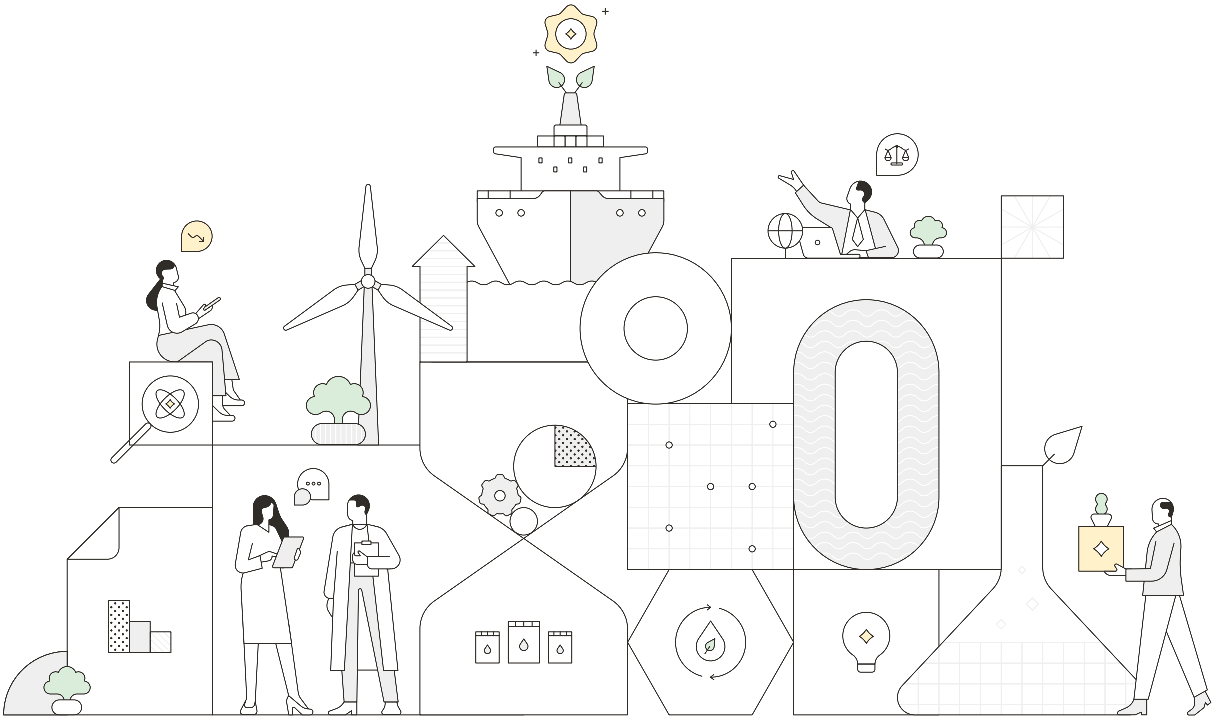
Biogas as a Source of Biofuels for Shipping

Insights into the Value Chain

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Contents



Executive Summary

Successful decarbonization of the shipping industry will depend on the maturation and adoption of a range of alternative maritime fuels. To this end, this series of reports presents a deep dive into the potential of biogas as a source of biofuels for shipping. Biogas, generated by anaerobic digestion of biogenic waste, is a mixture of methane (CH_4) and carbon dioxide (CO_2) that can be easily converted into various biofuels. In this series of publications, we explore details of the production of two specific biofuels from biogas: liquified bio-methane (LBM) and bio-methanol from biogas (hereinafter called bio-methanol) (Figure 1).

In this report, we review the main characteristics of biogas-based manufacturing value chains for LBM and bio-methanol with regard to availability, current and future perspectives for commercial deployment, and sustainability. We gather and synthesize real-world commercial information on the three main blocks in these value chains: feedstock selection, biogas production, and biofuel manufacturing, and highlight areas of maturity and the need for further development.

We conclude that biogas-based biofuels are strong candidates to support decarbonization of shipping and are particularly attractive for the early stages of the industry's transition away from fossil fuels. These biofuel pathways have many positive attributes, including:

- the ability to extract value from diverse feedstocks, including many types of waste,
- conversion technologies that are commercial and already deployed globally,
- supporting infrastructure that already exists in many countries,
- production capacities that can be scaled up to an attractive level, and
- resulting biofuels that can have a strong value for money.

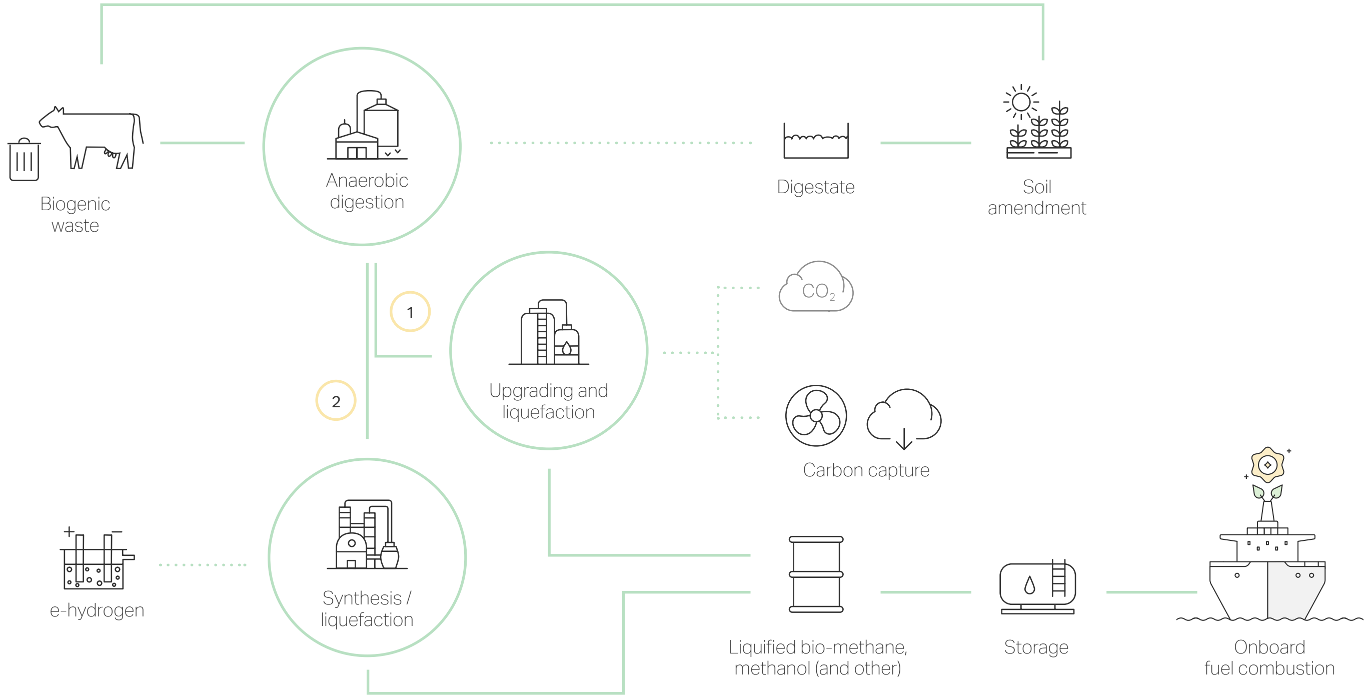
Our strongest area of concern is emissions of methane, a potent greenhouse gas. Methane emissions may appear throughout the whole well-to-wake (WTW) value chain of these fuels. Controlling methane emissions will require excellent engineering and equipment, management of operations, and maintenance. Other challenges include the potential for biofuel manufacturing from biogas to displace feedstocks for other industries, and the risks of competition or price instability based on biogas and bio-methane's multiple applications in both shipping and broader energy infrastructure, such as electricity generation and residential heating.

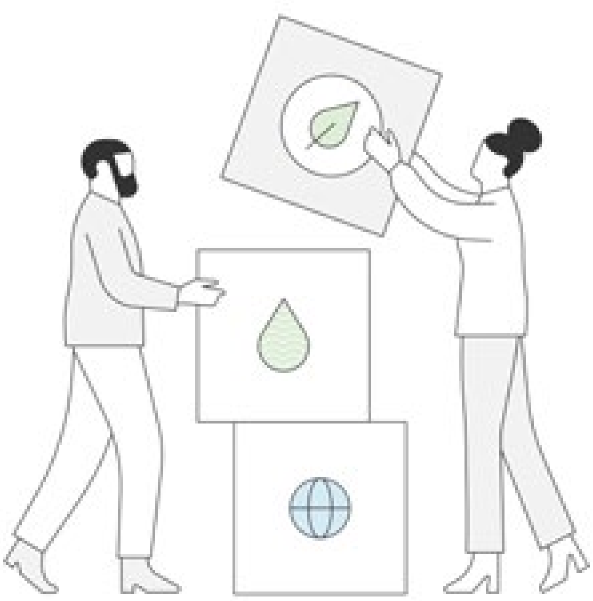
We identify several promising strategies to boost the sustainability and commercial attractiveness of biogas-based biofuels. These include emerging systems for green certificates trading and 'book and claim' of green attributes of biogas or biofuels. Shipping operators may also improve their ability to control and reduce the cost of decarbonization by investing in accurately selected manufacturing pathways and ensuring long-term supply agreements of biofuels with known emissions reductions and prices.

We suggest that those shipping operators who have not yet settled on a specific biofuel should consider approaching decarbonization with a "project first" mindset. This mindset implies that an operator should first select and invest in a biofuel project that affords an attractive total cost of ownership and secure the long-term biofuel supply regardless of the biofuel type. The operator should only then procure and build the ships that can operate on that biofuel.

The insights into biogas-based biofuels gained from this study are further built in a series of companion reports covering biomass availability, methane emissions, WTW GHG assessment, energy demand for emissions reduction compliance, and techno-economic trends.

Figure 1: Schematic of the value chain for biofuels from biogas.





1. Introduction

Anaerobic digestion, or the process of decomposing organic material by means of bacteria, is one of the few fully commercial processes for the conversion of biomass into sustainable fuels. This process is thoroughly described in the literature[1] and has been used as a source of energy for societal needs certainly since 1895 and possibly since Assyrian times.[2] Anaerobic digestion of biomass produces biogas, a mixture of methane (CH_4) and carbon dioxide (CO_2).

Anaerobic digestion stands out over alternative biofuel production pathways in several ways:

- It can use a wide variety of feedstocks, including many types of waste. In this way, anaerobic digestion solves problems of waste accumulation and emissions while creating useful energy.
- Suitable sustainable biomass is available in large amounts, albeit also subject to demand for many industrial and residential uses.
- The major components of biogas – methane and CO_2 – are two "darlings" of the chemical industry that can be converted into a vast array of synthetic molecules and fuels.
- Biogas plants can leverage their performance by integrating and aggregating energy and material flows, and the necessary infrastructure for this is well-known and well-developed in various parts of the world.
- There is a developing infrastructure for trading certificates of origin for biogas-based bio-methane.

Current global energy generation via biogas is estimated to be approximately 1.6-2.5 exajoules (EJ).[3,4] This energy is mostly used as a fuel in electrical generators or for combined heat and power (CHP). Alternatively, biogas can be upgraded into bio-methane by removing CO_2 and other impurities (pathway (1) in Figure 1). Bio-methane produced by this means can be subsequently liquified and bunkered. CO_2 is typically released into the atmosphere, but it may easily be compressed and stored instead. Future scenarios for biogas utilization could see biogas converted into other chemicals and fuels, including bio-methanol from biogas (hereinafter referred to as bio-methanol)[*], through processes involving green hydrogen (broadly summarized as pathway (2) in Figure 1).

One of the most traded molecules globally, methane is used for domestic heating and cooking, for power generation, and as a chemical building block. As the main component of natural gas, methane's global yearly production is in the range of 3 billion tonnes (t) (~150 EJ).[5] Most countries have infrastructure to handle methane at scale, and a capillary distribution of natural gas reaches most European countries and US states.[6] For use as a transport fuel, methane is either compressed into compressed natural gas (CNG, mostly for road transport) or liquified at -161 °C to produce liquified natural gas or liquified bio-methane (LNG and LBM, used in shipping applications). More than 250 worldwide regasification stations ensure local use,[7] and 140 bunkering units currently serve the nearly 400 LNG-fueled ships already in operation.[6]

Bio-methane is the same molecule as methane, with the prefix "bio" indicating that the molecule originates from contemporary renewable biomass[†] (also known as "biological" origin). Bio-methane can be used with or instead of natural gas, LNG, or CNG in all existing infrastructure for methane. As interest in sustainable fuels increases, registries to trade guarantees of origin for biogas-derived bio-methane are appearing at the national and supernational level, allowing flexibility in connecting producers to clients.[8] International Organization for Standardization (ISO) Specification 23306:2020[9] considers liquid bio-methane[‡] and liquid methane to be fully interchangeable for the purposes of fueling marine engines. Lam et al have recently reported that bio-methane could supply up to 3.1% of the energy required by the shipping industry by 2030 and 12.6% by 2050.[10]

Regardless of its origin, one of the main concerns regarding widespread use of methane as an energy carrier is humanity's scant track record in avoiding anthropogenic methane emissions to the atmosphere, which are currently estimated at 350 million t per year(~18 EJ).[11] Methane has a global warming potential (GWP) roughly 28 times that of CO_2 over 100 years and 81 times over 20 years.[11] For these reasons,

---

[*] Bio-methanol can be produced using many processes, with some of the most promising being via gasification, with or without the addition of green hydrogen. For the purposes of this series of reports, however, we focus on the biogas-based route.

[†] ASTM standard D-6866 can measure whether a carbon-based fuel is of fossil or contemporary origin by assessing the ratio between carbon isotopes ^{14}C or ^{13}C and ^{12}C.

[‡] Also known as bio-LNG or liquified biogas (LBG).

methane is the second most important contributor to global warming. The total yearly methane emissions from human energy activities (fossil and biomass) are in excess of 140 million tonnes[11] or 3.9 billion tonnes CO_2 equivalent (tCO_2eq) on a 100-year time horizon – roughly four times as high as the approximately 1 billion tCO_2eq caused by global shipping.[12] Biogas plants and LNG-fueled ships also generate significant methane emissions, which must be reined in as part of a successful decarbonization effort.

Biogas can also be used to produce bio-methanol. Fossil methanol is also produced in large volumes: over 100 million t globally as of 2022.[13] Methanol has recently been gaining traction as an alternative shipping fuel, with local methanol storage now present at approximately 120 ports worldwide. Twenty-five methanol-fueled vessels are already in operation and nearly 90 are on order.[6] An ISO specification for methanol as marine fuel is under development (ISO/AWI 6583).

Several qualities make bio-methanol an attractive alternative to bio-methane. Because bio-methanol is a liquid in ambient conditions, methanol infrastructure does not require cryogenic technologies and is therefore simpler than infrastructure required for LBM. In contrast to methane, bio-methanol quickly degrades if released into the atmosphere[14] and does not have an adverse impact on climate. While methanol is toxic to humans and other living organisms,[15, 16] a recent overall assessment found that methanol fuel is safer than alternatives.[17] However, a drawback of methanol as a fuel is its low energy density, which is less than half that of marine diesel.

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) has previously studied the use of both methane and methanol as marine fuels with a view to understanding the greenhouse gas (GHG) emissions associated with these fuels and the options for emissions reduction and after-treatment.[18, 19]

This study highlights commercial deployment status, characteristics, risks, and opportunities of biogas-based biofuel value chains. Our intention is to inform shipping operators and enable them to assess how these value chains can become part of their decarbonization strategy.

