions may facilitate biomethane production by smaller suppliers who can invest in a joint upgrading unit large enough to benefit from economies of scale (Thrän et al., 2014). For example, farmers in Brålanda in the southwestern part of Sweden have implemented a low-cost solution where raw biogas from multiple small AD plants is transported via simple pipelines to a central upgrading plant.

The upgrading technologies discussed have similar investment costs for standard biomethane applications (Hoyer et al., 2016; IRENA, 2018). Most upgrading technologies mainly consume electricity (0.2–0.3 kWh is needed to upgrade 1 Nm^3 of biogas) while the amine scrubber requires a significant amount of thermal energy (0.55 kWh/Nm^3 of biogas) and approximately half the electrical energy demand (Bauer et al., 2013). The excess heat from amine scrubbing processes can be used to preheat substrates at biogas plants (pasteurization/hygienization and AD heating) or to pre-heat cold amine in the upgrading system which increases the energy efficiency. Consumable use and operating costs vary between technologies based on reagent use, the extent of heat recovery, and how the processes are managed and maintained. When choosing an upgrading technology, it is essential to consider the raw biogas properties (carbon dioxide and impurities) as well as the required biomethane quality to find the best combination of cleaning and upgrading technologies. While standards outlining gas quality have become more well defined (Hoyer et al., 2016), the use of different feedstock types leads to more heterogeneous raw biogas and greater challenges in cleaning and upgrading to reach the purity required in standards.

2.3 LIQUEFACTION OF BIOMETHANE

2.3.1 Gaseous or liquid biomethane?

Biomethane can be utilized as a transport fuel in compressed or liquid form depending on the context. One strategy could be to maximize the use of compressed biomethane in regions with gas grid infrastructure, using vehicles fueled by compressed vehicle gas (biomethane, that may be blended with natural). In countries with limited gas grid systems (such as Sweden) liquefaction may be a favorable option to expand the geographical market for the use of biomethane as a transport fuel. Liquefaction can allow biogas plants to be built close to feedstock sources instead of near the biomethane end user as liquefied biomethane can be transported economically over a longer distance than compressed biomethane. Logistical considerations such as digestate management (amongst others) can also be vital when determining plant location.

Some countries, such as the United Kingdom and the Netherlands, allow biomethane to be injected into pipeline systems (in compressed form) and mass balanced with liquid natural gas (LNG). This liquid fuel is then referred to as bio-LNG, and thus no actual biomethane liquefaction plants are used.

2.3.2 Liquefaction and energy density

It is possible to liquefy both biomethane and natural gas by cooling to -162°C, at atmospheric pressure (1.03125 bar_{abs}) (Conton et al., 2018). The gas composition of biomethane and natural gas are not the same: natural gas contains methane along with potentially ethane, propane and heavier hydrocarbons (Capra et al., 2019), while biomethane is almost pure methane. The condensation temperature varies significantly for natural gas but is relatively constant for biomethane. Pressurization of the liquefaction process reduces the need for cooling as the boiling point of methane increases.

Gaseous biomethane at standard conditions (15 °C, 1.01325 bar_{abs}) has an energy content (net calorific value basis) of c. 33 MJ/m^3, comparable to natural gas but c. 1,000 times less than diesel and petrol. Compressed biomethane (15 °C, 200–250 bar_{abs}) has an energy content of 9,064 MJ/m^3, 275 times greater than uncompressed biomethane but still 3.97 times lower than diesel and 3.53 times lower than petrol. This low energy content of compressed biomethane limits the applications for use if there is no nearby gas grid for distribution. The high pressure of compressed biomethane requires storage in steel or composite vessels which are heavy and limit the amount of compressed biomethane that can be transported by truck. The energy content of liquified biomethane (15 °C, 1.01325 bar_{abs}) is c. 21 GJ/m^3, significantly higher than gaseous biomethane (uncompressed and compressed) and not too dissimilar to liquid diesel (36 GJ/m^3) and petrol (32 GJ/m^3), see Box 1.

The volume reduction from liquefaction is significant; 1 m^3 of gaseous biomethane (15 °C, 1.01325 bar_{abs}) contains the same mass of methane as 1.6 L of liquid biomethane (-162 °C, 1.01325 bar_{abs}), see Box 1. The energy density of liquefied biomethane is c. 643 times that of gaseous biomethane (15 °C, 1.01325 bar_{abs}) due to this volume reduction. In comparison to compressed biomethane (15 °C, 250 bar_{abs}) liquified biomethane has about 2.33 times the energy density (Box 1).

The higher energy density and low-pressure storage required for liquefied biomethane compared to compressed biomethane enables transportation of the liquified biomethane further and expands the market for use. Liquified biomethane is also more suitable for heavy duty vehicles and maritime vessels as they can achieve a similar range as when fueled by diesel without needing significantly larger fuel tanks. Liquified biomethane used in heavy duty vehicles is a relatively new phenomenon but there has been a rapid expansion with ongoing development in the Nordic countries, Italy, and the UK.

According to Capra et al. (2019) biomethane liquefaction requires between 14–20 % of the primary energy content of the produced liquid biomethane depending on the technology used.

Box 1: Energy content of biomethane
Methane net calorific value: 50 MJ/kg

Gaseous biomethane - standard conditions (15°C, 1.01325 bar_{abs})
Biomethane volume: 1 m^3
Methane concentration: 97 %vol
Methane volume: 1* 0.97 = 0.97 m^3
Methane density: 0.68 kg/m^3
Methane mass: 0.97 m^3 * 0.68 kg/m^3 = 0.66 kg
Energy content of biomethane: 0.66 kg * 50 MJ/kg = 32.96 MJ

Gaseous biomethane - compressed (15°C, 250 bar_{abs})
Biomethane volume: 1 m^3
Methane concentration: 97 %vol
Methane volume: 1* 0.97 = 0.97 m^3
Methane density: 186.88 kg/m^3
Methane mass: 0.97 m^3* 186.88 kg/m^3 = 181.27 kg
Energy content of biomethane: 181.27 kg * 50 MJ/kg /1000 GJ/MJ = 9.063 GJ

Liquid biomethane (-162°C, 1.01325 bar_{abs})
Biomethane volume: 1 m^3
Methane concentration: 99.995 %vol (50 ppm CO_2)
Methane volume: 1* 0.99995 = 0.99995 m^3
Methane density: 424.14 kg/m^3
Methane mass: 0.99995 * 424.14 = 424.12 kg
Energy content of biomethane: 424.12 kg * 50 MJ/kg /1000 GJ/MJ= 21.206 GJ

Equivalent volume calculation
1 m^3 biomethane (15°C, 1.01325 bar_{abs}) → 0.0036 m^3 compressed biomethane (15°C, 250 bar_{abs})
1 m^3 biomethane (15°C, 1.01325 bar_{abs}) → 0.0016 m^3 liquid biomethane (-162°C, 1.01325 bar_{abs})

Diesel (Liquid)
Energy content of diesel: 36 GJ/m^3 = 4 m^3 compressed or 1.70 m^3 liquid biomethane

Petrol (Liquid)
Energy content of petrol: 32 GJ/m^3 = 3.53 m^3 compressed or 1.51 m^3 liquid biomethane

2.3.3 Polishing

The low temperatures required to produce liquid biomethane mean that compounds present in biomethane such as carbon dioxide and hydrogen sulfide can freeze and solidify (Bauer et al., 2013). This may cause problems related to plugging of heat-exchangers leading to process failure; to avoid this the biomethane may need to be further cleaned in a polishing step prior to liquefaction. Table 3 shows purity requirements for biomethane prior to liquefaction; nitrogen (N_2) and oxygen (O_2) will remain gaseous even when cooled and do not cause problems as described for the other compounds (Olgemar and Partoft, 2017). The 50 ppm(v) limit regarding carbon dioxide is commonly the limiting constraint, a level that can be difficult to achieve in the upgrading process without polishing (Bauer et al., 2013). It is possible to achieve using efficient amine and cryogenic upgrading technologies, while other upgrading technologies generally need to be complemented with a polishing step.

Table 3. Purity requirements for common compounds of biomethane, to be reached before liquefaction. Based on: Bauer et al. (2013), referring to Flynn (2005).

Compound	Limit	Unit
Carbon dioxide, carbon dioxide	< 50	ppm(v)
Water, H_2O	< 0.5	ppm(v)
Hydrogen sulfide, H_2S	< 3.5 ppm (commonly 0)	ppm(v)

The technology used for polishing is similar to pressure swing adsorption (PSA) upgrading technology but with longer cycles due to the low carbon dioxide concentration (Bauer et al., 2013). The smaller methane molecules pass through the sieve while the large carbon dioxide molecules are retained. Some methane is present in the purge gas which can have a methane content of 60–70 $\%_{vol}$ and should be circulated back to the upgrading plant (Bauer et al., 2013). It has also become common to polish with chemical absorption, and there are new projects involving amine polishing. Other options for polishing include the use of ash filters (produced from ash from incineration plants) (Olgemar and Partoft, 2017).

2.3.4 Liquefaction technologies

The technologies for liquefaction of biomethane are the same as those for natural gas (Tybirk et al., 2018). However, biogas plants are small in comparison to natural gas facilities. A large natural gas liquefaction plant may produce over 1,000 tonnes of liquid natural gas per day (about 5 TWh/year) (Tybirk et al., 2018). In contrast, a biogas plant producing 100 GWh/yr (20 tonnes of biomethane per day) is considered large in the biogas sector despite being 50 times smaller. Most biogas plants correspond to the nano-scale for liquefaction of natural gas as they produce less than 10 tonnes of liquefied biomethane per day (Tybirk et al., 2018). The issue of scale may be mitigated if biomethane can be injected into a gas grid, followed by liquefaction of the natural gas-biomethane mixture at a larger scale. Another alternative is to have joint liquefaction facilities for multiple biogas plants in proximity to one another.

Liquid nitrogen vaporization is relatively simple and utilizes a liquid nitrogen tank and a heat exchanger. Heat is transferred from the warmer biomethane stream to the cold liquid nitrogen in the heat exchanger, the liquid nitrogen then evaporates (Figure 8 A). As cryogenic liquids easily absorb heat high quality vacuum insulated pipes are necessary to transport the liquid nitrogen. Liquid nitrogen vaporization technology is a relatively simple process to manage and control with the added health and safety advantage that the working fluid (nitrogen) is inert and non-flammable (Spoof-Tuomi, 2020).

Gas expander technologies make use of the so-called **Reverse Brayton cycle** designed to move heat rather than to produce work (Chakravarthy et al., 2011). The expansion of a gaseous refrigerant in a turbine provides the cooling duty. It is possible to use biomethane as a working fluid for liquefaction of a sub flow of biomethane, or to use nitrogen as a working fluid (Capra et al., 2019). These are closed loop systems so the feed gas and the refrigerants are kept apart, only interacting via heat exchangers (Pettersson et al., 2007). Additionally, no refrigerants are consumed except for leakage replacement. For the liquefaction of biomethane a single expander using nitrogen as a working fluid can be used

(Capra et al., 2019) (Figure 8 B). Nitrogen provides the required refrigeration for the full process, that commonly includes pre-cooling, liquefaction, and sub-cooling (Roberts et al., 2015; Spoof-Tuomi, 2020). It is possible to save energy by adding a pre-cooling unit that utilizes other refrigerants, such as carbon dioxide, propane or ammonia which could reduce the power consumption by 15–35 % (Spoof-Tuomi, 2020). This increases process cost and complexity (Tractebel Engineering, 2015). Expander based technology typically requires larger refrigerant flow rates for the same cooling capacity (leading to enlarged equipment) compared to other technologies (Capra et al., 2019; Roberts et al., 2015), and high compression energy requirements (Spoof-Tuomi, 2020). Advantages of this process include simplicity and the fact that the required nitrogen can be produced on site from air (Spoof-Tuomi, 2020). Furthermore, liquid nitrogen is inert and non-flammable which is beneficial from a health and safety standpoint (Spoof-Tuomi, 2020).

In the **Reverse Rankine cycle** (Figure 8 C), a heat pump system is used to remove heat. Reverse Rankine cycle liquefaction facilities consist of: heat exchangers (evaporators, condensers), compressors, and throttles (Khan et al., 2013; Kohler et al., 2014). Well insulated throttles utilize the Joule–Thomson effect (adiabatic expansion through a valve) which results in the gases passing the throttle being cooled. Mixed refrigerant systems are closed steady state systems (Capra et al., 2019). The refrigerants selected have different boiling points to spread the evaporation over a temperature range (Mohanraj et al., 2011) to match the evaporation curve of the refrigerant mix to the cooling curve of the biomethane (Nguyen et al., 2017). Mixtures of hydrocarbons with low boiling points as well as nitrogen are used (Spoof-Tuomi, 2020). The most common reverse Rankine cycle configurations use a regenerative single cycle loop, commonly referred to as Single Mixed Refrigerant (SMR) systems (Capra et al., 2019) which are compact, relatively efficient, and are commonly used for smaller applications (Spoof-Tuomi, 2020). Mixed refrigerant processes supplied by some equipment suppliers have a different topology with the mixed refrigerant separation prior to the heat exchanger.

The **Siemens Cycle** can be used to cool and liquefy gases via a cycle of gas compression, environmental cooling, cooling by return flow from later stages, and decompression in an expansion machine to cool the gas. The cooled gas is then be fed back to earlier stages, to provide cooling via heat exchangers, and is subsequently sent to the initial compression stage to go through the cycle again. This cycle uses no other refrigerants other than the gas to be cooled. The Linde Cycle is a development of the Siemens cycle that uses a Joule-Thomson device for the expansion (Spoof-Tuomi, 2020). When the Linde cycle is used for liquefaction of biomethane (Figure 8 D), the biomethane itself is the working fluid (it is thus an open loop system). The biomethane is compressed to 200–300 bar, which may require several steps with compression and inter cooling (Tybirk et al., 2018). After the final cycle step (the Joule–Thomson device) the flow is in the liquid–vapor phase, where the liquid biomethane goes to a liquid receiver and the uncondensed gas is recirculated (Spoof-Tuomi, 2020).

The **Claude Cycle** (Figure 8 E) is similar to the Linde cycle. The working gas first expands in a turbine while the final liquefaction step consists of a Joule–Thomson device. Open Claude systems compress the biomethane, which is then cooled by an after-cooler and split in two streams (Capra et al., 2019). One of the streams is led to the turbine, while the other goes to the Joule–Thomson device. Closed loop versions involving other refrigerants are also possible. In comparison with reverse Rankine cycles the Claude cycle processes can be more capital intensive as more machinery is required (both turbines and Joule–Thomson devices) and are thus more commonly used for larger applications (Capra et al., 2019; Chakravarthy et al., 2011).

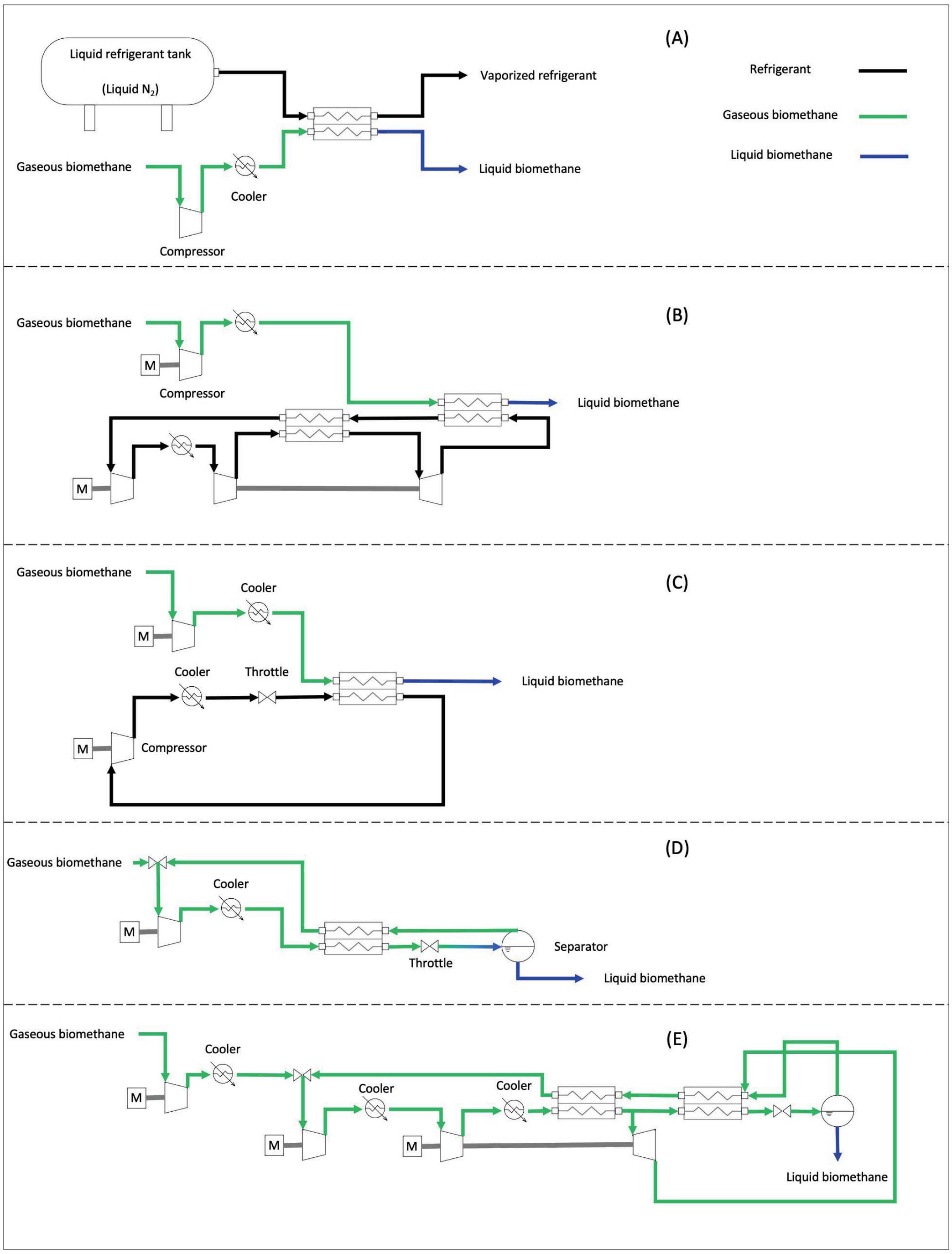


Figure 8. Biomethane liquefaction: (A) Liquid nitrogen vaporization, (B) Reverse Brayton cycle, (C) Reverse Rankine cycle, (D) Linde Cycle, and (E) Claude cycle.

2.4 DISTRIBUTION AND STORAGE

2.4.1 Grid injection of biomethane

Grid injection can be used for biomethane distribution when there is a local existing gas grid. The amount, availability, and standard of gas grid infrastructure varies significantly across the world. The biomethane needs to fulfil the quality requirements of the grid with regards to purity and pressure. A compressor unit may be needed to increase the pressure of the upgraded biomethane before it is injected into the grid (depending on the upgrading technology used and the grid pressure), and small amounts of propane may need to be added to match the energy content of natural gas (JRC, 2015). Elevated pressure from some upgrading technologies can reduce the need for final compression before grid injection. Injection into low pressure grid systems (below 4 bar) can be advantageous as the compression energy cost requirement is lower. An example of a grid injection facility is shown in Figure 9.

When biomethane is injected into natural gas grids, the user that buys biomethane from the system does not use methane molecules contained in the biomethane. As the trade of biomethane is separated from the actual flows, a mass balancing system is used to ensure that the renewable share of the gas used is correct.

There are also several examples of local grids where pipelines have been built for the purpose of transporting the biomethane to local compressed gas (CNG) filling stations that can be positioned in strategic places away from the biogas plant, for example, at truck distribution centers. Energy corresponding to 2–3 % of the energy content of the biomethane is needed to compress from 1 to 200 bar (a common minimum requirement for CNG filling stations, 250 bar for trucks in the UK) (Hoyer et al., 2016). Despite the relatively high investment costs, it may be beneficial to establish local or regional grids when there are large volumes of biomethane to be transported (Persson and Svensson, 2014). Such local grids have received attention in Sweden as they connect important actors (producers, industries, the transport sector, cities). There are also grids for the transportation of raw biogas to end users, for example to centralized upgrading facilities.

Figure 9. Biogas plant with biomethane upgrading and gas grid entry point. Also shown is the propane storage required to adjust gas calorific value. *Credit: John Baldwin, CNG Services Ltd, UK.*

2.4.2 Compressed biomethane virtual pipelines

In places with limited gas grid access the biomethane is commonly compressed and stored in mobile storage vessels (Persson and Svensson, 2014). Gas cylinders made of steel or composite material (rated for 200–250 bar) are normally used. Several cylinders can be placed in truck swap bodies (Figure 10). Full swap bodies are transported to (CNG) filling stations and remain there for short term storage, while "empty" swap bodies are taken back to be refilled with biomethane in a so-called "virtual pipeline".

There are also examples of biomethane injection into a low-pressure gas grid close to the biomethane production site, followed by withdrawal and compression at a remote location using mass balancing. The gas mixture (natural gas plus biomethane) withdrawn from the grid can be compressed to high pressure (200–250 bar_{abs}) and used to fill gas cylinders and mobile units as described above for distribution to sites away from the gas grid. Compression at the gas withdrawal site can make use of the higher flow rates of the mixed gas (natural gas plus biomethane) available resulting in lower unit costs for compression.

Liquefaction increases the mass of biomethane transported for a given volume of storage vessel. The density of liquefied biomethane (-162 °C, 1.01325 bar_{abs}) is 2.34 times higher than the density of compressed biomethane (15 °C, 250 bar_{abs}) (Box 2). The vessels used for liquid biomethane transportation are significantly lighter than those for compressed gas (owing to the lower pressure rating), reducing the mass of the vessels themselves. Liquid biomethane vessels can therefore carry a larger mass of biomethane than the heavier vessels used for compressed biomethane for a similar vessel volume.

Figure 10. Example of a swap body transport in Linköping, Sweden. The container holds compressed biomethane at 200 bar. In this case the truck used is fueled by liquid biomethane. It is a Volvo, 460 hp.
Source: Erik Nordell, Tekniska Verken, Sweden.

Box 2: Compressed vs. Liquefied Biomethane Transport

Gaseous biomethane - compressed (15°C, 250 bar_{abs})
Biomethane volume: 1 m^3
Methane concentration: 97 %vol
Methane volume: 1* 0.97 = 0.97 m^3
Methane density: 186.88 kg/m^3
Methane mass: 0.97 m^3 * 186.88 kg/m^3 = 181.27 kg

Liquid biomethane (-162°C, 1.01325 bar_{abs})
Biomethane volume: 1 m^3
Methane concentration: 99.995 %vol
Methane volume: 1* 0.99995 = 0.99995 m^3 (50 ppm CO_2)
Methane density: 424.14 kg/m^3
Methane mass: 0.99995 m^3 * 424.14 kg/m^3 = 424.12 kg
Liquid biomethane mass/
Compressed biomethane mass = 424.12/181.27 = 2.34

2.5 FILLING STATIONS

2.5.1 Filling stations for compressed biomethane

There are two main types of filling stations for compressed biomethane. The first comprises of **fast-filling stations** with sufficient storage of compressed gas to be injected into vehicles upon arrival (Figure 11 A). Fast-filling solutions can be as fast as diesel filling systems for liquid and compressed biomethane. The second type consists of **slow-filling stations** (time filling stations) that deliver biomethane directly from compressor stations to vehicles (Figure 11 B) over a longer period of time. This is a simpler but slower process as the biomethane is continuously compressed during the filling period which typically runs overnight. The slow-filling solution is popular for city buses, refuse trucks, or other captive fleets that can return to the same facility for several hours on a regular basis.

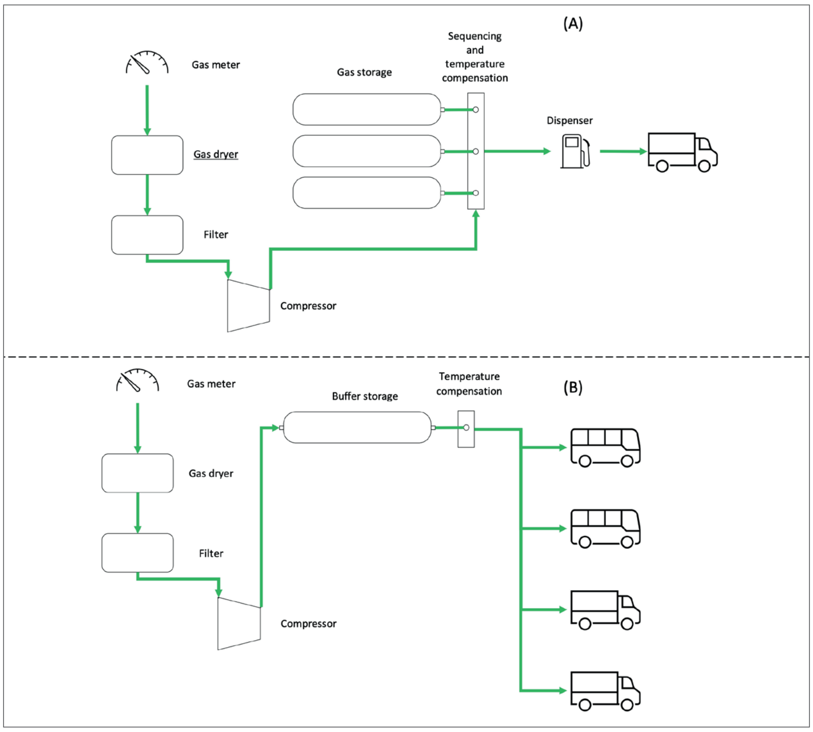


Figure 11. (A) Fast fill system (B) Slow fill system.

Gas grid pressure varies from a few bar in distribution grids to tens of bar in high pressure transmission grids. Gas flows from the grid to a compressor where it is compressed to 200 bar_{abs} prior to vehicle fueling. For off-grid stations biomethane is supplied to the station in mobile storage vessels and the compression requirement changes as the pressure in the biomethane storage vessel reduces as the vessel is emptied.

Higher compressor capacity is more costly but increases flexibility, makes faster fueling possible, and reduces problems related to slow or incomplete fueling. A continuous supply of compressed biomethane requires at least two compressors, each rated to provide the full compression requirement, so that one may be serviced without disrupting the biomethane supply (Ireblad and Dahlgren, 2012). Slow-filling stations are simpler with smaller compressor requirements than fast-filling solutions. Liquid biomethane can be pressurized using a pump and then vaporized to provide compressed biomethane. This removes the need for a compressor and reduces the energy use and associated costs.