1.1 About this project

This project was established to understand the hurdles for a widespread adoption of biogas-based LBM and bio-methanol fuels and to offer strategies for resolving these hurdles.

The results of the overall project are summarized in a series of reports from the MMMCZCS, which cover insights into the value chain (this report), methane emissions, energy demand for emissions reduction compliance, well-to-wake greenhouse gas (WTW GHG) emissions, techno-economic trends, and biomass availability.

The project was a collaboration between the MMMCZCS and our partners Boston Consulting Group, Cargill, Maersk, Norden, Topsoe, and TotalEnergies, as well as mission ambassadors Novonesis and Wärtsilä. Many additional individuals and organizations have given input to the study, as detailed in Section 4.

Our project partners

BOSTON CONSULTING GROUP

Cargill

NORDEN

novonesis

MAERSK

TOPSOE

TotalEnergies

WÄRTSILÄ

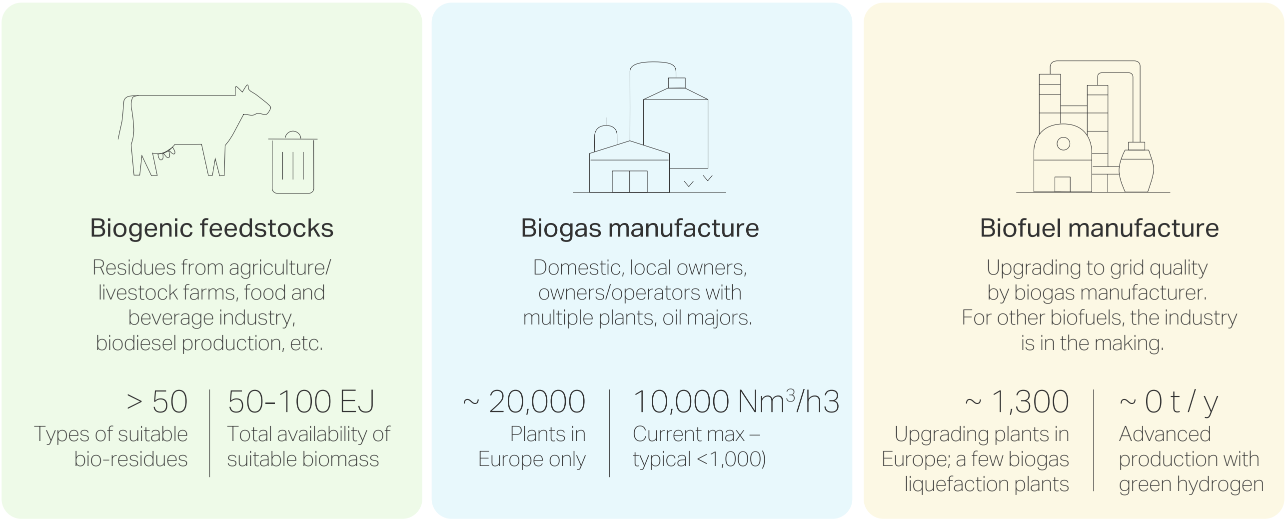
2. Manufacturing steps

The value chain of biofuels from biogas involves three main blocks, summarized in Figure 2:

1. Biogenic feedstocks
2. Biogas manufacturing
3. Biofuel manufacturing, with or without carbon capture and storage (CCS)

In this section, we discuss the potential of each of these blocks to increase the value of the resulting biofuels.

Figure 2: Generalized blocks in the value chain for biofuels from biogas.



Biogenic feedstocks

Residues from agriculture/ livestock farms, food and beverage industry, biodiesel production, etc.

> 50	50-100 EJ
Types of suitable bio-residues	Total availability of suitable biomass

Biogas manufacture

Domestic, local owners, owners/operators with multiple plants, oil majors.

~ 20,000	10,000 Nm^3/h3
Plants in Europe only	Current max – typical <1,000)

Biofuel manufacture

Upgrading to grid quality by biogas manufacturer. For other biofuels, the industry is in the making.

~ 1,300	~ 0 t / y
Upgrading plants in Europe; a few biogas liquefaction plants	Advanced production with green hydrogen

2.1 Biogenic feedstocks

Biomass that can be digested in anaerobic conditions provides suitable feedstock for biogas. Common biogas feedstocks include manure from animal farming, sewage sludge, agricultural residues, food waste from households and eateries, and a very large variety of residues from industrial food and beverage production.

A list of acceptable feedstocks provided by Danish biogas manufacturer Lemvig Biogas (Table 1) numbers more than 50 items, providing a window into the feedstock flexibility of biogas production.[20] The list also demonstrates anaerobic digestion's important role in extracting energy from waste and residues with few other options for efficient valorization.

Table 1: List of wastes and residues acceptable for biogas production at Lemvig Biogas.[20]

Manure and stable residues	Animal manure (cow, pig, chicken, etc.), deep litter
Animal residues/waste from animal processing industry (food, fur, etc.)	Bone meal, pig blood, blood meal; animal feed waste/residues; fish waste, fish meal, fish oil; chickens and minced chickens; meat meal; stomach/intestinal contents from slaughterhouses; mink food waste/residues and raw materials from the production of mink food; sawdust from mink fur series; slaughterhouse residual products; whey; eggs and egg waste products
Plant residues/waste from plant processing industry	Waste from soybean oil and margarine products; waste from spirits production; lemon peels; fruits and residues from fruit processing; potatoes and potato pulp; grain, barley, wheat, rye, oats with e.g., fusarium toxis, stink fire, powdery mildew, sprouts, or mold; olive oil and olive residues; plant oil, rapeseed oil, rapeseed cakes, sugar; vinasse and vinasse extract
Secondary food production	Bakery waste, flour, bread, and finished products; brown juice from grass protein production; food that is contaminated bacteriologically or chemically; dairy products, ice cream; milk with penicillin residues; soda and beer; bleaching earth; genetically modified organisms (GMO) products; hydrolyzed proteins
Other industries	Alcohol, ethanol and methanol glycerin, including de-icing products (e.g., from airports); yeast cream from pharmaceutical industry and breweries; coolant, antifreeze e.g., monoethylene glycol (blue coolant), organic acid coolant (green and red coolant); glue water; medicine residues from manufacturers of medicines; ochre from water treatment plants; paraffin; soap residues from soap manufacturing
Municipal waste (extended)	Fat sludge from sewage wells and grease trap; flotation sludge; sorted organic household waste
Other	Algae

Anaerobic digesters can also process large amounts of energy crops. These are crops with very high methane productivity, such as maize, which are purpose-grown to produce energy. However, the practice of using land for energy generates debate due to the resulting displacement of food production and biodiversity.[21]

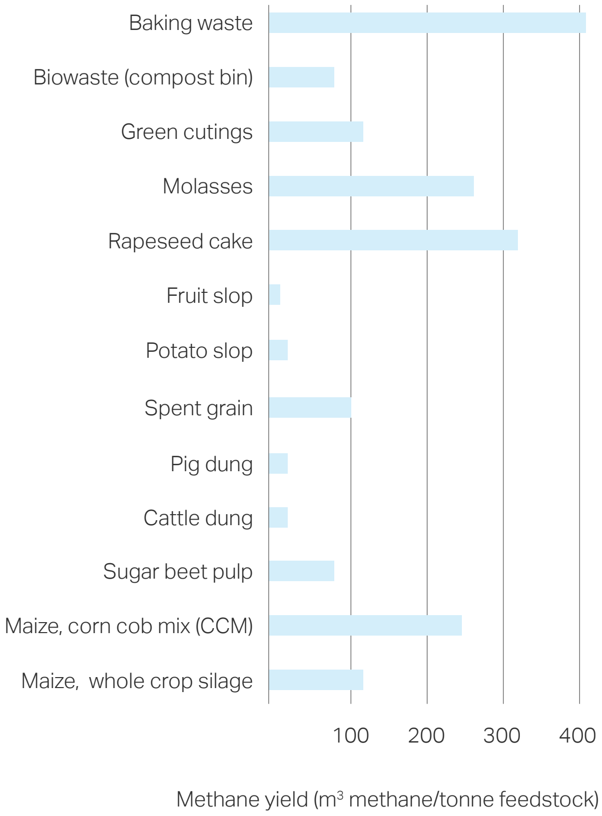
Europe takes a conservative stance on fuel versus food and biodiversity discussions, and European regulations impose a gradual reduction of the contribution of energy crops to the total biomass used for biogas production. The FuelEU Maritime regulation, which will enter into force in 2025, specifically requests that biofuels for shipping not rely on food and feed crops or have implications for land use change.[22] However, use of food or feed crops for anaerobic digestion is allowed in some non-European jurisdictions and in some EU regulations.

The overall global availability of sustainable biomass suitable for anaerobic digestion is attractive with respect to the shipping industry's demand for biofuels. Our accompanying biomass availability study delves into the issue of availability in greater detail.

2.1.1 Feedstock type and productivity

Anaerobic digesters are typically stirred reactors in which the biomass remains for a long time (20-40 days). The dry portion of a feedstock, known as the total solid, contains both volatile solid and ash. Volatile solids comprise total organic carbon and organic nitrogen. Nitrates, nitrites, phosphorus, and other nutrients feed the mix of living bacteria responsible for methane production and determine the quality of the digestate (degassed biomass) as a byproduct. The ability to valorize the digestate as a natural fertilizer is a critical component of an anaerobic digester's business case to such an extent that the specific fertilization requirements of the receiver's land can influence decisions concerning the mix of biomass used as feedstock.

Figure 3: Methane yield of selected biomass types.



Besides the apportion of nutrients, the selection and combination of various biomass types must consider methane productivity criteria. Each biomass type has a specific methane productivity. The range for this productivity is large, from 10-20 normal cubic meters per tonne (Nm^3/t) for manure and fruit slop to some 200-400 Nm^3/t for maize, rapeseed cake, molasses, and baking waste. Typical methane yields for selected biomass types are summarized in Figure 3. Estimates of methane productivity based on raw biomass are complicated by variations in water content (exceeding 90% for certain manure deliveries but close to 0% for industrial oils) and ash (as some feedstocks can be contaminated by soil and inorganic dirt). Very high-yield biomass types like fats, oils, greases, and free fatty acids may be added as "topping" — making up just a small percentage of the load — to boost the methane yield to the nominal production capacity.[23] These feedstocks are in high demand for fuels with higher added value and therefore tend to command high prices.

In terms of mass, the baseload for the digester is traditionally given by manure and agricultural residues. Figure 4 shows how different biomass types contribute to the loaded weight and the methane yield in one of the industrial reactors studied in our project. While animal manure makes up over 70% of the load by weight, the methane produced by this manure is just over 20% of the total. Maize silage, which represents less than 10% of the loaded mass, gives nearly as much methane as manure. Vegetable fats, which make up approximately 1% of the load, yield an impressive 14% of the total methane production.

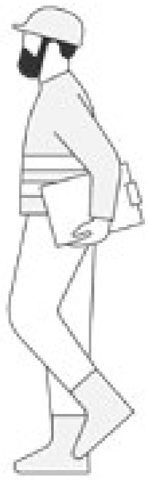
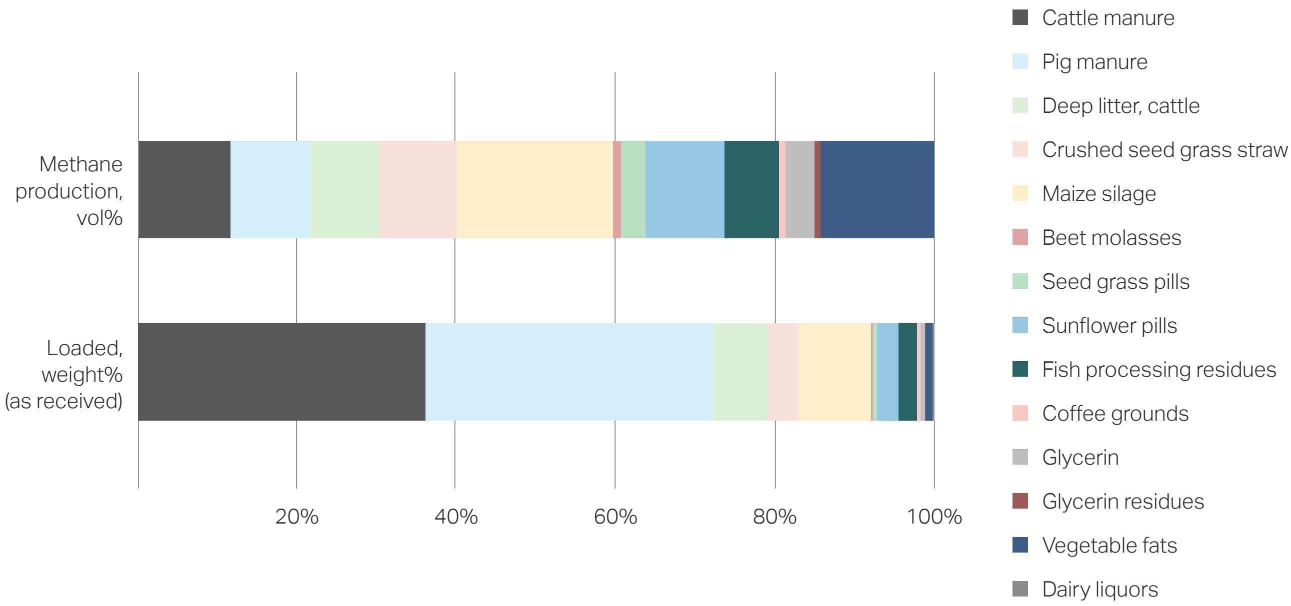


Figure 4: Weight fraction vs. methane production of a typical biomass plan for an anaerobic digester.



Traditional anaerobic digestion plants typically collect manure and agricultural residues from the local area (15-20 km from the plant) and deliver the digestate to local agricultural fields (similarly within 15-20 km) as natural fertilizer. Hence, cost-effective digestate management is one of the conditions for profitable operation, and digestate must have the right quality and classification to be used as fertilizer. When agricultural fields are close to the biogas plant, the digestate can be sent to storage at the fields without further treatment. Alternatively, the digestate can be treated to separate the fibers from the water, which in turn can be treated for nutrient recovery and subsequently disposed of.

The scale of anaerobic digestion plants and their feedstock sourcing strategy varies from country to country based on local regulations and financial support to the area. For example, the UK has many small plants (i.e., production capacity of less than 1,000 Nm^3/hour (h) of biogas) that solely process food waste. In Denmark, the Bigadan plant in Solrød (Solrød Biogas) processes 250,000 t/year (y) of food waste as a mono-feedstock plant.[24,25] In certain jurisdictions, a biogas plant that processes waste is classified as a waste treatment facility, meaning that the resulting digestate may not be spread on fields without further treatment. This imposes additional investment and operating costs that must be considered in a business case.

Currently, typical plants have a bio-methane production capacity of a few hundred Nm^3/h[§] and are small compared to the bunkering needs of a large ship, which may consume around 25,000 t/y of marine fuel. However, much larger plants are now being built or designed (see Section 2.2.1). These will be operated with a significant load of globally sourced high-yield biomass, such as olive pomace from the Mediterranean area or straw from eastern Europe.

This trend has some important business implications. For example, high-yield biomass that can be compacted to a high bulk density may be transported economically over long distances at a moderate cost and without excessive energy losses. However, if a biomass source has multiple off-takers, it can also typically command higher prices.

[§] For the sake of illustration, 500 Nm3/h of bio-methane is roughly 3,000 t/y.

Figure 5: Methane yield, density, and price per produced methane for a selection of biomass types. The scale for price is omitted to protect confidential information.

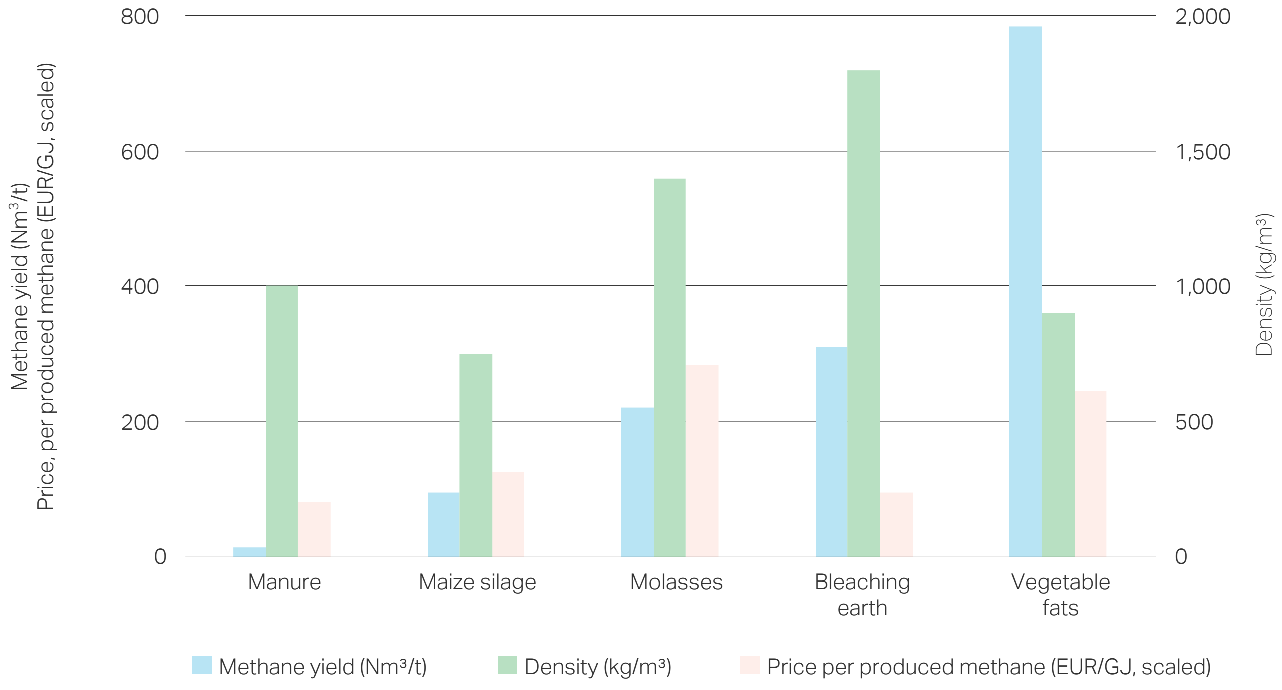


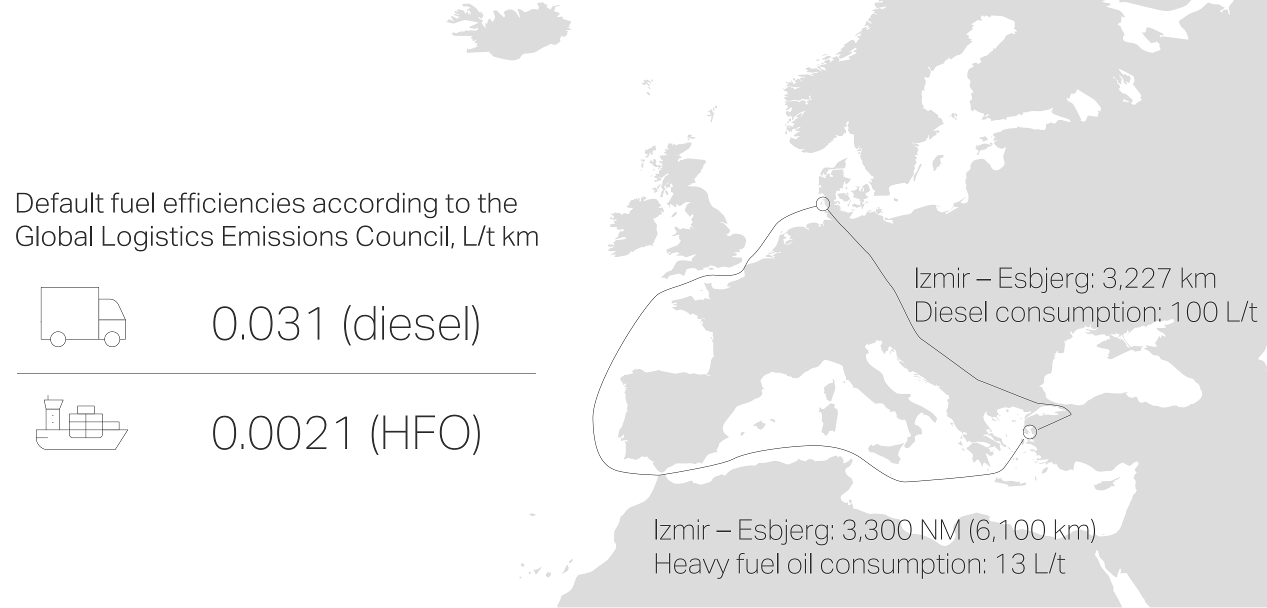
Figure 5 compares the yield and bulk density (both on an "as received" basis) of selected biomass types with the feedstock price per unit of produced methane. Most types show a correlation among the three parameters. An exception is spent bleaching earth, which has good yields, good density, and a low price — the same price as manure in relative terms, despite having considerably higher density and yield. Like manure, spent bleaching earth does not have other valorization options, and it is often sent to landfill in the absence of demand for anaerobic digestion.

2.1.2 Transportation

Large-scale biogas plants process residues that can be sourced from around the world; therefore, feedstock transportation must be considered in the total assessment of climate impact. The efficiency of transportation depends on the transportation mode.

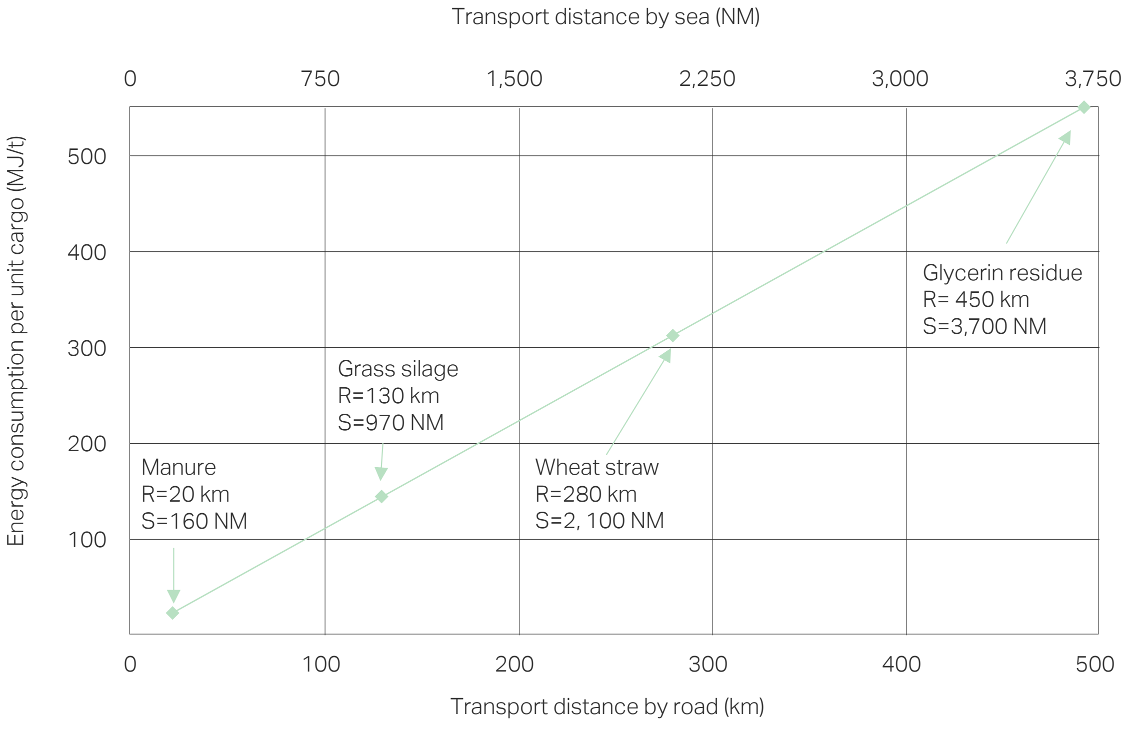
As an illustration, Figure 6 shows the fuel required for transporting 1 t of goods from Izmir to Esbjerg by road and by sea. This route would be relevant, for example, when transporting olive pomace from the Mediterranean region to biogas plants in Denmark. The road route is 3,200 km long, while the sea route is 3,300 nautical miles (NM, corresponding to 6,100 km or nearly double the road route). The Global Logistics Emissions Council (GLEC) recommends using a default diesel consumption of 0.031 liters per kilometer (L/km) for road transport and a default heavy fuel oil (HFO) consumption of 0.0021 L/km for sea transport, for each tonne of transported goods.[26] Using these values, transporting 1 t of goods from Izmir to Esbjerg requires 100 L diesel by road or 13 L HFO by sea.

Figure 6: Effect of transportation mode on fuel efficiency of transportation of goods from Izmir to Esbjerg.



To give an impression of the effect of distance on the sustainability of transportation, Figure 7 compares the energy that can be extracted from a feedstock via biogas production with the energy required for transportation of the same feedstock.

Figure 7: Energy for transportation of one tonne of biomass over various distances for road (R) and sea (S) freight. Diamond markers show the distance at which the energy used for transportation is 5% of the energy potentially yielded by anaerobic digestion of a feedstock.



In Figure 7, the energy consumption in megajoules (MJ) required to transport 1 t of cargo for a given distance is shown as a straight line. The energy consumption is scaled on the vertical axis, with distance for sea transport (in NM) on the upper horizontal axis and distance for road transport (in km) on the lower horizontal axis. The two horizontal axes are scaled such that they overlap on the chart. Green diamond markers show the distance at which the energy used for transportation is equal to 5% of the energy of the methane potentially yielded by various feedstocks. The 5% threshold is chosen to approximate current industry practice.

As an illustration, the first marker at the bottom left shows manure, which can be transported up to 20 km by road and up to 160 NM by sea before transportation consumes more than 5% of the potential energy yield. At the opposite end of the chart we show glycerin residues, a high-yield feedstock, which may be transported 450 km by road or 3,700 NM by sea before transportation consumes 5% of the yield. Other feedstocks can be transported over even greater distances: free fatty acids, for example, can be shipped for over 10,000 NM (not shown) before 5% of their potential energy yield is consumed by transportation. These results show that long-distance shipping of biomass does not significantly affect the overall efficiency of the associated value chain if the biomass has a good energy yield.

Our accompanying dedicated publications on energy demand for emissions reduction compliance and methane emissions show that energy losses during energy transformation may be substantial. To minimize the GHG emissions intensity of biofuels, it is important to contain these losses and improve energy use and conversion efficiencies wherever possible, including in transportation.

2.1.3 Prices

Biomass that can travel and that has alternative applications is exposed to price volatility. Following the start of the war in Ukraine and the energy crisis in Europe in the first part of 2022, the sky-high price of natural gas and resulting booming interest in biogas to replace natural gas saw the price of some feedstocks increase by as much as 70% within three months. Figure 8 shows the price increase of certain biomass types for a European biogas producer in summer 2022, calculated as the difference between the prices in June 2022 and March 2022 divided by the price in March 2022. The producer had some long-term supply contracts that partially protected their operations against volatility of the biomass price. However, the total procurement price of biomass was still affected, as shown in Figure 9.

The cost of biomass and biomass transportation is a major component of the price of production of a biofuel (further detailed in our report on techno-economic trends), and the ability to control the price of biomass — for example, via vertical integration — is a critical lever for control of biofuel prices.

Figure 8: Price increases for selected biomass types in June 2022 with respect to prices in March 2022.

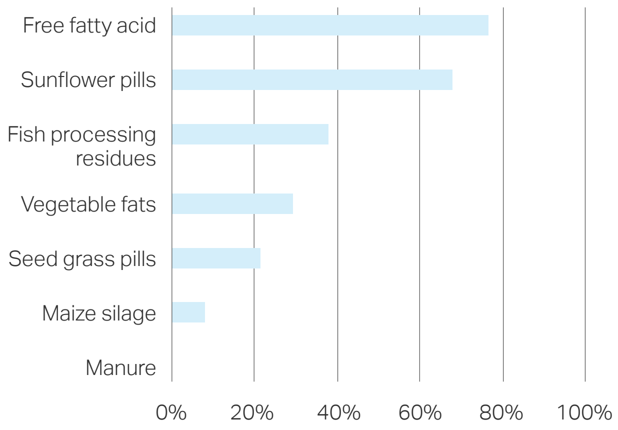
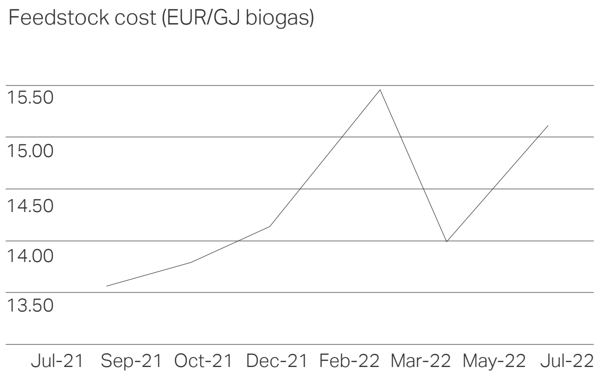


Figure 9: Cost of biomass per produced biogas energy in biogas for a typical plant in 2021-2022.



2.2 Biogas manufacturing and infrastructure

Biogas production is a very well-established process, documented in extensive existing literature. The International Energy Agency's (IEA) Bioenergy Group 37,[27] the World Biogas Association (WBA),[28] the European Biogas Association (EBA),[29] and the Deutsches Biomasseforschungszentrum (DBFZ)[30] are sources of expert knowledge on biogas production.

A comprehensive summary of technology and markets has recently been published by the IEA[3], and the IEA Bioenergy Group provides a good schematic of a biogas plant.[31] In this section, we focus on summarizing aspects of biogas production relevant to a potential value chain leading to biofuels for shipping.

2.2.1 Anaerobic digestion — capacity and economy of scale

Industrial anaerobic digestion leverages the natural process of bacterial decomposition of organic matter, with the main difference being that digestion in a biogas plant promotes the generation of methane over other bacterial metabolic functions. Anaerobic digestion is currently used in a wide variety of contexts, from sanitation for human waste in emerging economies (Figure 10) to industrial production sites with capacities of up to tens of millions of cubic meters of methane per year (Figure 11).

The chemical industry typically has a pronounced economy of scale, meaning that the cost of production tends to decrease with increasing production capacity. Thus, there is interest in understanding whether anaerobic digestion can support the construction of large biofuel plants with an attractive total cost of production.

Figure 10: Small-scale digester dome construction in Afghanistan.

Image credit: Sustainable Sanitation Alliance via Flickr.

Figure 11: Industrial-scale biogas production in Ukraine.