A slow-filling station that continuously withdraws and compresses gas from a grid system does not require a large volume of gas storage as the compressed gas is injected into vehicles immediately, however some buffer storage volume may be required (Ireblad and Dahlgren, 2012). Fast-filling stations need to store enough compressed gas to fuel customers' vehicles upon arrival, but larger volumes of compressed gas are normally stored to avoid frequent starts and stops of the compressors. Back-up tanks containing liquid biomethane or natural gas may be used if there are potential problems with the supply of gas. Grid connected stations commonly use stationary storage systems consisting of small, mobile vessels which can increase flexibility and minimize space requirements. Larger cylindrical or spherical storage tanks may also be used. Spherical tanks are favorable from a technical standpoint as the shape results in an even stress around the tank at the required storage pressure (200 – 250 bar_{abs}). Spherical tanks also have the smallest surface area to volume ratio which minimizes heat loss from liquid biomethane (Ninh and Janko, 2018). For off-grid stations mobile biomethane storage solutions are common.

In contrast to liquid fuels which have a stable density at common outdoor temperatures, the density of compressed biomethane varies significantly with changes in ambient temperature. This will alter the mass and therefore the energy content of a given volume of compressed biomethane. An example of the fluctuation of the density of methane and energy content of 1 m^3 of compressed biomethane (250 bar_{abs}, 97 $\%_{vol}$ CH_4) at different temperatures is provided in Figure 12. These dynamics must be considered in station design through the inclusion of a temperature compensation system and should also be communicated clearly to the users.

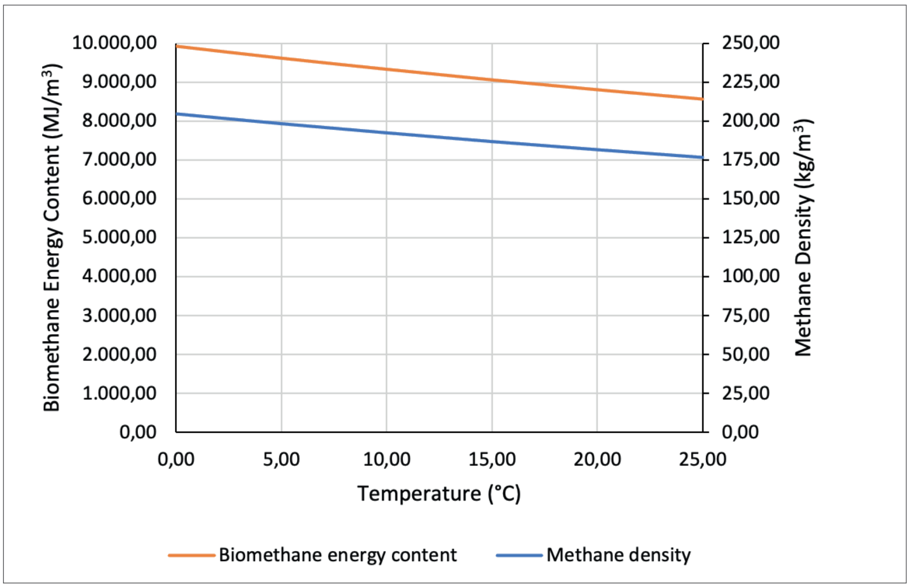


Figure 12. Impact of temperature on compressed biomethane density and energy content.

2.5.2 Filling stations for liquid biomethane

Liquid biomethane (or liquid natural gas) refueling systems are relatively simple. Liquid biomethane is stored in a tank sized to match demand. To keep the biomethane in liquid form, specially designed cryogenic tanks are required (Ninh and Janko, 2018). The tank can have two pipelines; one directly delivering the liquid biomethane to dispensers, the other can flow to a pump to increase the pressure and then flow to a vaporizer to provide compressed biomethane (Ireblad and Dahlgren, 2012). When investing in a station for liquid biomethane, it is a relatively small added cost to also provide compressed biomethane at the same station. If compressed biomethane is not provided to the customers (and there is no other use for this gas) a recondensation unit is required to manage boil-off gas as approximately 0.12 % of the stored liquid methane volume evaporates each day (Ireblad and Dahlgren, 2012).

Figure 13 shows two pictures from a filling station supplying liquid (and compressed) biomethane.

Figure 13. A filling station supplying liquid biomethane. A truck is fueling liquid biomethane to the left, while the picture to the right shows the storage of the liquid biomethane with a cryogenic tank and a vaporizer for the part of the biomethane which is filled as compressed biomethane.

2.5.3 Biomethane supply chains to filling stations

As biomethane filling stations can either be connected to the gas grid, connected to the biomethane producer, or use mobile storage of compressed or liquefied biomethane, several possible supply chain configurations are possible. Four examples are provided in Figure 14. Direct connection of the biomethane filling station (whether for gaseous or liquid biomethane) to the biomethane producer ensures that the biomethane delivered to the customer can be directly linked back to the producer and a mass balancing approach is not required. When a biomethane filling station is connected to the gas grid or to a supplier of liquefied natural gas, the use of a mass balancing approach consisting of green gas certs (or an equivalent system of tracing) is required to ensure that the renewable credentials of the biomethane are transferred to the customer and to avoid issues of double counting.

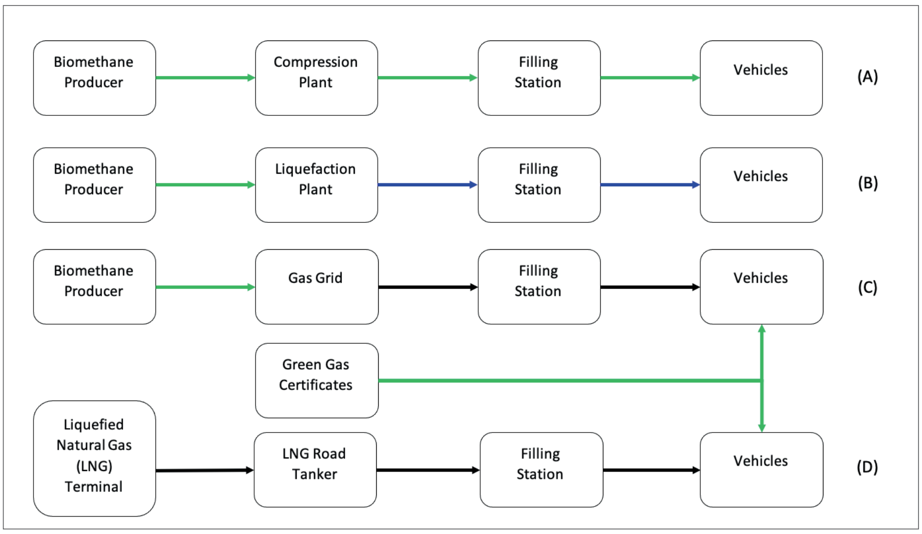


Figure 14. Biomethane supply chains to filling stations. (A) Direct connection to biomethane producer, compressed biomethane. (B) Direct connection to biomethane producer, liquefied biomethane. (C) Compressed biomethane via gas grid and green gas certificates. (D) Liquefied biomethane and green gas certificates.

Finally, Figure 15 shows a nicely designed biomethane filling station in Sweden.

Figure 15. A nicely designed biomethane filling station owned by the company Hagelsrums Biogas, run by very entrepreneurial farmers. *Picture taken by Joakim Ståhl, the Biogas Academy.*

2.6 VEHICLES

Vehicles which can be fueled using compressed natural gas, and as a result biomethane, include ships, heavy duty vehicles, buses, passenger cars, and agricultural tractors. Approximately 20–30 million vehicles globally are fueled by compressed natural gas or biomethane.

2.6.1 Biomethane as a vehicle fuel

Methane has been used as a vehicle fuel for at least a century. In comparison with diesel and gasoline it can be combusted with relatively low engine wear and low levels of emissions such as nitrogen oxides and particles. Methane fueled vehicles can be equipped with simpler exhaust cleaning technology than diesel or gasoline fueled vehicles to fulfill the same emission regulations. Methane driven vehicles are well proven from a technological standpoint. Biomethane has a significantly higher octane number (c. 130) than petrol (95) (Thrän et al., 2014) which can reduce knocking. However, this potential is only fully exploited in fully dedicated internal combustion engines.

2.6.2 Biomethane road vehicle technology

There are three main types of technologies used by methane fueled vehicles.

Dedicated vehicles are designed to run on methane only and have engines designed to benefit from the high-octane number of methane. When fueled by biomethane such vehicles can have a very competitive sustainability performance (chapter 4). A dedicated gas engine is a spark-ignited (Otto) engine adapted to run on methane. Typical dedicated vehicles are buses, light-duty vehicles (such as vans) and refuse collection trucks. Engines designed for the use of methane do not need to be modified to use liquid methane – it is evaporated before combustion. However, the use of liquid methane makes it possible to store a greater mass of fuel for a given tank volume, thus increasing vehicle range. Liquid methane is most commonly used for trucks but can also be used by buses and other vehicles.

Bi-fuel vehicles also use spark-ignited engines but are equipped with two separate fueling systems: one for methane and one for gasoline. Commonly, these vehicles start using gasoline, some automatically shift over to methane after a few seconds or when the engine reaches a desired temperature, others need to be shifted manually. In areas with reasonable coverage of methane refueling stations the vehicle may have a large share of the total tank volume used for methane with a small volume of gasoline for backup. In regions where methane refueling stations are less established an alternative is to have tanks which can provide an equal distance when using each fuel. Conversion of a dedicated gasoline vehicle to a bi-fuel vehicle is relatively simple and is done by companies in several countries through the addition of methane storage cylinders and a fuel supply system.

In the case of bi-fuel vehicles the sustainability performance is highly variable. Vehicles designed to be fueled by methane (large share of tank volume used for gas) can have excellent sustainability performance when using biomethane (similar to dedicated methane fueled vehicles using biomethane). However, the use of a combination of gasoline and natural gas may not lead to substantial environmental benefits.

Dual-fuel vehicles use diesel engines that are mainly fueled by methane but use some diesel to aid ignition (Stettler et al., 2019a). It may be required to spray a mixture of urea and de-mineralized water into the exhaust system to reduce nitrogen oxide emissions to stay below regulated levels. Dual-fuel technology is used by some manufacturers of heavy-duty vehicles.

While a combination of biomethane and biodiesel (such as hydrogenated vegetable oil, HVO) may lead to very competitive environmental performance, natural gas together with fossil diesel do not at all perform on the same level.

2.6.3 Biomethane fueled road vehicles

Passenger cars, vans, and light duty commercial vehicles

Most passenger cars designed to use methane are bi-fuel vehicles that run on compressed gas. The vehicle range when fueled by methane varies and can reach about 500 km for cars and 700 km for some vans. Models that are well designed for methane (methane tanks strategically placed and relevant support systems adapted to both fuels) largely function the same as gasoline or diesel fueled models. Other models are mainly designed for the use of gasoline with methane as an addon. A disadvantage of these models is that the added methane tanks need space not originally planned for in the design of the vehicle and thus some of the trunk space is used. Furthermore, driver support systems may not be designed for methane (a simple indicator may be added to indicate a need to refuel, instead of a fuel gauge that shows the specific level in the methane tank). Figure 16 shows examples of biomethane powered (bi-fuel) car models from Audi, Skoda and Volkswagen.

Figure 16. Some biomethane powered car models. *Photos: ©Audi Sweden, ©Skoda and © Mats Eklund.*

Buses and coaches

Methane powered buses (and coaches) fueled by compressed gas are common in several parts of the world, often used for public transport in cities. Such buses are available from several large manufactures. Many cities have opted to use biomethane to significantly reduce GHG emissions, air pollution and noise levels. There are also bus models designed to use liquid methane to increase the range up to 1,000 km. In addition, there are also bus rapid transit systems on which the buses run on methane.

Trucks for freight transport

Methane is also an option in the freight sector both for light and heavy-duty transport. Several different types of methane powered trucks are available on the market. Lighter trucks used for refuse collection and delivery services commonly use compressed gas. Models designed for regional and long-distance haulage may use either compressed or liquified methane, with a range of approximately 1,000 km, with compressed gas fueled trucks having a slightly shorter range. As heavy goods vehicles would be considered a hard to abate sector and present difficulties in phase-out of fossil fuels, trucks fueled by liquid biomethane may be of particular importance as they provide a competitive alternative to liquid fossil fuels in a sector where there are few other decarbonization solutions. Most manufacturers provide dedicated methane fueled trucks only using the spark-ignited engine. However, some truck manufacturers also provide dual-fuel diesel engines.

2.7 HEALTH AND SAFETY CONSIDERATIONS

All fuel and vehicle systems has associated hazards and risks in different parts of their life cycles. Methane powered transport systems are regulated, monitored and widely considered safe (Conton et al., 2018). Methane is a non-poisonous, odorless, gas with a higher ignition temperature than gasoline and diesel and a low density which means that methane will rapidly rise from ground levels and be diluted if a leak occurs outdoors. In enclosed spaces such a vehicle workshops adequate gas detection systems should be installed which can detect hazardous biomethane concentrations in air which may not be sufficiently odorized for humans to smell. However, while some countries are experienced with the use of methane as a transport fuel, other countries have less experience. This can result in driver hesitancy in fuel switching.

2.8 UTILIZATION OF CARBON DIOXIDE

Historically the carbon dioxide in biogas has been regarded a substance to be removed and discarded by biomethane producers seeking to produce transport fuel. However, carbon dioxide is also a valuable resource. Separated carbon dioxide from biogas plants can be purified and used to decarbonize the carbon dioxide market; in Denmark for example 65,000 t per year of carbon dioxide is used for slaughterhouses, carbonated drinks and medical, food and laboratory purposes. This can further improve the climate and environmental performance of the biomethane production system (Esposito et al., 2019). The separated carbon dioxide may also be used in greenhouses to enhance plant growth. Additionally, the carbon dioxide may be stored making the biomethane system a Bioenergy Carbon Capture and Storage (BECCS) system, resulting in net negative carbon dioxide emissions from biomethane production. The separation and capture of carbon dioxide for use as a valuable product is becoming common practice in the United Kingdom. The biomethane upgrading technology employed can impact the feasibility of carbon dioxide utilization; an example is the use of air to remove carbon dioxide from water in the water scrubbing process which prevents the recovery of high purity carbon dioxide.

Another strategy is to use the carbon dioxide to produce additional methane. This can be achieved via a methanation process where the carbon dioxide can be combined with hydrogen to generate methane ($4H_2 + CO_2 = CH_4 + 2H_2O$). This can be a realistic option in countries with a high share of renewable electricity generated by intermittent sources (such as wind and solar PV) – such as Denmark (Hamelin et al., 2020) and Ireland (McDonagh et al., 2018) where renewable electricity can be used to produce hydrogen gas (H_2) via water electrolysis. The methanation process can be biological or catalytic and may be used as an alternative to the biogas upgrading process whilst enhancing biomethane production (Liebetrau et al., 2020).

3 Markets, transitions, and economics for biomethane as a transport fuel

This chapter deals with different perspectives on how to transform the transport system by providing an overview based on some studies on sustainability transitions, market shaping, and some other related areas. It is a review based on some generic literature, but also many studies on biogas solutions and biomethane for transport. The main purpose is to identify critical factors for development. The chapter ends with a section on the economics of biomethane as a transport fuel.

3.1 MARKET POTENTIAL

There is a large potential to produce biogas from waste resources and other types of biomass worldwide, in a sustainable manner. Continuous and growing needs to produce food are expected, there are huge needs for fodder, and there seems to be an ongoing transformation towards a more biobased economy, involving a variety of biobased products. Consequently, there will be substantial amount of biowaste and residue streams that needs to be handled, where biogas solutions can provide good waste management and deliver valuable products such as energy carriers, biofertilizers, and carbon dioxide, while also contributing to different types of synergistic effects. Of course, some of these solutions depend on well-functioning systems for waste management, providing organic fractions of suitable quality and quantity. Cover/intermediary crops can also be important feedstock, contributing to the considerable feedstock potential.

Biogas can be used in different ways. From a global perspective, a relatively small share of the total biogas production is upgraded and used for transport, but there seems to be a growing interest and use for transportation purposes; this market is growing in several countries. As many countries and organizations struggle to phase out fossil fuels in the transport sector, there are strong arguments in favor of upgrading the biogas to biomethane and to use it for transport applications. The technological readiness level is high; there are existing solutions on the market, such as infrastructure and vehicles, with a competitive technical performance (Ternel et al., 2021). These cover the full range from small passenger cars to buses and heavy-duty trucks, and other types of vehicles including ships and agricultural and forest machinery. Consequently, from a feedstock and technical readiness level perspective, a large expansion of biomethane as a transport fuel is clearly possible in many countries; there is a great market potential. However, the national conditions vary, for example, due to differences regarding existing production, infrastructure, industrial sectors and standards, waste management and policy (Gustafsson and Anderberg, 2021; Nevzorova and Kutcherov, 2019). Arguably, factors other than technical (development) are more important for implementation of biogas solutions and the use for transport applications (D'Adamo et al., 2020; Piechota and Igliński, 2021), yet technical/efficiency improvements may be vital to several of the actors involved. Some countries are already using biomethane as a transport fuel (Gustafsson et al., 2020a), but still have great potential for expansion, while many other countries are lacking in a biogas industry. The geographical specific nature of biogas systems including for the feedstocks and how policy guides the use of biogas varies significantly between the producing nations.

3.2 DIFFERENT PERSPECTIVES ON MARKETS AND DEVELOPMENT

Globally, fossil fuels dominate the transport sector (and broader energy system). It is a very established regime that has been developed over more than a century: constituting mature socio-technical systems involving technologies, knowledge, institutions, and actor networks. Fossil fuels are supported and directly subsidized in different ways in many countries, but also indirectly as there are many externalities; environmental and health costs that the fossil fuel industry does not have to pay for (Coady et al., 2017; Parry et al., 2021). These systems generate substantial profit for a wide range of actors, such as "owners" of the resources, fuel producers and distributors, and vehicle producers and sellers. This has contributed to the creation of large and very powerful organizations that actively and efficiently engage in influencing developments of transportation and energy systems. There are also many customers/users, that are used to these technologies and find them convenient to use.

However, due to the wide array of sustainability challenges and huge long-term societal costs that come with fossil fuels, many actors worldwide request renewable and significantly more sustainable alternatives. There is a palette of such alternatives, including biomethane, but also efficiently produced biodiesel, renewable electricity, bioethanol and green hydrogen which could contribute to phasing out fossil fuels and significantly improving sustainability (Dahlgren and Ammenberg, 2021; Prussi et al., 2020). Several of these technologies are at good technological readiness level, while electrical transport solutions are becoming more mature and proven for lighter road transport, and technologies using hydrogen are expected to become commercially viable in the future for heavier transport. Although alternatives that seem competitive enough from a technical perspective have existed for many decades, with a much better sustainability performance than fossil fuels, the development of these alternatives has been slow, limited, and hindered by arguments and decisions that do not seem to be based on sound scientific evidence but rather business as usual. For different reasons renewable technologies have only taken a small share of the market for transport fuel, even in the countries with the highest shares. Renewable technologies in the transport sector commonly seem to be in competition with each other instead of integrating into a transport system where each constitute an important element.

3.2.1 Sustainability transitions

The major sustainability challenges we are facing require profound structural changes (Elzen et al., 2004), often referred to as socio-technical transitions (Geels, 2011), that not only comprise technologies and infrastructure, but also greatly depend on changes regarding governance and institutions, businesses and markets, customer and consumer behavior, and other related issues (Fallde and Eklund, 2015). Many studies accentuate the importance of formal institutions (like regulations and standards), but informal institutions (such as beliefs and expectations) can also significantly affect existing and emerging technologies (Geels and Raven, 2006; Wirth et al., 2013). There are many studies on how to transform socio technical systems in a sustainable direction, such as systems for transport, energy, waste management and agriculture (Köhler et al., 2019; Markard et al., 2012). Importantly, biogas solutions can be part of transforming all these examples and other industrial systems (Biogas Research Center, 2019; D'Adamo et al., 2021). Within the area of sustainability transitions, researchers have studied biogas solutions from different perspectives, for example, involving multi-actor and multi-level perspectives, business model innovation, and industrial ecology/symbiosis (Nevzorova and Karakaya, 2020). The multi-actor and multi-level perspective can be used as a tool to analyze complex systems and transitions towards sustainability and resilience, by regarding micro (niche, radical innovation level), meso (regime, established technologies) and macro (landscape, external conditions) levels (Fallde and Eklund, 2015; Geels, 2011). For example, biogas solutions used for transport applications may be seen as relatively radical innovations (or technological innovation systems, Markard et al., 2016; Martin and Coenen, 2015) on the niche level in many contexts (Ammenberg et al., 2018; Fallde and Eklund, 2015). There they commonly have a great potential to expand and can provide several essential functions, but biogas solutions may need to be further refined in combination with expanded infrastructure investments and continued adaptation of regulations and practices (Ottosson et al., 2017), to be fully competitive with fossil fuel, and other, technologies (on the regime level). However, the competitive relation would look very differently if biogas solutions would be fully compensated for the positive values they bring (Acharya and Cave, 2021; Dahlgren and Ammenberg, 2021; Westlund et al., 2019; cf. Roopnarain et al., 2020) and the fossil systems would have to take their full costs. This is also the case in relation to other technologies that are not multifunctional, such as electrification in many cases.

Significant changes of large socio-technical systems take considerable time (normally decades), due to lock-ins, path dependence and resistance to change (Köhler et al., 2019; van der Laak et al., 2007). Seen from a historical socio-technical systems development perspective, the biomethane driven transport systems are young and thus potentially have room for significant further improvements. However, even small improvements can be critical for some of the involved actors. Factors on the three levels – niche, regime and landscape – influence the development (e.g. van Eijck and Romijn, 2008), both for existing systems and more novel alternatives. New technologies may require protected niches (including niche markets, Levinthal, 1998) while they are developing, attracting resources, and forming social networks around them, to sustain the competition from established alternatives (Hoogma et al., 2002). Such niches may involve investment support, tax exemptions, production support, information and education. Niche markets may be local markets, specific segments or applications, that can be stepping stones on the way to expansion (Geels, 2002; van der Laak et al., 2007); such as biomethane used for buses in public transport (Aldenius, 2018; Aldenius and Khan, 2017), spreading over to other transport segments. However, Lazarevic and Valve (2020), in a study of biogas solutions in Finland, show the importance of specific niche configurations to steer towards the visions/goals (like a circular economy), and in a comparison between Sweden and the Brazilian state Parana, Magnusson et al (2021) point to the strong influence of socio-economic structures.

According to Nevzorova and Karakaya (2020), there is an emphasis in the growing literature on understanding and assessing the actor networks and institutions from a systemic perspective, for example, to learn more about the roles different actors have (or could have) in the transition processes, such as "system builders" (Hughes, 1979). Within the technological innovation system area researchers have identified and assessed system functions and mechanisms that induce or block development (Bergek et al., 2008), and competition between emerging innovation systems and the need for policies to assist redeployment (Magnusson and Berggren, 2018). In addition to focusing on *what* (e.g. what technology), it is important to consider *why* and *how*: Nevzorova and Karakaya (2020) have studied the driving forces behind biogas technologies in seven countries, trying to understand differences in development by looking at four categories of innovation system drivers: proaction to challenges; policy support; cooperation; and capability of technology (cf. Suurs, 2009: motors of innovation). Very related to this, the review by Nevzorova and Kutcherov (2019) focuses on a range of barriers: technical, economic, market, institutional, socio-cultural, and environmental. They conclude *"The findings show the importance of involvement of all stakeholders, especially of the private sector (in order to promote biogas energy to the market and make it commercially stable), governments (in order to introduce support programmes and form a clear policy landscape), financial institutions (in order to provide bank loans with preferential terms), R&D institutions (in order to improve technology innovation and enhance biogas processes), lobby groups, the media, and local communities (in order to provide a necessary information about energy utilization and environmental impacts of biogas, as well as to inform the public of the necessity of waste management, maintaining sustainable development etc."* Noteworthy, these conclusions are focused on biogas, while there are similar needs regarding the additional products of biofertilizers and carbon dioxide.

Within the area of strategic niche management, socio-technical experiments are emphasized as important to assess new technologies and generate learning for their refinement, network building and acceptance (Steinhilber et al., 2013), which is also the case for biogas solutions (Raven and Gregersen, 2007). Visions/Imaginaries and expectations may be important (e.g. see Auvinen and Tuominen, 2014), but expectations should be reasonable and endurance is required for larger transformations to be realized (Kemp and Loorbach, 2006; Mutter, 2020; van der Laak et al., 2007). Changes regarding legitimacy may strongly influence the development (Markard et al., 2016). van der Laak et al. (2007), and many others, also emphasize network building (to involve all relevant actors) and reflexive learning as essential components of strategic niche management. Martin and Coenen (2015) emphasize similar factors in their study of biogas industrial evolution. Within the field of transitions management, Loorbach (2010) developed a four-step framework for managing sustainability transitions:

- strategic activities; vision, problem formulation, long-term goals, landscape level culture.
- tactical activities; interaction among key actors to identify essential activities needed and barriers to address, landscape and regime level. Translation of visions into individual actors' agendas.
- operational activities; implementation, experiments, learning by doing.
- reflexive activities; learning, generating improved knowledge that can be used to revise visions, goals, and activities.

The different steps can be ongoing in parallel, in an iterative process, looking for transition paths that are accepted and trying to avoid lock-ins (Steinhilber et al., 2013). Referring to this framework, Magnusson et al. (2020) show how socio-technical scenario construction is useful as a technique to engage key stakeholders in dialogues on transition pathways and to catalyze transformative processes.

Steinhilber et al. (2013) suggest six key instruments/mechanisms for transitions. In addition to the factors already mentioned in this section, they also underscore the importance of governmental research programs, business model innovation, and issues related to user acceptance including how organizations and humans make choices (rationalist perspectives vs broader perspectives including lifestyles/cultures) and value creation.

There are also relevant publications dealing with similar factors in publications on technological innovation systems (e.g. Bergek et al., 2008; Gava et al., 2017; Markard et al., 2016; Steen et al., 2019).

3.2.2 Market shaping and key actors

[This section is largely based on the knowledge and work of Mikael Ottosson, Thomas Magnusson and Hans Andersson at the Biogas Research Center, Linköping University, and specifically their article: (Ottosson et al., 2020).]