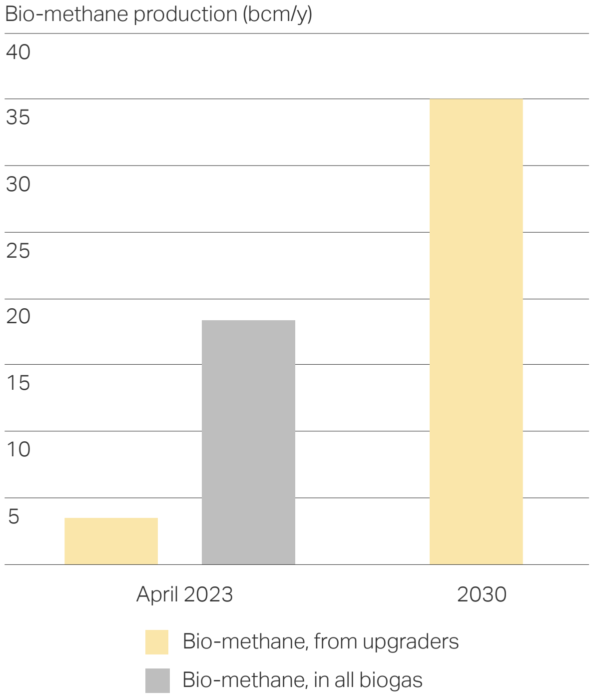
Image credit: Vadym Terelyuk via iStock.

Bio-methane production plants are biogas production plants that include an upgrading unit to separate bio-methane from the rest of the biogas (mostly CO_2). According to a recent summary, by April 2023 there were more than 1,300 bio-methane production plants in Europe, collectively delivering around 3.5 billion cubic meters (bcm) of bio-methane per year.[32,33] This figure is 20% higher than the year before — a production boom triggered by REPower EU[33] — and yet is equivalent to only around 1% of the total gas consumption of the countries represented in the EBA's statistics, based on data from Statistical Review of World Energy.[34] Locally, however, bio-methane can make a much higher contribution: for example, in Denmark the share of bio-methane has increased steadily over the years, up to nearly 40% of total gas consumption in June 2023.[35] Of the approximately 1,300 European bio-methane production plants, almost all are connected to the natural gas grid, with the rest producing CNG or LBM in decentralized plants.

The total number of biogas production facilities, including those that do not upgrade bio-methane, currently vastly outnumbers the number of bio-methane production facilities. In Europe, there were about 20,000 biogas production facilities in 2020.[36] Most of these plants produce electricity in generator sets or CHP. The excess electricity is sold to the grid, often with subsidized tariffs. While biogas production is particularly prevalent in Europe, other regions also have an established industry: for example, the reported total number of biogas plants in China exceeds 100,000 without accounting for domestic microdigesters, with a total production of 70,000 terawatt-hours (TWh) biogas or approximately 7,000 bcm/y bio-methane.[37]

Total bio-methane production in Europe from all biogas plants was approximately 18 bcm/y in 2021[38] — more than five times the amount of bio-methane that is currently upgraded, as shown in Figure 12. Diverting the biogas already produced in Europe today from electricity to bio-methane production could therefore generate an additional 15 bcm/y of bio-methane (Figure 12). This equates to approximately 12 million tonnes of oil equivalent (TOE) per year, or about 14% of the 83 million tonnes of fuel used by shipping in Europe.**

Figure 12: Current and predicted European production of bio-methane and biogas, assuming universal implementation of biogas upgrading in both old and new plants by 2030.



Diving further into the makeup of the biogas production market, Figure 13 shows that most biogas plants in Europe produce less than 1,000 Nm^3/y bio-methane (equivalent to about 5,500-6,000 t/y). Currently, half of the total European bio-methane production capacity comes from plants of this scale (Figure 14). A single ship bunkering 20,000–40,000 t/y of bio-methane would absorb the entire production of 5–10 of these small biogas plants, meaning that full decarbonization of shipping by means of individual small plants would involve a very significant procurement task. However, even small plants may be able to support the shipping industry in meeting interim IMO and FuelEU Maritime targets of 5-10% emissions reduction by 2030. For example, a bio-methane capacity of 6,000 t/y corresponds to a HFO capacity of about 8,000 t/y. Assuming that the bio-methane value chain affords a genuinely zero-carbon fuel,†† this plant may provide enough energy for a fleet currently using 130,000 t/y of HFO to comply with FuelEU Maritime's 2030 requirements.

** Back-calculated from OECD statistics[12] using a conversion factor of 3.12 tonnes CO_2 per tonne of marine fuel.

†† We delve into this assumption in greater detail in the accompanying WTW GHG and energy demand for emissions reduction compliance studies in this series.

Figure 13: Number of European biogas plants versus bio-methane production capacity, based on MMMCZCS analysis of EBA data.[39]

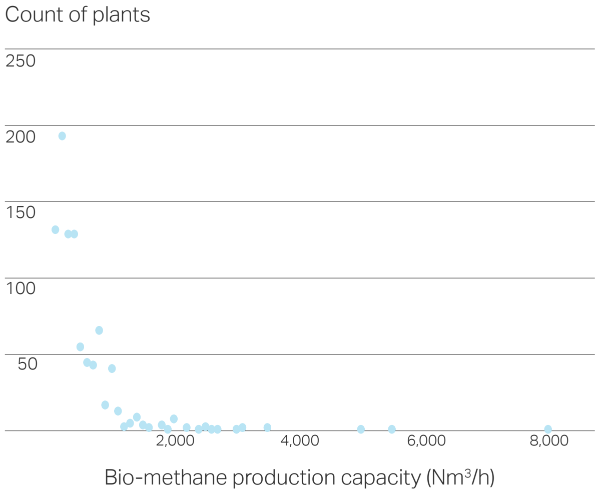
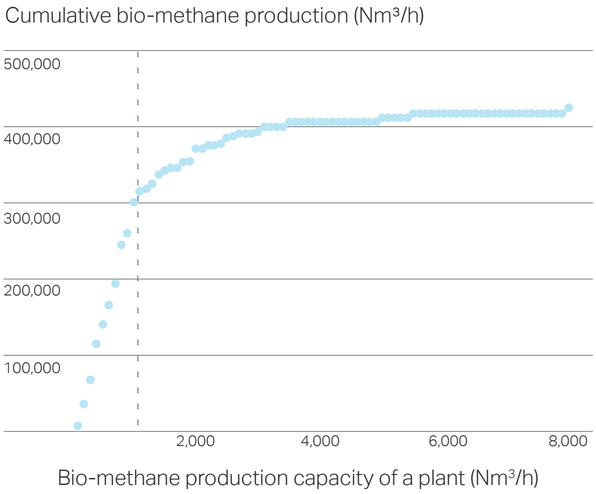
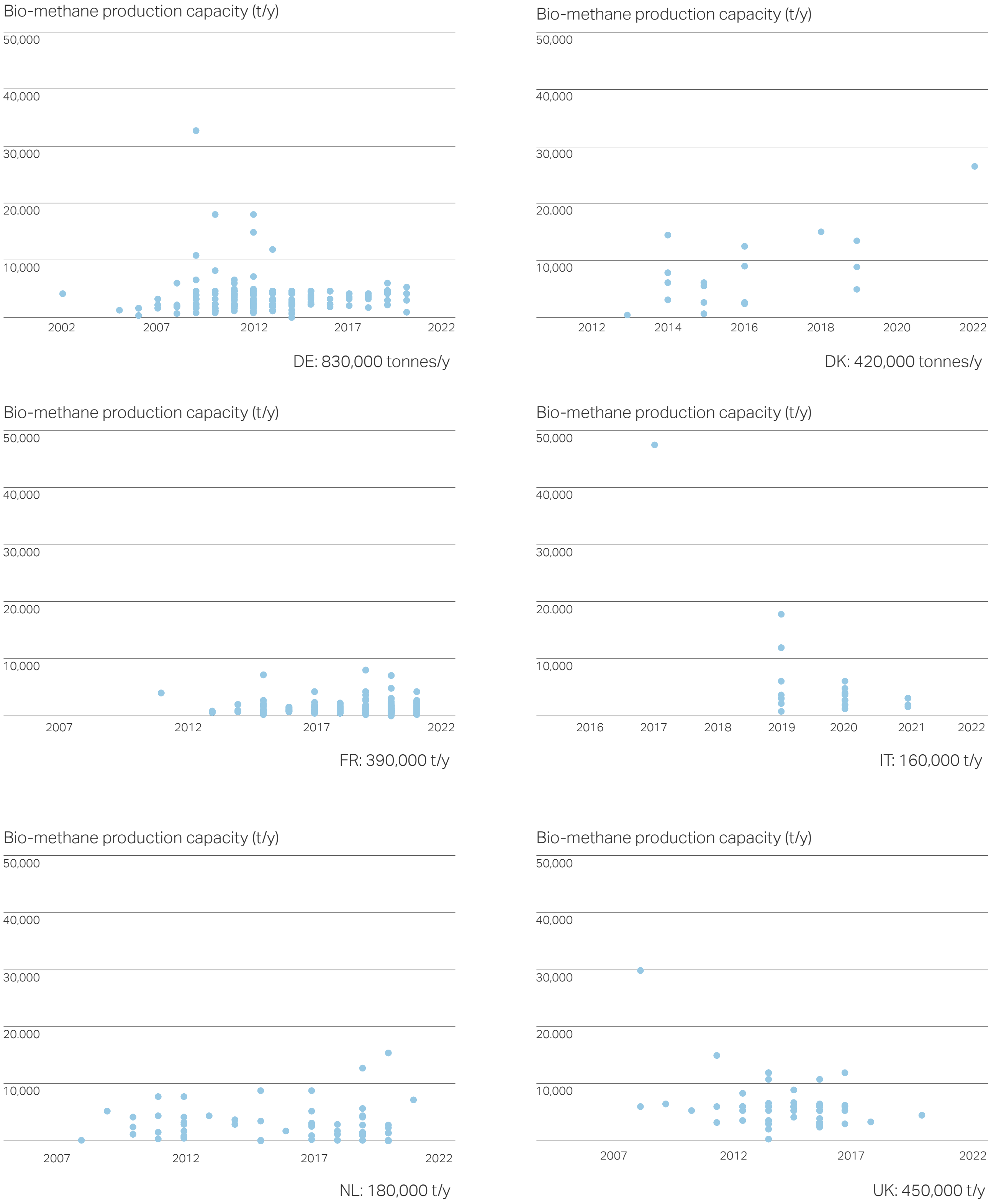


Figure 14: Cumulative bio-methane production in European biogas plants versus bio-methane production capacity (vertical dashed line represents current median plant size), based on MMMCZCS analysis of EBA data.[39]



Some larger biogas plants also exist in Europe, with plants generating more than 5,000 Nm^3/h of bio-methane currently in operation or being built in Denmark, the UK, Germany, and Italy. While a common narrative in the industry is that the future of biogas is in large plants, we cannot confirm this as a general trend in Europe based on statistical data provided by the EBA at the end of 2021.[39] Figure 15 shows our analysis of the EBA data and summarizes the evolution of biogas plant size in selected European countries over time, with each individual plot showing the bio-methane production capacity of each plant (in t/y) arranged by the plants' first year of operation.

Figure 15: Evolution of bio-methane production capacity of biogas plants over time in various European countries (Germany – DE, Denmark – DK, France – FR, Italy – IT, Netherlands – NL, and United Kingdom – UK), including total bio-methane capacity of the country in t/y for 2021 (bottom right corner of each plot). MMMCZCS analysis based on EBA data.[39]

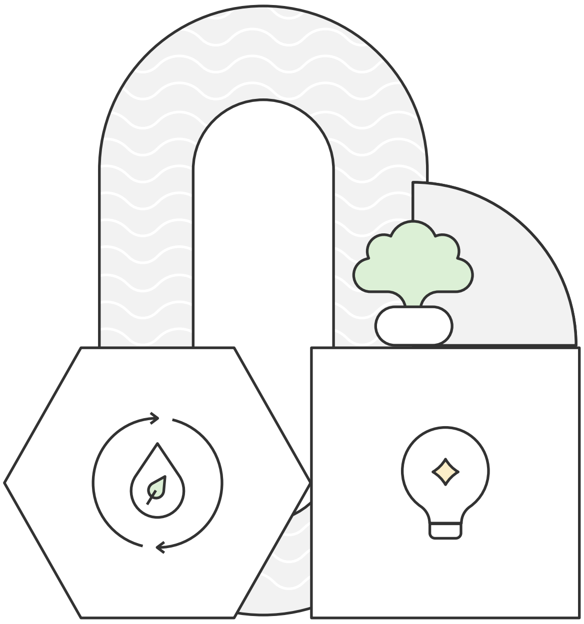


As shown in Figure 15, a trend towards larger plants is clear in Denmark and the Netherlands. However, in other countries, the typical plant size has not changed in recent years. Our accompanying report on techno-economic trends highlights that the cost of biogas production in an anaerobic digester is subject to an economy of scale for investments and fixed cost, and a diseconomy of scale for biomass transport. Thus, trends towards larger plant size may be determined by the availability of local waste.

Large plants are well-suited as stand-alone production plants for marine biofuels. This concept is being demonstrated at Anaergia (now Copenhagen Infrastructure Partners, CIP) Tønder, a world-scale biogas plant in Denmark that is currently in the start-up phase. The biogas produced from this plant is upgraded to bio-methane (supplied to the natural gas grid) and CO_2. The CO_2 is then compressed or liquified and trucked to Aabenraa, where it is used by European Energy for synthesis of e-methanol that will power, among other things, the new container ships being built for Maersk.[40]

Appetite for construction of large biogas plants may be boosted by recent technological developments in compacting and processing straw in an anaerobic digester. Straw is widely available as a residue of cereal production: however, due to its fibers' close pore structure, anaerobic digestion of straw has traditionally achieved only modest efficiencies[41] and straw has been used mostly for combustion. Straw has also presented logistical difficulties, as the traditional compaction technology in bales does not ensure a good energy density and causes comparatively high costs and fuel consumption for transport. However, briquetting of straw has recently been reported to treble the bulk density of the straw and effectively increase digestion efficiency.[42] Industrial suppliers of biogas indicate in personal communications that once such technologies become fully commercial, the capacity of biogas plants will see a steep increase (up to an estimated 30,000-50,000 Nm^3/h biogas production).

Small plants can also efficiently supply energy to large consumers if the product is aggregated — for example, via the natural gas transmission grid — or if the green attribute is sold via an exchange of green certificates. Where policies do not support the construction of large-capacity plants, availability of physical or virtual infrastructure becomes critically important to the availability of biofuels for shipping.



2.2.2 Upgrading and aggregation

Biogas is a true 'joker' as an energy carrier. Its composition, ability to connect with and balance established energy infrastructure, versatility in participating in new energy infrastructure, and key anticipated role in reducing the climate impact of energy systems make biogas a key component of future energy systems. Production of biogas and biogas-based biofuels can interface with several different types of existing and emerging physical infrastructure for upgrading and aggregation. Biogas products are currently aggregated by the following types of infrastructure:

1. **Electrical power** (see Figure 16, points (3)-(6): Generation of electrical power using a generator is currently the most common use of biogas, thanks to widespread subsidies (feed-in tariffs). Generators have low efficiency, with only around 35% of biogas being converted into electricity[43] and the rest becoming heat. Like marine engines, generators are also prone to methane slip. Some countries, including Germany and The Netherlands, regulate methane slip from biogas-based electrical generators. thereby minimizing emissions. If not regulated, methane slip may be as high as 1-3% of the processed methane.[31]
2. **Natural gas** (see Figure 16, points 15-17): Biogas is upgraded to bio-methane by removing the CO_2. This bio-methane is then compressed, odorized, and injected into the natural gas network. The degree of compression depends on the access point: four bars are typically sufficient to access the local distribution network, while around 70-80 bars are needed for transmission. The upgrading process also consumes energy in the form of power and heat, with the specific consumption of each dependent on the upgrading technology. More details on this process will be available in our upcoming publication on energy demand for emissions reduction compliance.