The huge market for fossil fuels constitutes a great potential market for renewable alternatives: such as biofuels, electricity, and hydrogen. However, while older marketing literature may have seen markets as pre-existing, focused on products (such as a fuel) and their promotion, and have been occupied with the producer-customer relations, contemporary literature rather describes markets as dynamic systems that are commonly shaped by the activities of a multitude of actors, and involve broader value creation (Mele et al., 2015; Storbacka and Nenonen, 2011). The market shaping activities (include but) go beyond traditional promotion, to cover entire systems and attempts to influence institutional conditions and technical structures (Mele et al., 2015). This appears to be very much in line with the finding regarding sustainability transitions, however they may be importantly complemented by more bottom-up and business-oriented market shaping studies. All of this is the basis of a study conducted by Ottosson et al. (2020), that have merged findings from transition studies with literature on market-shaping, to establish a conceptual framework on the shaping of sustainable markets. Their framework consists of three critical processes: enabling exchange practices (traded value), proving the system (demonstrated value) and constructing the narrative (expected value). This was applied to analyze biogas solutions in Sweden. Among other interesting information, Ottosson et al. (2020) have mapped key actors and the roles they have taken in shaping the Swedish biogas/biomethane markets – see the 14 actors and 17 activities in Table 4. Sweden is one of the fore runners regarding biomethane for transport (IRENA, 2018). The Swedish case is relevant to practically show what actors can play essential roles and how important factors and conditions may come into play. Local and regional public organizations have played very essential roles as system builders, advocates, investors, producers, distributors, and users (Ottosson et al., 2020). This has been motivated by the local values they find related to biogas solutions, where the traded values exceeded the traditional cost and revenue dimensions and comprise environmental and societal benefits, including local business opportunities. Such public actors can importantly function as catalysts and have vital roles concerning networking. Municipalities (and their utilities) have been active both on the supply and demand side, while regional (county level) public transport authorities have been important regarding the demand. They have used public procurement to steer towards renewable fuels, including biomethane, mainly for public bus transports but also for other types of vehicles (Aldenius, 2021; Ammenberg et al., 2018; Lönnqvist et al., 2019). Together they have managed to achieve a major shift of the public bus fleets. There are also examples of different types of measures, aiming for other vehicle categories, like reduced parking fees or innovative taxi queuing systems at airports favoring fuels with low emissions (Ammenberg et al., 2018). Ottosson et al. (2020) found that the collaboration centered around the public organizations has contributed to the development of relatively local biogas solutions, importantly supported by governmental investment grants (in line with Martin and Coenen, 2015) and internationally negotiated subsidies. In addition, many other actors have been involved, such as utility companies, specialized biogas producers, distributors, and biogas technology firms. The public organizations also have joined forces with private firms and sector associations to influence the institutional conditions.

Table 4. Key activities and key actor categories in Swedish biogas market-shaping processes, Ottosson et al. (2020).

		Type of actors													
		Public			Private								Public & private		
Processes	Activities	Municipalities & their utilities	Public transport authorities	Governments and their agencies	Specialized biogas producers/distributors.	Biogas technology firms	Bus operators	Vehicle manufacturers	Gas incumbents	Farmers	Food industry firms	Citizens	Researchers	Industry associations	Biogas adv. coalitions
Enabling exchange practices	Demanding	■	■				■			■					
	Supplying	■			■				■	■					
	Negotiating	■		■	■		■		■						
	Investing	■			■		■		■						
	Subsidizing			■											
Proving the system	Experimenting	■	■		■	■		■		■			■		
	Validating	■			■	■		■							
	System-building	■													
	Providing substrates	■								■	■	■			
	Providing equipment					■		■							
	Producing	■			■				■						
	Using	■					■			■		■			
Constructing the narrative	Promoting	■	■		■	■			■				■	■	■
	Lobbying	■			■	■			■					■	■
	Envisioning	■											■	■	■
	Informing	■		■									■	■	■
	Translating	■	■						■	■		■		■	

Ottosson et al. (2020) found the narration of biogas solutions as local circular systems to be central for the previous development (a shared identity), but also that this valuable asset could be challenged in cases where non-local feedstock is used, when biogas (such as liquid biomethane) is bought on a national or international market, and due to the fact that large international companies have entered the stage, for example, involved in production and distribution. However, further studies by Brett et. al. (2021)[1] on the regional perspective, showed that narratives could be connected to both local and national visions. Increasingly, biomethane when used for transport has been promoted by the regional and municipal actors as a part of reaching a fossil-free Sweden by 2045. However, the local narratives remain to play a significant role and were found to build off specific local circularity visions which were tailored to the geographical, societal, and economic local conditions. Actors were found to discursively connect biomethane to solving existing locally contingent problems which differed for each region studied. In the animal agriculture intensive region of Kalmar, the local narrative is heavily connected to the role increased biomethane production can play in enabling support and expansion of the industry, while on the island of Gotland, in addition to resource circularity, biomethane is also linked to the long-standing concern of energy security.

In addition to the emphasized public organizations, several private companies have also shown their importance in biogas and biomethane (biogas plants, upgrading and distribution), but recently the role of private actors has expanded significantly.

[1] *Manuscript, forthcoming: Brett, Nancy; Magnusson, Thomas; Andersson, Hans. 2021. From global goals to local practice - mission-oriented policy enactment in three Swedish regions. Linköping University, Biogas Research Center (BRC).*

In a related study Magnusson et al. (2018) stated that the multitude of actors involved complicates market formation for biogas (including biomethane for transport). They further mention that the offer is a core element in market formation, and that different perceptions influence market formation: biogas/biomethane may be perceived as a simple product (fuel) but also be understood as a complex system that may help solve various societal and environmental problems. It may thus be important to clarify and communicate on what is being exchanged.

From the platform with public buses, including slow filling stations, public filling stations have also been established and additional types of biomethane powered vehicles have entered the stage, including passenger cars and light duty vehicles. For example, larger passenger car models from some manufacturers were popular in Sweden for many years, appreciated by taxi drivers and their customers, and seen as suitable company cars (also important for the secondhand market). However, these manufacturers chose to shift the methane option to smaller models and/or less prestigious brands within their corporate group, which influenced the demand (Ammenberg et al., 2018). Instead, electric vehicles seem to have taken these positions, while the gas driven cars where downgraded. It appears important to highlight the incentives behind such a development.

Markets for heavy duty freight transport (liquid biomethane)

Biomethane is already used for a wide range of vehicles. However, there has recently been an increased interest and development regarding liquid biomethane and heavy-duty freight transport (based on statistics from the Natural Gas Vehicle Association, NGVA), in several countries like Italy, France, Germany, the Netherlands, Norway, Sweden, the United Kingdom, and the United States. On this topic, Alexander Flaig and Mikael Ottosson (Swedish National Biogas Research Center https://liu.se/medarbetare/alefl44) have found that despite increasingly visible market developments in the Nordic heavy vehicle market, most of the activities are happening on the supply-side. Especially, 'energy companies' such as Gasum are significantly investing in the construction and expansion of the necessary supply infrastructure, to facilitate a shift to (liquid) biomethane driven long haulage. Several biogas plants already deliver liquid biomethane, and several others are under construction or are planning large scale plants. Several manufacturers have developed efficient truck models running on biomethane that are viable alternatives to fossil-based trucks. The number of heavy-duty trucks fueled by liquid biomethane is steadily increasing in the Nordic countries, but Werner et al. (2022) report that truck manufacturers interviewed seem to be more focused on the market for electrified heavy vehicles. Thus, it remains to be seen what market share these technologies will take, and if they can grow significantly in parallel. Biomethane driven trucks are viewed by some as transitory solutions on the way to a larger shift towards fully electrified vehicles. The policy landscape will be influential.

3.2.3 Some other 'market-related' studies

In addition to the broader studies presented above, there are many other 'market related' studies that deal with topics of strong relevance for biomethane as a transport fuel, of which a few are presented here. They typically have a more specific focus, for example dealing with a few actors and/or factors.

The connection to natural gas

Biomethane is very similar to natural gas and when used as a fuel utilizes the same type of infrastructure and vehicles. Many countries world-wide have well developed gas grids and some also have a significant share of natural gas driven vehicles, such as Argentina, Brazil, India, Italy and Pakistan (Gnann and Plötz, 2015; Goulding et al., 2019; Khan, 2017; Yeh, 2007). According to Goulding et al. (2019), China already has more than 3 million natural gas vehicles and has launched a program for expansion of the natural gas industry. Piechota and Igliński (2021) state that there are many gas driven vehicles in Poland and that they are popular. Of course, having an important part of the infrastructure in place, it can be more straightforward for these countries to implement biomethane as a transport fuel. The availability/assortment of well-functioning vehicles is essential, which seems to be an important barrier in some contexts (Ammenberg et al., 2018; von Rosenstiel et al., 2015), and it is advantageous that both drivers/customers and the broader society accept the technology and are used to it. However, the development in Sweden demonstrates that biomethane can be used in the transport sector even in countries with very limited natural gas infrastructure and almost no experience of natural gas as a (road) vehicle fuel. Regarding infrastructure and waste-based biogas solutions, of course, well-functioning waste management systems to sort out organic fractions (and other conditions) are also very essential (for a straightforward implementation).

Natural gas systems may facilitate the introduction of biogas solutions and biomethane for transport, but the relation is paradoxical. The significant sustainability problems that are associated with natural gas negatively impact the view of biomethane (Mutter, 2019), which for example influences policy development. The share of biomethane in the vehicle gas mix, or liquid fuel mix, varies a lot between different countries (Gustafsson et al., 2021). For example, Sweden had a share of more than 95% biomethane in vehicle gas in 2020 (Statistics Sweden, 2021), and the shares were also high in countries like Denmark, Germany, Netherlands, the United Kingdom, Norway and Finland, while other countries may have dominant shares of natural gas. Countries investing in biomethane for sustainability reasons, should consider different aspects of this problem (Safari et al., 2019); including the role natural gas can play in cases of rapidly increased demand for vehicle gas and the consequences this brings. If replacing petrol or diesel, natural gas lowers some essential emissions (climate, air pollution), but the sustainability performance is much better for efficiently produced biomethane (Gustafsson and Svensson, 2021). Commonly, with the current settings in many countries, the price of natural gas is lower than that of biomethane, which may influence the choice of actors (D'Adamo et al., 2020). For many different types of products there may be good information on origin and ingredients, but that may be partly/completely non-regulated and missing for fuels, although it can be decisive regarding sustainability performance and energy security. Most of the respondents interviewed by Herbes et al. (2018) thought ecolabels would make biomethane-based product more attractive, if provided by an independent entity that would verify the producers' claims.

Commercialization, infrastructure and the "chicken-egg-problem"

Several studies have investigated the commercialization of alternative fuels (meaning alternatives to petrol and diesel), of which many studied natural gas. The so called "chicken-egg-problem" is evident, as important actors need a critical mass of customers for profit, and thus may wait for others to act (Flynn, 2002; Pääkkönen et al., 2019; von Rosenstiel et al., 2015):

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

Gnann and Plötz (2015) accentuate the importance of refueling infrastructure. Several researchers have studied the vehicle-to-refueling-station index (Gnann and Plötz, 2015; Janssen et al., 2006; Yeh, 2007). It is a balance, where a certain level is needed to make fueling stations profitable, while a low coverage causes problems for the drivers. It has been estimated that about 200 – 400 gas vehicles per filling station are needed for economic viability, for such stations (Wang-Helmreich and Lochner, 2011). Specifically for biomethane, Prussi et al. (2021) argue that an appropriate refueling infrastructure is a key asset for deployment, as both the fuel production potential and demand exist. They find it paramount to avoid that too limited infrastructure hinders the development, where biomethane importantly can replace fossil fuels in the transport systems. Prussi et al. (2021) highlight the need of a policy perspective to achieve a synchronized deployment of biomethane production, refueling infrastructure, and gas driven vehicles; for both compressed and liquid methane. They also provide information on the number of vehicles per filling station for Europe, in 2018 and 2030, and considered a ratio of less than 600 gas driven vehicles per (public) refueling point sufficient for users. A relatively faster growth in vehicles is expected to render lowered service levels for vehicle owners in 2030. Uusitalo et al. (2015), found the ratio to be about 65 gas-operated vehicles per refueling station in Finland – an important barrier for development.

There is research on the distribution of biomethane. For example, Goulding et al. (2019) have developed a strategic infrastructure framework for Ireland, to live up to EU regulations on alternative transport infrastructure. They collected information on key conditions and requirements, for example, regarding existing gas infrastructure (pipelines), feedstock and biogas production, user convenience, regulations and advice, to suggest where to localize 22 refueling stations.

Customer preferences

Customers are key actors in the development and provision of sustainable products and services. Regarding transport many types of 'customers' are influential. In the following text a few essential 'customer groups' are briefly commented on, including those that can use biomethane themselves, and some transport buyers (and some that cover both roles).

Public organizations can utilize public procurement to contribute to the development of transport systems with superior sustainability performance; this has contributed to important niche-level development regarding biomethane in Sweden and other countries (Aldenius and Khan, 2017; Ammenberg and Dahlgren, 2021). Such procurements can involve public bus transport systems provided by external suppliers, but also other transport services, and the public organizations can also contribute by greening their own fleet of vehicles (Ammenberg et al., 2018). Although there are several good examples, there is a large potential to utilize public procurement further.

Shippers may be defined as the organizer of the shipment who bear the costs of transportation. Shippers, especially large shippers, can contribute to important shifts having the role of transport buyers (Evangelista et al., 2013; Pålsson and Kovács, 2014; Rossi et al., 2013). However, companies tend to focus on strategic suppliers and customers, and according to Gil-Saura et al. (2018), logistics and especially goods transportation have been considered ancillary activities to business management; however this has received more attention of late. Shippers that purchase freight transport services commonly seem to focus on costs, service reliability, and geographic coverage (Bask et al., 2018; Björklund and Forslund, 2013; Lammgård and Andersson, 2014), and may not be willing to pay extra for improved environmental sustainability (Bask et al., 2018; Sallnäs and Huge-Brodin, 2018). It seems relatively uncommon that transport buying companies have specific requirements on fuels (Multaharju et al., 2017), although there are several examples regarding renewable fuels, including some specifically for biomethane (Dahlgren and Ammenberg, 2021 in Dahlgren, 2021). Lately, there are several signs of growing interest.

Freight forwarders and haulers can develop green logistics/transport practices and in cooperation with the shippers orchestrate a development toward significantly improved sustainability performance (Sallnäs and Huge-Brodin, 2018). Nevertheless, some of these organizations, especially a few large ones, are also known for low ambition and sometimes seem to hinder progress (Dahlgren and Ammenberg, 2021 in Dahlgren, 2021; Navarro et al., 2018). At least some shippers have found it easier to cooperate with smaller haulers, regarding renewable alternatives such as biomethane or electricity (Dahlgren and Ammenberg, 2021 in Dahlgren, 2021). Via long-term contracts, shippers can facilitate for transport and haulers to shift to vehicles run on renewable fuels. Regarding biomethane, there are significant investments in liquid biomethane production and distribution systems, and an interesting rise in use of heavy-duty trucks in some countries.

Personal transport service providers such as relatively large taxi fleets have used biomethane (Ammenberg et al., 2018). In Sweden, such development has been accelerated by actors such as the state-owned company Swedavia, using an innovative queuing system for taxis at Sweden's largest airport (Arlanda, Stockholm): Firstly, only taxis fulfilling the national environmental car requirements were allowed. Secondly, the time of queuing was shortened for vehicles with low carbon dioxide emissions, which was an important driver for choosing biomethane driven vehicles.

Private vehicle owners have a large share of the road vehicle fleet and consume significant amounts of fuel (von Rosenstiel et al., 2015). Biomethane driven cars exist in several countries. Company cars have also played an important role regarding biomethane for transport, driven by policy in Sweden (Ammenberg et al., 2018). There are many examples of biomethane driven vehicles in different sectors, that seem to work well from a technical perspective. There are a few studies on customer preferences and behavior but depending on the type of actor (transport buyer or vehicle owner) the conditions may be very different. Regarding consumers, von Rosenstiel et al. (2015) state that cars are the second largest investment and that new vehicle technologies (methane driven vehicles) need to be regarded as "technologically mature, safe, financially attractive, and supported by a sufficient number of fueling stations" to be prioritized. They, and several other researchers, also emphasize that buying behavior is strongly influenced by values, beliefs, and brand preferences – purchase decisions are not fully rational (bounded rationality, ibid). This means that purchase decisions only to a minor extent are determined by fuel prices. Yeh (2007, studying natural gas), and others, indicate that significantly lower costs are needed for customers to shift to another technology/fuel (cf. Uusitalo et al., 2015). Patterson et al. (2011) mention any additional cost of purchasing or maintaining biomethane fueled vehicles as a potentially limiting factor. To acknowledge and act on user concerns may be vital, for example, regarding technical performance and maturity, service level and safety (Gnann and Plötz, 2015; von Rosenstiel et al., 2015). Nevertheless, early adopters and interested customer groups may be very tolerant (ibid), and it may be different to shift from a fossil fuel to biomethane, than from one fossil alternative to another (diesel to natural gas, as studied). Turning back to the texts on transitions and market shaping, this indicates a possibility to reach a certain level in some kind of niche, that can be framed by a particular area (geographically, a local solution), or application, and/or in relation to a distinct group of users that have specific interests or requirements (such as sustainability). However, regarding biomethane and other biofuels, it is critical how to contribute to further expansion, from the niche to the larger regime, to ensure that several renewable fuels are growing in parallel and replace fossil fuels.

Herbes et al. (2018) studied French consumers' perception of biomethane. Although this study did not focus on transport applications in particular, the results seem relevant. They found many consumers to be uninformed and uncertain about biomethane, although having overarching ideas about both pros and cons. Consequently, they recommend communication efforts, among other things.

Market failure!?

von Rosenstiel et al. (2015) investigated the challenges regarding natural gas vehicles in Germany, using market failure theory that encompasses externalities, coordination failure in complementary markets, failure of competition, imperfect information, bounded rationality, and principal–agent problems, referring to (Stiglitz, 2000). For example, they found poor balances between vehicles and the corresponding infrastructure. Germany had a significantly lower vehicle-to-refueling-station index than Argentina, Brazil, and Italy, which have more established markets with vehicle conversion. von Rosenstiel et al. (2015) focused on four key actor groups: consumers, vehicle manufacturers, gas businesses, and filling station operators. The supplying actors were not coordinated enough to generate attractive offers for consumers, in turn being uninformed about the alternative fuel/technology.

Business model innovation, circular business models

Previous research on renewable energy, including biofuels, shows that business model innovation can facilitate market introduction of new technologies (Nair and Paulose, 2014; Richter, 2013a, 2013b). While the traditional business focus has been on relatively short term profit maximation for shareholders, sustainable business models are more oriented towards long-term value creation for a multitude of stakeholders (Geissdoerfer et al., 2018), which could also be the case for circular business models. It is an effort to combine business profitability with maintained or improved social and environmental conditions. As described in other parts of this report, anaerobic digestion can function as a key component in making industrial production and societies more circular (Donner et al., 2020; Hagman et al., 2017). However, it is challenging for the sometimes relatively complex biogas solutions not only to generate a broad range of values, but for the involved companies to be able to capture them (get paid for the provided services). Kanda et al. (2021) studied several biogas producers in relation to the concept of circular business models. They emphasize that traditional firm level analysis is too limited to grasp relevant aspects, since biogas systems commonly involve complex sets of actors which create, deliver, and capture value of different types. Thus, these researchers suggest a broader 'ecosystems' approach. Karlsson et al. (2017) studied how to address profitability challenges for agricultural based biogas plants using business model innovation to "develop agricultural networks and to implement new strategies for arranging, producing, and marketing farm-produced biogas".

SWOT and PESTEL analysis

Researchers have studied biogas solutions and biomethane using SWOT (Strengths, Weaknesses, Opportunities and Threats), Environment and Legal aspects (EL) and PEST (Political, Economic, Social, Technological).

D'Adamo et al., (2020) conducted a literature review to identify SWOT factors regarding biomethane and used the literature and experts to rank these factors in a policy context, including local and global priorities. Piechota and Iglinski (2021) studied the conditions for biomethane in Poland, both using SWOT and PEST analysis.

Figure 17 presents key actors and important factors/conditions regarding a transition towards a significantly larger share of biomethane for transport based on the information in sections 3.1 and 3.2.

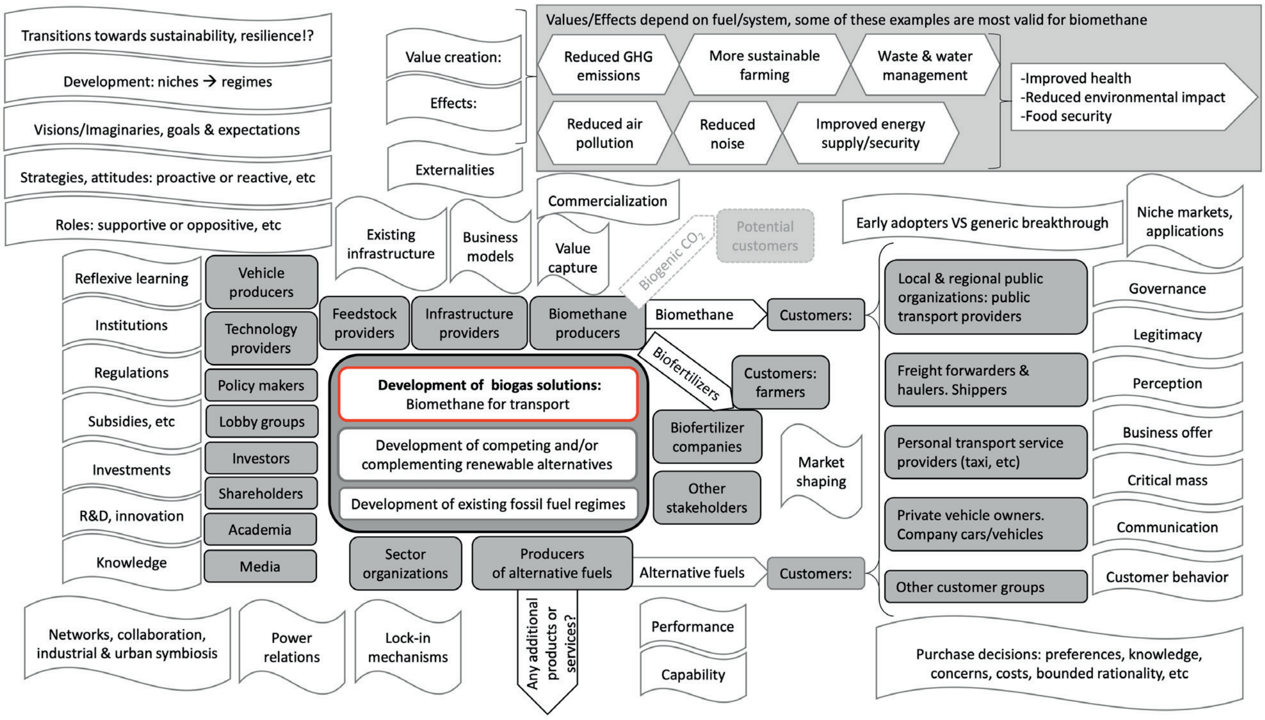


Figure 17. Biogas solutions may importantly contribute to a sustainability transition, improving the environmental and health performance of the systems for transport, energy, agriculture, and waste and water management. To what extent such a transition is realized depends on key actors and factors, of which several significant ones are illustrated in the figure, both concerning biogas solutions, complementing renewable alternatives and the existing fossil systems.

3.3 THE ECONOMICS OF BIOMETHANE AS A TRANSPORT FUEL

This section briefly deals with the economics of biomethane as a transport fuel. In contrast to the chapter on technology, it presents some information on the production of the raw biogas. It is difficult to provide good generic information on the economics of biomethane. Many influential factors are dynamic and uncertain – there is an ongoing development both regarding biomethane and complementing/competing alternatives. The economics are influenced by many of the factors dealt with in this chapter and in other parts of the report, including great uncertainties regarding future policy and demand. The conditions vary significantly between different contexts.

3.3.1 Biogas production costs – raw biogas

The raw biogas production cost can vary considerably between different production plants depending on feedstock, technology, scale, and other factors (Börjesson et al., 2016). It consists of the cost of capital, feedstock, process energy, operation and management, and transport of gas, feedstock and digestate. There is potential income from the digestate/biofertilizers, that should not be neglected (but digestate management can also be challenging). The overall production cost is significantly affected by the feedstock costs (or income from gate fees) and the amount of raw biogas produced per amount of feedstock and per reactor volume (ibid). The capital cost primarily depends on the feedstock and the plant capacity (Browne et al., 2011). Typically, the cost of biogas production per unit of energy output decreases with plant scale, as characterized by plant capacity (see Figure 18). Therefore, the centralized anaerobic digestion model has been suggested to take advantage of economies of scale. In this model, large centralized plants are utilized, typically digesting between 20,000 – 80,000 tonnes of feedstock per year, however the optimum size of a biogas facility is highly dependent on local conditions (Singh et al., 2010). Biogas production using smaller plant sizes (such as on-farm anaerobic digestion) is relatively more expensive as there are high specific costs.

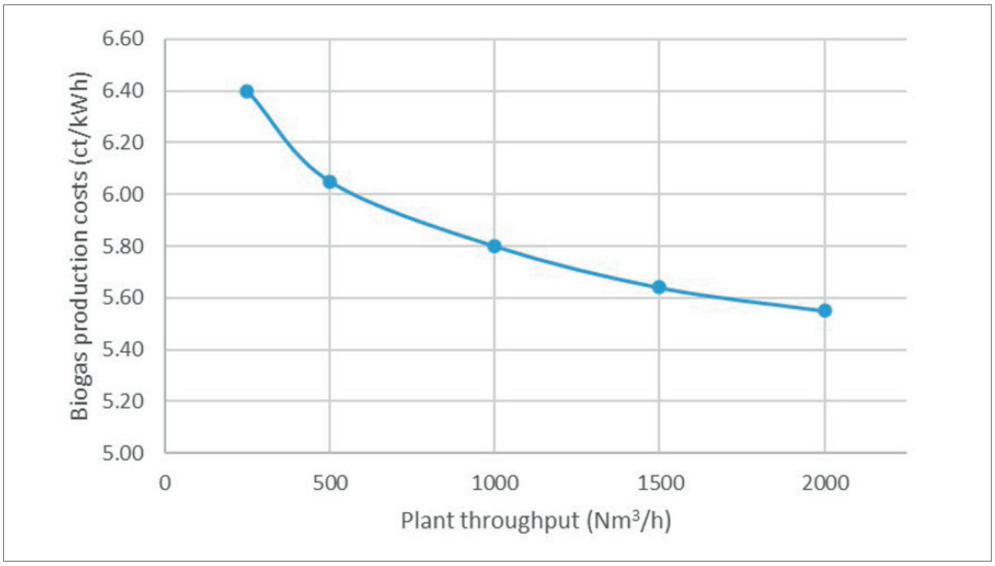


Figure 18. Biogas production costs (euro cents) with increasing plant size for a biogas facility co-digesting maize and slurry (90% maize, 10% slurry). Data from IRENA (2018).