Other less prevalent or nascent networks that can further boost biogas-based value chains are:

3. **District heating network** (see Figure 16, points 7-10): These networks generate heat in a centralized plant and distribute it to local consumers, thereby increasing the overall energy efficiency of the system. This infrastructure is often used to make excess heat produced by a manufacturing plant available to other industrial or residential consumers. Industrial hubs where energy and material streams are shared among various production facilities already exist, with probably the most famous example being the BASF Verbund sites. In Denmark, district heating serves more than 55% of total residential area.[44] However, as district heating is not globally widespread, the availability of off-takers for a district heating network cannot be taken for granted and must be assessed locally.
4. **Biogas network** (see Figure 16, points 12-14): This type of network may aggregate the raw (often dehumidified) biogas from various plants with the purpose of processing it in larger facilities that can benefit from economies of scale. An example of this setup is the Nature Energy upgrading facility of Hemmet,[45] which collects biogas from three small anaerobic digesters located 1.5-6 km away. A rule of thumb is that this type of aggregation is only attractive if the anaerobic digesters are located no more than 7 km away from each other, due to the costs of laying the pipeline(s). However, this critical distance is project-specific, as the cost of laying the pipelines depends upon the terrain and the safety requirements for the laying works. Our report on techno-economic trends shows that the economical distance of laying pipelines increases for large methane transport capacities.
5. **CO_2 network** (see Figure 16, points 17-20): A biogas upgrading plant is an excellent point source of biogenic CO_2. While today this is emitted into the atmosphere, in the future it may be collected in a separate CO_2 network. The aggregated CO_2 may be used to manufacture electro-fuels (fuels produced solely using biogenic CO_2 and green hydrogen), or it can be liquified or compressed for storage, thus even further reducing the GHG intensity of the associated biofuel. In Europe, an example of this approach has been pioneered by Ineos,[46] which is preparing to collect CO_2 from various renewable point sources in northern Europe[47] and pump it into underground facilities in the North Sea. More broadly, CO_2 infrastructure is taking off globally, with more than 200 projects at various stages of execution in the US, Europe, and the Middle East.[48] Our accompanying studies on energy demand for compliance and WTW GHG emissions indicate that the availability of facilities for biomass energy carbon capture and storage is critical to reducing the GHG emissions intensity of biofuels and to greatly increasing the value of these fuels.

6. **Hydrogen network** (see Figure 16, point 23): Finally, a hydrogen network may also be connected to biofuel manufacturing plants to supply hydrogen for bio-methanol manufacturing or for boosting bio-methane production.

These interconnections are shown schematically in Figure 16. In the most common layout, biomass feeds (1) an anaerobic digestion plant, which produces biogas and digestate. The latter is a good soil amendment and is returned to agricultural fields (2). The biogas is sent (3) to a local generator to produce electricity, which is dispatched to the electrical power grid (4) and made available to consumers (5). The biogas plant may receive electricity from its own generator (6) or from the grid.

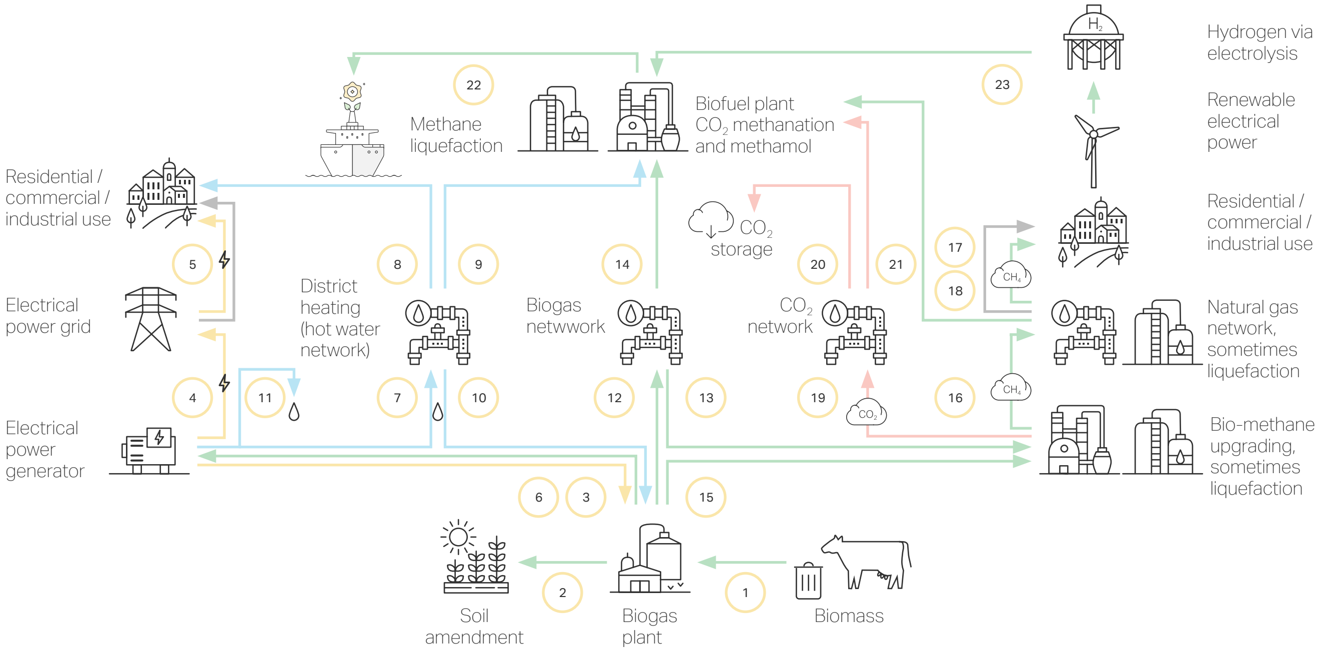
Combustion of biogas in a CHP plant produces electrical power and hot water. The hot water can be supplied (7) to district heating, which serves other consumers (8). Thermal energy may be needed at the biogas plant (10) or for upgrading/synthesis (9), as not all plants have both a genset and an upgrader. In the absence of district heating, the excess heat produced at the generator is lost (11).

Alternatively, biogas (12) may be collected in a local biogas network and aggregated with biogas streams produced in other anaerobic digesters, which can feed an individual upgrader (13) with or without further aggregation of bio-methane via the natural gas grid (18). This pathway is an attractive concept to increase the capacity of future biofuel plants (14).

Furthermore, the anaerobic digester may be connected (15) to an upgrader that separates methane from CO_2. From the upgrader, a methane stream may be liquified directly and supplied to off-takers. Alternatively, methane may be sent to the natural gas network (16). This may supply residential use (17), a liquefaction plant, or a biofuel plant (18). The CO_2 stream produced in the upgrader may be vented or aggregated with other CO_2 streams from other industrial production processes (19). Finally, the CO_2 may be stored (20) or used for biofuel manufacture (21).

In summary, a biofuel plant may benefit from the electrical power grid (5), biogas (14), CO_2 (21), hot water (9), and bio-methane (18) networks. The biofuel plant might need green hydrogen (23) from an electrolysis plant connected to its renewable power generation. Hydrogen might also come from a network that may be separate or part of the natural gas network. If the biofuel is methane, it must be liquified prior to bunkering (22). If the biofuel is methanol, no further processing is required.

Figure 16: Connection of biogas-based biofuel production with different types of physical infrastructure.



Bio-methane in the natural gas network is blended with natural gas and distributed to households for residential heating, to industrial off-takers, to power plants, and so on. Amid the energy crisis triggered by the invasion of Ukraine, this use of bio-methane is seen as a great asset by the EU.[49] Furthermore, as a renewable energy source able to balance the intermittency of wind and solar power in the grid,[50] biogas is often seen as a fundamental component of the transition of broader energy systems towards net-zero-carbon electricity.

Due to the critical role that bio-methane may end up playing in interconnected energy systems, some shipping operators consider that sourcing bio-methane from the national natural gas grid may expose their investment to risks related to both availability and price.

While the natural gas network is well-developed in most of Europe and North America, this infrastructure is not widespread in many other countries with strong agricultural industries. Figure 17 shows the natural gas networks of Northern Scandinavia, Southeast Asia, and South America — all areas with important agroforestry production that, due to lack of capillary natural gas network, may have fewer off-taking channels for bio-methane. Biofuel plants in these geographies may be exposed to fewer competing off-takers for the product.

Figure 17: Natural gas networks in Northern Scandinavia (left), Southeast Asia (center) and South America (right). Data sourced from Global Energy Monitor.[51]

2.2.3 Virtual infrastructure: mass balances and trading of certificates

From both an environmental and economic point of view, physical bunkering of LBM or bio-methanol might often be a suboptimal choice. The small capacity of many biogas plants cannot leverage economies of scale and physical transportation of biofuels to ports might require processing and logistics that add complexity, costs, and GHG emissions. Furthermore, requiring physical bunkering of a biofuel may cause unnecessary use of energy for construction, operations, and transportation. This outcome conflicts with the basic principle that saving energy is the most efficient way to reduce GHG emissions.

In certain situations, therefore, the option of trading a biofuel's green attributes, defined as "any and all credits, benefits, emissions reductions, offsets, and allowances [...] attributable to the generation from the project,"[52] might be preferable to trading the biofuel itself. Systems for trading green attributes are very well known in the power industry.[53] Renewable energy certificates and Guarantees of Origin are traded in the US and EU, respectively, via registers typically managed by the transmission system operators (TSOs) that buy, sell, and retire certified and verified units of renewable energy. Contracts for purchasing power from a producer can be physical, where a TSO purchases electricity from a producer that provides renewable power for the TSO's grid via a power purchasing agreement (PPA), or virtual, where a TSO purchases the green attributes of power that is fed into a different grid. Virtual PPAs promote the production of renewable power in locations that have higher production efficiency and consequently cheaper prices.

Figure 18 provides a visual description of green attributes trading. A biogas manufacturer uses their product (1) to operate a generator and produce electrical power (2) with green attributes. The green attributes are traded (3) via a certificate trading system. Both the electrical power and the green certificate are sold to a TSO that operates an electrical power grid and pays (4) for both. The electrical power in the TSO's grid is now a mix of renewable and fossil power. The grid dispatches its electrical power to various off-takers and a biofuel plant (5). The biofuel plant aims to maximize the apportion of renewable energy to ensure that its biofuel has lowest possible emissions intensity, so it buys the certificate from the TSO, which retires the certificate. The biofuel (7) can then claim use of renewable power even if the physical electrical power that operates the biofuel plant is a mix of renewable and non-renewable.

Figure 18: Transfer of green certificates for renewable electricity via an electrical power grid.

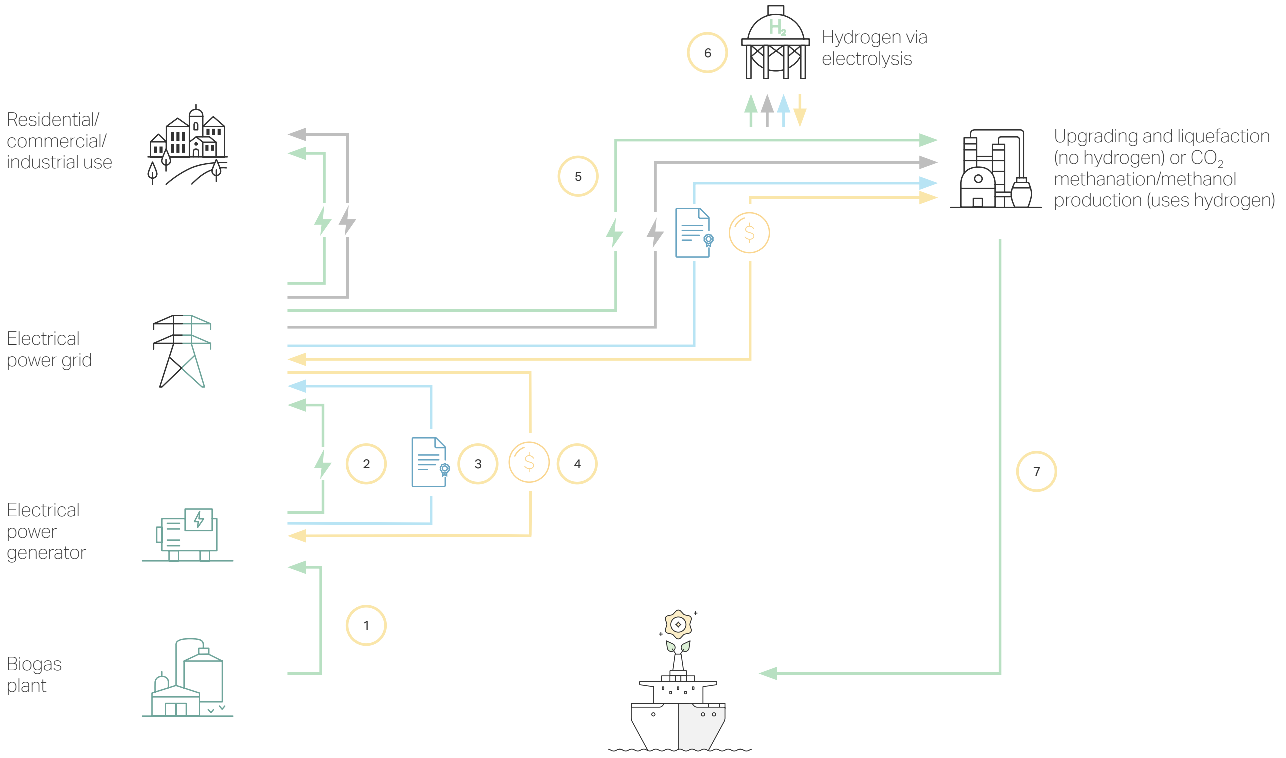
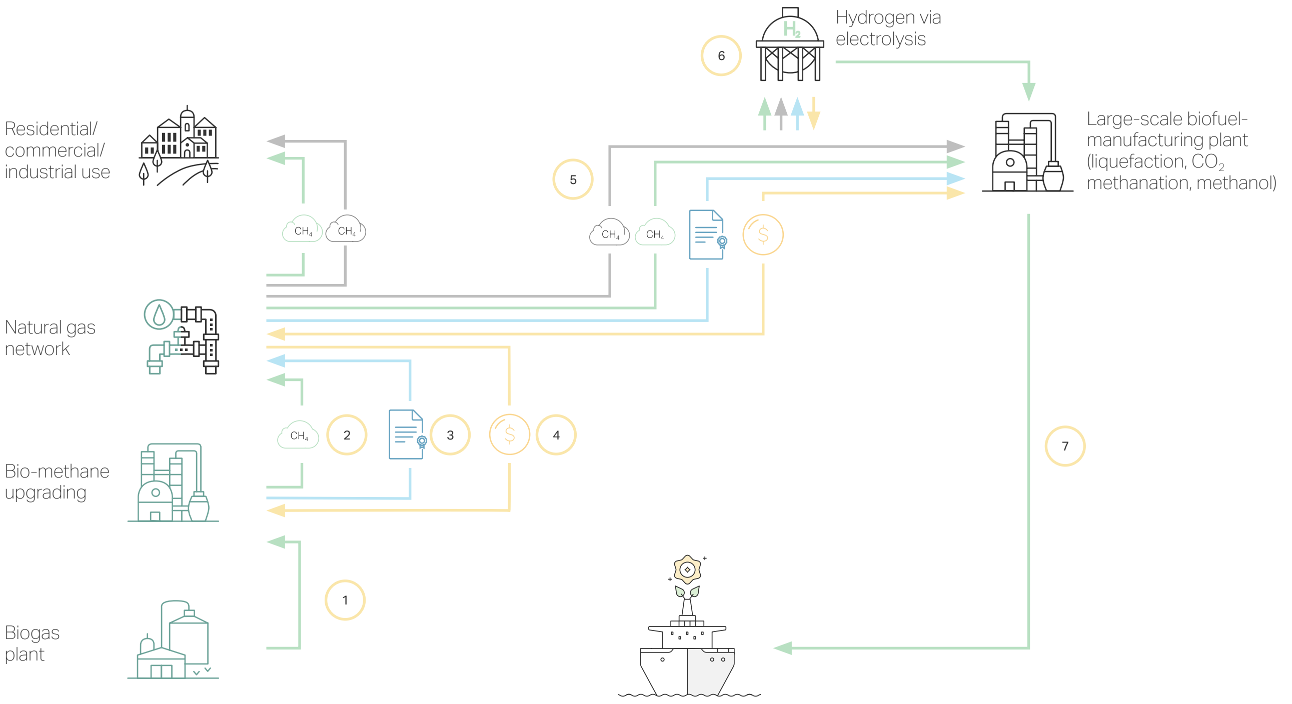


Figure 19: Transfer of green certificates for bio-methane via a natural gas network.