Capital costs for biogas projects include the cost of constructing the anaerobic digesters, all mechanical and electrical installations, feedstock storage and other facilities, and end of life decommissioning costs (Browne et al., 2011; Urban et al., 2008). Depending on where economic boundaries are drawn, it is common that capital-related costs for biogas production from wastes and residues are lower than from energy crops. This is because, especially for facilities processing industrial organic waste, infrastructure for handling and storing feedstock is already installed and therefore does not lead to additional costs for biogas production (IRENA, 2018). The cost of constructing the digester itself represents the largest single investment for biogas facilities, accounting for c. 45 % of capital costs for energy crops and c. 57 % of capital costs for agricultural or industrials wastes (IRENA, 2018; Urban et al., 2008). These numbers refer to the costs of the digester in relation to the total investment costs for AD plants (producing raw biogas, but not including upgrading and/or liquefaction). Operational and maintenance costs for biogas facilities vary based on plant size, biogas quality, and other local factors but typically ranges from between 2–7 % of capital costs per year (IRENA, 2018).

There is great variation in feedstock costs, depending on feedstock type and geographic location. Issues related to control and competition are influential (Ammenberg and Feiz, 2017; Feiz and Ammenberg, 2017). Typically, feedstock costs for energy crops are higher than for wastes and residues, due to the agricultural inputs needed to grow energy crops. Furthermore, feedstocks that are classified as a waste (such as organic municipal waste), often attract a gate fee, which acts as a significant source of revenue for biogas producers. This is highlighted by Browne et al. (2011), who assess the cost of biogas production from grass silage and slurry to be 0.822 €/m^{3}of biomethane (corresponding to about 0.082 €/kWh), while the production cost of biogas from organic municipal waste was deemed to be negligible due to the gate fee received for processing a waste product.

The heat and electrical demand for biogas production again are strongly influenced by the feedstock type and technology choice. Feedstocks with a high water content, such as animal slurries, typically require more thermal energy to heat. Additionally, the thermal demand for biogas production is influenced by the climatic conditions at the location of the biogas plant, with colder climates requiring greater levels of heating. Access to cheap renewable heat or heat recovered from industry can be advantageous (Viklund Broberg and Lindkvist, 2015). Electricity is used to operate pumps, monitor the digestion process, and carry out other essential tasks. Electrical demand mainly depends on the choice of technology for biogas production, but typically lies within the range of between 20–30 kWh per MWh of biogas produced (IRENA, 2018).

While emphasizing the uncertainties, Börjesson et al. (2016), based on other studies on Swedish conditions, assumed a production cost of about 0.06 €/kWh of raw biogas, and a range of about plus or minus 0.02 €/kWh for their sensitivity analysis. This was based on a feedstock mix of food waste, manure, industrial waste, and slaughterhouse waste for biogas plants with annual production capacities of 30 GWh and 100 GWh.

3.3.2 Upgrading costs

Cleaning and upgrading facilities are needed to remove carbon dioxide and impurities in the raw biogas, to increase the biomethane content to at least 97% and thus meet the fuel quality requirements for combustion in vehicles. In a similar manner to biogas production, upgrading costs are dependent on plant capacity and technology used. While different upgrading technologies do have differing costs, the most important factor is plant size, with specific costs decreasing significantly with larger installed capacities, see Figure 19. Hoyer et al. (2016) have similar results on the overarching level (about the same cost levels) but found that it was difficult to separate the technologies (see Figure 22 in their report).

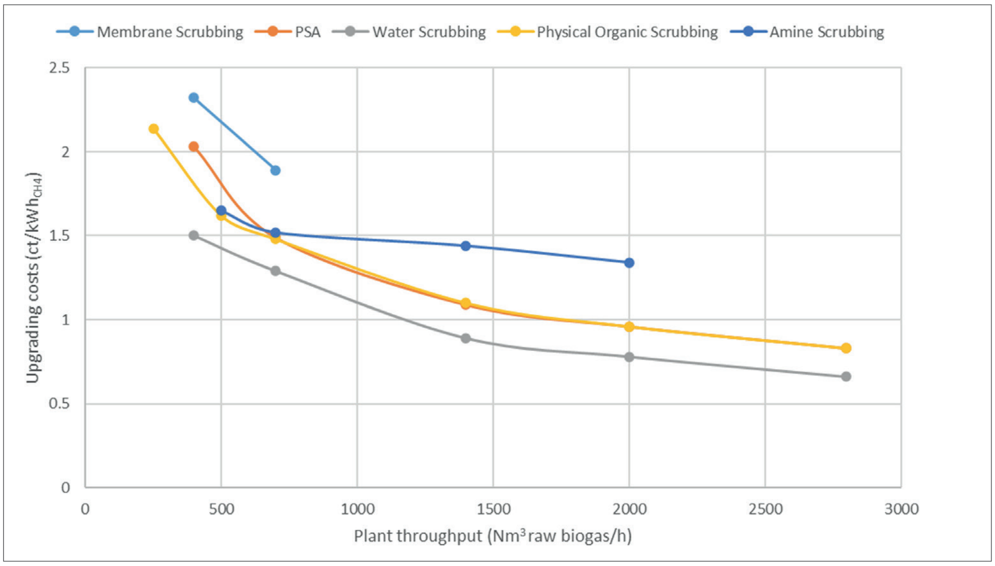


Figure 19. Specific costs (euro cents) for biogas upgrading technologies. Data from Billig et al. (2014).

The costs shown in Figure 19 highlight the most commercially viable technologies for biogas upgrading (water scrubbing, amine scrubbing, pressure swing adsorption, and membrane separation). The results indicate that for an upgrading facility processing 500 m^3 of raw biogas per hour, upgrading costs are between 1.4 and 2.2 €ct per kWh of upgraded methane. For a plant upgrading 2000 m^3 per hour of raw biogas, upgrading costs fall to between 0.8 and 1.4 €ct per kWh of upgraded methane, highlighting the benefits of large upgrading facilities.

Choice of upgrading technology for specific biogas plants is strongly influenced by project-specific circumstances. For example, amine scrubbing may have an economic advantage if cheap heat is available locally to meet the thermal demand, whereas if the biomethane is to be injected directly into the gas grid, upgrading technologies that operate under high pressure (such as high-pressure water scrubbing) may save compression costs. According to Patterson et al. (2011), the upgrading costs can vary significantly between different plants/contexts. Hoyer et al. (2016) found no significant general difference concerning the investment costs of different upgrading technologies (studying a standard case), and their results indicate that the choice of supplier may be very influential. Furthermore, they found the total energy use to be of similar magnitude, independent of technology.

Thrän et al. (2014) also acknowledge the scale issue, but provided information on how small-scale biogas plants can use centralized upgrading. According to this study, a scale of about 500 Nm^3 raw gas per hour (or higher) is required for profitability.

3.3.3 Liquefaction costs

Spoof-Tuomi (2020) provides a good overview of liquefaction costs, based on several other studies. The capital investment costs relate to the main equipment; refrigeration compressors and drivers, cryogenic heat exchangers, power and control systems, auxiliary equipment, installation, and indirect costs related to engineering, freight charges, taxes and insurance. The average specific capital cost ranged from 440–1400 € per tonne per annum (t/a) for liquefaction plants that deliver below 15 tonnes of liquid biomethane per day. The liquid nitrogen vaporization and Single Mixed Refrigerant (SMR) systems were at the lower end of the price range, while the Linde cycle represented the upper end of the price range. The average specific costs of nitrogen expander-based technologies and pre-cooled mixed refrigerant systems ranged from 760–990 €/t/a (Spoof-Tuomi, 2020).

Spoof-Tuomi (2020) discussed operating costs including for feed gas, electricity, labor, maintenance, water cycling, refrigerants, and cooling. She presents the specific energy use for each technology and concludes that similar processes may have varying specific energy use. The study also deals with costs due to operating work, maintenance work, and maintenance materials, that were assumed to correspond to 2.5 % of the total investment. For comparison, Börjesson et al. (2016) assumed cost for operation and maintenance to be 3 % of the investment cost.

The collected information is used for an economic analysis of a case: the existing biogas production in Ostrobothnia, and the capacity to liquefy 5 tonnes per day (nano-scale). The levelized costs are in the range from about 10 €/MWh for a Single Mixed Refrigerant (SMR) system, to about 25 €/MWh for Liquid Nitrogen Vaporization.

Börjesson et al. (2016) generally noted the importance of scale, where larger scales commonly means improved efficiency, especially for liquefaction.

3.3.4 Distribution costs

Once the biogas has been upgraded to biomethane, it must be transported to a fueling station for use as a vehicle fuel. In cases where fueling stations are near the biomethane plant, low costs are incurred for distribution. However, in many situations, the production and consumption of biomethane occurs at different locations. There are two main ways of distributing biomethane from its production site to a filling station:

1. Injection into (natural) gas grids/networks
2. Transport by road as either compressed or liquefied biomethane

In regions with a well-developed (natural gas) grid, direct injection is often the most cost-efficient solution. Typically, the biomethane facility must be within 5 km of the existing gas network to be deemed viable. It has been reported that the capital costs for setting up a direct injection point lie in the range of €200,000 to €300,000 in Ireland (Browne et al., 2011). However, the corresponding costs are suggested as five times higher in Germany (via personal communication with Professor Frank Scholwin, Institut für Biogas, Germany). Thus, the specific costs are highly region specific, with different countries applying different fees for grid access.

For locations without a gas network, it is possible to compress or liquefy the biomethane and transport it by truck to the filling station. In general, producing liquified biomethane is more expensive than compressed biomethane, but is a more attractive option for larger transport distances (greater than 100 km) due to the increased energy density of liquified biomethane (IRENA, 2018). In a similar manner to grid injection, specific costs for distribution of biomethane by road is highly region specific, with the distance transported being the most significant factor.

Gustafsson et al. (2020b) investigated economic, energy and environmental aspects of different technologies for upgrading, liquefaction and distribution of biomethane for transport. Liquefaction was studied as a method for efficient long-distance distribution. This study provides results with a well-to-wheel perspective (see chapter 4), but specifically regarding distribution, it was concluded that liquefaction can pay back economically after 25 – 250 km (depending on the number of trailers used) compared to transport of compressed gas in steel container trailers. Gustafsson et al. (2020b) found distribution in existing gas grids to be better in all aspects (economy, energy & environment), where no addition of propane is required. Addition of fossil propane gas makes distribution via gas grids less advantageous.

Dahlgren and Ammenberg (2021) provide information on biomethane for buses, in comparison with other fuels/technologies, partly based on information from Börjesson et al. (2016). Both studies deal with information on distribution costs in a Swedish context.

3.3.5 Vehicle costs

Börjesson et al. (2016) studied the costs of (bio-)methane fueled vehicles in comparison to corresponding models using petrol or diesel. They found light-duty bi-fuel vehicles (using a combination of gas & petrol) to have approximately 10 percent higher selling price, but with variations depending on the brand. The heavy-duty gas fueled vehicles were estimated to be 10-30 percent more expensive to buy. For comparison, Speirs et al. (2019) state that natural gas fueled heavy duty vehicles and ships are about 20 percent more expensive.

Dahlgren and Ammenberg (2021) investigated the costs of city buses, and found that diesel buses were least expensive (around 220 – 260 k€), with similar ranges for buses fueled with biodiesel (HVO & FAME). Methane- and ethanol-powered buses seemed to be slightly more expensive (240 – 290 k€), while electric buses could be significantly more expensive (290 k€, fast-charging bus with a very limited battery; 570 k€ for a slow-charging bus with a large battery).

The additional costs of biomethane vehicles when compared to conventional diesel vehicles are mostly associated with the storage tanks for compressed or liquified biomethane. The unit costs for storage of compressed biomethane is typically lower than the unit cost for storage of liquified biomethane. These costs have been estimated at 1.25 €/MJ for biomethane compressed to 250 bar, and 2.14 €/MJ for liquefied biomethane (Gray et al., 2021). When these costs are applied to a heavy goods vehicle with a range of 800 km, they translate to an additional cost of approximately €13,000 and €22,800 respectively, which is roughly reflected in the market price of the vehicles available on the market (Gray et al., 2021; International Energy Agency, 2017). Furthermore, dual-fuel vehicles, which only require storage tanks, are typically less expensive than dedicated biomethane vehicles, which require storage tanks as well as niche engine design (Brightman et al., 2011).

3.3.6 Filling station costs

Common types of filling station are described in section 2.5. However, Atkins (2016) uses these categories in his work, based on the UK context (with some modification):

1. Grid connected station, compressed gas: natural gas is extracted from the gas network and compressed to 250 bar to be dispensed to a vehicle. Biomethane can be purchased at these fueling stations via Green Gas certificates. In other contexts, the gas grid could supply vehicle gas with a mixed content (of biomethane and natural gas) or pure biomethane.
2. Liquid gas (LNG, LBM) station: not connected to the gas network. Liquid natural gas (LNG), or liquid biomethane (LBM), is cryogenically stored in low pressure insulated tanks. This type of station may be equipped with an evaporator and compressor to deliver compressed gas as well (L-CNG stations).

Across the refueling station configurations, there are common costs which include engineering and development, project management, electrical control systems, and auxiliary equipment. There are also project specific costs, dependent on the refueling station configuration chosen. For a CNG station, the cost of grid connection, CNG storage and dispensers must be taken into account, while for an LNG station, only the cost of LNG storage and dispensers must be considered. The estimated capital costs for the three station configurations are shown in Table 5.

Table 5. Capital cost for CNG and LNG refueling stations, UK context. Data from Brightman et al. (2011).

Station Size (kg/day)	CNG Capital Costs (€)	LNG Capital Costs (€)	L-CNG Capital Costs (€)
500	160,000	73,000	150,000
1,000	200,000	93,000	200,000
2,000	250,000	190,000	350,000
5,000	350,000	260,000	500,000
10,000	700,000	350,000	800,000

It should be noted that although the capital costs for grid connected stations (termed CBG stations, by Brightman et al. , 2016) are higher than for those supplying liquid fuel (LNG/LBM stations), the additional costs associated with the liquefaction and transportation of liquefied fuel mean that compressed methane can typically be dispensed at a lower price (Brightman et al., 2011). Nonetheless, liquified biomethane filling stations are a viable option for regions without a well-developed gas network. Furthermore, as larger stations can take advantage of economies of scale, it would appear to be sensible to strategically locate larger biomethane refueling stations along key transport corridors to minimize fuel costs.

Börjesson et al. (2016) emphasize that the costs vary considerably between different stations due to local conditions and choices made regarding capacity, equipment, redundancy, etc. They estimated the investment costs to be about 7–800 k€ for stations with the capacity to fuel both light duty and heavy-duty vehicles with compressed gas (about 10 GWh/year, or about 2100 kg/day). These costs are about 3 times higher than those in Table 5, from Brightman et al. (2011). Börjesson et al. (2016) assumed about 1500 k€ for a station delivering liquid gas (about 30 GWh/year, or about 6300 kg/day).

Ninh and Janko (2018) also provide information on filling station costs, in a Danish context. While several cost categories are similar, they also mention costs associated with necessary permits and the purchase of land. They emphasize that fast-fill stations are typically more expensive than slow-fill stations (in line with Smith and Gonzales, 2014). However, Ireblad and Dahlgren (2012) found the difference in investment costs between fast and slow filling to be marginal, for a bus depot designed for 100 buses. The choice between slow and fast-fill stations is dependent on project circumstances. Slow-fill stations are better suited to public fleets of vehicles (such as buses), that return to the same depot every night, whereas fast-fill stations are better suited to private refueling.

3.3.7 Life-cycle costs and comparisons

Börjesson et al. (2016) found the biomethane productions costs (production in AD-plant, including upgrading and/or liquefaction, distribution and filling stations) to range from about 0.090 – 0.097 €/kWh of methane, at an interest rate of 6 %. The raw biogas production represented c. 60 – 80 percent of the total costs for delivering the fuel (with significant uncertainties), while the post-treatment (upgrading, liquefaction, compression) represented 20 – 40 percent.

Including the vehicles (well-to-wheel), the costs for light and heavy duty gas fueled vehicle systems were about 15 – 20% higher than for similar petrol and diesel fueled vehicles, while the costs were similar or somewhat lower regarding liquid biomethane (or natural gas) for heavy vehicles in comparison to vehicles systems using petrol or diesel.

Gustafsson and Svensson (2021) compared well-to-wheel scenarios for production, distribution and use of liquid biomethane (from food waste and manure), liquid natural gas and diesel, in a European context. Like many others, they found the scale to be essential; large-scale production of liquid biomethane is required to compete with liquid natural gas economically, without altered economic policy instruments. The pathway involving biogas from food waste that was upgraded by an amine scrubber and liquefied using mixed refrigerant technology, came closest to the lower end of the natural gas price. With a production capacity of 120 GWh/year and 95 % utilization rate, the cost was estimated to 0.028 €/kWh.

Dahlgren and Ammenberg (2021) studied the total cost of ownership of city buses run on different fuels and on electricity. Figure 20 shows how the mean values of the costs related to purchasing, maintenance and fuel/electricity as elements of the total cost of ownership.

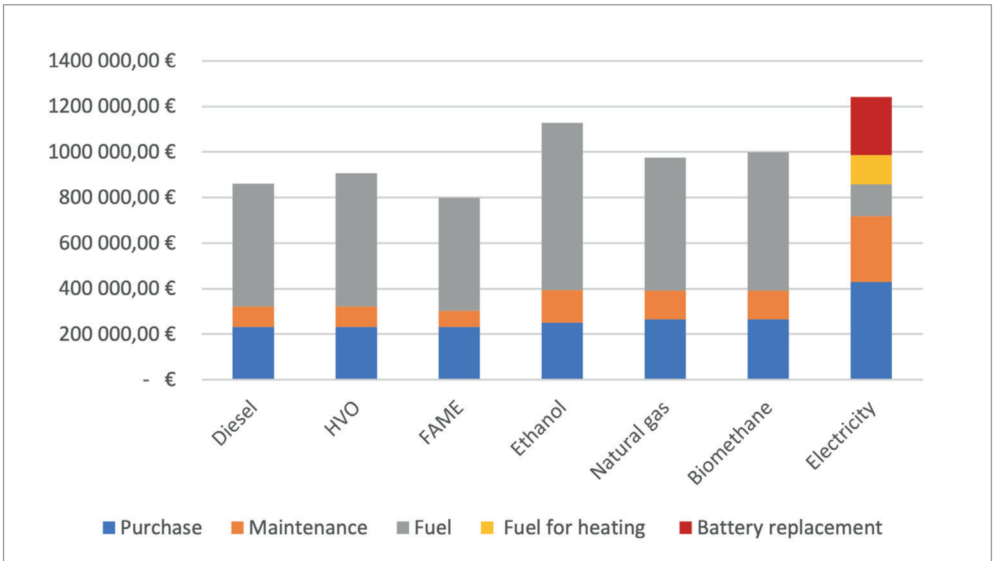


Figure 20. The total cost of ownership divided into costs for purchasing, maintenance and fuel/electricity. The numbers are mean values between the lowest and highest found costs for each part. Based on Dahlgren and Ammenberg (2021).

Dahlgren and Ammenberg (2021) graded all the alternatives on a five graded scale from Very Poor to Very Good. The reviewed literature contained data ranging over 3–5 levels for most of the alternatives due to, for example, different possible fuel efficiencies and purchase costs (Figure 21). The authors reported a relatively low level of certainty, meaning that there was not enough relevant and trustworthy information.

Previous calculations commonly seem to have assumed high secondhand values for diesel or petrol fueled vehicles; new policies to address climate change and air pollution may well impact on the secondhand value of fossil fueled vehicles.

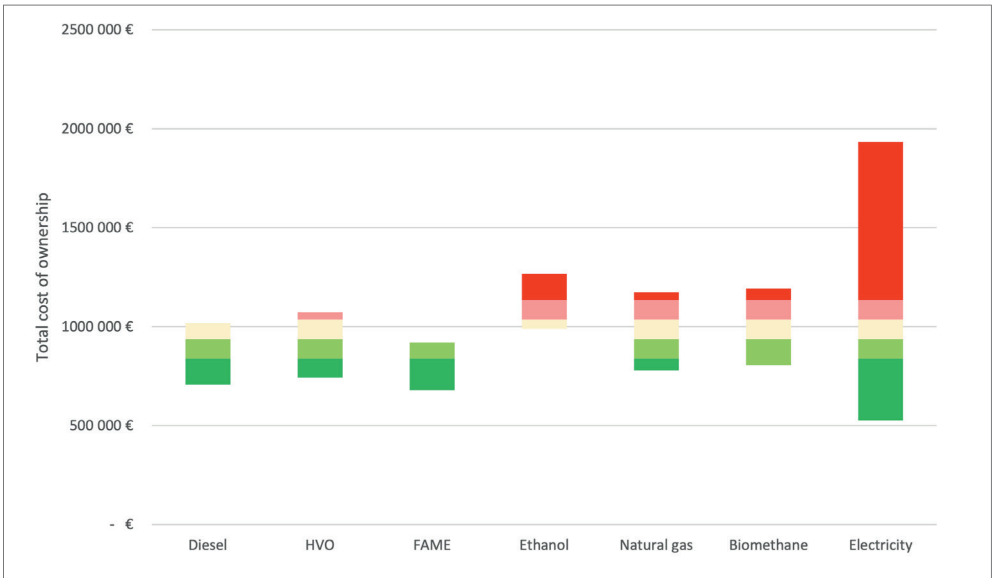


Figure 21. The total cost of ownership during the 10 years of use. The colors indicate how the costs relate to the scale of the indicator (dark green = Very Good, dark red = Very Poor). Based on Dahlgren and Ammenberg (2021).

Atkins et al. (2021) studied heavy duty trucks in UK and found that the trucks fueled by biomethane (produced from sewage and surplus grass cuttings in a truck with a spark ignition engine) could have lifecycle costs approximately 30 % lower than diesel trucks; they were also shown to be very competitive as compared to electric trucks (both in terms of cost and GHG emissions). The authors emphasize that the results depend on assumptions such as current fuel prices and provide references to studies in other contexts where the lifecycle costs for biomethane fueled vehicles have been found to be similar to diesel vehicles or somewhat higher, which they discuss. Nevertheless, their study shows that biomethane as a fuel can be a cost-effective strategy to reduce the climate impact associated with the heavy duty transport sector and other sectors in society. In line with the findings of Atkins et al. (2021), some haulage firms in Sweden that have shifted to biomethane fueled trucks report positive economic outcomes after a few years of use (based on experiences within the Swedish Biogas Research Center (BRC)). The somewhat more expensive vehicles are compensated by increased incomes (better contracts) and/or lower operational costs. In addition, the positive impact on company brands may be substantial, but more challenging to predict and quantify.

3.3.8 Socio-economic perspectives, cost efficiency

Decision makers, on varying levels in different organizations, commonly search for cost-efficient solutions. It should then be observed that many studies on economy have a relatively narrow perspective, for example, focusing on a single service, function, or sector, with a short-term perspective. Likewise, several parts of section 3.3 on the economics of biomethane as transport fuel, are focused on the costs associated with the fuel and vehicles. It is of course essential for actors such as transport service providers and haulers that the biomethane driven vehicles serve their businesses well; this is also the case for other types of vehicles owners, and additional actors linked to this value chain.

However, it may also be of fundamental importance to recognize that biogas solutions commonly are multifunctional and are associated with additional products (such as biofertilizers) and services (Westlund et al., 2019). In many cases multifunctional systems are compared to mono-functional systems, which may lead to suboptimal decisions, including problem shifting (Lindfors et al., 2019). It may be very misleading to assess biogas (or biomethane) solutions as a transport technology only, for example, in comparison to mono-functional electric vehicle systems (cf. Atkins et al., 2021).

There are several different types of biogas solutions, of which some are more oriented towards profit from biogas/biomethane, while others may be an essential part of a larger industrial complex, such as a biorefinery. In the latter case, biogas solutions may very well be cost-efficient from the broader industrial perspective (contributing to cost-efficient cleaning of process water), even if the income from biomethane (in cases where the biogas is upgraded and sold externally) alone does not match the full investment costs. Likewise, there are examples of farmers cooperatively establishing profitable biogas production, but it may be more relevant (and positive) when they also account for the impact on their farming activities (considering biofertilizers). The costs, and cost-efficiency, vary significantly depending on the type of biogas solution and the applied perspectives.

Regarding the socio-economic implications of biogas solutions, and biomethane as a transport fuel, Chapter 4 provides an overview of several essential sustainability aspects. This chapter deals with broad and long-term implications on the environment, natural resource management, health, and other relevant issues, which are crucial from a socio-economic perspective.

4 Sustainability performance

4.1 SYSTEMS ANALYSIS OF BIOMETHANE FOR TRANSPORT

This chapter is largely based on environmental and sustainability systems analysis (ESSA) studies, where *systems analysis* indicates a focus on larger systems rather than on smaller parts (the components of the system). Common study objects are technical systems and products, and the process usually involves development and use of models or tools for analysis/assessment. The 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). For example, to look at the whole life cycle of a transport technology, rather than on just the use phase, or vehicles only (which is the case with the narrowly delimited 'zero emission vehicle' concept). Even vehicles driven on electricity or fuel cells (fueled by hydrogen) are associated with significant emissions of particles, related to tire, brake, and road wear. Electric vehicles are commonly heavier and thus associated with larger wear related emissions (Requia et al., 2018; Simons, 2016; Timmers and Achten, 2016).

Similarly, it is important to broaden the scope from climate change oriented to consider a wider range of sustainability indicators (cf. Lazarevic and Martin, 2016). ESSA studies commonly involve extensive inventories to map flows of material and energy, and to clarify the adherent environmental impact. Regarding transport, this necessitates inventories that comprise fuel production, distribution, and use, and ideally also production, maintenance and end-of-life phases of vehicles and infrastructure. But vehicles and infrastructure are commonly excluded, although they may contribute significantly (Edwards, Robert et al., 2014). For many of the different fuels available, the impact (and energy use) related to vehicles and infrastructure are similar. While electric vehicles may have a larger energy/environmental footprint, mainly related to the battery production and management (ibid., Lindfors and Ammenberg, 2020; Marmiroli et al., 2020; Nordelöf et al., 2019; Ternel et al., 2021). Systems analysis can be conducted on both existing and hypothetical systems to gain better understanding, for example, regarding risks, efficiency in relation to other systems and on how to improve (to achieve more efficiently the goals of a system). In addition to sustainability impact/performance, such studies may include the potential and feasibility of different alternatives (Lindfors et al., 2019). Thus, the purpose is commonly to facilitate decision making, in many different contexts. For ESSA studies, it is very essential to consider aspects such as the validity of models, critical assumptions, what indicators are studied (and excluded), data quality, and uncertainty management (Brandão et al., 2021).

As biogas solutions usually stretch over several sectors, have different purposes, and are linked to a wide variety of sustainability related effects/benefits, broad and transdisciplinary studies are needed to capture the relevant issues (cf. Gowd et al., 2022). The wide spectrum of biogas solutions (involving different feedstocks, conversion pathways including production facilities, distribution technologies, and vehicle types) in many parts of the world with differing systems for energy, water, waste management, means varying sustainability performance. In the following sections we have summarized selected systems analysis studies of biogas solutions, focusing on transportation. While the specific studies may focus on different types of transportation, it should be noted that for several areas and vehicle categories the results are relatively generic; for example, results regarding buses may be highly relevant for heavy duty trucks as well. The studies have mainly been conducted by using Life-Cycle Analysis (LCA), Energy Analysis (EA) and Multi-Criteria Analysis (MCA). For different sustainability areas, the performance of biomethane based transport solutions is briefly presented and compared to competing technologies. This is done on an overarching and generic level, with the ambition to present average results and best practice, but also the width of the analysis is indicated by showing less good performance. The chapter also deals with potential problem areas and points at critical factors for good performance.

Regarding LCA, the Renewable Energy Directive provides guidelines for how to conduct analysis within the EU (regarding objectives, related to production support and tax exemptions), which are not in line with the ISO standards on LCA (ISO 14040, ISO 14044). It also provides sustainability criteria and default values that can be used. *For example, see F3 FACT SHEET, CATEGORY: MISC, No 1, JUNE 2021, EU sustainability criteria for biofuels, at: https://f3centre.se/app/uploads/Misc_Fact-sheet-No-1_EU-Sustainability-Criteria_210621.pdf*

The Renewable Energy Directive steers towards analyzing biogas systems as generic *"energy production"* systems, meaning that the allocation of emissions between the biomethane (considered to be the main product) and other flows (such as digestate/biofertilizers and CO_2, considered to be secondary) is to be based on energy content (Manninen et al., 2013). Thus, biogas solutions are not fully analyzed as the multi-functional systems they commonly are, because the sustainability aspects of waste and wastewater management as well as biofertilizer production are excluded. This approach may for some systems lead to significantly underestimated benefits/effects (Börjesson et al., 2015) and hinder the development of biorefineries (Vera et al., 2020). A commonly used strategy to address the stated problems in LCA is to use system expansion (in line with ISO 14044), where these mentioned aspects are accounted for by considering avoided processes for alternative waste and wastewater management and fertilizer production, assuming that the biogas system will replace an equivalent amount of these alternative processes. This approach is referred to as "avoided production" in the following sections.

4.2 ENERGY EFFICIENCY

The amount and type of energy used to provide different functions is of importance from a sustainability perspective. The world transport systems of today, comprise a wide array of solutions, ranging from systems based on limited fossil or nuclear stock resources to those mainly using renewable flow resources, and there is a lot of ongoing development. Information about the life cycle energy use of different transport technologies indirectly tells about their environmental performance, for example, concerning climate impact and air pollution. In several regions and countries there is a focus on clean energy and efficient energy use.

To assess the energy efficiency of transport technologies it is reasonable to apply a "well-to-wheel" (WTW) perspective and consider the primary energy use (Börjesson et al., 2016; Edwards, Robert et al., 2014), in relation to the services provided (per vehicle kilometers or passenger kilometers). The non-renewable primary energy use may be of particular importance from an environmental and health perspective (Gustafsson et al., 2018). Dahlgren and Ammenberg (2021) studied buses and found HVO and biomethane to have the highest non-renewable primary energy efficiencies (in comparison with electricity, ethanol, FAME and some fossil fuels). Energy inventories are needed to provide information on the energy use, and they should at least cover the fuel production, distribution and use phases, and the energy use is then related to the transport function provided. However, as biogas solutions commonly provide several functions/services it may be misleading to assess them as a transport technology only. One should be careful when comparing a mono-functional system to a multi-functional system (Lindfors et al., 2019), for example, when comparing sun or wind powered electric vehicle systems (mono) to biogas/biomethane solutions that may provide energy recovery, transportation, waste management, production of food grade CO_2 and nutrient recovery.

Regarding comparisons with electric vehicles (EVs), it is important to consider that EVs may require a significant amount of energy for heating, since the engines do not provide heat as is the case with internal combustion engines. For example, Dahlgren and Ammenberg (2021) concluded that electric buses in Sweden may require almost as much energy for heating as for transport, during the coldest months of the year.

The next two sections deal with the transport energy use and efficiency, where the first is focused on fuel production and distribution ("well-to-tank" (WTT)), and the second on use in vehicles ("tank-to-wheel" (TTW)). This means that we are focusing on transport services (mono assessment), but the perspectives are broadened in later parts of the chapter

4.2.1 Energy balance, well-to-tank (WTT)

Sweden is a country with long experience of using biomethane in the transport sector. Börjesson et al. (2016) conducted a comparative study of the energy performance of methane-based vehicle systems. The study focused on Swedish conditions for biomethane: a feedstock mix of food waste, manure, industrial waste, and slaughterhouse waste was considered and biogas plants with two different annual production capacities (30 GWh and 100 GWh). The researchers mainly used data from 2013 or newer, compared to European generic data for fossil alternatives (natural gas, diesel, and petrol). Börjesson et al. (2016) found the (non-renewable) primary energy input to be approximately in the range 0.3 – 0.4 MJ/MJ_{fuel}, (average of 0.32), for both compressed and liquefied biomethane. This meant about 1.3 – 2.4 times more WTT energy than the conventional fossil fuels they used as reference, which is judged as a competitive performance contributing to the recommendation from Börjesson et al. (2016) to further implement biomethane based transport solutions. Gustafsson et al. (2020b) calculated a (non-renewable) primary energy input for different waste-based biomethane pathways in a Nordic context of 0.10 – 0.15 MJ/MJ_{fuel} for compressed biomethane and 0.14 – 0.22 MJ/MJ_{fuel} for liquefied biomethane. Moghaddam et al. (2015) found the primary energy input to be 0.19 MJ/MJ_{fuel} for compressed biomethane and 0.26 MJ/MJ_{fuel} for liquefied biomethane, given a Nordic energy system. These values are very competitive when contrasted to fossil diesel and petrol (Prussi et al., 2020).

Prussi et al. (2020) conducted a very comprehensive study, including 252 energy carrier pathways, with an emphasis on European conditions but also covering examples on the international arena. They used relatively generic data, from 2004 and onwards, for biogas production from municipal organic waste, wet manure, sewage sludge, maize, and double cropping of barley and maize. According to Prussi et al. (2020), compressed and liquefied biomethane require significantly more energy input than conventional fossil based CNG and LNG. However, the non-renewable share of the primary energy input was around 0.2 – 0.5 MJ/MJ for compressed biomethane and 0.3 – 0.6 MJ/MJ for liquid biomethane, whereas fossil fuel pathways typically have 100% non-renewable primary energy input.

There are also other relevant perspectives on efficiency. For example, Börjesson and Mattiasson (2008) studied biofuels from energy crops (and residues) and found biomethane very competitive regarding land use (high energy yield per hectare of arable land) and climate impact reduction, in comparison with other biofuels on the market. These results are in line with IRENA (IRENA, 2018).

Regarding the efficiency in relation to optimizing the energy content in the feedstock, one should consider that AD processes may leave relatively stable carbon structures in the digestate/biofertilizer, which are beneficial both regarding carbon sequestration (climate change) and soil fertility/soil organic content. Thus, it may be reasonable to have a broadened perspective on efficiency for AD processes and biomethane, in comparisons with alternatives that do not have such features (cf. Börjesson et al., 2015).

4.2.2 Energy balance, tank-to-wheel (TTW)

The TTW energy balance of biomethane depends a lot on in what type of vehicle and engine in which it is used. Biomethane can be used either in gasoline (Spark Ignition (SI) Otto-cycle) engines or in diesel (compression ignition) engines. SI engines for gas are used in passenger cars as well as buses and trucks, while the dual fuel technology is mainly implemented in heavy duty trucks, for example by Volvo.

Most combustion engines work more efficiently in continuous operation, while electric engines are not affected by frequent starts and stops in the same way, thus having superior TTW efficiency. Compared to diesel in similar driving conditions, gas-fueled vehicles require around 20% more energy (Gustafsson et al., 2021; Prussi et al., 2020; Stettler et al., 2019b) , although the difference can be expected to decrease with engine development (Prussi et al., 2020). For example, several representatives from Scania have stated that their recently developed gas engines perform similar to diesel engines (based on presentations within the Swedish Biogas Research Center, BRC). Examples of TTW energy use of diesel and gas vehicles reported in the literature are listed in Table 6.

Table 6. TTW energy use with diesel and CNG for different vehicle types.

Reference	Vehicle type	Energy use, MJ/km		
		Diesel	CNG, SI	CNG, dual fuel
Zhang et al. (2014)	City bus	11.8	16.1	
Xylia and Sylveira (2017)	City bus	13.0	23.2	
Lajunen and Lipman (2016)	Suburban bus	18.0	22.5	
Börjesson et al. (2016)	Long-haul truck	9.7	11.4	9.7
Gustafsson et al. (2021)	City bus	22.0	25.9	
	Suburban bus	11.4	13.5	
	Long-haul truck, 20 tonne	7.5	8.8	
	Long-haul truck, 40 tonne	9.9	11.7	
Prussi et al. (2020)	Passenger car	1.5	1.7	
Cignini et al. (2020)	Passenger car		1.5	

4.3 CLIMATE CHANGE

Climate change may lead to huge negative and irreversible effects on ecosystems and humanity, associated with vast socioeconomic implications (IPCC et al., 2021). It is urgent to reduce anthropogenic greenhouse gas (GHG) emissions, mainly caused by extraction and combustion of fossil fuels (Gaulin and Billon, 2020), if global warming is to be kept below 1.5 °C, as stated in the COP 2015 Paris Agreement. The transport sector has a big part in this; a sector with extensive use of fossil fuels (Tian et al., 2018). Biomethane used for transportation can importantly contribute to reduced use of fossil fuels and significantly lowered GHG emissions.

To understand the climate related effects of biogas solutions it is essential to apply a WTW perspective, as the impacts and benefits occur in several parts of the life cycle. For example, when manure is used as biogas feedstock, it is possible to avoid climate impact associated with conventional manure handling where methane is formed and released in an uncontrolled manner, due to open storage (Olesen et al., 2020). If manure is instead collected and fed into a biogas plant the methane formation is controlled, and CO_2 is generated when the methane is combusted in an engine, which is a much less potent greenhouse gas (Liebetrau et al., 2017). A well designed process for handling and digesting manure, involving good fertilizing practices, can thus be a net negative emission technology on a whole lifecycle basis from a climate perspective (Börjesson et al., 2016).

Regarding potential impacts on climate change, the largest impact in the life cycle of fossil fuels typically come from the use phase, while the production phase dominates for renewable alternatives (heat and electricity input) as the CO_2 emitted through combustion is part of the natural carbon cycle (Lyng and Brekke, 2019). In general, biomethane produced from waste or byproducts has superior (environmental and) climate performance to biomethane from energy crops, as the environmental burden of byproducts to a large extent is attributed to the main product or service. However, cover/intermediary crops (such as ley crops) are exceptions that may have very good climate performance; when accounting for increase of soil organic carbon the reduction of GHG emissions can surpass 100% as compared to fossil fuels (Björnsson et al., 2013; Börjesson et al., 2015). Digestate related aspects are not always included and well-managed in systems studies of biogas solutions, including biomethane for transport. Although commonly of significant importance, they have so far not been fully acknowledged in the EU RED methodology. For example, the use of digestate as biofertilizer may reduce the need of chemical fertilizer production (McCabe, B. et al., 2020). As chemical fertilizer production commonly involves significant consumption of natural gas (via the Haber-Bosch process), there are important indirect positive climate effects associated with the nutrient recycling that come with biogas solutions. These can be included by accounting for avoided production, by considering the avoided impact related to alternative systems for waste handling and fertilizer production.

The report by Prussi et al. (2020) provides information on the 252 energy carrier pathways studied, divided into WTT and TTW impact. Their results show that biomethane, either compressed or liquefied, has among the lowest WTW GHG emissions of all energy carriers for road transport: c. -67 g CO_2-eq./MJ when manure is used as feedstock, assuming the alternative treatment of manure to involve open storage with leakage to the atmosphere. Gustafsson and Svensson (2021) found the WTW GHG emissions of liquefied biomethane from manure to be c. -9 g CO_2-eq./MJ, including the use of digestate as biofertilizer, while Börjesson et al. (2016) calculated the WTW GHG emissions for compressed biomethane from a mix of manure and food waste to be 0.6 g CO_2-eq./MJ with system expansion (considering avoided production/impact). It is clear from these and the other studies summarized in Table 7 that the exact value of WTW GHG emissions of biomethane can vary a lot depending on the feedstock and how the system boundaries are defined (cf. Brandão et al., 2021, however not including any byproducts for biogas). Of course, other methodological issues are also influential. The division between WTT and TTW emissions can vary depending on how one accounts for biogenic CO_2 emissions, either by setting the TTW CO_2 emissions to 0, or by accounting for the uptake of an equivalent amount of CO_2, through the photosynthesis of green plants, in the WTT phase. For example, Gustafsson and Svensson (2021) used the former approach, while Prussi et al. (2020) used the latter.

Even though the WTW climate change performance of biomethane can vary depending on feedstock, technology, and system boundaries, it is generally quite good compared to other energy carriers for transport, not least fossil fuels. In the broad comparison made by Prussi et al. (2020), biomethane stands out with its low WTW GHG emissions, both for heavy vehicles and for passenger cars (Figure 22).

Table 7. GHG emissions of biomethane production systems

Reference	Biogas production	Feedstock	Biomethane form	Avoided production	GHG emissions, g CO_2-eq./MJ		
					WTT	TTW	WTW
Prussi et al. (2020)	AD	Manure	Compressed	Yes	-103	36	-67
		Food waste	Compressed	No	9.5	36	46
		Manure	Liquefied	Yes	-99	36	-63
		Food waste	Liquefied	No	14	36	50
Gustafsson and Svensson (2021)	AD	Manure	Liquefied	No	32	1.8	33.8
				Yes	-11	1.8	-9.2
		Food waste		No	26.4	1.8	28.2
				Yes	3.4	1.8	5.2
Börjesson et al. (2016)	AD	Mixed	Compressed	No	12.3	1.7	14.0
			Compressed	Yes	-1.1	1.7	0.6
			Liquefied	No	13.0	1.7	14.7
			Liquefied	Yes	-0.4	1.7	1.3
Moghaddamet al. (2015)	Not included		Compressed	No	17		
			Liquefied	No	22		
Lyng and Brekke (2019)	AD	Food waste	Compressed	No	9.3	0.5	9.8
		Manure		No	16.0	0.5	16.5
Hallberg et al. (2013)	AD	Sugar beet	Compressed	No	18	5	23
				Yes	13	5	18
		Industrial waste		No	8	5	13
				Yes	-17	5	-12
		Household waste		No	12	5	17
				Yes	-3	5	2
		Manure		No	12	5	17
				Yes	-41	5	-36
		Sewage sludge		No	3	5	8
				Yes	-6	5	-1
RED II (European Comission, 2018)	AD	Manure	Compressed	No			-96
		Maize		No			35
		Biowaste		No			19

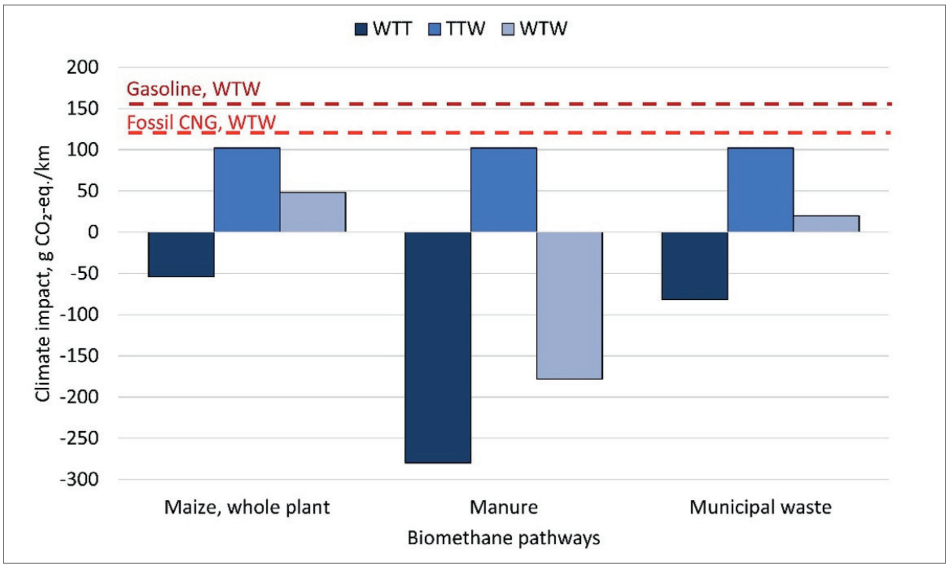


Figure 22. WTW climate impact of different biomethane pathways compared to fossil compressed natural gas and gasoline for passenger cars.
Based on Prussi et al. (2020).

Gustafsson et al. (2021) found that biomethane from municipal organic waste had among the lowest WTW GHG emissions of energy carriers for heavy transport, regardless of how the process electricity is produced. While biomethane production does require some electricity, it still has a very low climate change impact within any electricity mix, as shown in Figure 23. Biogas solutions can valorize low-grade biomass to high quality fuel and biofertilizers, with relatively low dependence on high quality energy.

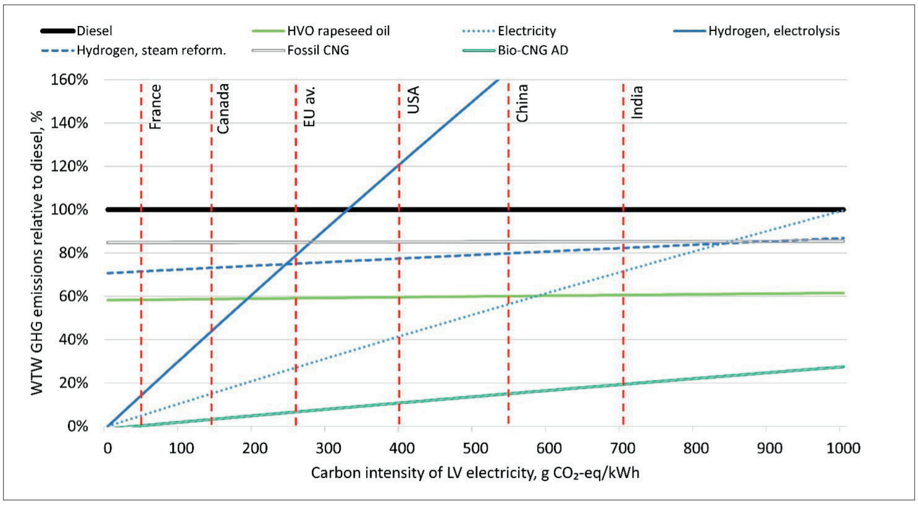


Figure 23. Well-to-wheel greenhouse gas emissions (relative to diesel) of energy carriers for a suburban bus, as a function of carbon intensity of the electricity system. Based on Gustafsson et al. (2021).

4.3.1 Methane slip

In the context of biogas solutions biomethane slip is a common topic. It is important to minimize methane slippages along the whole life cycle of biomethane (Liebetrau et al., 2017). For example, a study by Brynolf et al. (2014) showed that the use of liquid biomethane may significantly reduce the impact on climate change from shipping, and that the reduction will depend on the magnitude of the methane slip in the biogas value chain. Methane has a global warming potential of c. 28 times higher than carbon dioxide (perspective of 100 years), which means that such emissions from the biomethane production chain reduces the climate benefits of biogas solutions. The emissions are regulated, measured, and reported in many biogas contexts, and they are included in the systems analysis studies mainly referred to in this section. As previously shown, well-designed biogas solutions commonly have very competitive climate performance, in spite of accounting for normal methane slippage levels (Börjesson et al., 2016; Gustafsson et al., 2021; Prussi et al., 2020). However, higher methane emission levels mean worse climate performance and there are studies indicating significant emissions in some contexts. An example is in the following report in Danish (https://ens.dk/sites/ens.dk/files/Bioenergi/metantab_rapport.pdf). An IEA Task 37 report by Liebetrau et al. (2017) contains detailed information on methane emissions related to biogas/biomethane production, including technology for measurement and measures to minimize such emissions. It also puts into context the relationship between methane slippage and sustainability.

From a more comprehensive societal perspective, it does not appear logical that biogas solutions receives so much attention when it comes to fugitive methane emissions. In relation to the methane emissions associated with the extraction and use of natural gas, the emissions from biogas solutions are extremely small (Alvarez et al., 2012; Littlefield et al., 2017; Zhang et al., 2020). There are also very large emissions of methane (existing and potential) from the ground, increasing as climate change leads to higher temperatures and permafrost thaw, causing the release of greenhouse gases from decomposing soil organic carbon (Anisimov, 2007; Nauta et al., 2015).

In synthesis well-designed and managed biogas solutions greatly reduce fugitive methane emissions (such as would occur in open slurry tanks) and may be regarded as cost efficient climate abatement strategies (Westlund et al., 2019).

4.4 AIR POLLUTION

Air pollution is associated with a wide range of environmental and health issues such as acid rain, smog, and cardiovascular and respiratory diseases causing premature mortality and other negative consequences (Anenberg et al., 2019; Lelieveld et al., 2015). Road transport is a major contributor to air pollutants, such as CO, non-methane volatile organic compounds (NMVOC), NO_x and particle emissions (European Environment Agency, 2019; Fan et al., 2018). Shipping generates significant amounts of such emissions, but also SO_x due to sulphur fuel content (oil refined to petrol and diesel for road transportation is commonly desulphurized). In Europe, emissions of air pollutants have declined for all transport modes, except for shipping and aviation (ibid). Commonly, there is a large focus on emissions from driving, but there can also be significant impacts from raw material extraction, production, and distribution.

For road transport, biomethane is commonly reported as a favourable alternative concerning air pollution, compared to diesel and petrol, and several of the renewable options. Börjesson and Berglund (2007) found 50–80% lower life-cycle particulate emissions when biomethane replaces diesel in heavy-duty vehicles, and 15–60% when replacing petrol in light-duty vehicles. In line with this, Pérez-Camacho et al. (2019) found considerably lower particulate matter formation (g PM 10-equivalents) for biomethane, when compared to diesel and petrol. Lindfors and Ammenberg (2020) assessed a range of renewable and fossil fuels for buses and trucks in Sweden. Vehicles driven on waste-based biomethane, electricity and natural gas came out best regarding air pollution, where the assessment was focused on NO_x and particles. It should be noted that electricity in Sweden is largely generated via hydro and nuclear power, resulting in low air pollution. Crop-based biomethane was found to be better than fossil diesel, but the upstream effects related to farming gives higher emissions than the waste-based alternatives.

Some studies deal with photochemical oxidant formation (POCP), the creation of ozone near ground level, which can lead to respiratory diseases and inhibited growth of plants and other parts of the ecosystem. Börjesson and Berglund (2007) found that this formation could be reduced by approximately 50–70% when biomethane replaces petrol in light-duty vehicles and by about 20–65% when diesel is shifted out of heavy-duty vehicles. Manure-based biomethane could give even further reduction. Studying bus transport, Lyng and Brekke (2019) found better performance for biomethane from manure and foodwaste, compared to fossil diesel and biodiesel (FAME) from palm oil and rapeseed. While the emissions from the use phase were found to be relatively equal among available fuels on the market, there are large differences regarding the upstream phases. For biodiesel these impacts are caused by palm oil mill operation and rapeseed production, while for fossil diesel the impacts are caused by the petroleum production.

A WTW perspective on the average world electricity production, shows that electric vehicles can be associated with significant problems of air pollution, although not having any tail pipe emissions (Nordelöf et al., 2019; Requia et al., 2018; Timmers and Achten, 2016; cf. Prussi et al., 2020). A bus powered by electricity from a coal power plant gives similar photochemical oxidant formation as biomethane from food waste (Lyng and Brekke, 2019).

In the European Union, there are emission standards with limits of exhaust emissions for new vehicles. However, for earlier versions of these standards (Euro V and older), the real-world driving emissions have been found to significantly exceed the limits (Carslaw and Rhys-Tyler, 2013; Fontaras et al., 2017; Kadijk et al., 2015; Rosero et al., 2020). Recently, the regulations have been sharpened, involving new types of tests supposed to better match real driving conditions (but still focused on new vehicles). Lowered limits and improved tests mean less air polluting emissions from all vehicles fulfilling Euro VI, even if driven on diesel and petrol (Hagman, 2016). But, there are a few studies indicating high real world emissions for Euro VI certified vehicles as well (Grigoratos et al., 2019; Mendoza-Villafuerte et al., 2017; Moody and Tate, 2017). In general, gaseous fuels as biomethane and natural gas, require less complicated cleaning technology than, for example, fossil diesel. Focusing on the tail pipe emissions only, electric vehicles are extremely competitive and can be favourable in central city areas to reduce or avoid local pollution (Ruggieri et al., 2021).