Trading of green certificates for bio-methane, as outlined in Figure 19, also exists: a contemporary example is the Energinet 'guarantees of origin for renewable gas' in Denmark.[54] The philosophy of this kind of trading system mirrors the system established for renewable electrical power: the biogas plant (1) dispatches biogas to an upgrading facility, which separates and purifies bio-methane and injects it into the natural gas network. The TSO purchases (4) bio-methane (2) and its associated green attributes via a green certificate (3). The natural gas network now contains a mixture of fossil natural gas and bio-methane. A biofuel manufacturing plant can pull this mixture from the network (5) to produce biofuels with a low emissions intensity thanks to trading of the green certificates. Depending on the fuel produced, hydrogen may also be used (6). The resulting biofuel with certified low emissions intensity is transferred to a ship (7).

In Europe, the 2018 revision of the EU Renewable Energy Directive (RED II)[55] contains provisions for establishing tradable Guarantees of Origin for bio-methane. RED II also contains provisions for using mass balances to calculate the GHG emissions savings of biofuels produced partly from biogenic feedstocks and partly from fossil sources within the member states. Section 2.3 shows some examples.

Finally, book and claim systems are also expected to facilitate the adoption of biofuels in the shipping industry.[56] Book and claim systems enable the green attribute of a bunkered biofuel to be claimed from a different ship at another geographic location. In a similar spirit, the FuelEU Maritime allows ships of the same fleet, but also ships from different fleets, to pool their use of low-carbon fuels for compliance purposes. Importantly, mass balancing and book and claim approaches are not approved in all regulatory frameworks, and their applicability therefore cannot be taken for granted. The establishment of robust systems to track the chain of custody and verify the green credentials of biofuels will be critical to reduce fraud and enable widespread use of mass balancing and book and claim systems.

2.2.4 Methane emissions and sustainability of biogas manufacturing

The biogas industry primarily evolved as a method to harvest useful energy from waste treatment. Historically, this was done at a community level to treat wastewater, or at a farm level to obtain cheap electricity or heat for the farm's needs. As a result, rigorous engineering attention to design and operational details of biogas production facilities has only recently been applied. Studies now find that many existing biogas plants have difficulty controlling methane emissions to the atmosphere.[31,57] We have studied this issue in more detail in a separate report on methane emissions.

Our accompanying WTW GHG study confirms that life-cycle methane emissions must be minimal for the value chain to deliver biofuels with attractive emissions intensities. While biogas plants and bio-feedstocks can be certified for compliance with regulatory frameworks such as RED II, these frameworks mostly do not require individual determination of methane emissions and rely on default values that are not always conservative.

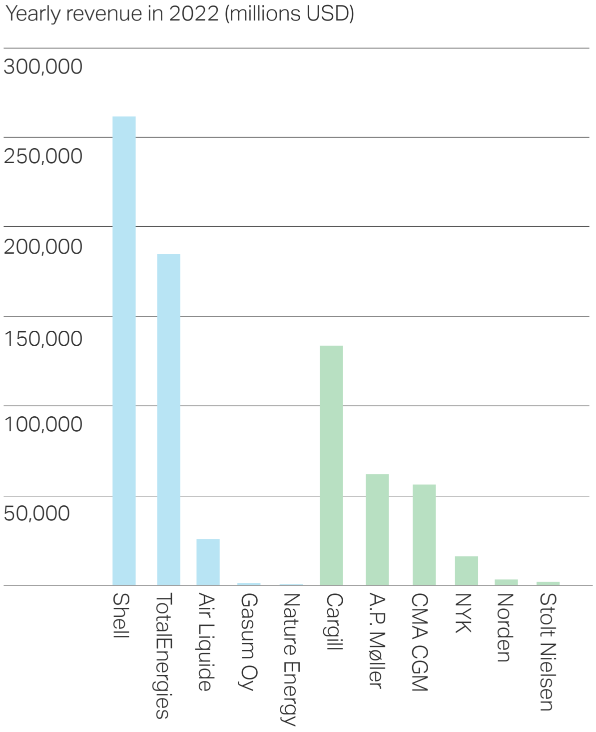
The Global Methane Pledge signed at the 26th Conference of the Parties (COP26) in Glasgow creates a global framework for regulation of methane emissions.[58] The IEA also maintains a list of current policies on methane emissions.[59] While the list keeps expanding, regulatory efforts targeting biogas plants are still sporadic.[60] To ensure that biofuels used in shipping afford the expected emissions reductions, we recommend that biofuels are procured only from supply chains that are specifically certified for methane emissions by recognized methods and agencies.

2.2.5 Players in the industry

While individual farm-owned biogas plants still exist, the industry is consolidating, and its potential has triggered the interest of very large companies. The list of members of the World Biogas Association or the EBA can provide a starting point to study the actors in the industry.

Figure 20 compares the yearly revenue of some selected actors in the biogas and shipping industries. Biogas is of course still only a very minor fraction of the yearly revenue of oil majors, but such corporations are showing a keen interest in biogas. For example, BP announced a deal to buy Houston-based biogas producer Archaea in October 2022.[61] In November 2022, Shell announced its acquisition of Danish Nature Energy,[62] and TotalEnergies have also announced their intention to grow their biogas business to 2 TWh by 2025.[63] While a single world-scale 10,000 Nm^3/h biogas plant only produces sufficient methane to supply 1-2 large ships per year (40,000-70,000 TOE), the concern that shipping majors will need to establish hundreds of different supply contracts with local small producers to supply their ships with biofuels may therefore be unfounded.

Figure 20: Yearly revenue of selected actors in the biogas (left) and shipping (right) industries.



2.3 Biofuel manufacturing and delivery

Manufacture and delivery of LBM and bio-methanol from biogas are still in the early stages of development, but there are already important examples of these value chains being established. A summary of the current status of the value chain for both biofuels is shown in Tables 2 and 3.

Biogas producers have stated that they are ready to consider the construction of large facilities, including liquefaction plants near ports, if long-term supply agreements can be made. This model was adopted, for example, by Harvey Gulf PSV[64] and Furetank[65] in early 2022.

Table 2: Current status of the value chain for liquified bio-methane (LBM) as bunker fuel.

Value chain step	Status and examples
Bio-methane production	
Biogas upgrading (separation of CO$_2$ from methane)	Fully commercial (more than 1,300 plants in Europe alone), various technologies
Catalytic methanation of CO$_2$	Processing steps demonstrated in a handful of synthetic natural gas (SNG) plants worldwide (mostly based on fossil energy)
Biological methanation of CO$_2$	Demonstrated, with commercial plants under construction
Bio-methane liquefaction	
In small liquefaction plants connected to individual upgrading units	Some examples of commercial operations: • Gasum: Linköping, Sweden (4,600 t/y)[66]; Turku, Finland (4,300 t /y)[67]; and Nymölla, Sweden (5,400 t/y)[68] • Ege biogass, Oslo, Norway (3,600 t/y)[69] • EnviTec biogas, Rostock, Germany (9,000 t/y)[70] • Ñuble, Chile (4,300 t/y) (announced)[71] • TotalEnergies, Port of Marseille, France (announced)[72] • Frederikshavn, Denmark (initially 20,000 t/y, scalable to 120,000 t/y) (under construction)[73]
In medium- to large-scale plants receiving methane from the natural gas network (mixture of bio- and fossil methane)	• Port of Amsterdam, Netherlands (200,000 t/y by 2025) (announced)[74] • Godorf, Germany (100,000 t/y)[75]
In medium- to large-scale plants receiving methane from interconnected upgrading units	Only theoretical so far
Bunkering of liquified bio-methane (LBM)	• Since 2018, the Port of Gothenburg (Sweden) has had a permanent LBG bunkering facility owned and operated by Swedegas[76] • In 2020, TotalEnergies demonstrated ship-to-ship LNG bunkering in Rotterdam, with a portion of the bunker being bio-methane produced from a local biogas facility[77] • The more than 150 ports currently operating LNG bunkering infrastructure[78] can bunker LBM if it is made available
Navigation on liquified bio-methane (LBM)	• Harvey Gulf PSV, bunkered on own facilities at Port Fourchon, Gulf of Mexico (operating)[64] • Furetank (announced)[65] • There are currently nearly 400 LNG-fueled ships already in operation and many more on order, with the LNG-fueled fleet expected to surpass 900 units by the end of the decade.[78] These ships could also operate on bio-methane. For context, a yearly marine diesel consumption between 500 t/y for a fishing boat and 45,000 t/y of a large cruise ship is equivalent to yearly LNG consumption between a few hundred and ~40,000 t/y of methane.
Shipping services based on bio-methane with Guarantee of Origin	Offered by CMA CGM since 2021[79]

Table 3: Current status of the value chain for bio-methanol as bunker fuel.

Value chain step	Status and examples
Production of bio-methanol from biogas (excluding gasification)	
Bio-methanol from biogas via addition of H_2	No known commercial plants
Bio-methanol from biogas via partial removal of CO_2	No known commercial plants
Bio-methanol from biogas via addition of CH_4	No known commercial plants
Bio-methanol from natural gas grid gas (blended bio- and fossil methane) via reforming (with mass balances applied as stipulated by RED directive)	Some examples of commercial operations: • OCI/BioMCN has pioneered the production of bio-methanol from biogas (Delfzijl, Netherlands)[80] • BASF produces REDcert-certified methanol for sales[81]
Bio-methanol from biogas-derived CO_2 (e-methanol)	Maersk's agreement with European Energy[40] that converts CO_2 from the CIP biogas plant in Tønder, Denmark
Bio-methanol from landfill gas	Maersk's investment in bio-methanol from landfill gas producer WasteFuel[82]
Bunkering of bio-methanol	20 ports worldwide[78] currently have methanol storage capacity; further bunkering infrastructure needs development
Navigation on bio-methanol	There are currently 26 methanol-fueled ships in operation (mostly oil/chemical tankers), with the global methanol-fueled fleet expected to exceed 100 units by the end of the decade (new orders being mostly container ships).[78] For context, a yearly marine diesel consumption between 500 t/y for a fishing boat and 45,000 t/y for a large cruise ship is equivalent to yearly methanol consumption between ~1,000t/y and ~90,000 t/y due to methanol's lower energy density.

2.4 Biofuel sustainability and certification

Along with choice and productivity, a biofuel value chain must also consider sustainability. Biofuel manufacturing requires biomass and various materials for processing, and energy for transport and processing. The sustainability of a biofuel is therefore heavily influenced by the sustainability of the materials and energy used in the corresponding value chain, and of the operations carried out along that value chain.

The factors that have the most impact are the source of electricity — fossil or renewable — and the origin of the biomass — whether a true waste with no alternative uses or a substance with other industrial applications. If using biomass for energy purposes deprives other industries, then they must find alternatives, and the sustainability impact of such a switch causes a "displacement effect". The source and availability of other materials, such as water or rare minerals, can also have a sustainability impact. Our accompanying WTW GHG study summarizes an overall assessment of the GHG emissions associated with the supply of LBM and bio-methanol from biogas as marine fuels. The study calculates the emissions intensity, or the total GHG emissions of a biofuel per unit energy, for several different scenarios.

Furthermore, the emissions intensity of a biofuel affects the biofuel's decarbonization efficiency, and since reducing GHG emissions is the primary objective of using biofuels as marine fuels, the emissions intensity eventually affects a biofuel's value. We discuss this in detail in our accompanying reports on energy demand for compliance and techno-economic trends.

Biofuels' sustainability can be certified, with leading certification systems including the International Sustainability and Carbon Certification (ISCC), REDcert, and the Roundtable on Sustainable Biomaterials (RSB). These organizations have established processes to verify that the entire supply chain of a product conforms to certain ecological, social, and legal requirements: for example, the latest requirements of the EU Renewable Energy Directive (RED). These certification bodies keep a public list of active certificates[83, 84, 85] so that compliance claims can be verified by potential clients. Some biofuel producers are also trying to establish physical track-and-trace methods to verify that biofuels have not been diluted or tampered with.[86] This unfortunately seems necessary because cases of fraud in the biofuel industry are frequent.[87, 88, 89]

2.5 Typical timeline of biogas construction projects

To match the demand for low-carbon fuels, the biogas industry must expand quickly and dramatically. With respect to the current bio-methane production (upgraded biogas only), the EBA foresees a 10-fold increase in bio-methane production by 2030 and 26-fold by 2050.[32, 90] Given this pace, the execution time of construction projects may be the bottleneck for the transition. We have therefore investigated the typical project execution timelines for individual technologies within the biofuels supply chain.

Tables 4 and 5 show the results of this investigation. The numbers in these tables are valid in a European context and integrate the experience of project participants with numbers from the literature. The time required for feasibility studies, bidding, contract negotiation, and contract award is largely in the hands of the project owner. It can be limited to the duration of the feasibility study if the project owner also owns the technology, or it can last years for very complex projects. Similarly, the durations given for engineering, procurement, and construction are only indicative: construction projects can be somewhat accelerated if activities are run in parallel, or they can be delayed by unanticipated long-lead supplies, inadequate training of construction crews, and more.. Our results do not include execution of electrolysis projects due to the lack of relevant reference data on large-scale project execution times. Once large-scale electrolysis becomes fully commercial, project development times in line with other chemical synthesis projects seem realistic. However, there is still uncertainty as to when electrolysis will be ready for full commercial deployment.