In the shipping industry air emissions have received much attention in recent years and the focus has been on SO_x, NO_x, and particulate matter, in addition to greenhouse gas emissions. Brynolf et al. (2014) compared the conventional marine heavy fuel oil (HFO) with liquid biomethane, liquid natural gas and methanol (produced from natural gas) in a life cycle perspective (well-to-wake). The results showed that all alternative fuels led to significant reductions on particulate matter formation and photochemical ozone formation.

4.5 ACIDIFICATION AND EUTROPHICATION

Acidification is caused by nitrogen and sulphur related emissions to air and can contribute to decreasing pH in soil and water. This can lead to imbalance in the natural eco systems. By eutrophication we mainly refer to problems due to local excess of nutrients related to human activities. Inefficient waste management and agricultural nutrient imbalances lead to eutrophication of marine ecosystems (Metson et al., 2020). Lindfors and Ammenberg (2020) found that waste based biomethane has negligible, small positive or small negative effect on reduced acidification and eutrophication, while biomethane (and other biofuels) based on crops may be coupled with significant negative effects stemming from soil conditioning and fertilization practices. These impacts related to agriculture will occur as long as the crops are produced in the same way (also for other applications, such as food and fodder). Electricity from coal also has a negative impact on acidification (ibid).

Lyng and Brekke (2019) concluded that biodiesel from rapeseed had the largest acidification potential amongst available fuels for bus transport due to emissions from rapeseed production. Palm oil-based biodiesel, and fossil diesel, also were shown to have a relatively high potential contribution to acidification, while biomethane from waste and manure was found to have a low contribution in comparison. Similarly, FAME based on rapeseed and on palm oil has a high potential impact on eutrophication (ibid). A comparison between petrol, diesel and biomethane performed by Pérez-Camacho et al. (2019), showed that changing from diesel or petrol to biomethane as a fuel can lead to more than 50% reduction in terrestrial acidification.

According to Börjesson and Berglund (2007), the acidification potential can be substantially reduced compared with conventional fossil fuels when biomethane from manure, organic waste, tops and leaves of sugar beets, are utilised. This is mainly due to the reduced leakages of nitrate and emissions of NH_3. Biomethane from ley crops and straw can also lead to a reduced contribution when diesel is replaced in heavy-duty vehicles, whereas replacement of petrol in light-duty vehicles may lead to an increased contribution. The acidification potential is significantly affected by the variations in emissions of ammonia (NH_3) to air caused by changed cropping practices and handling of the wastes and residues (ibid).

In addition to the acidification studies focused on NO_x and SO_x, it should be mentioned that oceans absorb a significant share of the anthropogenic CO_2 emissions which makes them more acidic. This means that biomethane for transport, via reduced CO_2 emissions, contributes to reduced ocean acidification.

4.6 NOISE

Noise is a common problem for which transport systems are one of the most significant sources (Braubach et al., 2015; Lercher, 2019); this causes disturbance for people and wildlife (Shannon et al., 2016). For speeds exceeding c. 50 km/h, noise from the tires/road dominates (Larsson and Holmes, 2016). Thus, in areas where vehicles commonly have a speed around 50 km/h or higher, it is less important to focus on vehicle or engine noise, while it may be essential in slow moving urban traffic.

Many scientific articles and technical reports contain relatively generic statements that vehicles using methane generate significantly less engine noise than corresponding models using diesel and/or petrol, however few seem to base those statements on thorough reviews (Amrouche et al., 2012; Chala et al., 2018; Hagos and Ahlgren, 2017; Kakaee and Paykani, 2013; Makarova et al., 2018; Orzechowska et al., 2014; Petrović et al., 2016; Sachdeva and Mansuri, 2013; SGC, 1995; Ugay et al., 2014; Urbanik and Tchórzewska-Cieślak, 2015; Waluszewski et al., 2011; Wang-Helmreich and Lochner, 2011). Several of these sources report 2 – 10 dB reduction, where it should be noted that a 3dB reduction means halved noise. Thus, this indicates a great potential for gas driven vehicles to contribute to mitigating noise related problems, in comparison with diesel or petrol, although further studies seem to be needed. A contrasting view from Nijboer (2010), suggests that light-duty gas vehicles do not perform better than corresponding petrol or diesel vehicles in terms of noise. Of course, electric vehicles have better noise performance than gas driven vehicles of similar type (in slow moving traffic). In Sweden, gas vehicles are allowed to enter the toughest low emission zones (SFS 2018:1562), based on legislation aimed at improved air quality and lowering noise levels in cities. Some sources more specifically explain why gas engines may be less noisy, where the lower compression level in a spark-ignited (SI) engine may be favorable, due to the slower rate of pressure rise in the cylinder. For example, sources mention general issues such as a smoother engine performance (Sachdeva and Mansuri, 2013) and point at more specific favorable fuel characteristics such as the high octane number and spontaneous ignition temperature (Kaszkowiak et al., 2017), and that the gaseous form ensures more complete and homogenous mixing with air in a SI engine (Abou-Arab et al., 2009).

Other sources focus on heavy vehicles and report significantly better noise performance for gas driven trucks and buses in comparison to similar diesel vehicles, including dual-fuel models (Abdelaal and Hegab, 2012; Abou-Arab et al., 2009; Hoffmann et al., 2014; Mårten Larsson, 2015; Milojević, 2017; Takman et al., 2018; Wilde, H.P.J. de et al., 2014). Several truck suppliers have gas driven models certified in accordance with the Stichting Piek-Keur Certification, with a 72 dB(A) limit during loading and unloading, regarded as suitable for nighttime deliveries without causing noise disturbance (cf. Osorio-Tejada et al., 2017). It should be mentioned that some sources report higher noise levels for gas driven buses (Borén, 2019; Ross and Staiano, 2007), although the study by Borén (2019) only seems to cover one bus, and Ross and Staiano (2007) do not seem to compare similar bus models. Commonly so-called A-weighted sound levels are used (dB(A)) to adjust the measurements to the sensitivity of the human ear, with a focus on the range between 1 to 4 kHz (US Federal Highway Administration, 2018). However, it can be relevant to pay more attention to low frequency noise which can be of relevance for (heavy) transportation, including buses driven on methane (Dahlgren and Ammenberg, 2021). Transport noise in the range from about 10Hz to 200Hz can cause indoor noise annoyance (Leventhall, 2004; Waye, 2004), while higher frequencies contribute more to outdoor problems (Höstmad et al., 2016).

4.7 SUSTAINABLE FARMING AND FOOD SUPPLY

Biogas solutions contribute to more sustainable nutrient management, as they provide great opportunities to circulate essential nutrients and other relevant components (Drosg et al., 2015; Feiz et al., 2021; Metson et al., 2020). They may thus be essential regarding food/nutrient supply, reducing the need for imported nutrients and making regions more resilient. Linear societal systems (extraction → production → use → disposal) such as those involving mining, landfilling and/or incineration, may be replaced by more circular practices, which is critical for safe nutrient flows (e.g. considering planetary boundaries, Steffen et al., 2015). For example, when biogas is produced from food waste, essential nutrients can be recycled back to the agricultural sector via biofertilizers. As the digestate from biogas plants (via AD process) contains most of the nutrients in the feedstock (Drosg et al., 2015), there is a great potential for nutrient economization. The use of biofertilizers may significantly reduce the need for synthetic/mineral fertilizers, which are clearly non-sustainable as they are associated with mining of limited phosphorus resources (Cordell et al., 2009) and industrial nitrogen fixation largely involving natural gas (Chen et al., 2019). In addition to recycling nutrients, AD processing increases the share of plant available nitrogen (due to mineralization), which may result in improved crop yields (Crolla et al., 2013; Drosg et al., 2015; Santamaria-Fernandez et al., 2019). Further along the chain, the use of biofertilizers may contribute to improved soil fertility due to the organic matter content, but this depends on the type of feedstock, its origin, the alternative use, and the characteristics of the soil, (Bezzi et al., 2016; Prade et al., 2017). For example, biofertilizers from industrial bio-waste that would otherwise have been landfilled, can importantly contribute to the level of soil organic matter in crop producing regions with low levels of soil organic matter. On the other hand, production of biogas and biofertilizers from straw (that would otherwise have been left of the fields), involves removal of some organic matter (Ammenberg and Feiz, 2017). The situation is similar for manure, as the digestate returned to the fields has a lower total amount of carbon in comparison with recycling without AD. However, studies indicate low or even positive impacts on soil carbon, as the digestate contains more stabilized organic matter in fertile land (Höglund et al., 2013; Insam et al., 2015; Wentzel et al., 2015). Further on, biogas systems may help animal farms with odor related problems, which may result in less complaints from neighbors, as the digestate contains less odorous compounds in comparison to raw manure (Crolla et al., 2013). There is also a possibility to use the CO_2 from biogas production, that is removed in the cleaning and upgrading steps. For example, it can be used in greenhouses, and may replace CO_2 of fossil origin (IEA Bioenergy Task 37, 2020).

In conclusion, well-designed and applied biogas systems, may be essential to transform conventional farming to more sustainable farming, with significantly improved management of nutrients and soils (Koppelmäki et al., 2019; Metson et al., 2020), where the latter can involve smartly designed crop rotation systems with cover/intermediary crops (Magnolo et al., 2021; such as ley crops, Prade et al., 2014). For example, Hagman (2018) has found that biogas plants are essential for organic farming in Sweden, as the biofertilizers can be certified/approved for organic farming schemes. Organic farming is important for biodiversity (Rundlöf et al., 2016). Depending on the demand, improved opportunities for organic farming may strengthen farmers competitiveness (IEA Bioenergy Task 37, 2019). In addition, the biogas or biomethane may be used internally withing farms or sold externally resulting in another revenue stream.

4.8 WASTE AND WATER MANAGEMENT SERVICES

Common types of biogas solutions provide essential sociotechnical systems services as components of systems for waste and (waste) water management. In several parts of the world they are elements in municipal waste water treatment plants (Bachmann et al., 2015; Gustafsson et al., 2020a; Shen et al., 2015), delivering functions such as hygienization (inactivating pathogens, Liu et al., 2019) and reduced sludge volumes, and opportunities to recycle nutrients and recover energy. There are also many industrial examples, involving treatment of waste water in several sectors, such as the food industrial sector and the pulp and paper industry (Ekstrand et al., 2013; Feiz et al., 2021; Madeleine Larsson, 2015). In cases where biogas solutions bring more sustainable nutrient management, they contribute to improved water quality, for example, as reduced nutrient leakages means less eutrophication (Akram et al., 2019; Carpenter and Bennett, 2011). However, some types of crops may also be problematic in this context, due to emissions causing eutrophication (Börjesson and Tufvesson, 2011; Lindfors and Ammenberg, 2020).

Biogas from organic waste, such as food waste, involves separation of the organic fractions from other types of waste fractions, which then may be easier to treat and/or recycle. In this perspective, biomethane used for transportation comes with sociotechnical systems services that most competing alternatives do not match (Dahlgren and Ammenberg, 2021; Lindfors and Ammenberg, 2020). The possible transformation of wastes (commonly seen as costs) to valuable products, may partly finance the waste (water) management systems, while also being part of a societal transformation towards a more biobased and circular economy (socio-economically sound developments). Biogas systems also comprise trapping and use of landfill gas and can thus significantly reduce fugitive methane emissions from such waste management facilities. The largest emissions reductions are obtained when several sectors are coupled (such as waste, transport, and agricultural sectors) (Lyng et al. 2018)

4.9 ENERGY SUPPLY AND FLEXIBILITY

In recent decades there has been a re-emerged interest in energy security, driven by rising demand, disrupted supplies and the strive towards decarbonization (Cherp and Jewell, 2014). A transition to more renewable energy systems, can make countries and provinces more self-sustaining. Biogas systems are commonly relatively decentralized and 'local', with many examples of 'local' feedstock used to produce gas for 'local' use, and where biofertilizers are distributed to farms nearby. This gives local/national actors better control over the access to energy (and nutrients) and associated costs (Naseem et al., 2020; Piwowar et al., 2016; Surroop et al., 2019). Liebetrau et al. (2020) wrote *"As a decentralized component of the overall energy system biogas systems can function as an infrastructure hub for local energy consumers in rural areas"*.

However, depending on the physical form, energy content and business agreements, feedstock can also be transported over longer distances (O'Shea et al., 2017, 2016). For example, food waste transported 400 km between different municipalities, or even residual oils shipped between continents. Biomethane can be transported further when liquified or when gas grids are available. Nevertheless, most biogas solutions should support provincial/regional energy security, and fit well within, for example, the strategies of the European Union (cf. Jonsson et al., 2015). In addition, the liquid form makes it easier to store biomethane.

There is an ongoing shift to more renewable and intermittent energy sources for production of electricity, that are not dispatchable. Electricity from wind, sun and hydro power brings challenges in balancing supply and demand, as well as in controlling the voltage and frequency. Bioenergy sources can provide baseload electrical power (Chiaramonti et al., 2017; Reid et al., 2020) and flexibility (Budzianowski and Brodacka, 2017; Liebetrau et al., 2020), as the production can be adapted to the energy generated from other sources and the current demand. Liebetrau et al. (2020) conclude that biogas systems can have a highly scalable energy provision, while facilitating voltage and grid stability. They also mention that biogas systems can serve as a sink for electricity when the demand is low, reducing curtailment and constraints; a possibility to use biogas systems as biological batteries, where the electricity and gas grids are coupled, and surplus electricity used to produce biomethane from hydrogen and (biogenic) CO_2. The level of flexibility depends on the feedstock, specific biogas plant configuration, associated technical systems, available infrastructure and to other systems.

The sustainability performance as detailed in chapter 4 is synthesised in section 7.2 and in particular Table 9.

5 Policy regarding biomethane for transport

Policies regarding biomethane can look very different in different countries, ranging from a very strong focus on use for road transport to no policies directed towards transport at all. In general, there has been a stronger focus on utilization of biogas and biomethane for electricity and heat production than on biomethane as a transport fuel. Several countries are however moving toward an increased use of biomethane in transport (Gustafsson et al., 2020a), as a strategy to meet national goals and international agreements on use of renewable energy and climate change mitigation. On average, 17 % of the vehicle gas sold in Europe 2019 was biomethane (Hörmann, 2020), and gas is an increasing, although still marginal, fuel alternative in European vehicles (Eurostat, 2020a).

While the share of renewable energy in Europe has had a considerable increase (Eurostat, 2020b), the share of renewables in the transport sector is changing at a slower pace. In 2019, the share of renewable resources in the total final energy production was around 18 % globally (REN21, 2019), while the share of renewables in the transport sector was estimated to be 3.3 % globally (REN21, 2019) and 7.6 % in the European Union (Eurostat, 2019). A transition towards a renewable transport sector will require a combination of energy carriers and technological solutions, where biomethane has potential to give an important contribution.

Biogas policies can be categorized as economic, regulative or voluntary, and also enforcing or encouraging (Gustafsson and Anderberg, 2021). Policies influencing biogas production and use are found on different administrative levels, from local or regional to national or international (such as EU regulations or global goals). Biogas solutions are applicable across a wide range of sectors, of which the transport sector represents only one. Biogas policy will influence biogas systems employed. However, the production and use of biomethane is also influenced by policies on waste management, agriculture, and wastewater treatment (Figure 24). It must also be considered that regulations and incentives for biogas and biomethane can be directed towards different parts of the value chain (Gustafsson and Anderberg, 2021). In some countries the economic instruments are directed towards input material and investment support, while other countries incentivize the output (use of the biogas or biomethane) (Lyng et al., 2020). The connection between supply and demand usually makes it sufficient to subsidize one of the two. However, with international trade of biomethane, the link between domestic supply and demand is weakened. One example of this is Sweden, where the main economic instrument for biogas and biomethane is the exemption from energy and carbon taxes, putting a focus on the use of biogas and biomethane. While the demand for biomethane in Sweden has increased steadily in the last years, domestic production has stagnated in favor of imported biomethane and green certificates from Denmark, where the economic incentives are directed towards the biogas producers. Hence, the disharmony of the economic instruments in Sweden and Denmark gives Danish biogas producers the opportunity of receiving double incentives, making it difficult for Swedish biogas producers to compete with Danish biogas producers (Westlund et al., 2019).

Figure 24. Examples of policies affecting biogas solutions within 8 different administrative areas: Energy, Environment, Waste, Water, Agriculture, Transport, Economy and Construction. Based on Gustafsson and Anderberg (2021).

In the European Union, the use of biomethane in transport is governed by the Renewable Energy Directive recast (RED II) (European Commission, 2018), the Fuel Quality Directive (FQD) (European Commission, 2015), the Directive on Alternative Fuels Infrastructure (DAFI) (European Commission, 2014) and the Clean Vehicles Directive (CVD) (European Commission, 2009a). The revised version of RED puts stronger emphasis on the development of advanced biofuels, based on waste products rather than dedicated energy crops. This limits the share of biogas that can be included in calculations against the renewable energy targets, especially in countries like Germany and Italy where energy crops are central substrates for biogas production (EBA, 2020). However, there are many types of biogas substrates that do fall under the advanced biofuel definition, including organic household or industrial waste, agricultural residues and manure, perennial rye grass, ley crops, and sewage sludge.

On a national or local level, policies, and incentives to promote biomethane in transport include green vehicle standards, green zones in cities where petrol and diesel vehicles are not allowed, tax reductions or exemptions (energy tax, carbon tax or vehicle tax), road toll systems, and investment subsidies. With tax revenues from fuel tax and registration tax amounting to 40 billion and 8 billion Euro respectively, the combination of these taxes contributes 7.7 % to the national tax income of €620 billion in Germany. Von Rosenstiel et al. (2015) emphasize the importance of fuel taxes and vehicle registration taxes, in order to reduce negative externalities.

In Italy, the Netherlands and UK, biomethane is included in blending obligation systems, setting specific quotas for renewable content in vehicle gas (van Grinsven et al., 2017). Other possible support schemes include investment grants for new infrastructure and production plants, subsidies for purchasing or retrofitting vehicles, and low-interest loans for investments in biomethane vehicles and infrastructure (van Grinsven et al., 2017).

Combining different types of support and regulations can be tricky, not least in the EU where it is not allowed to subsidize renewable alternatives more than the extra cost compared to the fossil alternatives. This means that national authorities need to keep track of how much support each unit of biofuel has received, from production to use, to make sure that it is not over-compensated. Moreover, enforcing measures such as a blend-in quota are not compatible with economic support such as tax exemption for the same activity (in this case, use of biomethane in transport), due to the regulatory framework on over-compensation.

The development of liquefaction technologies has opened up new markets for biomethane in heavy road transport as well as in marine transport. Both of these sectors are currently taking measures to reduce their use of fossil fuels, in order to comply with increasingly strict regulations on emissions of CO_2 and particulates. This gives an opportunity for biomethane to enter these sectors, at least as a renewable complement to natural gas. In areas with scarce or no gas grid infrastructure – such as Norway, Sweden and Finland – liquefaction of biomethane can also enable longer distribution ranges, since the higher energy density of liquefied gas compared to compressed gas makes distribution by semi-trailer more cost-efficient (Gustafsson et al., 2020b).

5.1 EXAMPLES FROM DIFFERENT COUNTRIES

Sweden has a long tradition of using biomethane for road transport. In 2019, 94 % of the vehicle gas sold in Sweden was biomethane (Hörmann, 2020). More than 50 % of the domestically produced biogas was used as transport fuel, along with one third of the imported biomethane (Klackenberg, 2019). Biomethane has thus contributed to the early achievement of the national goal on 10 % renewable energy in transport by 2020 and will continue to be important for the work towards the 2030 vision of a transport sector independent of fossil fuels. The Swedish development of gas mobility has been driven mainly by tax exemptions for biomethane, and the fact that several regions and municipalities have invested in gas buses in public transport procurement. The tax exemption has also made gas vehicles a good option for taxi companies looking to improve their environmental profile. The complete exemption from carbon tax and energy tax for biogas and biomethane is classified by the EU as a form of state aid that must be approved by the European Commission. Finland has a similar support system as Sweden, with tax exemption for biomethane and procurement aid for heavy-duty vehicles as fundamental pillars. In addition, Finland have implemented a subsidy for converting gasoline and diesel vehicles to gas or ethanol (Särkijärvi et al., 2018).

Countries like France, Germany, Italy, the Netherlands and UK have lower taxes for gas than for diesel and petrol, but without differentiating between biomethane and natural gas (van Grinsven et al., 2017). In 2020, the Swedish tax exemption for biogas and biomethane was prolonged until 2030 (European Commission, 2020). Since 2006 all fueling stations in Sweden are obliged to provide at least one form of renewable fuel. This has however been of marginal importance for the number of biomethane pumps, due to the higher investment cost compared to ethanol pumps and to some extent the limited production capacity of biomethane. It is also possible to get support for infrastructure investments such as biogas plants, upgrading plants and fueling stations, as well as for heavy vehicles with gas engines. For light vehicles, there is a system called "Bonus-Malus" which puts an increased CO_2 tax for the first three years for petrol and diesel cars ("Malus"), while low-emitting vehicles such as gas cars are subsidized ("Bonus"). A national inquiry on the future development of biogas solutions in Sweden proposed additional premiums for producers of biogas that is upgraded and/or liquefied (Westlund et al., 2019).

In Italy, there are over 1 million gas vehicles (Eurostat, 2020a) and around 1400 fueling stations for gas (NGVA Europe, 2020), more than in any other European country. Incentives for biogas producers changed in 2018 from a Feed In Tariff (FiT) for electricity to only supporting biomethane for transport (Maggioni et al., 2018). However, the share of biomethane in vehicle gas is still quite low, only 9 % (Hörmann, 2020). Biogas plants that were already up and running before the change of support system will continue to receive FiT for electricity production throughout their contracted periods of 15-20 years (Maggioni et al., 2018). Similar inertia in support systems exist in Germany, Denmark and France, which could be considered as an impediment to a swift transition from electricity production to use in transport (Gustafsson and Anderberg, 2021). On the other hand, rigid conditions provide a stable financial framework for biogas producers to rely on, which in many studies is described as a desirable quality in policy design (Ammenberg et al., 2018; Capodaglio et al., 2016; Dahlgren et al., 2019; Hermann and Hermann, 2018; Huttunen et al., 2014; Kampman et al., 2016; Torrijos, 2016).

Germany has, like Italy, transitioned from a FiT for electricity from biogas to supporting biomethane for road transport (Gustafsson and Anderberg, 2021). However, the fact that many biogas producers already have contracts for electricity production for several years will delay the transition towards biomethane production. Nevertheless, the number of fueling stations offering pure or blended biomethane, as well as the share of biomethane in vehicle gas, has increased quite rapidly from 100 stations and 20 % biomethane in 2018 to 545 stations and 80 % biomethane in 2021 (personal communication with Professor Frank Scholwin, Institut für Biogas, Germany and https://cng-club.de/cng_tankstellen_deutschland_europa). The shift in policy focus is economically motivated, as solar power and wind power have become more cost efficient for electricity production while the prices for transport fuels are rising. Several German vehicle manufacturers have developed cars and trucks with gas engines, and the German parliament have removed taxes for gas-driven trucks (Deutscher Bundestag, 2018).

In UK, there are no cars or small vans on sale that run on natural gas and all focus is on the heavy goods sector, either with bio-CNG or bio-LNG. Bio-CNG is mass balanced between biomethane injection to the gas grid and an equal amount (mass) of gas taken out of the grid at the filling station and compressed into the truck. In the case of bio-LNG, biomethane injected into the gas grid is mass balanced with fossil LNG imported to UK from Qatar and US shale. Biomethane producers delivering to the gas grid can either receive a feed-in tariff of 0.055 €/kWh, or Renewable Transport Fuel Certificates of 0.10 €/kWh, if the biomethane is sold as a vehicle fuel through the mass balance system. Under this system with mass balance and certificates (and existing grids), there is no financial motivation to produce liquefied biomethane in the UK. Hence, there are no liquid biomethane plants in operation or under development in the UK. For compressed biomethane, the feedstock is 100 % waste, as this gives double the value of renewable certificates. There is significant year on year growth of bio-CNG and bio-LNG in heavy goods vehicles in the UK, as both these fuels are considered to yield c. 85 % GHG saving compared to diesel and there is no alternative for de-carbonization of this vehicle segment at present.

In the US, California is leading the development of biomethane as a transport fuel. The use of biomethane – or renewable natural gas (RNG) – in transport is part of the work towards the state's climate policy, including goals to reduce methane emissions to 40 % below 2013 levels by 2030 and to become carbon neutral by 2045 (Governing Law, 2016 – SB1383 and Executive Order B-55-18 to achieve carbon neutrality). Investment costs for biogas projects in California are subsidized through tax credits for the producers (Haines, 2018).

In Colombia, the cities of Cartagena and Bogotá have invested in gas buses to reduce local air pollution and noise (https://news.cision.com/scania/r/scania-delivers-741-gas-buses-to-bogota,c2708497). The buses currently run-on natural gas, but the bus manufacturer Scania envisions a transition to biomethane in the near future, with development of a local waste handling system with anaerobic digestion and biomethane production.

5.2 SUSTAINABILITY CRITERIA AND CALCULATIONS

In Europe, the RED recast defines a set of sustainability criteria that biofuels must meet in order to be included in calculations for renewable energy targets and obligations, and to be eligible for financial support for biofuels (European Commission, 2018). These criteria are designed to ensure that biofuels provide a certain level of greenhouse gas (GHG) emission savings and that they are not produced in a way that has a negative effect on forestry, land use or biodiversity. The GHG emission saving requirements for biofuels use in transport are set to 50% for biofuels produced in installations that were in operation before October 5th 2015, 60% for biofuels from installations taken into operation between October 6th 2015 and December 31st 2020, and 65% from January 1st 2021. These levels are higher than in the 2009 version of RED (European Commission, 2009b), in which the minimum GHG emission saving requirement for biofuels was set to 35%, increasing to 50% from January 1st 2017 for existing installations and to 60% for installations taken into operation after that date. The sustainability criteria for land use change and other aspects have also been extended in the RED recast. These include that raw material for biofuels should not be produced from land with a high biodiversity value, land with high-carbon stock, or from peatlands (European Commission, 2018). It is possible for individual member states to set even higher levels for greenhouse gas emission savings and other sustainability criteria (European Commission, 2018).

Long and Murphy (2019) examined the RED recast directive in terms of sustainability of biomethane for renewable heat as compared to transport. Applying the procedures of the Directive, the results are as shown in Table 8. The biomethane was in this example produced from grass silage and slurry, which was assessed as having a carbon footprint of 22.95 g CO_2/MJ. When assessing for renewable heat the procedure requires the boiler efficiency to be considered; here 85% efficiency is assumed. When assessed for transport the tank–to-wheel efficiency is not considered to be different from the fossil fuel comparator. The fossil fuel comparator for heat is less than transport (80 g CO_2/MJ versus 94 g CO_2/MJ). This generates a 66 % emissions savings for the biomethane used as a renewable heat source and a 76 % emissions savings when used as a renewable transport fuel. A third advantage for transport fuel is that the emissions savings criteria in 2026 for heat is 80 % while for transport it is 65 %. The foregoing and the table below all highlight the policy driver to use biogas as a transport fuel rather than a heat source.

Table 8. Sustainability criteria of biomethane for heat and transport (European Commission, 2018; Long and Murphy, 2019)

	Heat	Transport
Emissions before conversion (g CO_2-eq/$MJ_{biomethane}$)	22.95	22.95
Conversion efficiency	0.85	1
Total emissions (g CO_2-eq/$MJ_{biomethane}$)	27	22.95
Fossil fuel comparator (g CO_2-eq/MJ)	80	94
Emissions saving	66%	76%
Emissions saving criteria 2026	80%	65%

5.3 POLICY BARRIERS FOR BIOMETHANE IN TRANSPORT

A possible risk for gas mobility is the use of a tank-to-wheel perspective on transport fuels rather than well-to-wheel. The definition of zero emission vehicles (ZEV) with its focus on tailpipe emissions promotes a suboptimal view on environmental impact of transportation, through not taking into account how the energy carriers are produced. This discourse threatens to destabilize the institutional conditions for biomethane in transport, and thereby for biogas producers, who would then have to move into other markets.

There is also a risk with a sharply increased demand for biomethane that if the demand increases faster than biomethane production, this will initially lead to an increased share of fossil natural gas use in the vehicle gas, which will in turn impair the environmental performance and make gas vehicles seem less beneficial from an environmental perspective. In the long term, the biomethane production should be able to catch up with the demand, but the short-term drawback could be used as an argument by opponents to gas mobility.

The cross-sectoral nature of the biogas value chain (waste, energy, transport, agriculture) represents a strength when it comes to reduction of greenhouse gas emissions (Lyng et al., 2018). This may, however, lead to conflicting political priorities and shifting strategic objectives, which has resulted in mixed signals concerning the role and viability of biogas for transportation (Fenton and Kanda, 2017).

In Denmark, a very concrete barrier against biomethane in transport is the unfavorable taxes for gas vehicles and biofuels. The taxes for vehicle registration and fuel are up to 40 % higher for gas vehicles and gas than for diesel vehicles and diesel (Gustafsson et al., 2020a). While this has not stopped the domestic biomethane production from increasing, there is political interest in removing this tax difference to enable a larger share of renewables in the transport sector.

Finally, it is widely acknowledged that there needs to be stable and predictable conditions for the biogas sector to develop. Ambiguous and volatile policies and incentives are therefore a barrier to the development of biogas solutions and biomethane in transport.

6 Exemplars

This chapter contains some exemplars, chosen to illustrate biogas solutions of different types in different contexts, that involve biomethane powered transportation.

6.1 SKOGN, AN INTEGRATIVE INDUSTRIAL APPROACH PROVIDING SUBSTANTIAL AMOUNTS OF LIQUID BIOMETHANE

Source: The text is largely based on the book "One Solution to many challenges -A book about biogas in the sustainable society – the Nordic way" (Biogas Research Center, 2019). In addition, updates from Francesco Ometto, Scandinavian Biogas, are included.

An hour north of the coastal municipality of Trondheim in central Norway, the small town of Skogn with approximately 18,000 inhabitants may be found. Skogn has until now been most well-known for its paper mill, owned by Norske Skog and located on the Fiborgtangen peninsula. However, Skogn will in the future be associated with world-class industrial symbiosis, in which bio-sludge from the internal water purification of the paper mill is digested to produce renewable biogas, and in the process saves large amounts of electricity in the water purification plant (Figure 25).

Figure 25. The Skogn biogas plant, on the Norwegian west coast.
Photo: courtesy of Biokraft AB.

This circular process sees raw gas upgraded to liquid biomethane (Figure 26). *"It is, however, not solely bio-sludge from the paper mill that is digested in this huge facility. Boats with waste from neighboring fish farming facilities arrive here, and waste from surrounding food industries"* says Jörgen Ejlertsson, Head of Research and Development at Scandinavian Biogas, one of Sweden's largest producers of biogas. Scandinavian Biogas is the company behind the facility concept in Skogn and has a long experience in, and expert knowledge of, how biogas facilities should be designed and operated to achieve optimal and stable biogas production. Scandinavian biogas tested these processes with the different substrates in five-liter vessels in the laboratory and then transferred them to a full-scale plant, in this case the largest in Scandinavia. The facility (started in 2018) produces 125 GWh biogas-derived energy per year, which corresponds to 12.5 million liters of diesel. An expansion project started in 2021, aims to double the production capacity to 250 GWh. Today the liquefied biomethane is used as vehicle fuel in public transport and trucks, while with the additional production capacity the facility will also be able to supply ferries and the maritime sector. The factory at Skogn is a flagship of industrial symbiosis with sustainable and environmentally sensitive use of resources, while at the same time highlighting a profitable activity that creates employment opportunities and added value for society.

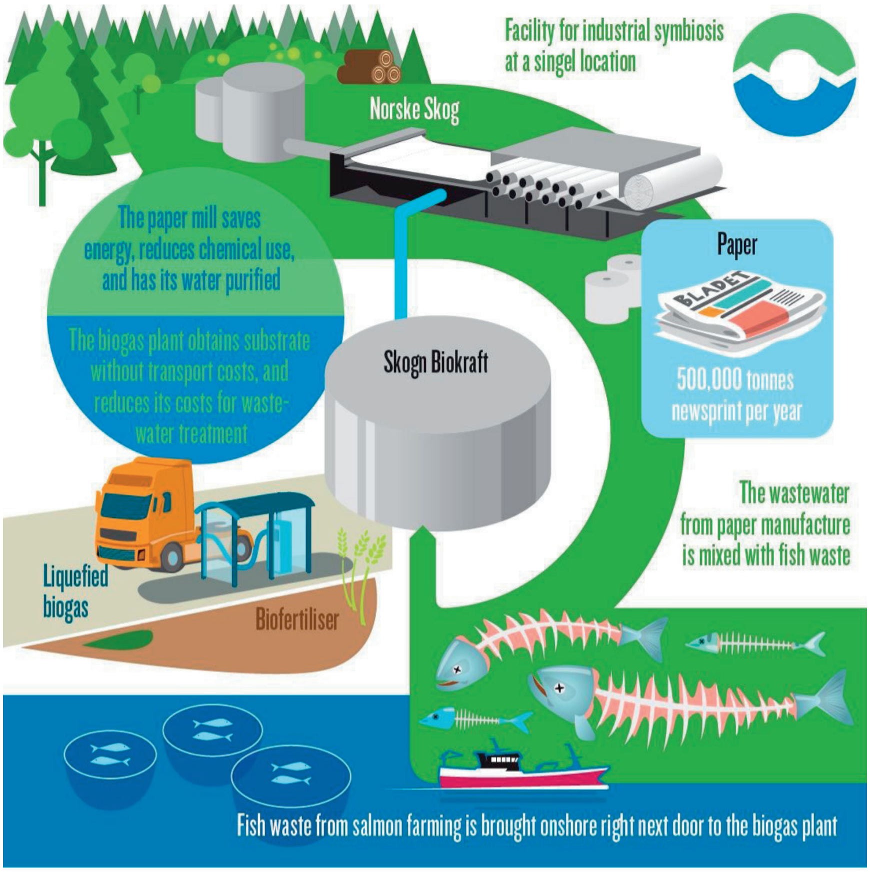


Figure 26. Illustration of the industrial symbiosis system at Skogn, where the biogas plant is an important cornerstone.
Illustration: Mattias Schläger.

Biomethane is generated from two different digestion processes. Most of the methane is obtained from the anaerobic digestion of different type of fish waste, manure, and wood-based bio-sludge (waste activated sludge) from the co-located pulp and paper mill. A minor fraction, up to 20 GWh biogas equivalent, is generated from the digestion of the industrial wastewater from the mill applying Up-flow Anaerobic Sludge Blanket (UASB) technology. Beside the conversion of waste into biogas, what is innovative at Skogn is how nutrients are recovered and reused. From the digested material, nutrients are recovered in the form of solid, liquid, and concentrated fractions. The solid fraction is a base product for the commercial production of biofertilizer. The liquid fraction is (1) partially evaporated to generate a concentrated fraction enriched in nitrogen and (2) partially reused internally to replace chemical dosing of nitrogen and phosphorus for the biological treatment of wastewater at the mill.

This type of integration between a biogas plant and pulp and paper mill, is what Scandinavian Biogas call the EffiSludge concept. The residual products from paper production become a raw material for biogas production, while owing to co-digestion with other nutrient enriched waste (such as fish waste), sustainable nutrients are recovered and reused to replace chemical based production. EffiSludge for LIFE is a project co-funded by the European LIFE Programme to demonstrate a more sustainable way to process wastewaters from the pulp and paper industry. The project showed up to 100 % replacement of chemical-based Nitrogen (Urea) and 80 % of Phosphorus (Phosphoric acid). In addition, further optimization of the wastewater treatment to generate waste activated sludge of higher value in terms of methane content and degradation rate, allows for significant energy savings in aeration. Overall, the environmental benefits of the EffiSludge concept showed a carbon emissions reduction of over 100 % in transitioning from a situation where treating industrial wastewater produced 3500 tonnes/year of CO_2 emissions, to a situation with a net saving of -7500 tonne CO_2 per annum (depending on the carbon factors applied).

"It's traditional within industry to focus on core activities. The example of Skogn shows that it is possible through collaboration in biogas-based solutions to solve problems and create value for several actors at the same time. The forestry industry, fishing industry, energy and transport sectors, agriculture, and, not least, the complete region in which such systems are used all become winners. This knowledge must be spread and systematized in education, government, and business. In this way, sustainable industry that solves more problems than it creates can be developed."

-Mats Eklund, Professor of Environmental Technology and Management, Linköping university

6.2 THE ROLE OF BIOGAS SOLUTIONS IN ESTABLISHING THE MOST RESOURCE-EFFICIENT REGION IN THE WORLD

Source: The text is largely based on the book "One Solution to many challenges -A book about biogas in the sustainable society – the Nordic way" (Biogas Research Center, 2019).

When Linköping initiated the production of biogas and biomethane in 1997 the driver was to solve several long-term problems. One of these was to reduce pollution from bus exhaust emissions in the city centre; several methods to rid the city of diesel fumes and particulate matter had been weighed against each other. Another problem was how to manage in a sustainable manner, large amounts of organic material in wastewater, waste from the local abattoir and the significant quantity of manure from livestock farming around the city. Biogas solutions that treated the organic waste in a sustainable manner were established which produced biomethane which fueled city buses which reduced particulate matter emissions and as such improved air quality.

Over 20 years later, after several technological leaps and many years of research, municipally owned Tekniska Verken receives around 100,000 tonnes of organic waste each year, from which it produces approximately 120 GWh of biomethane in Sweden's largest biogas facility (Figure 27). This amount of fuel can replace about 13 million litres of petrol. Of the total production of biomethane, 20 GWh is delivered each year (as raw gas) from digesters at the wastewater treatment system. The digestate is converted to biofertilizer containing valuable nutrients that are delivered to farms nearby.

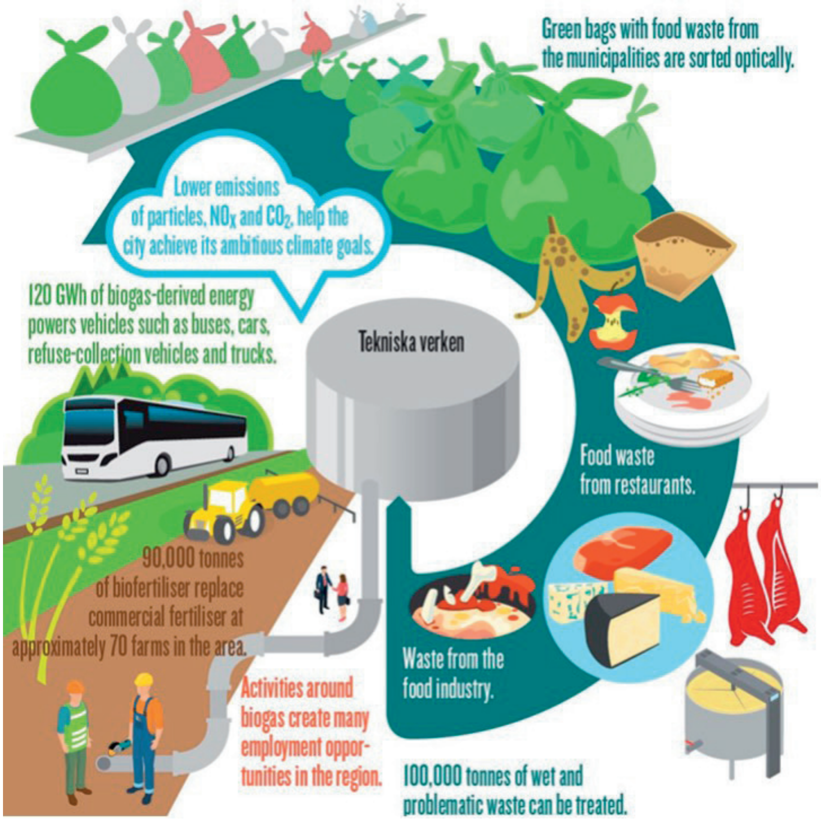


Figure 27. Illustration of biogas solutions in and around Linköping, where the municipally owned utility Tekniska Verken has a central position.
Illustration: Mattias Schläger.

"Right from the start, Tekniska Verken has invested in R&D in the biogas field, such as in its biogas lab, where pilot plants are built before implementation at full scale. The work we do in development means that more gas can be produced from the same amount of material: that processes can be controlled to ensure reliable delivery without downtime, and that the efficiency has been improved. In recent years, R&D is also carried out within the framework of the Swedish Biogas Research Centre", says Anna Lövsén, business area manager for biogas at Tekniska Verken. The biogas systems are part of the company's vision to build the most resource-efficient region in the world, which require circular solutions.

Food waste is collected from 15 municipalities in Sweden and a few in Norway along with restaurants and catering kitchens at preschools, schools, and sheltered accommodation within the region. The collection, which has been given the name 'The Green Line', is made in separate vessels that are collected by special vehicles. All refuse collection vehicles in Linköping are powered by biomethane highlighting how the biogas solutions directly and indirectly create jobs and business development. *"We never talk about refuse at Tekniska Verken. Linköping has been a pioneer in seeing waste as a resource – and this is what the business idea of Tekniska Verken is based on"*, says Rebecka Hovenberg, vice chair of the board at Tekniska Verken.

Organic waste arises in several parts of the food industry, such as at abattoirs and various types of processing. For example, waste arises in the dairy industry when a plant switches from one product to another and washes the equipment between processes. It also happens that a product is subject to a production fault and as such cannot be delivered as food.

Furthermore, the biofertilizer that qualifies for ecological certification makes it possible for more farms to use organic farming procedures than would otherwise be possible without the biofertilizer that Tekniska Verken delivers. *"With the help of supplementary biofertilizer, the farmers can cultivate crops that are used as food and animal fodder. The animal fodder is used in animal husbandry that produces food. The locally produced food is sold in shops and served at restaurants. We consume, put food waste into the green bag – and the circle cycle is closed"*, says Anna Lövsén, business area manager for biogas at Tekniska Verken.

The biomethane is distributed and sold by Svensk Biogas, a subsidiary of Tekniska Verken. It currently has 13 of its own filling points in the region, where cars, refuse-collection vehicles and vans can fill up with compressed biogas. One important customer is Toyota Material Handling Manufacturing Sweden AB (TMHMS) in Mjölby (Figure 28), which produces warehouse trucks, and works mainly with automated comprehensive solutions for goods and storage management. A long-term contract between TMHMS and Tekniska Verken on liquid biomethane, was one important factor that led to investment in facilities for liquefaction of biomethane at the Linköping biogas plant, in the year 2020. The liquid biomethane is mainly used by TMHMS for industrial purposes, but also for transportation. The production of liquid biomethane in Linköping has widened the market geographically for Tekniska Verken and is a backbone for important developments regarding use in heavy duty trucks.

Figure 28. A truck filling liquid biomethane, at a filling station that has been establish as part of the cooperation between Tekniska Verken and Toyota Material Handling Manufacturing Sweden. *Source: Svensk Biogas*

6.3 FARMERS COOPERATING TO VALORIZE MANURE AND SUPPLY FUEL

Sources: The book "One Solution to many challenges – A book about biogas in the sustainable society – the Nordic way" (Biogas Research Center, 2019), and an article originally written by Monica Westman Svenselius, 2017, Linköping University.

Eleven farmers around the town of Alvesta in Sweden agreed in 2014 to build a joint biogas facility, including onsite upgrading. Together they manage 1,500 cows, 2,300 young cattle and 1,900 pigs. Manure is transported to the joint biogas facility where it is digested together with abattoir waste from Kalmar and food waste from Lantmännen Reppe (a company within the agricultural cooperative Lantmännen). The average distance between the biogas plant and the farms is 7 km.

The evidence from the facility is that the yearly production of manure from one cow is sufficient to provide fuel that can propel a car about 5,000 km. The daily production at the Alvesta biogas plant is enough for one car to travel around the world twice. A total of 80,000 tonnes of substrate is handled each year, providing about 1,500 tonnes of biomethane equivalent to approximately two million liters of petrol per annum.

"We transport as much as we used to, from the farms out to the fields, but we take a detour via the digestion facility and in this way obtain higher quality fertilizer and biogas," Joakim Granefelt, farmer and managing director of Alvesta Biogas says. The farmers have managed to establish a profitable biomethane production facility, mainly based on the income from the biomethane fuel. But the digestion process in the biogas plant also means that the manure is valorized, since it improves the nutrient plant availability. When the digested manure is spread on the fields, it is more efficient in cultivation of feed for their animals than the undigested material.

The biomethane is sold at a local filling station, but also transported to other places as compressed biomethane in containers (placed in truck swap bodies, as described in Chapter 2). See Figure 29.

The sign to the left says: "Here the farmers of Alvesta produce biogas. Fuel at factory prices". The photo to the right shows a truck swap body with biomethane containers inside. The text says: "If this one can run on biogas, so can you".

Figure 29. Alvesta Biogas facility as photographed by Monica Svenselius, Linköping University.

6.4 LOS ANGELES - A PIONEER FOR GAS DRIVEN BUSES IN THE US

Source: Text written by Anna Brunzell and John Marthinson, Swedish Biogas Research Center (BRC) with information from:

- *https://americanbiogascouncil.org/biogas-market-snapshot/ and*
- *https://www.biogasakademin.se/sv-SE/cases/sverige-leder-v%C3%A4rlden-38408645*

Los Angeles became the pioneer for gas for transport in the US when the city replaced 2,200 diesel buses with buses powered by natural gas in 1993. But it wasn't until 2017 that natural gas was replaced by biomethane. Since then, the United States has built around 2,200 sites producing biogas, and the market is growing. The American Biogas Council can provide evidence of up to 15,000 other locations where a biogas plant could be a beneficial investment.

Figure 30. Gas Buses in the US as photographed by Axel Lindfors, the Swedish Biogas Research Center, Linköping University.

6.5 DOUBLE DECKER BUSES POWERED BY BIOMETHANE IN THE UK

Source: Text written by Oliver Harwood (RH & RW Clutton, UK Task 37 chairman) and Jonas Ammenberg Swedish Biogas Research Center (BRC).

The first bus powered by biomethane in Britain was trialed by the public company GENEco in 2015, when the city of Bristol was named the European Green Capital. This showcased the possibilities of biomethane powered transport in the UK. The biomethane is mainly produced from local food waste and sewage sludge. The number of buses running on biomethane has significantly increased in Bristol since the company First West of England launched 77 biomethane-powered buses. This investment involved a new filling station, that in tandem with the existing one, can supply compressed biomethane to up to 100 buses (Figure 31). The biomethane is distributed via the existing gas grid to these filling stations on the equivalence principle (biomethane injection to the UK gas grid is matched by use of gas elsewhere in the grid with certification).

The initiative is partly funded by a government grant of £4.79 million under the Low Emission Bus Scheme. According to managers of the private and public organizations involved, the new buses have led to improved customer satisfaction while significantly reducing climate impact and improving local air quality. The filling station overcapacity gives opportunities to third party commercial operations that would like to operate green fleets.

Nottingham City has also adopted biomethane buses (and now operates 100 such buses). However London has yet to move to biogas fuel instead preferring hybrid diesel electric buses. Biomethane is also being rolled out in the UK's heavy good transport (HGV) transport sector, with a number of major retailers switching to compressed gas trucks. The John Lewis Partnership (which operates John Lewis and Waitrose retailers) will convert its 500-strong fleet of diesel delivery trucks to biomethane fueled vehicles by 2028). Other large retailers such as B&Q, Sainsburys, Tesco, are proposing to invest in biomethane (or Bio-LNG).

Figure 31. Double decker buses fueled by biomethane in Bristol;
photo from Jon Craig, Jon Craig Photography, courtesy of JBP Bristol.

6.6 COMPETITIVE HEAVY DUTY BIOMETHANE POWERED VEHICLES

Source: The text is largely based on the book "One Solution to many challenges - A book about biogas in the sustainable society – the Nordic way" (Biogas Research Center, 2019).

Increasing amounts of biomethane are used in Sweden as vehicle fuel. Buses, taxis, company cars, private cars and vans have used biogas as a fuel; the change of late is a large and rapid expansion of the use of liquid biomethane as fuel for heavy goods vehicles (Figures 32, 33 and 34). *"There's no difference for me when driving, but it does take a bit longer to fill up"* is a common refrain from those who drive trucks with liquefied biogas, which are becoming ever more common on Swedish roads.

Sustainable transport is under intense discussion with the climate emergency, and more and more actors realize that biogas will play a key role in global challenges associated with sustainable cities. It has been estimated that a billion people will move to cities around the world between now and 2030, and that the need for increased mobility will grow by a factor of three during the same period. The population of cities will grow most in the suburbs, and most transport will take place here, as opposed to city centers.

"For us at Scania, biogas is much more than just a fuel: it is, quite simply, the foundation of a circular and resource-efficient society. Together with many others in the industry, we are happy to see that the work in Sweden based on collaboration between public and private actors is a model that many are interested in, both here and abroad", says Henrik Dahlsson, senior advisor in sustainable transport at Scania Sweden. He continues: *"Aggressive political drive and broad unity will be decisive ingredients if the Agenda 2030 goals for sustainability are to be reached. Within Scania we are contributing to the best of our ability by being a pioneer in collaboration and partnership for biogas-based solutions. A comprehensive view and the use of system-based solutions give a large reduction in carbon dioxide emissions for each krona invested."*

Figure 32. A biomethane powered truck from Scania to the right. To the left, a truck is filled with liquid biomethane. *Photos taken by Peggy Bergman, Scania CV AB and Mirja-Lisa Niemi, Klara Språket.*

Volvo Lastvagnar is thinking along the same lines: *"If all parts of the transport chain work towards the same goal, we can reduce our impact on the climate considerably more. Better logistics, increased access to biofuels, driver education in soft driving, aerodynamic design of trailers, better quality roads and better opportunities to use high-capacity vehicles are examples of measures that different actors can take"*, says Lars Mårtensson, environment and innovation manager. Volvo Lastvagnar believes also that rapid examination and certification by government agencies would make it easier to introduce innovations in the transport field.

Henrik Dahlsson argues that measures within the following three areas are principally required here and now, if the UN Agenda 2030 global goals for sustainable development are to be met: biofuels, electrification, and transport efficiency. *"The latter will require smarter logistics, and this is a major challenge.*

Figure 33. A biomethane powered bus from Scania.
Photo taken by Roozbeh Feiz, Swedish Biogas Research Center (BRC).

Scania has a broad range of trucks and buses powered by renewable fuels – and these alternatives are available here and now."

When it comes to renewable fuels, Henrik Dahlsson believes that we must consider the degree of commercial maturity the various alternatives have reached, the availability of the fuel and its infrastructure, and the costs. He points out: *"And you have to realize that different types and circumstances of transport require different solutions. This is why we need many alternatives: it's like solving a puzzle of renewability. And we want to deliver as many parts as possible. We help our customers, and their customers, to reduce their impact on* CO_2 *levels for the lowest possible cost."*

Figure 34. A long distance coach powered by liquid biomethane operating the Stockholm-Oslo route. This is based on collaboration between Scania, mobility provider Flixbus and gas supplier Gasum. *Scania CV AB.*

6.7 LARGE SCALE BIOMETHANE FILLING STATION

Source: Text written by Anna Brunzell and John Marthinson, Swedish Biogas Research Center (BRC).

The demand for biomethane has increased by over 800 % since 2017 in the UK. To answer this demand CNG Fuels, has built Europe's largest refueling station for Heavy Goods Vehicles in Warrington (Figure 35). The site can refill up to 12 vehicles at the same time. The company has secured supplies of biomethane from manure to create a fuel that will be net-zero emissions on a well-to-wheel basis. It expects to offer carbon-neutral biomethane from next year at the same price as the renewable biomethane fuel it currently supplies.

Figure 35. The large scale biomethane filling station in Warrington, UK. *John Baldwin, CNG Services.*

“We’re at a tipping point. Fleet operators are waking up to the urgency and scale of decarbonisation necessary for net-zero emissions by 2050 and we’re seeing demand for our fuel increase rapidly as a result. Our customers ordered hundreds of new biomethane fueled trucks in 2019 and that trend is only set to accelerate over the next decade. We’re making the transition to carbon neutrality easier for fleet operators by developing a nationwide network of public access biomethane stations on major trucking routes and at key logistics hubs”, said Philip Field, CEO of CNG Fuels.

6.8 BIOMETHANE FOR TRANSPORT IN A *“TRIPLE-WIN CONCEPT”*

Source: Text written by John Marthinson, Swedish Biogas Research Center (BRC).