The time needed to obtain permits requires special consideration. In Europe, it may take several years to achieve a permit decision for construction projects that may cause important environmental impacts or risks to health and safety. Both onshore and offshore wind power installations, for example, require compliance with applicable legislation (including potentially tens of regulations addressing various aspects of the impacts); extensive analysis of the natural conditions prior, during, and after the construction work; mitigation strategies; local acceptance; and so on. Hence, it is not uncommon for European wind power projects to take 8 – 9 years to achieve a permit decision, bringing the total timeline for the project to 10 – 12 years. The EU is acutely aware of this problem and has initiated activities to reduce permitting times for some renewable energy project categories.[91] In a separate study, the MMMCZCS found that permitting is less lengthy in other countries than in the EU — however, rollout of renewable electricity manufacturing projects might also be delayed by availability of raw material and labor.[92]

At the opposite end of the spectrum, the project timeline for a biogas-based LBM production plant, including anaerobic digestion, desulfurization, upgrading, and liquefaction, is in the range of 3 – 4 years. The process may be longer for a plant involving catalytic synthesis, with timelines for catalytic methanation and methanol production projects requiring 5-6 years including permitting. As CO_2 methanation and methanol synthesis also require large amounts of electrical power, if the regulatory framework requires biofuel production to receive electrical power from a renewable energy plant built for that specific purpose, the permitting process might again become an important bottleneck.

A permitting and construction time for biofuel projects in the range of 3 – 4 years is compatible with the construction time of a new ship. Shipping operators may improve their ability to control and reduce the cost of decarbonization by investing in carefully selected manufacturing pathways and ensuring long-term supply agreements of biofuels with known emissions reductions and prices. Furthermore, we suggest those shipping operators who have not yet settled on a specific biofuel should consider approaching decarbonization with a “project first” mindset. This mindset implies that an operator may consider first selecting and investing in a biofuel project that affords an attractive total cost of ownership and securing the long-term biofuel supply regardless of the biofuel type. The operator should only then procure and build the ships that can operate on that biofuel.

Table 4: Representative project execution timeline for securing biomass supply.

Project execution steps	Time to secure/develop biomass supply (months)
Search for new supply opportunity	6
Feasibility study	3
Design of supply chain	2
Permitting	1
Setup of logistics	1

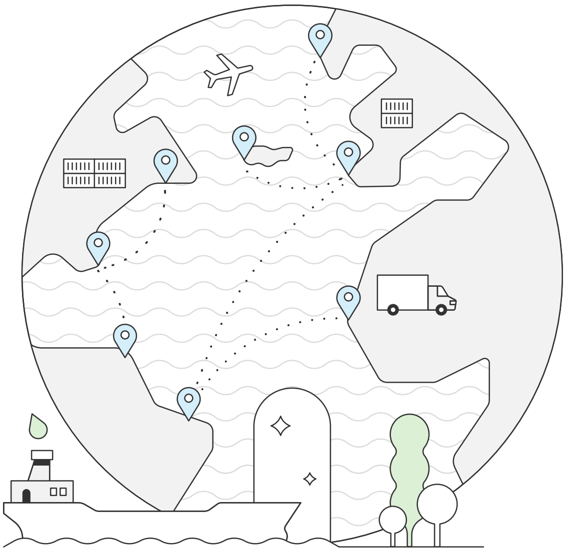
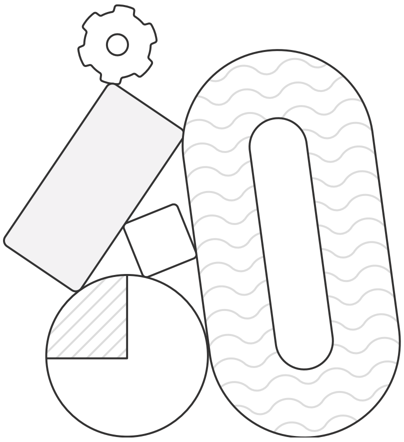


Table 5: Typical execution timeline of construction projects relating to biofuel production (all times given in months; TPD = tonnes per day).

Project execution steps	Anaerobic digestion/ pre-treatment	Desulfurization	Upgrading	Liquefaction	Renewable power (wind, onshore)[93]	Renewable power (wind, offshore (e.g., from UK))	Renewable power (solar)‡‡	Catalytic methanation	Methanol synthesis	CCS[94]
Feasibility study	2	0	3-4		2-4	Pre-bid: 12-24	12	3	3	?
Bidding, contract negotiation and award	0-6	0-6	0-6	0-6	6-12	6-12	0-6	2-12	2-12	?
Basic engineering	6	1	3	< 6	48-96	Post-bid: 60	40-48	6	6	36-48
Permitting	12	12	12	12 (part of biogas permitting)				9-15	9-15	
Detailed engineering	4	1	8	14-16 (10-100 TPD) 20-22 (180-300 TPD)	6-12	24	16-24	30	30	36-48
Procurement	2	1	9-12							
Construction	14	1	2		10-14	36				
Commissioning	6	2	1		2-4	1	1	2	2	



---

‡‡ https://www.seia.org/research-resources/development-timeline-utility-scale-solar-power-plant

3. Conclusions

Biogas, a mixture of mainly methane and CO_2, can be easily converted into a variety of biofuels of interest to the shipping industry. This report studies the main characteristics of biogas-based manufacturing value chains of liquified bio-methane and bio-methanol with regard to availability, current and future perspectives for commercial deployment, and sustainability. We conclude that biogas can be an important source of low-carbon fuels for shipping, especially during the early stages of the industry's transition away from fossil fuels.

Biogas is manufactured from anaerobic digestion of a large variety of feedstocks, most interestingly many types of waste — thereby sidestepping debates on food versus energy, land use change, and biodiversity — and there is waste capacity worldwide to support thousands of plants. The basic process for producing biogas is well understood and already applied in thousands of plants globally.

Most biogas plants worldwide are small to medium-sized, belonging to an era in which anaerobic digestion was seen as a waste treatment option rather than an energy source. Nevertheless, even small plants can give a valuable contribution to decarbonization of shipping in the early stage of the transition, when decarbonization targets are still low. For example, a biogas plant producing 1,000 Nm^3/h bio-methane (~5,500 – 6,000 t/y) with a 'zero' GHG emissions intensity is sufficient to ensure compliance with the FuelEU Maritime 2030 target for a fleet using approximately 120,000 t/y HFO.

Large plants are attractive because of the economy of scale and simplicity of procurement for large off-takers. Large biogas plants can be built, but careful consideration of the feedstock sourcing strategy must be applied regarding feedstock availability and prices. Large biogas and bio-methane capacity can, however, also be obtained by aggregating the raw biogas from multiple plants via dedicated pipelines, or aggregating bio-methane by leveraging the existing natural gas networks in many parts of the world.

Biogas can be upgraded into bio-methane through established separation processes. Liquefaction of bio-methane even in small plants is also well known. Liquified bio-methane (LBM) is a "drop-in" fuel for LNG-powered ships, which already enjoy extensive port infrastructure. Overall, the value chain to bunkered LBM from biogas can be established using known technologies.

As an alternative to upgrading, biogas can be converted into bio-methanol, or the bio-methane content can be further enhanced by converting CO_2 into methane via the SNG process. Both processes use green hydrogen, obtained via electrolysis using renewable electricity and water. Some of these conversion processes are known from large-scale fossil-energy-based manufacturing routes and can benefit from that experience. However, green hydrogen manufacturing does not yet exist at a large scale. Infrastructure for bio-methanol storage exists in many ports, since methanol is a globally traded molecule, and bunkering infrastructure is also emerging. All in all, the value chain to bunkered bio-methanol from biogas is somewhat less developed than that for LBM, and some maturation is required before widespread use.

Virtual infrastructure to trade green certificates for biogas to enable mass balancing is appearing and being developed in front-running examples of legislation. Similarly, book and claim systems to trade the green attributes of biofuels are also being established in public and private settings. Both green certificate trading and book and claim systems are important means to reduce the total cost of ownership of biofuels and support sustainability.

The sustainability of the value chain may be challenged in many ways. Unsustainable origin of feedstocks, electricity, and/or hydrogen, as well as methane emissions to the atmosphere, can erase the sustainability benefits that these biogas-based biofuel value chains aim to achieve. It is therefore of utmost importance to understand a value chain well, to use only certified products and operations, and to scrutinize all elements of the value chain against fraud, which unfortunately can be seen when control is lacking.

Finally, we examined the scope for short-term scale-up of these biofuel production pathways. Permitting and construction of a traditional, fully commercial bio-methane plant takes 3–4 years, while biofuels requiring green hydrogen may require longer. Interestingly, a timeframe of 3–4 years is compatible with the time for construction of a new ship. Shipping operators might want to consider whether investing in economically attractive biofuel value chains before ordering new ships can offer opportunities to de-risk their bunker procurement and decarbonization strategies.

4. The project team

This report was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners.

Lead author
Roberta Cenni (MMMCZCS).

Contributing authors and project participants
Joachim Jacobsen (Topsoe), Siddharth Dwivedi (Topsoe), Loic Francke (TotalEnergies), Federica Conti (Norden), Anker Jacobsen (Ammongas), Stephane Bosc (Ammongas), Alexander Ryhl (Ammongas), Thorkil Dahlgreen (BiogasClean), Jesper Hørlyk-Jensen (BiogasClean), Peter Thygesen (BiogasClean), Derya Topcu (E.ON), Michael Bruhn (E.ON), Rene Korsholm (E.ON), Anton Jell (Linde Engineering), Josef Schwarzhuber (Linde Engineering), Hugo Villalba (Novonesis, formerly Novozymes), Adrian Rochefort (Novonesis, formerly Novozymes), Einar Gudmundsson (Rambøll), Magnus Folkelid (Wärtsilä), Frank Harteveld (Wärtsilä), Peter Jonathan Jameson (Boston Consulting Group), Maurice Jansen (Boston Consulting Group), Kevin Maloney (Boston Consulting Group), Jacob Hjerrild Zeuthen (Maersk), Ester Ceriani (MMMCZCS), Harshil Desai (MMMCZCS).

Steering committee
Jean Bernard (TotalEnergies), Keith Dawe (Cargill), Estela Vázquez Esmerode (MMMCZCS), Kim Grøn Knudsen (Topsoe), Torben Nørgaard (MMMCZCS), Henrik Røjel (Norden), Maria Strandesen (Maersk).

Reviewers
Torben Nørgaard (MMMCZCS), Federica Conti (Norden).

For insightful conversations, we would like to acknowledge
Bodil Kliem (Anaergia), Jens Peter Lunden (Asdal Hovedgaard), Erik Lundsgaard, (Solrød Bioenergi – Bigadan), Helle Gottschalk Nygård (DGC), Bettina Knudsen (Explicit), Søren Tafdrup (Energistyrelse), Jeppe Bjerg (Energinet), Torben Brabo (Energinet), Niels Franck (Energinet), Signe Sonne (Energinet), Tine Lindgren (Energinet), Harmen Dekker (European Biogas Association), Martin Therkildsen (Evida), Jesse Scharf (Green Gas Certification Scheme), Steen Hintze (GreenPort North), Anker Laden-Andersen (Hjulmand Kaptajn), Jan Liebetrau (IEA Task 37), Barbara Jinks (IRENA), Imen Gherboudj (IRENA), Georges Tijbosch (MIQ), Saima Yarrow (MIQ), Troels Vittrup Christiansen (Nature Energy), Kurt Hjort-Gregersen (Teknologisk Institut), Charlotte Morton (World Biogas Association), Josh Hawthorne (World Biogas Association).

Editors
Matilda Handsley-Davis (MMMCZCS),
Emily Nordvang (MMMCZCS),
Asha Mahadevan (MMMCZCS).

Design
Tina Milosevic (By Milo).

Abbreviations

AD	Anaerobic digester or digestion
bcm	Billion cubic meters
CCS	Carbon capture and storage or sequestration
CH_4	Methane
CHP	Combined heat and power
CNG	Compressed natural gas
CO_2	Carbon dioxide
CO_2eq	CO_2 equivalent
COP	Conference of the Parties
DBFZ	Deutsches Biomasseforschungszentrum
EBA	European Biogas Association
EJ	Exajoule (1x10^{18} joules)
F (subscript)	Fossil
GHG	Greenhouse gas
GJ	Gigajoule (1x10^{9} joules)
GLEC	Global Logistics Emissions Council
GMO	Genetically modified organisms
GWP	Global warming potential
h	Hour
HFO	Heavy fuel oil
IEA	International Energy Agency
IMO	International Maritime Organization
ISCC	International Sustainability and Carbon Certification
ISO	International Organization for Standardization
km	1,000 meters
L	Liter
LBM	Liquified bio-methane (same as LBG: liquified biogas or bio-LNG)
LNG	Liquified natural gas
m^3	Cubic meter
MJ	Megajoule (1x10^{6} joule)
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
Mt	Million (or mega) tonnes
NM	Nautical mile (1,852 km)
Nm^3	Normal cubic meter
PPA	Power purchasing agreement
RED	Renewable Energy Directive of the European Union
RSB	Roundtable on Sustainable Biomaterials
SNG	Synthetic or substitute natural gas: an almost pure stream of methane resulting from the catalytic or biological reaction of CO_2 with hydrogen
t	tonnes, metric tons (1,000 kg)
TOE	Tonnes of Oil Equivalent (calculated for low calorific value of 42.6 kg/MJ)
TPD	Tonnes per day
TSO	Transmission system operator
TWh	Tera (1x10^{12}) watt-hour
WBA	World Biogas Association
WTW	Well-to-wake
y	Year

References

1 Oehmichen, K. et al. Technical principles and methodology for calculating GHG balances of biomethane. DBFZ (2016). https://www.dbfz.de/fileadmin/user_upload/Referenzen/Broschueren/Handreichung_Biomethane_englisch.pdf.

2 Kasinath, A. et al. Biomass in biogas production: Pretreatment and codigestion. Renewable and Sustainable Energy Reviews 150, (2021). https://www.sciencedirect.com/science/article/pii/S1364032121007887

3 IEA. Outlook for biogas and Prospects for organic growth World Energy Outlook Special Report biomethane. (2020) https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth.

4 World Biogas Association. Global potential of biogas (2019). https://www.worldbiogasassociation.org/wp-content/uploads/2019/09/WBA-globalreport-56ppa4_digital-Sept-2019.pdf.

5 Global Natural Gas Production | World gas natural statistics | Enerdata. https://yearbook.enerdata.net/natural-gas/world-natural-gas-production-statistics.html.

6 Alternative Fuels Insight. https://afi.dnv.com/Map.

7 Interactive World LNG Dashboard | V4.0. http://gulf-pub-gisstg.esriemcs.com/pe_exxonmobil_dash/tabs/LNG.html.

8 European Renewable Gas Registry. ERGaR: Web page. https://www.ergar.org/.

9 ISO 23306:2020 - Specification of liquefied natural gas as a fuel for marine applications. https://www.iso.org/standard/75199.html.

10 Lam, J.S.L, Piga, B. & Zengqi, X. Role of bio-LNG in shipping industry decarbonisation (2022). https://safety4sea.com/wp-content/uploads/2022/10/Sea-LNG-Role-of-bio-LNG-in-shipping-industry-decarbonisation-2022_10.pdf.

11 Understanding methane emissions – Global Methane Tracker 2023 – Analysis - IEA. https://www.iea.org/reports/global-methane-tracker-2023/understanding-methane-emissions#abstract.

12 Clarke, D. New estimates provide insights on CO_2 emissions from global shipping. OECD Statistics Blog (2023). https://oecdstatistics.blog/2023/06/15/new-estimates-provide-insights-on-co2-emissions-from-global-shipping/.

13 Global methanol production 2022 | Statista. https://www.statista.com/statistics/1323406/methanol-production-worldwide/.

14 Yang, M. et al. Atmospheric deposition of methanol over the Atlantic Ocean. Proc Natl Acad Sci U S A 110, 20034–20039 (2013).