In the city of Jönköping, Sweden, the municipality sold their old biogas plant to the privately owned Swiss-Japanese company Hitachi-Zosen Inova. The old biogas plant was replaced by modern facilities, utilizing “dry digestion” (high-solids digestion) of food waste, manure, and some other types of feedstock. A biogas production plant such as the one in Jönköping creates a so-called “tripple-win” effect for society:

1) Prevents methane gas from reaching the atmosphere.
2) Produces renewable energy that replaces fossil fuels.
3) Produces biofertilizers that replaces artificial fertilizers.

The biomethane produced is transported to filling stations serving 52 local buses, 23 garbage trucks, and 500 gas-powered cars (Figure 36).

Figure 36. A biomethane powered bus in front of the biogas plant owned by Hitachi Zosen Inova, John Marthinson, Swedish Biogas Research Center (BRC).

7 Concluding chapter, summary for policy makers

7.1 BIOGAS SOLUTIONS AND THEIR POTENTIAL

A great advantage of biogas is that it can be produced from most wet organic wastes or by-products, including for food waste, animal by-products (such as manure), agricultural residues, sewage sludge, industrial biowaste (such as from slaughterhouses and food and beverage processing industries). In addition to the biogas/biomethane, biogas plants also deliver another important product, digestate, which contains most of the nutrients in the feedstock and can be an excellent biofertilizer. In addition, it is possible to utilize the carbon dioxide removed in upgrading biogas to biomethane.

Enormous amounts of organic wastes are landfilled around the world, that instead could be used to produce biogas and biofertilizers and food grade CO_2. Furthermore, in more advanced bio-industrial contexts (such as paper mills, food production facilities, or other types of biorefineries), there are commonly residue streams of low value that can be suitable for AD.

There seems to be an ongoing shift away from ‘energy crops’ towards more waste-based biogas systems. However, there are also examples of primary feedstocks, such as different types of crops, that could be selected to avoid competition with food or fodder production. For example, a well-designed sequential cropping scheme can involve cover/intermediary crops (such as ley crops) and deliver biomethane in combination with strengthened food and fodder production, biofertilizers, and improved soil fertility. In Italy this is known as the BiogasDoneRight system.

There is a great potential to produce significantly more biogas/biomethane even in countries which already have a relatively large production. For example, Cappannelli et al. (IEA, 2020) estimated that the 2018 world total biogas production could have been about 16 times larger – reaching almost 7 PWh/year – without utilization of any agricultural land that could be used for food production. The actual potential becomes substantially larger adding cover/intermediary crops and aquatic feedstocks. Of course, biogas solutions cannot alone solve the whole energy or transport puzzle, but the potential contribution is considerable.

7.2 SUSTAINABILITY PERFORMANCE

There are many sustainability studies of biogas solutions in general, biomethane for transport in particular, and alternative technologies/fuels. Table 9 summarizes important findings from Chapter 4. As biomethane is commonly compared to electricity, this comparison is sometimes emphasized in the table. However, the authors do not believe focus should be placed on what technology/fuel is best, rather on how technologies can be efficiently combined (including ethanol, biodiesel, green hydrogen) since no single technology can replace fossil fuels on its own.

Table 9. Summary of the sustainability performance of biomethane for transport, contrasted to alternative technologies/fuels, with an emphasis on electricity

Sector	Key results
General	**Biogas solutions commonly provide several functions - it may be misleading to assess them just as a transport or energy technology.** Decisions should be based on broad sustainability studies (like multi-criteria analysis) & consider the full life cycle of involved products. When undertaking a Life Cycle Analysis, it is important to consider relevant impact categories & account for avoided production.
Energy efficiency	**Biomethane has a competitive performance compared with fossil fuels and other biofuels on a whole life cycle analysis and is particularly suited to long distance heavy vehicles.** Electric vehicles may be significantly more efficient, but that overall efficiency depends on source of electricity. On a global basis at present electricity production is quiet fossil fuel based. In the long term biomethane may have applications for long distance heavy haulage. Biomethane has a high non-renewable primary energy efficiency and can have a competitive climate performance even if the production involves fossil electricity.
Climate change	**Biomethane from manure, residues, waste & catch crops is estimated to have low GHG emissions as compared to other renewable fuels.** Broad biogas solutions may involve carbon savings and sinks, such as displaced fugitive methane emissions and increases in soil organic content. Biomethane based on catch crops may be competitive depending on feedstock, actual conditions, models, and methods for analysis. It is essential to minimize methane emissions/slip & note that soil characteristics and biogenic emissions (N_2O, CO_2) both may be influential and difficult to estimate.
Air pollution	**Biomethane may contribute to reduced air pollution in comparison with diesel, petrol, and other biofuels.** Emission standards (vehicle models) are influential. Electric vehicles have no exhaust emissions and thus are clearly favorable in central city areas. All road vehicles have emissions from tyre, brake, and road wear. In reality there are no truly zero emission technologies. Non-renewable electricity production may be associated with air pollution and risks related to nuclear power.
Acidification	**Biomethane can contribute to substantial reduction in acidification compared with fossil fuels**, when produced from manure, residues, and waste. Biomethane based on energy crops may have significant negative impact, stemming from soil conditioning and fertilization practices.
Noise	**Biomethane may contribute to significantly reduced noise levels in comparison with diesel heavy goods vehicles;** the results are unclear for smaller vehicles. Electric vehicles have the best performance in slow moving urban traffic where the speed is less than 50 km/h. Low frequency noise may be important to consider.
Sustainable farming, food supply & eutrophication	**Well-designed and applied biogas systems may be essential to transform conventional farming to more sustainable farming and to organic farming**, with significantly improved management of nutrients and soils and reduced eutrophication. This is essential for food supply/security. Energy crops may be used as food/fodder in critical situations.
Waste and water management services	**Common types of biogas solutions provide essential sociotechnical systems services as components of systems for waste and (waste) water management**, involving separation, hygienization, reduced sludge volumes and avoided methane leakages. Furthermore, industrial waste systems (and larger industrial systems) may become more efficient when they involve anaerobic digestion.
Energy supply & flexibility	**Biogas solutions may importantly contribute to improved energy supply/security and flexibility.**

Due to the multifunctionality of biogas solutions, broad assessment methods are needed to grasp the wide spectrum of relevant factors, for example, when comparing different technologies. Based on Dahlgren et al. (2021) and Lindfors et al. (2020), Figure 37 presents a schematic overview of some of the sustainability related results. A high score is positive for all the indicators. The figure indicates common generic results, while more detailed specific studies are needed for accurate comparisons taking local conditions into account. Nevertheless, it clearly illustrates that biogas solutions (and biomethane for transport) may be competitive from broad sustainability perspectives (cf. Atkins et al., 2021).

It may be shown for example, that biogas biomethane transport systems effectively combined with renewable electricity transport systems (given priority in central city areas with air pollution or noise related problems), show great potential to achieve substantial improvements in environment, air quality and sustainability.

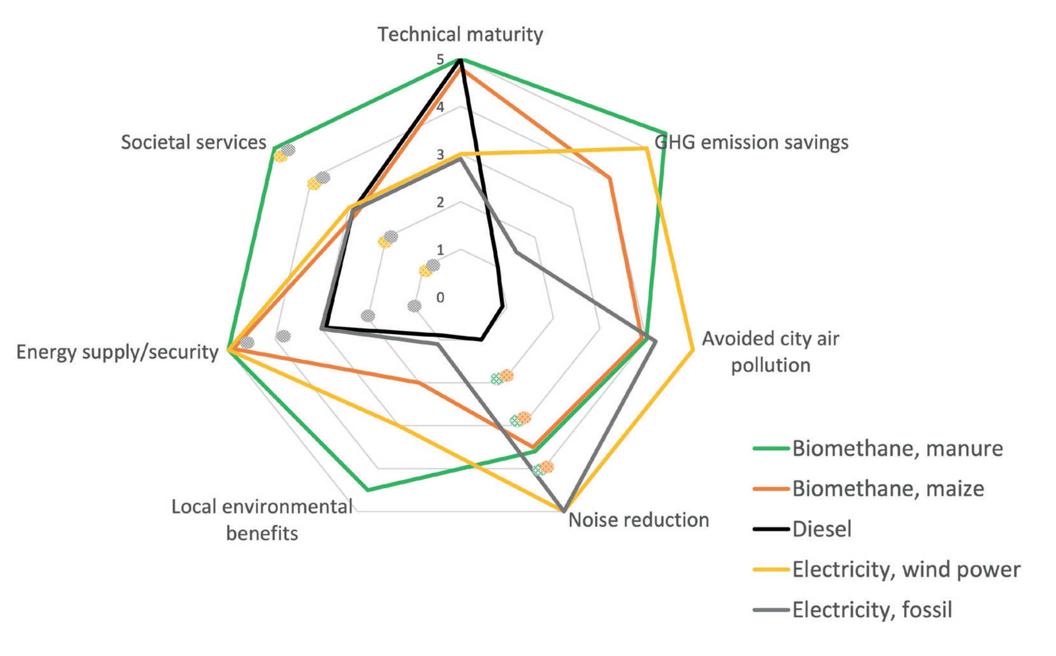


Figure 37. Schematic illustration of multi-criteria analysis results for two types of biomethane, in comparison with two types of electricity and fossil diesel. Alternative results presented with pattern filled circles, which indicates larger uncertainties.

The best biomethane solutions are from manure (green color in figure 37) and perform well for many indicators, while the results are more varied and uncertain for noise reduction - see the alternative results presented with pattern filled circles for that indicator. Maize biomethane (orange in Figure 37) can also importantly contribute to reduced GHG emissions and other benefits, but such solutions do not provide the same societal services and may be associated with some local/regional environmental impact (like acidification).

Electric vehicles can also significantly contribute to several areas, but the performance is determined by the source of electricity. While renewable electricity (yellow for wind power in Figure 37) reduces city air pollution and noise in slow moving urban traffic and brings substantial GHG emission savings, fossil-based electricity (grey in Figure 37) contributes to reduced noise and local pollution but not to GHG emissions savings. Electric solutions commonly do not involve the same type of broad societal services, as do biogas solutions to waste and wastewater management, sustainable farming and food supply (see Table 9 and Figure 38). At least in the short-term, many regions may face challenges in provision of the electricity power system stability needed for significant shift in electrification of all sectors, while there could be more long-term societal benefits from electrification of transport (see the pattern filled circles).

Electric transport systems are also somewhat less technically mature (especially for heavy transport), even if there is a fast development under way. In terms of energy supply and security of supply, the results depend on the origin of the raw materials for batteries (cobalt, lithium), the worldwide availability of battery electric vehicles and the proportion of world supply available to a particular country; where the production of electricity takes place obviously also impacts energy security. However, the figure simply indicates that biogas solutions commonly have a local/regional character (small scale proximity principle, Figure 38) and that wind power (or solar power) is relatively easy to establish locally. Figure 38 illustrates the multifunctionality of biogas solutions, with an emphasis on the 'Nordic model' as described in the book published by the Swedish Biogas Research Center (BRC, 2019). 'Waste-based' feedstock and the use for transportation is characteristic for this model.

Figure 38. Multifunctionality of biogas solutions in accordance with the so-called Nordic model. The photo shows Linköping City in Sweden.
Photo taken by Tekniska Verken, Linköping, Sweden.

7.3 CONDITIONS FOR EXPANDED IMPLEMENTATION

Biomethane is a high-quality fuel, that can be delivered and used both in compressed (gaseous) and liquid form in the transport sector. The technical readiness level is high across the full supply chain and use as vehicle fuel. Raw biogas has been industrially produced for more than a century, and has been upgraded to biomethane and used for transport for almost a century (Lampinen, 2013). There are already many different types of vehicles operating on biomethane such as passenger cars, taxis, vans, buses and coaches, light and heavy-duty trucks, ships, tractors, and forestry machinery. From a technical standpoint, gas driven vehicles (for biomethane and natural gas) have similar performance as those driven on petrol and diesel. There are no major technical barriers that hinder a significant expansion of biomethane as a transport fuel – not regarding the fuel itself, nor the vehicles or infrastructure. On the contrary, the vehicle production lines are similar to those for petrol driven vehicles, and thus do not require substantial investments for existing producers of such vehicles, as would be required for example for hydrogen fuel cells.

However, competitive sustainability performance and good technical functionality are not sufficient for a large breakthrough. Development of biomethane, and other biofuels, has been slow and too limited. For different reasons these renewable technologies have only taken a small share of the market for transport fuel, even in the countries with the highest shares.

On one hand biofuels and biomethane must combat the dominating fossil fuel regime in heavy transport (trucks, ships, and planes). However, the fossil industry has very powerful actors and fossil fuels are supported and directly subsidized in different ways in many countries. There are many externalities to the fossil fuel industry; including for environmental and health costs that the fossil fuel industry does not fully pay for. On the other hand, decision makers, fuel users and other stakeholders often seem to look for a single renewable solution that will replace all fossil fuels and solve essential problems in one fell swoop; although, clearly, no such solution exists or will exist within the foreseeable future. This is problematic. Instead of an idealized parallel development of a series of renewable transport systems optimized for their role in solving the energy jigsaw where the renewable technologies all constitute an important piece, the actors behind the renewables commonly seem to be in competition with each other. There appears to be an ongoing debate between those who advocate for electricity only solutions for all sectors, who wish to remove the gas grid from the ground, who do not want to burn anything including bioenergy and others who argue for the need of multiple solutions and broadened perspectives and would argue that striving for (a narrow definition of) perfection slows down progress. This has led to a situation whereby energy and particularly transport is not as green as it could be; this is irrational when it is considered that we are in a climate emergency where there is an urgent need for an energy transition with several renewable technologies needed to be optimized and commercialized to reduce and ultimately remove the market for fossil fuels. It appears essential to the authors that attention is paid to circular economy, energy, and environmental systems and their ability to address urgent sustainability challenges at local and regional level.

There are many studies on how to transform socio-technical systems in a sustainable manner: in particular systems for transport, energy, waste management and agriculture (Köhler et al., 2019; Markard et al., 2012). Importantly, biogas solutions can be part of transforming all these examples, and other industrial systems, by (re-)connecting actors and sectors in more sustainable systems that increase the value of the handled resources and solve sustainability-related problems in several sectors simultaneously (Biogas Research Center, 2019; D'Adamo et al., 2021). Regarding sustainability transitions, biogas solutions used for transport applications could be described as innovations on the niche level, that may need to be further refined in combination with expanded infrastructure investments and continued adaptation of regulations and practices to become fully competitive. However, the competitive relation would look very different if biogas solutions would be fully compensated for the positive values they bring, and the fossil systems would have to take their full life cycle costs (including fossil-based electricity). Seen from a historical socio-technical systems development perspective, the current biomethane driven transport systems are fairly young and thus potentially have room for significant further improvements. For example, there is ongoing development in upgrading and liquefaction technologies and infrastructure and vehicles can be greatly improved upon. New technologies may require protected niches (including niche markets) while they are developing, attracting resources, and social networks are formed around them, to sustain the competition from established alternatives. Such niches may involve investment support, tax exemptions and production support. The niche markets may be local markets, specific segments or applications, that can be steppingstones on the way to expansion, such as biomethane used for buses in public transport, and learnings from public transport exported to other transport sectors such as long-distance trucks and ships.

The question remains as to how to realize a larger shift to biomethane within the transport sector especially for buses and trucks. The literature emphasizes that markets are rather dynamic systems shaped by the activities of several actors and involve value creation in a broad sense. The answer may lie in trying to grasp the broad range of values/effects that are or may be of particular importance for biogas solutions. Ottosson et al. (2020) mapped key actors and the roles they have taken in shaping the Swedish biogas/biomethane markets. They found that 14 actor groups have been involved in 17 market shaping activities/processes. Local and regional public organizations have played very essential roles as system builders, advocates, investors, producers, distributors, and users. This has been motivated by the local values they find associated with biogas solutions, and their responsibilities in relation to waste, wastewater management and public transport. The public organizations have joined forces with private firms and sector associations to influence the institutional conditions and other issues. Ottosson et al. (2020) found the narration of biogas solutions as local circular economy, energy, and environmental systems to be central for the previous development (a shared identity), but also emphasized that some of the ongoing development may make biogas solutions less locally attached. Still, the narration of biogas solutions as value adding is of utmost importance, which may encompass larger (national, international) scales. Public procurement, environmental investment grants, and initiatives of publicly owned organizations have, for example, been influential in progressing biomethane for transport. Public bus transport has been an important base in several places, but vehicles driven on biomethane are used in several sectors, in many different types of vehicles, for varying purposes. This can be seen as a strength, but also as a scattered picture involving many uncertainties regarding the future: how much biogas/biomethane will be produced, how sustainable is it, shall it be used for transport, and if so for what type of transport? Recently, there has been an increased interest and development in liquid biomethane and heavy-duty freight transport; for example, this is now seen as the main application of biogas in the UK. This involves great possibilities, but it remains to be seen what market share these technologies will take.

In addition to these transport focused conclusions, it should be emphasized that well designed and functioning waste management systems are essential for (at least the waste-based) biogas solutions. A societal shift towards more sustainable agriculture and nutrient management would facilitate biogas actors in securing payment for services they provide in relation to food and fodder production.

Natural gas systems should be a facilitator of the introduction of biogas solutions and biomethane for transport, but the sustainability problems associated with natural gas negatively impact the view of biomethane. This is where arguments amongst the renewable sector actors can hinder progress. Biomethane and (power to methane) can utilize the existing gas grid and accelerate progress to decarbonization of the overall energy sector beyond just electricity and also to decarbonize chemical (such as ammonia and methanol) and steel production. This should be advantageous especially when realizing that more energy is procured from the natural gas grid than the electricity grid in the EU and the US; however, suggestions that biomethane is only greenwashing the natural gas industry, and in doing so extending the lifetime of natural gas, greatly impedes this progress.

Further investments in the needed infrastructure for biomethane as a vehicle fuel are crucial for expansion, for example, to establish sufficient networks of fueling stations, providing biomethane in both compressed and liquid form. The attractiveness of the fueling stations is one important aspect, involving their localization, service level, and design. There is a need of a synchronized deployment of biomethane production, refueling infrastructure, and gas driven vehicles. This however requires a shared vision and pathway for the biomethane transport industry.

This report deals with the economics of biogas solutions and biomethane as a transport fuel from several perspectives. Clearly, there is great variation, involving differently designed biogas solutions in different contexts, resulting in different costs, incomes (as well as effects and values). The fuel costs are largely determined by the costs of raw biogas production, but there are also significant costs associated with post-treatment (upgrading, liquefaction, and compression). The reviewed studies indicate that the life cycle costs of biomethane fueled light vehicles may be higher (around 15-20%) than for similar petrol- and diesel-fueled vehicles, while they may be more equal or even lower for (liquid) biomethane fueled heavy duty trucks in comparison to diesel. It should however be a major consideration that the acceptance of diesel fueled trucks and buses is limited due to the impact on air quality and the climate emergency; after 2030 diesel may not be the competition anymore. Concerning buses, the data on total cost of ownership in the literature varies greatly, for biomethane (and other alternatives, such as electricity). In terms of socioeconomics, it is of fundamental importance to account for the fact that biogas solutions are multifunctional and are associated with additional products (such as biofertilizers) and provision of food grade CO_2 and other services.

7.4 CURRENT POLICY AND REFLECTIONS ON FUTURE DEVELOPMENT

Policies regarding biomethane vary considerably between countries, ranging from an emphasis on use for road transport to no policies directed towards transport at all. There has generally been a stronger focus on utilization for electricity and heat, however, several countries are shifting focus towards transport use of biomethane.

In many ways it is a strength that biogas solutions span across several sectors, as they importantly connect different sectors and may improve the resource efficiency of these sectors. However, there is an apparent risk that the responsibility for biogas policy is diffuse, and policy structures can be intricate, not well coordinated and difficult to overview and evaluate (Gustafsson and Anderberg, 2021).

Biogas related policies are of different character: economic, regulative, or voluntary. They may also be enforcing or encouraging policy (ibid). Policies influencing biogas production and use are found on different administrative levels (local to international), and the transport sector is just one of several that biogas solutions span across. Thus, the production and use of biomethane is also influenced by policies on waste management, agriculture, wastewater treatment, and other areas. In addition, regulations and incentives influencing biogas/biomethane are directed towards different parts of the value chain. For example, policy may strongly influence: the choice of feedstock; localization of production plants and infrastructure, and the technical design; and the use of biogas/biomethane, biofertilizers, and any additional products. For producers, investors, and other stakeholders it may be important to have clear and stable conditions, in essence a good planning horizon. However, there are several examples of dynamic policy landscapes, making it difficult to navigate.

The article by Gustafsson and Anderberg (2021) provides a good overview focusing on Europe. They present central EU directives and mention policies and incentives on a national or local level that promote biomethane, such as green vehicle standards, green zones in cities, tax reductions or exemptions (and "Bonus-Malus" systems), blending obligation systems, investment grants, subsidies for purchasing or retrofitting vehicles, and low-interest loans. Gustafsson and Anderberg (2021) further give several examples from different countries. Evidently, policy largely influences the development, both in terms of biogas solutions and other alternatives.

7.4.1 Advice for policy makers

There is great potential to produce more biogas and provide significantly larger amounts of biomethane for transport. It is essential to consider how to best stimulate an expansion for different types of feedstocks, to promote biogas solutions that improve the societal resource efficiency. This, for example, involves policy pertaining to more sustainable waste management and initiatives promoting intermediary/cover crops in sustainable cropping schemes. In this context, it is relevant to note that organizations controlling feedstocks of interest commonly are not primarily biogas producers but have other core businesses. An expansion within these sectors will require sufficiently strong incentives, and probably both technical and organizational development.

Biogas solutions are commonly cross sectoral and multifunctional which may be very beneficial from a societal perspective, but this may also require improved competency among governmental and public organizations regarding assessment and management/coordination (including policy). A "silo mentality" is a major barrier to biogas solutions, where there is no obvious champion or owner, where too limited perspectives may lead to socio-economic sub-optimization, and the potential for technologies which are less beneficial and not the most sustainable been prioritized. Biogas solutions, for example in the form of biomethane for transport, can contribute to a wide range of societal benefits, as described in this report. If well-designed, they will have many positive links to the UN Sustainable Development Goals. Thus, it is commonly wise to look upon biogas systems from several different angles, using a broader sustainability framing, and for example not to see them just as an energy or transport technology. Biogas solutions may be better understood as a decathlete rather than the 100-meter sprinter; where though a great all round technology when assessed based on only one criteria (say sprinting) may fail to account for many other essential skills/outcomes. This is highly important for decision makers to understand and account for. One such example is the commonly used tank-to-wheel perspective; the focus on tailpipe emissions is very limited and a possible risk for biomethane mobility. There are no *zero emission vehicles* on a whole life cycle basis and to understand the sustainability implications the full life cycle of the transport systems must be considered, including several environmental impact categories and management of natural resources.

It may be challenging for the business actors to internalize payments for the broad range of values that may be associated with biogas solutions such as reduced fugitive methane emissions or lower carbon-based agriculture. Sometimes the 'biogas sector' is described as subsidized, and there are different types of formal *subsidies* that are important for key actors. However, fossil fuels are also heavily subsidized in particular in the lack of accounting of externalities such as those associated with air quality and the climate emergency. It may be argued that in lieu of subsidies for biogas systems it would make more sense to use *"production premiums"*, as a payment for well-defined sustainability-related services relating to the role of biogas in reduced greenhouse gas emissions, nutrient circulation and improved food and energy security.

In a world where a lot of the economy is globalized, and resources are largely traded as commodities, there are risks related to supply and price development. Policymakers may consider a significant value of creating a better balance between on one hand local and regional production systems and on the other the global commodity trading. The larger share of local/regional and waste-based feedstock potentially makes biomethane less dependent on global price volatility. Bus operators that use waste based HVO in Sweden have experienced much larger price fluctuations than for biomethane. Supply contracts of local and regional biomethane may stretch over longer time periods and come with less risk for drastic price changes.

An expanded use of biomethane depends on many societal conditions that may be influenced by policy. For example, these are some points to consider:

- There is a need to develop infrastructure for distribution and refueling, including fueling stations that are attractive in terms of their location, service level, and design. In the future, it is likely that raw biogas grids will also be needed to create large enough scale for biomethane upgrading and liquefaction.
- There is a requirement for unanimous and well-coordinated policy, based on a comprehensive and evidence-based understanding of, and consensus on, biogas solutions with competitive sustainability performance within a circular economy, energy, and environmental system, which provides clear long-term (bankable) conditions for critical actors. Large sustainability transitions require endurance.
- There needs to be a mechanism whereby 'biogas actors' can internalize the values generated by the biogas system. This may be based on penalties for pollution, higher carbon taxes and payments for systems that reduce pollution.
- It appears essential to shift focus towards a strategy on how to efficiently combine different renewable technologies to simultaneously provide the functions wanted and address urgent sustainability challenges, that should allow for adaption to essential local and regional conditions and opportunities.
  - For efficiency, it may be prudent to prioritize multi-functional solutions that may simultaneously address several essential needs and challenges.
  - It is important to recognize the importance of gaseous energy carriers, that can play an important parallel to electrical solutions, and other alternatives.

- Introduction of policy, standards, and incentives for the use of biomethane in transport, that places the focus on the sustainability performance of the specific fuel, or energy carrier across a wider set of boundaries within a circular economy, energy, and environment system.
  - Focusing on climate change, could involve low-(fossil-)carbon standards to clarify the renewable share of gases (such as vehicle gas), electricity, hydrogen, and liquid fuels.
  - Detailed accountancy of carbon content of all energy vectors could involve guarantees of origin and country-of-origin labelling.
- It is advisable to ensure public procurement includes for evidence-based assessment of sustainability and other measures, to ensure a niche demand that can serve as a platform for further expansion. Investment grants coupled to sustainability performance may importantly strengthen the development.
- Policy makers need to consider how to best support biogas upgrading (and liquefaction) initiatives in hard to abate sectors with limited alternative routes to decarbonization (such as long-distance haulage), especially in countries/regions with a relatively large share of smaller biogas plants that presently produce electricity and heat but that could shift towards biomethane production and use.

This report provides exemplars of very good biomethane based transport solutions, with a high technological readiness level for all elements of the chain from production to vehicles. Transport biomethane sits well in the broad circular economy, energy, and environmental system providing services across a range of sectors including reduction in fugitive methane emissions from slurries, treatment of residues, environmental protection, provision of biofertiliser, provision of food grade CO_2 and a fuel readily available for long distance heavy haulage. What we do not have is time to postpone the sustainable implementation of such circular economy biomethane systems as the climate emergency will not wait for absolutely perfect zero emission solutions; should they exist.

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