15 Ashurst, J. V. & Nappe, T. M. Methanol Toxicity. StatPearls (2022).

16 Kaviraj, A., Bhunia, F. & Saha, N. C. Toxicity of Methanol to Fish, Crustacean, Oligochaete Worm, and Aquatic Ecosystem. Int J Toxicol 23, 55–63 (2004).

17 Together in Safety. Future Fuels Risk Assessment (2022). https://togetherinsafety.info/wp-content/uploads/2022/06/Future-Fuels-Report.pdf.

18 Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. On-Demand Webinar | Reducing methane emissions onboard vessels (2022). https://www.zerocarbonshipping.com/news/webinar-reducing-methane-emissions-onboard-vessels-2-2/ .

19 Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. Reducing methane emissions on board vessels (2022). https://www.zerocarbonshipping.com/publications/reducing-methane-emissions-onboard-vessels/.

20 Lemvig Biogas. Affald (n.d.). https://lemvigbiogas.com/.

21 Tudge, S. J., Purvis, A. & De Palma, A. The impacts of biofuel crops on local biodiversity: a global synthesis. Biodivers Conserv 30, 2863–2883 (2021).

22 European Parliament & Council of the European union. Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (2023). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.234.01.0048.01.ENG&toc=OJ%3AL%3A2023%3A234%3ATOC.

23 Paulista, L. O., Boaventura, R. A. R., Vilar, V. J. P., Pinheiro, A. L. N. & Martins, R. J. E. Enhancing methane yield from crude glycerol anaerobic digestion by coupling with ultrasound or A. niger/E. coli biodegradation. Environmental Science and Pollution Research 27, 1461–1474 (2020).

24 Pedersen, M. Nyt biogasanlæg i Solrød en realitet: Skal også køre på madaffald – Energy Supply (2021). https://www.energy-supply.dk/article/view/815391/nyt_biogasanlaeg_i_solrod_en_realitet_skal_ogsa_kore_pa_madaffald.

25 Kristensen, E. Nyt biogasanlæg forvandler madvarer til grøn energi - Nyhed - Sjællandske Nyheder (2023). https://www.sn.dk/solroed-kommune/nyt-biogasanlaeg-forvandler-madvarer-til-groen-energi/.

26 Smart Freight Centre. Global Logistics Emissions Council (GLEC) Framework for Logistics Emissions Accounting and Reporting, version 3.0 (2023). https://smart-freight-centre-media.s3.amazonaws.com/documents/GLEC_FRAMEWORK_v3_UPDATED_25_10_23.pdf.

27 About Task 37 - IEA Bioenergy Task 37. https://task37.ieabioenergy.com/about-task-37.html.

28 World Biogas Association | Making biogas happen. https://www.worldbiogasassociation.org/.

29 European Biogas Association. https://www.europeanbiogas.eu/.

30 Scientific assignment | Deutsches Biomasseforschungszentrum. https://www.dbfz.de/en/the-dbfz/scientific-assignment.

31 Liebetrau, J., Reinelt, T., Agostini, A. & Linke, B. Methane emissions from biogas plants: Methods for measurement, results and effect on greenhouse gas balance of electricity produced (2018). https://www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf.

32 European Biogas Association. Biomethane Map 2022-2023 | European Biogas Association. https://www.europeanbiogas.eu/wp-content/uploads/2023/05/GIE_EBA_Biomethane-Map-2022-2023.pdf.

33 REPowerEU. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131.

34 Home | Statistical Review of World Energy. https://www.energyinst.org/statistical-review.

35 EnergiNet. Biomethane. https://en.energinet.dk/gas/biomethane/.

36 European Biogas Association. Record-breaking year for biomethane production – shows EBA/GIE Biomethane Map 2021 | European Biogas Association. https://www.europeanbiogas.eu/record-breaking-year-for-biomethane-production-shows-eba-gie-biomethane-map-2021/.

37 Gustafsson, M., Ammenberg, J. & Murphy, J. IEA Bioenergy Task 37 - A perspective on the state of the biogas industry from selected member countries (2022). https://www.ieabioenergy.com/wp-content/uploads/2022/03/IEA_T37_CountryReportSummary_2021.pdf.

38 European Biogas Association. EBA Statistical Report 2022 – open interactive version (2022). https://www.europeanbiogas.eu/SR-2022/EBA/.

39 Gas Infrastructure Europe (GIE) & European Biogas Association (EBA). European biomethane map 2021 (2022). https://www.europeanbiogas.eu/wp-content/uploads/2022/01/GIE_EBA_BIO_2021_A0_FULL_3D_253_online.pdf.

40 World Biogas Association. Anaergia's Tønder Plant will Supply CO_2 to European Energy A/S for Green E-Methanol Production as Fuel for Container Ships (2022). https://www.worldbiogasassociation.org/member-press-release-anaergias-tonder-plant-will-supply-co2-to-european-energy-a-s-for-green-e-methanol-production-as-fuel-for-container-ships/.

41 Andersen, L. F., Parsin, S., Lüdtke, O. & Kaltschmitt, M. Biogas production from straw—the challenge feedstock pretreatment. Biomass Convers Biorefin 12, 379–402 (2020).

42 Kinetic Biofuel. Briquetted straw more than doubles biogas production (2015). https://issuu.com/kineticbiofuel/docs/a4_8siders_brochure_uk_print-mq.

43 Gustafsson, M. & Ammenberg, J. IEA Bioenergy Task 37 - Country Report Summaries 2019. (2020). https://www.ieabioenergy.com/wp-content/uploads/2020/03/IEA-Task-37-Country-Report-Summaries-2019-1.pdf.

44 Danmarks Statistik. NYT: Fjernvarme og naturgas mest udbredt opvarmning (2022). https://www.dst.dk/da/Statistik/nyheder-analyser-publ/nyt/NytHtml?cid=37833.

45 NIRAS. Miljorapport for udvidelsen af biogasanlægget Nature Energy Hemmet (2021). Please contact Ringkøbing Kommune for access to the report.

46 Falkengaard, M.J. Ineos plans to send biogas plant CO_2 to North Sea storage - EnergyWatch (2022). https://energywatch.com/EnergyNews/Cleantech/article14646451.ece.

47 Evida. Nyt banebrydende samarbejde om fangst og lagring af biogen CO_2 i Nordjylland (2022). https://evida.dk/nyheder/greenport-scandinavia/.

48 Clean Air Task Force. Europe Carbon Capture Project Map. https://www.catf.us/ccsmapeurope/.

49 European Biogas Association. The REPowerEU puts forward a Biomethane Action Plan to scale-up the sector by 2030 (2022). https://www.europeanbiogas.eu/the-repowereu-puts-forward-a-biomethane-action-plan-to-scale-up-the-sector-by-2030/.

50 Arasto, A. et al. Bioenergy's role in balancing the electricity grid and providing storage options - an EU perspective (2017). https://www.researchgate.net/publication/319396133.

51 Global Energy Monitor. Global Gas Infrastructure Tracker. https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/tracker/.

52 Green Attributes Definition: 561 Samples | Law Insider. https://www.lawinsider.com/dictionary/green-attributes.

53 Sino-German Energy Partnership. Green certificates: trends and ideas from Europe and U.S. (n.d.). | https://www.energypartnership.cn/home/green-certificates-trends-and-ideas-from-europe-and-north-america/.

54 EnergiNet. Guarantees of origin for renewable gas (n.d.). https://en.energinet.dk/gas/biomethane/go-gas/.

55 European Parliament and Council of the European Union. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. Official Journal of the European Union (2018). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001&qid=1702036869219.

56 Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. Maritime Book & Claim (2023). https://www.zerocarbonshipping.com/publications/maritime-book-claim/.

57 Gudmundsson, E. et al. Målrettet indsats for at mindske metantab fra danske biogasanlaeg, Energistyrelsen (2021). https://ens.dk/sites/ens.dk/files/Bioenergi/metantab_rapport.pdf.

58 Homepage | Global Methane Pledge. https://www.globalmethanepledge.org/.

59 International Energy Agency. Policy database – Data & Statistics - IEA. https://www.iea.org/policies?topic%5B0%5D=Methane%20abatement.

60 European Biogas Association. Design, build, and monitor biogas and biomethane plants to slash methane emissions. (2023). www.europeanbiogas.eu/design-build-and-monitor-biogas-and-biomethane-plants-to-slash-methane-emissions/.

61 Klinge, N. BP buys US biogas company for $4.1 billion | Upstream Online (2022). https://www.upstreamonline.com/energy-transition/bp-buys-us-biogas-company-for-4-1-billion/2-1-1336850.

62 Shell to acquire renewable natural gas producer Nature Energy | Shell Global (2022). https://www.shell.com/media/news-and-media-releases/2022/shell-to-acquire-renewable-natural-gas-producer-nature-energy.html.

63 TotalEnergies picks up pace in biogas | TotalEnergies.com (n.d.). https://totalenergies.com/infographics/totalenergies-picks-pace-biogas.

64 Harvey Gulf's PSV running on bio-LNG and battery power - LNG Prime (2022). https://lngprime.com/americas/harvey-gulfs-psv-running-on-bio-lng-and-battery-power/41605/.

65 Biogas - Furetank Secures Biogas Supply as Step Towards Fossil-Free Shipping - Renewable Energy Magazine (2022). https://www.renewableenergymagazine.com/biogas/furetank-secures-biogas-supply-as-step-towards-20220217.

66 Sönne, M. Biogasresan 2: Flytande gas för tunga transporter. Linköpings universitet (2019). https://liu.se/nyhet/biogasresan-2-flytande-gas-for-tunga-transporter.

67 Gasum. Turku biogas plant (n.d.). https://www.gasum.com/en/About-gas/biogas/Biogas-plants/turku-biogas-plant/.

68 Gasum. Nymölla biogas plant in Sweden (n.d.) . https://www.gasum.com/en/our-operations/biogas-production/biogas-plants/nymolla-biogas-plant/.

69 Wärtsilä Gas System. Wärtsilä biogas liquefaction plant | EGE Biogass, Oslo, Norway. (2014).

70 Habibic, A. Largest component for Germany's bio-LNG plant arrives in Rostock - Offshore Energy (2022). https://www.offshore-energy.biz/largest-component-for-germanys-bio-lng-plant-arrives-in-rostock/.

71 Habibic, A. HAM Group, CycleØ to build and operate first bioLNG plant in Chile - Offshore Energy (2022). https://www.offshore-energy.biz/ham-group-cycleo-to-build-and-operate-first-biolng-plant-in-chile/.

72 Elengy. MetamorFos: a liquefaction project for household waste biogas coming from the Marseilles Provence metropolis (2022). https://www.elengy.com/en/media/our-projects-making/metamorfos-liquefaction-project-household-waste-biogas-coming-marseilles-provence-metropolis.

73 Nature Energy. Grønt brændstof til skibe og lastbiler kan tankes i Frederikshavn (2022). https://nature-energy.com/dk-da/nyheder/gront-braendstof-til-skibe-og-lastbiler-kan-tankes-i-frederikshavn.

74 Titan to build the world's largest biomethane liquefaction plant - Titan LNG (2022). https://titan-cleanfuels.com/titan-to-build-the-worlds-largest-biomethane-liquefaction-plant/.

75 Czechanowsky, T. Construction of Shell's Bio-LNG plant in Cologne-Godorf starts - energate messenger (2022). https://www.energate-messenger.com/news/219960/construction-of-shell-s-bio-lng-plant-in-cologne-godorf-starts.

76 Gothenburg: Swedegas in liquefied biogas agreement with FordonsGas. Manifold Times (2019). https://www.manifoldtimes.com/news/gothenburg-swedegas-in-liquefied-biogas-agreement-with-fordonsgas/.

77 European Biogas Association. TOTAL and CMA CGM Complete World's Largest Liquified Natural Gas Bunkering Operation at Port of Rotterdam (2020). https://www.europeanbiogas.eu/total-and-cma-cgm-complete-worlds-largest-liquified-natural-gas-bunkering-operation-at-port-of-rotterdam/.

78 DNV. Alternative Fuels Insights for the shipping industry – AFI platform. https://www.dnv.com/services/alternative-fuels-insight-128171.

79 CMA CGM. CMA CGM launches the first low-carbon shipping offer by choosing biomethane (2021). https://www.cma-cgm.com/news/3643/cma-cgm-launches-the-first-low-carbon-shipping-offer-by-choosing-biomethane?cat=corporateinformation.

80 Biofuels International. World's largest biomethanol plant begins production (2010). https://biofuels-news.com/news/worlds-largest-biomethanol-plant-begins-production/.

81 BASF. BASF news release | BASF produces methanol according to the biomass balance approach. (2018) https://www.basf.com/global/en/media/news-releases/2018/11/p-18-370.html.

82 Sporrer, A. Maersk invests in bio-methanol production company WasteFuel - FreightWaves (2021). https://www.freightwaves.com/news/maersk-invests-in-bio-methanol-production-company-wastefuel

83 All Certificates – ISCC System. https://www.iscc-system.org/certification/certificate-database/all-certificates/.

84 REDcert. Zertifizierungssystem REDcert. https://redcert.eu/ZertifikateDatenAnzeige.aspx.

85 RSB Participating Operators Certification. https://rsb.org/certification/rsb-certificates/.

86 GoodFuels, Norden, Control Union and IDS Group successfully test isotopic tracer for marine biofuels GoodFuels - (2022). https://www.goodfuels.com/news/isotop-ic-tracer-for-marine-biofuels.

87 Hurtes, S. & Cai, W. Europe Is Sacrificing Its Ancient Forests for Energy - The New York Times (2022). https://www.nytimes.com/interactive/2022/09/07/world/europe/eu-logging-wood-pellets.html?searchResultPosition=1.

88 Carr, D. Grease thieves, corn oil and fraud: How biofuel scam artists bilked U.S. taxpayers of billions | Environmental Working Group (2021). https://www.ewg.org/news-insights/news/grease-thieves-corn-oil-and-fraud-how-biofuel-scam-artists-bilked-us-taxpayers.

89 Browning, N. & Blenkinsop, P. Germany triggers EU investigation into Chinese biofuels | Reuters (2023). https://www.reuters.com/business/energy/germany-triggers-eu-investigation-into-chinese-biofuels-sources-2023-06-07/.

90 Alberici, S., Grimme, W. & Toop, G. Biomethane production potentials in the EU: Feasibility of REPowerEU 2030 targets, production potentials in the Member States and outlook to 2050. Gas for Climate & Guidehouse (2022). https://www.europeanbiogas.eu/wp-content/uploads/2022/07/GfC_Biomethane-potentials_2022.pdf.

91 Consilium. EU to speed up permitting process for renewable energy projects (2022). https://www.consilium.europa.eu/en/press/press-releases/2022/11/24/eu-to-speed-up-permitting-process-for-renewable-energy-projects/.

92 Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. Will renewable electricity availability limit e-fuels in the maritime industry? (2023). https://www.zerocarbonshipping.com/publications/will-renewable-electricity-availability-limit-e-fuels-in-the-maritime-industry/.

93 Irish Wind Energy Association. Life-cycle of an Onshore Wind Farm (2019). https://windenergyireland.com/images/files/iwea-onshore-wind-farm-report.pdf.

94 Global CCS Institute. Scaling up the CCS Market to Deliver Net-Zero Emissions (2020). https://www.globalccsinstitute.com/wp-content/uploads/2020/04/Thought-Leadership-Scaling-up-the-CCS-Market-to-Deliver-Net-Zero-Emissions-Digital-6.pdf.

Visit our website for more
zerocarbonshipping.com

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping