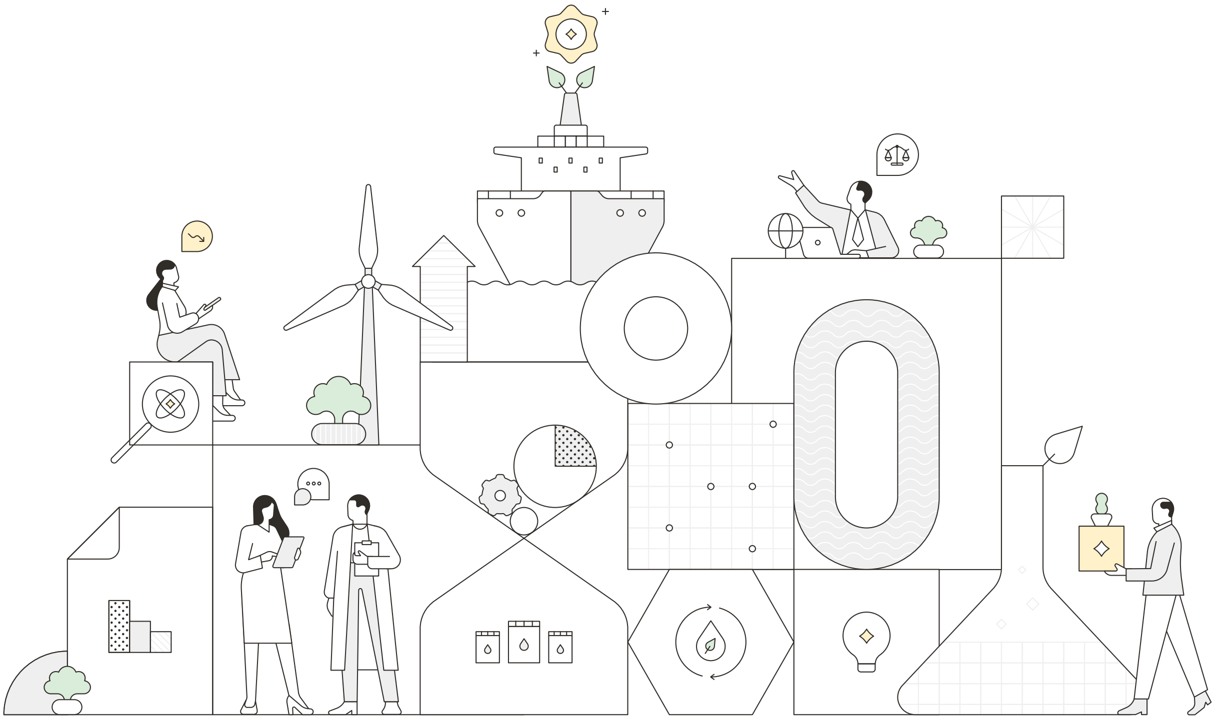
Biogas as a Source of Biofuels for Shipping

Biomass Availability

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 biomass, 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).

As the maritime industry moves to develop sustainable means of shipping the world's goods, it does so along with other difficult-to-decarbonize industries. The International Energy Agency (IEA) estimates that marine shipping currently consumes around 11 exajoules per year (EJ/y) of mostly petroleum-derived fuel. This is only a small fraction of the global energy supply, which exceeds 600 EJ/y, according to the IEA. A sustainable future will need to effectively address the energy needs of both shipping and other industries and applications.

Biofuel manufacturing routes based on biogas are appealing solutions, as they incorporate fully commercial technologies, rely on broadly available infrastructure, and can be based on waste biomass — thereby helping to solve waste accumulation problems. However, biofuels' potential as a transitional or long-term solution to energy needs is hotly debated. A key question in this debate is whether the world produces sufficient biomass to make a difference to fossil fuel consumption — and if so, then how much of a difference. Therefore, this study examines issues surrounding sustainable biomass supply estimates and translates these findings to the context of LBM and bio-methanol production from biogas.

Searching the literature reveals a very wide range of estimates for global biomass potential, with very different implications for biofuels' role in the global energy transition. Our best estimate is approximately 100 EJ/year, including a curtailed availability of energy crops — which are only permitted in certain geographies due to competition with food and biodiversity — and of unconventional biomass resources, such as those grown on low-producing land.

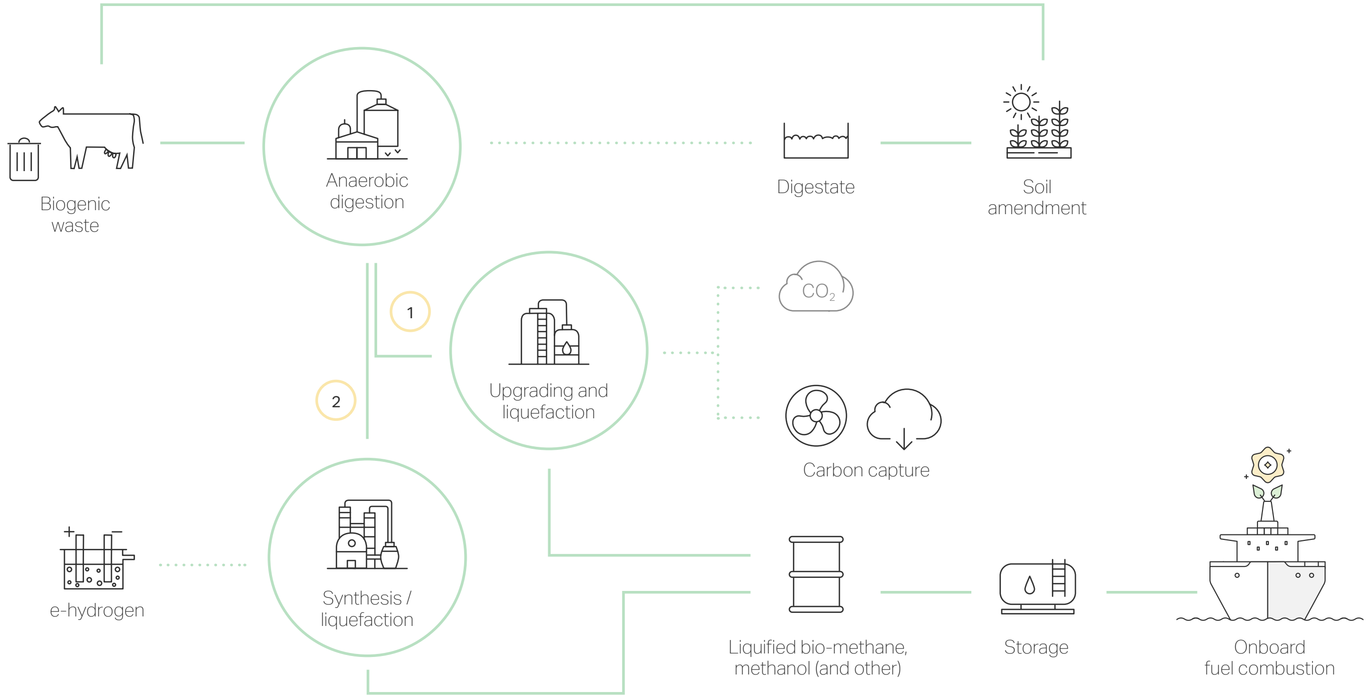
Other publications in our "Biogas as a source of biofuels for shipping" series have studied the conversion of biomass to bio-methane and bio-methanol from biogas and the well-to-wake greenhouse gas emissions of selected LBM and bio-methanol production pathways. The biofuel yields vary depending on the feedstock type and manufacturing processes. Based on our above estimate of global biomass availability, we estimate that if all biomass were converted to one individual biofuel, the global energy potential would be approximately 50-120 EJ/year for LBM and around 50-90 EJ/year for bio-methanol.

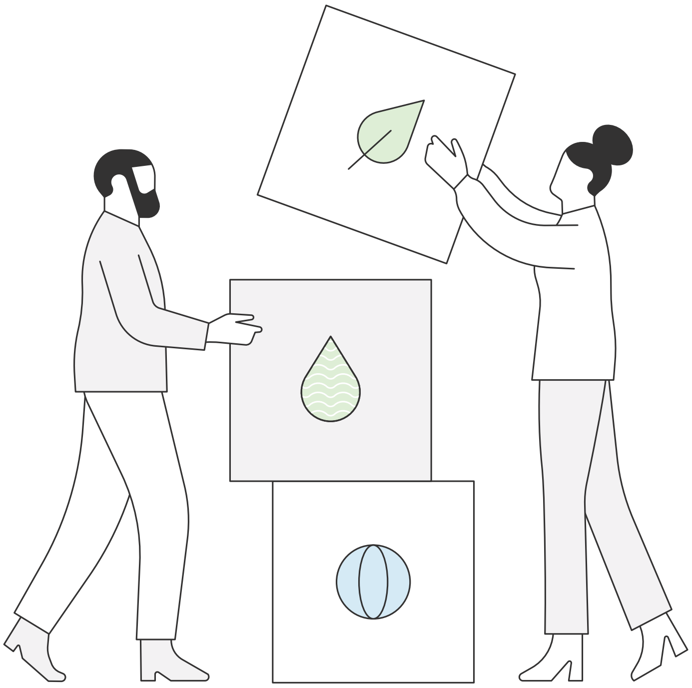
Importantly, demand for biofuels will not necessarily be determined purely by energy use, but also by these fuels' capacity to reduce greenhouse gas (GHG) emissions. We, therefore, analyzed selected manufacturing processes for LBM and bio-methanol from biogas in the context of both biomass requirements and emissions reduction potential. We find that these biofuels could help the shipping industry meet the Paris Agreement's 2030 goal of 40% GHG emissions reduction using only 5-10 EJ/y of biomass, which is 5-10% of our total availability estimate. The exact biofuel volume depends on both the fuels' associated emissions intensity and the efficiency of converting biomass to biofuels.

Similar to biomass availability estimates, biomass demand estimates vary widely in the literature. While the development of alternative energy carriers for industrial and residential use may reduce future biomass demand, biofuels are currently one of the most available and cheapest options. Hence, we anticipate intense competition for these fuels in the short term. We therefore recommend that shipping operators look upstream and consider how to vertically integrate the biofuel supply chain for shipping to ensure adequate volumes and potentially improved price management.

Finally, we highlight that uncertainty in data and other factors contributes to the large ranges in current estimates of biomass potential, and therefore of biofuel potential. Further research should seek to achieve more local analyses of biomass availability, harmonization of land use change methodology, and more global application of food versus fuel and biodiversity balancing.

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





1. Introduction

Switching from fossil-based fuels to alternative marine fuels is a key prerequisite for decarbonization of the shipping industry. Biogas-based biofuels represent an attractive option as part of the alternative fuel mix available to the industry, especially in the shorter term. Biogas is a gas composed mainly of methane and carbon dioxide (CO_2), produced by anaerobic digestion of biomass. Notably, biogas can be used to produce both liquified bio-methane (LBM), a drop-in replacement fuel for liquified natural gas (LNG), and bio-methanol, tapping into the growing industry interest in methanol-fueled vessels.

More detailed context on the background, advantages, and challenges surrounding these biogas-based biofuels can be found in our companion publication 'Biogas as a source of biofuels for shipping: insights into the value chain'. That report also lays out various manufacturing pathways for production of LBM and bio-methanol from biogas and highlights the diversity of options available for a biogas plant to integrate into current and plausible future energy infrastructure.

The scale at which these biofuels can alleviate future use of fossil fuels depends, in part, upon the available volumes of sustainable biomass. Understanding these volumes is, therefore, critical in estimating these biofuels' potential to decarbonize the industry and in establishing the strategic role for products like LBM and bio-methanol.

Existing studies report a wide range of estimated biomass availability values, creating uncertainty in industries that see biofuels as an important support for their decarbonization journey. In a shipping context, the current demand of approximately 11 exajoules per year (EJ/y) for marine fuels is projected to remain roughly constant towards 2050 in the International Energy Agency's (IEA) Net Zero Emissions and Announced Pledges scenarios.1 However, shipping will be competing for low-carbon-intensity solutions with other large energy users in hard-to-decarbonize sectors. For reference, the current global energy consumption is approximately 450EJ/y, which is the net useable from a total supply of nearly 650 EJ/y.[1]

This report highlights the issue of biomass availability and makes recommendations in the context of biogas-based biofuels such as LBM and bio-methanol. We explain some assumptions that lead to different estimates of biomass availability in the literature, and we discuss the importance of various biomass sources as well as the difficulties in defining biomass sustainability. We offer our own current best estimate of global biomass availability, which we then use as an input to calculate the likely availability of biogas-based LBM and bio-methanol for both shipping and other applications, as well as these biofuels' decarbonization and energy conversion efficiencies. Finally, we investigate the potential for LBM and bio-methanol to help the shipping industry meet its short- and mid-term emissions reduction targets against the backdrop of our biomass availability estimates.

1.1. About this project

This study forms part of a broader project established to understand the hurdles to a widespread adoption of biogas-based LBM and bio-methanol fuels in shipping and to offer strategies for resolving these hurdles.

This report is part of a series on “Biogas as a source of biofuels for shipping”. Other reports in the series deal with insights into the value chain, methane emissions, well-to-wake (WTW) greenhouse gas (GHG) emissions, energy demand for emissions reduction compliance, and techno-economic trends.

The project was a collaboration between the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (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 6.

Three webinars hosted by the MMMCZCS and various collaborators, which are available on the MMMCZCS website,[2,3,4] inform a large portion of the background knowledge for this study.

Our project partners

2. Biomass availability

Availability of suitable biomass is necessary to justify interest in biofuels in the first place. The MMMCZCS has followed this topic for some years and realized that available estimates of global biomass potential point to such disparate amounts that it is impossible to derive meaningful conclusions on the potential offered by this energy source without an extraordinary effort to consolidate results from the current literature. In the early months of 2022, we learned that a similar conclusion had been reached by a group of international companies forming the MIT Climate and Sustainability Consortium.[5] This group had tasked the Massachusetts Institute of Technology (MIT) to carry out the necessary consolidation work. The final results of this work are yet to be published at time of writing, but an excerpt of an earlier stage of the study was presented by its authors at a webinar hosted by MMMCZCS and the Clean Energy Ministerial – Biofuture Campaign in December 2022.[2]

The MIT team (Katrin Daehn, Evan Coleman, and Florian Allroggen, hereinafter Daehn et al) completed a broad survey of the published literature on biomass availability (roughly 80 articles) to capture the range of reported values and discuss the factors that drive the distribution of results. Daehn et al found that the overall range of reported values for waste biomass spans between 8 and 215 EJ/y. For energy crops, the range is even greater: between 2 and 1,200 EJ/y.[2] The study highlights how authors use different categories to group biomass sources, and decisions on grouping criteria are often determined by how source data is presented or by convenience in the data processing steps. Daehn et al also found that important differences among estimated values are related to how authors assess the sustainability of certain biomass types.[2] The study concludes that increased emphasis on sustainability is the reason for the progressive decrease in estimated biomass availability values over the years.[2] We further explore the topic of biomass sustainability in Info Box 1 and in our accompanying report on WTW GHG emissions.

The consolidation work by Daehn et al resulted in median biomass availability estimates of 56 EJ/y for waste biomass and 100 EJ/y for energy crops. Table 1 shows these estimates broken down by biomass source.

Table 1: Median biomass availability estimates according to Daehn et al.[2]

Biomass source	Biomass supply (EJ/y)
Agricultural residues and industrial wastes from food and beverage manufacture (husks, straw, and pulp left over from harvesting cash crops)	28
Manure and animal waste	13
Municipal waste (food waste and sewage)	6
Forestry residues	9
Energy crops (not allowed in all regulatory frameworks)	100

The median availability value for energy crops should be used with caution because, due to biodiversity and food versus energy concerns, the practice of using crops to generate energy is controversial and not accepted under certain regulatory frameworks. The FuelEU Maritime regulation, for example, specifically excludes biofuels generated from energy crops as relevant alternatives (see also Info Box 1).

Conversely, the study by Daehn et al did not include a few other categories of waste and biomass types that can be converted into energy: landfill gas, industrial wastes, recycled carbon, sequential crops, and biomass from regeneration of low-producing land. The results of a rapid literature search on each of these categories are shown in Table 2. Having learned the challenges of assessing biomass availability estimates,[2] this literature search is only meant to provide indicative values.

Of the categories included in Table 2, we note that the contribution of biomass from low-producing land is particularly attractive, both for the magnitude of its potential but also because this biomass is associated with emissions credits in some regulatory frameworks.[6] We also note a high theoretical potential from existing landfills and dumps. However, an in-depth study of whether the latter is a practical feedstock for biofuels was outside the scope of this project.

Table 2: Bioenergy sources not covered by the Daehn et al (MIT) review.

Category	Calculated energy availability	Reference
Landfill gas	38 Mt methane, or ~1.8 EJ/y	US EPA[7]
Industrial wastes from food and beverage production	6-18 EJ/y	IRENA[8]
Sequential, intermediate, and cover crops (typically annual grasses, oilseeds, or legumes)[9]	~175 Mt/y (mixed oil products) or ~7 EJ/y	World Economic Forum[10]
Biomass from degraded land[11]	25-32 EJ/y	Nijsen et al.[12]
Recycled carbon from currently mismanaged plastic waste	100 Mt/y or ~4 EJ/y	Ritchie[13]
Additional recycled carbon from already accumulated waste	We do not know the practical potential yet. By 2018, waste was being produced at a rate of ~2 billion t/y, 75% of which is amenable to combustion. 70% of this waste is disposed of in landfills and open dumps. Part of this potential is accounted for under 'landfill gas'.	The World Bank[14]

~ = approximately

To obtain an estimate of how much biomass is available for conversion into biofuels, we have combined the biomass availability estimates resulting from the study by Daehn et al (Table 1) with the estimates for additional sources of bioenergy (Table 2) in a separate Table 3. Table 3 also distinguishes the various sources based on their suitability for anaerobic digestion. Biomass sources that are not suitable for anaerobic digestion can be converted into biofuels using other processes, such as gasification or pyrolysis. Finally, remaining mindful of the controversial acceptance of energy crops and of the difficulties in generating global availability numbers, and with the intention of determining a conservative number for sustainable biomass availability, we curtail to 30% the availability of energy crops and some other uncertain categories. We conclude that a global estimate of approximately 100 EJ/y of biomass suitable for anaerobic digestion is realistic (Table 3).

Table 3: Total and sustainable biomass availability estimates, by biomass type.

Suitable for anaerobic digestion	Biomass supply (EJ/y)	Note	Sustainable biomass supply (EJ/y)
Agricultural residues and industrial wastes from food and beverage manufacture (husks, straw, and pulp leftover from harvesting cash crops)	28	-	28
Manure and animal waste	13	-	13
Municipal waste (food waste and sewage)	6	-	6
Energy crops (not allowed in all regulatory frameworks)	100	Due to controversial use, we consider only one third	~33
Landfill gas, sequential crops, biomass from degraded land (qualitative from this study, uncertainties in the economic availability)	~50	Due to uncertain estimates, we consider only one third	~17
Total	~200 EJ/y	-	~100 EJ/y
Suitable for gasification, pyrolysis etc. but not for anaerobic digestion		-	
Forestry residues	9	-	9
Recycled carbon from currently mismanaged plastic waste (qualitative from this study)	~4	Due to uncertain estimates, we consider only one third	1
Other non-methane recycled carbon in existing landfills and dumps	-	Data not available yet	-

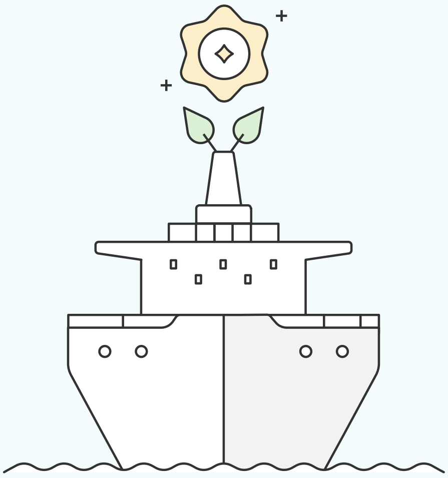
~ = approximately

INFO BOX 1

Sustainable biomass – are the same constraints applied everywhere?

Our investigation of the literature on biomass availability also highlights challenges in defining the very concept of 'sustainable biomass'. At the MMMCZCS, we define sustainable biomass as: "Biomass that has been cultivated and/or sourced from a system of agricultural practices aimed at maintaining the relevant ecological, economic, and social functions of the land used to cultivate the biomass now and in the future."

Translating this definition into a regulatory framework is not simple, as these ecological, economic, and social functions are context-specific and often in conflict. As typical examples, we can think of policies advancing the production of biofuels that increase energy security and promote the local economy but severely reduce the abundance and richness of biodiversity;[15] or EU requirements on biomass feedstock sustainability, which may increase the sustainability practices of other nations aiming to export or effectively be a trade barrier for those nations in their sustainable development.[16,17] In addition to these considerations, our accompanying WTW GHG emissions study discusses the question of feedstocks' environmental sustainability in more detail.



The complexity in defining sustainability may generate incoherent policies that do not necessarily incentivize reducing a biofuel's climate impact.[18,19,20] This incoherence, coupled with local differences in agricultural practices, creates large uncertainties in the assessment of the sustainability of a biomass type as feedstock to produce bioenergy, and these uncertainties are reflected in the large variability of biomass availability assessments that are seen in the literature.

Regarding energy crops, Olivier Dubois, the former coordinator of the Energy Program at the Food and Agriculture Organization of the United Nations (FAO), highlights the importance of studying sustainability in a local context rather than approaching the problem in general terms.[2] Soil health, biodiversity, and ecosystem services can be improved by accurate selection of crops and sound agricultural procedures, including, for example, sequential crops.[21,22,23,24,25] However, if a biofuel market is created in a context of policies that fail to adequately promote such improvements, then there is a risk that including sequential crops could, in fact, lead to less sustainable practices.[26]

When considering feedstock supplies, our recommendation is, therefore, to study the supply chain and have an independent sustainability assessment. This can help ensure that the venture is a long-term success with respect to both the decarbonization schedule imposed by law and the companies' own climate and sustainability targets.

INFO BOX 2

Improving biomass availability estimates with localized analysis

A major shortcoming of published methods for calculating wv is their adoption of broad assumptions to simplify the analysis and data collection. However, not all crops produce the same amount of residue, and global estimates vary greatly due to variations in climate, soil, topography, crops, economics, policy, and other factors. As a result, analyses attempted at a global scale will by necessity lead to a (sometimes wide) range of values.

Therefore, improving biomass potential estimates also requires more local analyses. IRENA has already developed a bioenergy simulator that gives local estimates of biomass availability.[27,28]

However, the available documentation for the simulator is sparse regarding the assumptions behind the calculation. This and other efforts to generate localized biomass availability assessments are listed in Table 4.

Table 4: Selected localized biomass availability calculation tools.

Organization	Name of assessment project or tool
International Renewable Energy Agency (IRENA)	Bioenergy simulator[27,28]
Food and Agriculture Organization of the United Nations (FAO)	Bioenergy and Food Security Rapid Appraisal (BEFS RA)[29,30]
	BIOPLAT-EU[31]
United States Federal Aviation Administration (FAA)	Collaborative Research Network for Global SAF Supply Chain[32]

3. Bio-methane and bio-methanol availability

Our accompanying study on energy demand for emissions reduction compliance establishes the performance of various processes for manufacturing bio-methane and bio-methanol from biogas. In this section, we use that knowledge to calculate the anticipated yields of these biofuels from the biomass that we estimate will be available.

In this report, we use a 70% factor (yield) to relate the production of biogas to the input biomass in terms of energy. This factor is a rough average of several reported values for conversion efficiency of organic matter into bio-methane (see Table 5).

Table 5: Values for energy conversion efficiency of organic matter into bio-methane.

Reference	Biomass type studied	Biogas yield based on energy conversion
Murphy et al[33]	Various plants and plant materials	25-100%
Liebetrau et al[34]	Various manure types	75-100%*
Kasinath et al[35]	Various waste materials	40-90%

*Liebetrau et al also reported that productivity can vary considerably depending on system optimization.

In order to calculate the biomass required to manufacture the LBM and bio-methanol, we use data generated in our companion report on energy demand for emissions reduction compliance. Figure 2, based on Figure 5 of that report, shows the overall energy flows, energy conversion efficiency, and biogas yield for the nine biofuel production pathways thoroughly described in that report. The pathways showed multiple methods to produce LBM and bio-methanol from biogas.

Specifically, Figure 2 includes four pathways for LBM production:

- **Pathway 1a**: standard commercial LBM production;
- **Pathway 1b**: standard commercial LBM production with carbon capture and storage (CCS);
- **Pathway 2:** enhanced LBM production with hydrogen addition and *catalytic* conversion of CO_2 into methane;
- **Pathway 3**: enhanced LBM production with hydrogen addition and *biological* conversion of CO_2 into methane;

And five pathways for bio-methanol production:

- **Pathway 4**: production of fuel-grade (raw) bio-methanol by means of traditional reforming;
- **Pathway 5**: production of fuel-grade (raw) bio-methanol by means of electrical reforming;
- **Pathway 6a**: production of AA-grade (purified) bio-methanol by means of traditional reforming and partial hydrogen addition;
- **Pathway 6b**: production of AA-grade (purified) bio-methanol (as in 6a) with CCS;
- **Pathway 7**: production of AA-grade (purified) bio-methanol by means of electrical reforming.

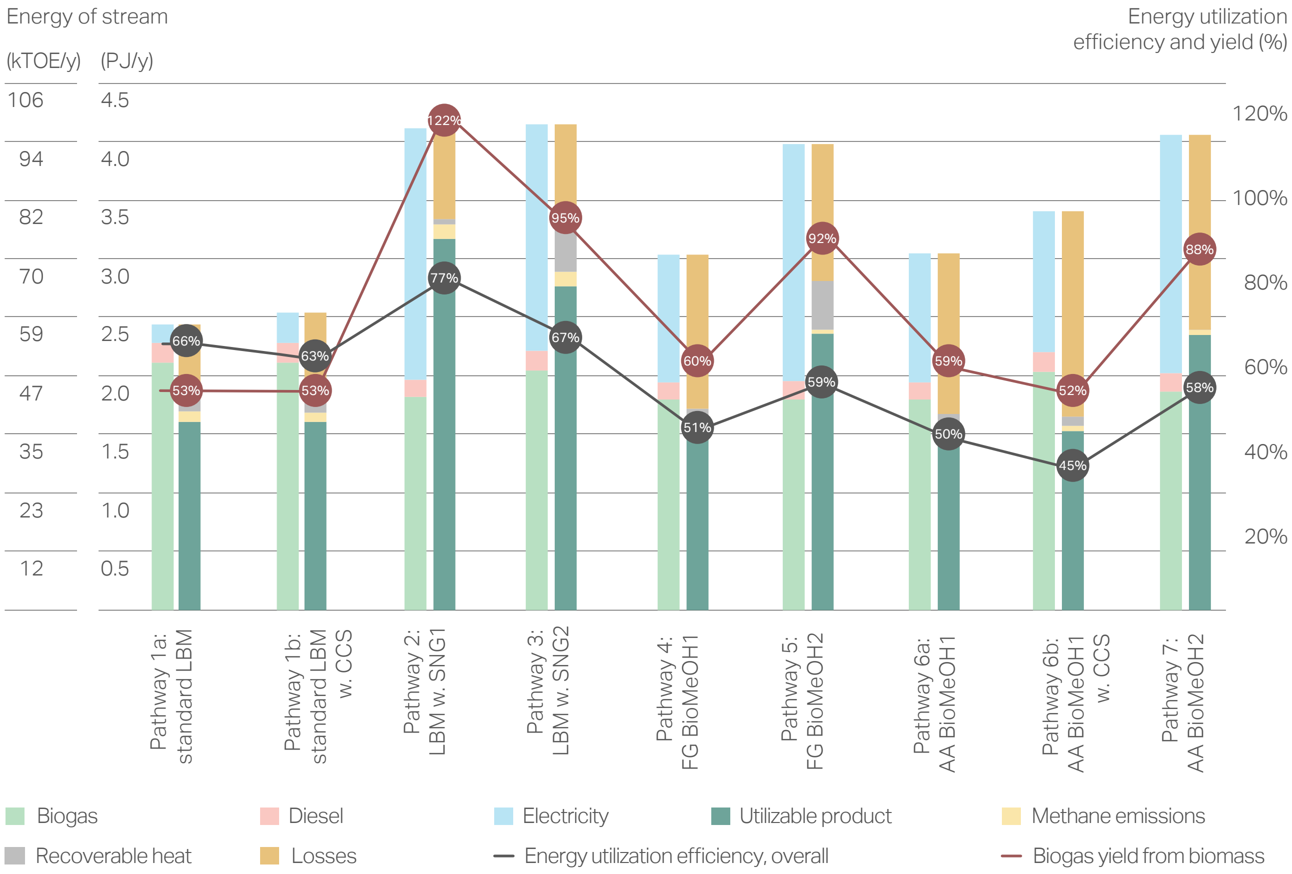
Table 6 visually summarizes the key features of the nine biofuel production pathways and highlights the processing unit belonging to each pathway. The table shows a simplified description. Full descriptions of each pathway can be found in our accompanying study on energy demand for emissions reduction compliance.

Table 6: Summary of selected biofuel production pathways.

No.	Description	Anaerobic digestion	CO$_2$ separation	Catalytic SNG	Biological SNG	CCS	Standard SMR/ MeOH	eREACT™ /MeOH	MeOH distillation	Product
1a	Standard LBM	◆	◆							LBM
1b	Standard LBM w. CCS	◆	◆			◆				
2	SNG1	◆		◆						
3	SNG2	◆	◆		◆					
4	FG BioMeOH1	◆					◆			FG bio-methanol
5	FG BioMeOH2	◆						◆		
6a	AA BioMeOH1	◆					◆		◆	AA bio-methanol
6b	AA BioMeOH1 w. CCS	◆	◆			◆	◆		◆	
7	AA BioMeOH2	◆						◆	◆	

LBM = liquified bio-methane, CCS = carbon capture and storage, SNG = synthetic natural gas, FG BioMeOH = fuel-grade bio-methanol, AA BioMeOH = AA-grade bio-methanol, SMR = steam methane reforming, eREACT™ = electric SMR.

Figure 2: Energy flows, energy utilization efficiency, and biogas yield for various biofuel production pathways. More detail is available in our accompanying report on energy demand for emissions reduction compliance.



In Figure 2, energy flows (inputs and outputs) are scaled on the left-hand side of the figure. The energy inputs are from biogas (pale green bars), electricity for various processing operations (light blue bars), and diesel fuel for transport (pink bars). Energy outputs are the utilizable product (LBM or bio-methanol, dark green bars), methane emissions (light yellow bars), and recoverable heat (gray bars). The differences between the sum of energy inputs and outputs are energy losses (mustard bars).

Figure 2 also shows two conversion efficiency values, scaled on the right-hand side, for the nine pathways. 'Energy utilization efficiency, overall' (gray line) is the ratio between the energy of utilizable product and the sum of all energy inputs, and must always be less than 100%.

'Biogas yield from biomass' (dark peach line) is the ratio between the energy of utilizable product and energy of biomass at input. The energy input from biomass was calculated dividing the energy input from biogas by 70%, as established above. This number can be higher than 100% when a substantial portion of the energy required for manufacturing is from a source other than biomass. In this context, we specifically think of electricity, particularly when manufacturing synthetic natural gas (SNG) or methanol, for which electricity is used to make hydrogen via electrolysis.

Next, we coupled our values for energy conversion from biomass with our total estimated biomass availability of approximately 100 EJ/y to obtain estimates of available LBM or bio-methanol. In Table 7, we show the results of this calculation for six selected pathways, namely 1a, 1b, 2, 6a, 6b, and 7.

Table 7: Estimates of global available energy from biomass and usable energy as liquified bio-methane (LBM) and AA-grade bio-methanol from biogas. Pathways that include carbon capture and storage are colored green and pathways that require green hydrogen are colored pink.

Biomass feedstock (EJ/y)	LBM (EJ/y)			AA-grade bio-methanol (EJ/y)		
	Pathway 1a	Pathway 1b	Pathway 2	Pathway 6a	Pathway 6b	Pathway 7
100	53	53	122	59	52	88

Our calculated total available potential of LBM via the standard manufacturing route (Pathway 1a) is 53 EJ/y. This value compares reasonably well with the total potential calculated by the IEA (570 Mtoe/y, or 28 EJ/y by 2050 — an estimate that does not include energy crops or bioenergy produced on degraded land).[36] An estimate from the World Biogas Association is more optimistic at 57 EJ/y, even excluding bioenergy grown on low-producing land.[37]

Table 7 highlights that applying CCS has different impacts on the usable energy from LBM versus bio-methanol production. Comparing Pathways 1a and 1b shows that applying CCS to the standard LBM manufacturing process has practically no impact on energy, since the CO_2 is already separated from methane through the biogas upgrading process. Hence, 100 EJ/y of biomass can be converted to 53 EJ/y of LBM whether or not CCS is used. The impact of CCS on bio-methanol production is larger, since an additional CO_2 separation process must be implemented. Out of 100 EJ/y biomass, 59 EJ/y bio-methanol may be obtained via traditional reforming and partial hydrogen addition (Pathway 6a), but only 52 EJ/y bio-methanol may be obtained if CCS is applied to the same process (Pathway 6b).

Table 7 also illustrates that full CO_2 utilization by means of hydrogen addition (Pathways 2 and 7) greatly increases the availability of both LBM and bio-methanol with respect to the more 'standard' pathways (Pathways 1 and 6). Particularly, thanks to hydrogen, the SNG manufacturing process acts as a multiplier of the original biomass energy, with the resulting LBM energy (122 EJ/y) exceeding the energy in the biomass (100 EJ/y).

On the other hand, full CO_2 utilization by means of hydrogen addition requires a large electricity input, and the commercial success of such processes will be dependent on an adequate supply of renewable electricity.[34] In addition, doubling the production capacity of a biofuel through hydrogen-supported processes does not imply a straightforward doubling of the emissions reduction potential of the resulting biofuels, as we will see in Section 4.

4. Bio-methane and bio-methanol demand to meet emissions reductions targets

Following the Paris Agreement and the intensification of climate change impacts, concrete decarbonization targets have been placed on shipping. The International Maritime Organization (IMO) has recently set a target for the industry to use a minimum of 5%, pursuing efforts towards 10%, alternative fuels, technologies, and/or energy sources by 2030.[38] Details on eligible alternative fuels are still pending at time of writing. In parallel, the FuelEU Maritime regulation now imposes a European fleet-level GHG emissions reduction of 2% by 2025 and 6% by 2030.[39] This reduction must be exclusively achieved by using low-carbon fuels or alternative propulsion methods.

Considering this need for the shipping industry to reduce emissions, it is relevant to study biomass and biofuel availability in view of the emissions reductions that they may afford. Our companion report on WTW GHG emissions discusses how biofuels' emissions intensity depends on both the production method of biofuels and the emissions intensity of the resources used for production. Table 8 shows representative emissions intensity results from that report for selected LBM and bio-methanol production pathways. These numbers illustrate that the emissions intensity of both fuels can be either strongly negative or positive, depending on the level of optimization of the biofuel manufacturing process.

Table 8: Selected emissions intensity estimates for liquified bio-methane (LBM) and AA-grade bio-methanol from biogas, based on manufacturing process.* Pathways that include carbon capture and storage are colored green and pathways that require green hydrogen are colored pink.

	LBM			AA-grade bio-methanol		
Emissions intensity	Pathway 1a	Pathway 1b	Pathway 2	Pathway 6a	Pathway 6b	Pathway 7
(gCO_2eq/MJ)	3	-40	13	2	-32	6

* Data are sourced from Figure 3 of our accompanying WTW GHG emissions report, base case (FR grid).

In our companion report on energy demand for emissions reduction compliance, we show how the emissions intensity of a given biofuel affects the amount of biofuel required to achieve a given emissions reduction target. This information, coupled with knowledge of the biogas yield from biomass as calculated in Section 3 of the current report, allows us to calculate the amount of biomass required to support shipping's transition according to various 2030 targets, if the decarbonization targets were to be achieved using only one type of biofuel. Figure 3 shows the results of this calculation. The chart was generated assuming that the energy required by shipping in 2030 is 12.8 EJ/y and that the Paris Agreement target is reached only by means of alternative fuels.

Regarding the 5-10% IMO ambition level,[40] we note that the GHG emissions reduction strategy requires 5-10% of the propulsion energy to come from zero or near-zero alternative fuels. The sustainability criteria for these fuels have not yet been finally defined; therefore, we have generated Figure 3 after considering a target to reduce GHG emissions by 5-10% instead.

The IPCC has created various scenarios to reach the Paris Agreement target.[41] These scenarios consider CO_2 and other GHGs separately, since they often originate from separate industrial activities. For shipping, emissions of CO_2, methane, and black carbon are relevant. CO_2 emissions must be reduced by at least 41% by 2030, which is more restrictive than the emissions reduction demand for methane and black carbon (35% by 2030). Since CO_2 emissions represent the largest proportion of shipping-related GHG emissions, and since methane and black carbon emissions are more difficult to assess, we have taken the target of 41% to apply for all GHGs.

Figure 3: Biomass energy required for shipping's compliance with selected climate mandates and targets through increased adoption of biogas-based liquified bio-methane (LBM) and bio-methanol fuels

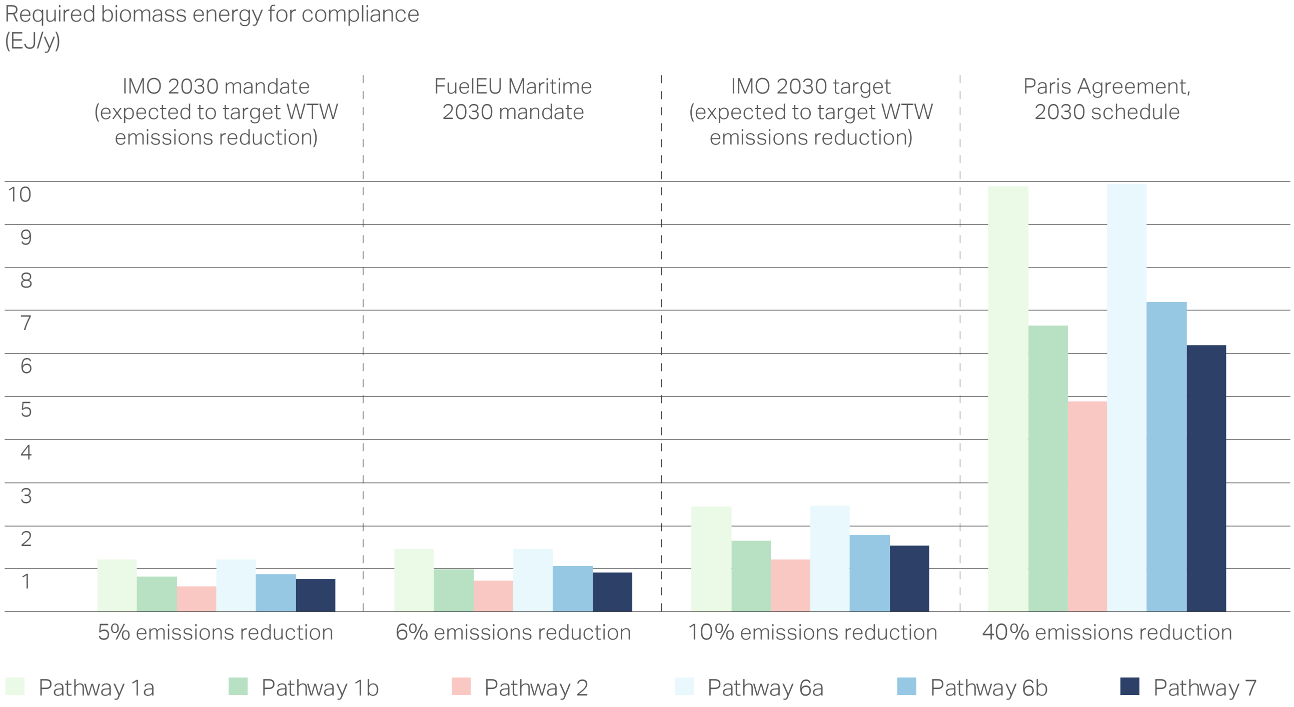


Figure 3 shows that both for LBM and bio-methanol, storing the excess CO_2 by means of CCS effectively uses the lower emissions intensity to reduce the biomass demand by roughly 30% (comparing Pathway 1a with 1b and Pathway 6a with 6b). However, using the excess CO_2 to manufacture more biofuel with the support of hydrogen results in the greatest reduction in biomass demand: for example, the SNG1 production pathway (Pathway 2) reduces biomass demand by around 50% compared to standard LBM manufacturing (Pathway 1a), and use of an electric reformer (Pathway 7) reduces biomass demand by nearly 40% compared to bio-methanol manufacturing based on traditional reforming (Pathway 6a). Thus, hydrogen-supported processes reduce the sensitivity of the biofuel manufacturing cost to biomass price, but increase the sensitivity to electricity price, since green hydrogen manufacture relies on electricity.

Figure 3 indicates that a 10% GHG emissions reduction target (upper end of the IMO's current 2030 target) could be achieved with 1-2.5 EJ/y of biomass and a 40% GHG emissions reduction (roughly corresponding to the Paris Agreement's 2030 target) would require 5-10 EJ/y of biomass – depending on the biofuel selected and the characteristics of the manufacturing process. These amounts correspond to 1-2.5% and 5-10%, respectively, of the total global biomass availability we have estimated in this study. While it seems plausible to imagine that shipping can access this quantity of biomass or biofuels, shipping will compete against other sectors for the same resources and therefore must be prepared to pay the market price.

INFO BOX 3

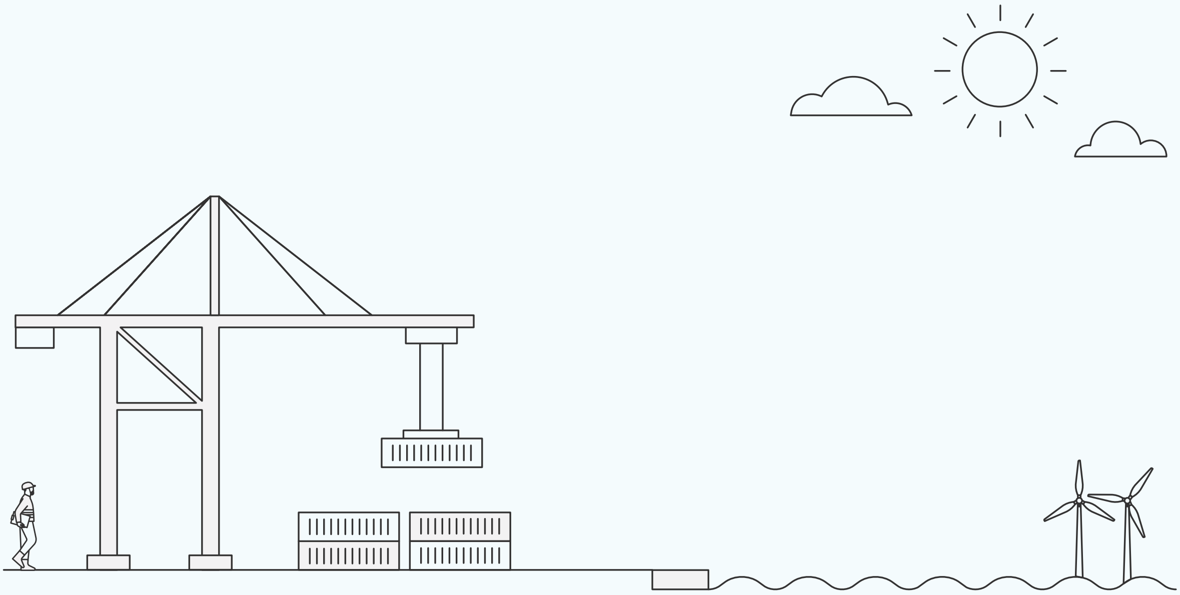
Biomass demand and competition from other applications

Against a backdrop shaped by energy supply, the future demand for biomass and bio-methane is very uncertain. Similar to biomass availability, estimates of biomass demand vary widely. Here, the challenge is to predict the pace of implementation and acceptance of alternative technologies.

For example, The Energy Transition Commission (ETC) has estimated that by 2050, biomass is likely to be required for aviation, power seasonal balancing, and applications of biomass as material (e.g., timber, paper, plastics), resulting in a biomass demand of 250 EJ/y.[42] However, Henrik Wenzel of the University of Southern Denmark anticipates a biomass demand between 190 and 440 EJ/y, mostly due to demand for plastic and other materials,[4] thereby suggesting a largely inadequate global biomass supply. In contrast, the International Energy Agency predicts that by 2050, the demand for bioenergy will be in the range of 100 EJ/y, most of it for electricity and buildings.[1] According to this IEA estimate, the supply of sustainable biomass could be sufficient to match demand.

Biofuels are, of course, not the only option for low- or zero-carbon fuels that can support decarbonization in shipping and other industries. However, biofuels are one of the most commercially mature fuel options. We also note that a previous MMMCZCS publication has estimated that the manufacturing cost of biofuels will be cheaper than that of e-fuels for the foreseeable future.[43]

Regardless of long-term estimates of supply-demand balances, until alternatives have established themselves and become more affordable, biofuels offer the only viable decarbonization pathway for many industries, which are competing to ensure supply. Therefore, we recommend that the shipping industry consider securing the supply of biofuels, including biomass supply, in the medium to long term, as an interim solution while technologies evolve and decarbonization strategies of multiple industries become clearer.



5. Conclusion

The challenge of a warming planet is driving governments, companies, and other institutions to enact changes that will inevitably impact the maritime industry. The IMO has now committed to a vision for the future of shipping in line with the goals of the Paris Agreement, which means that the industry will increasingly focus on solutions to reduce its carbon intensity. Meeting this challenge will require multiple approaches and technologies.

Against this backdrop, this report examines the potential availability of sustainable biomass, the key ingredient for biofuels, and the resulting potential production volumes of biogas-based bio-methane and bio-methanol fuels. We also explore the scalability of producing these biofuels with respect to the energy needs of the shipping industry and IMO proposals to reduce emissions.

The availability of sustainable biomass is a key issue for marine shipping and other industries as they grapple with shaping a strategic path to decarbonization. Published reports on the total amount of sustainable biomass available worldwide give widely differing answers. This creates confusion about the plausibility of a biomass-based approach to decarbonization. These differences are driven by many factors, including data quality and availability, categorization of biomass types, and complexities in defining 'sustainable' biomass. We suggest that estimates can be improved in future with better data collection and more attention to regional and local context.

Based on our analysis, we estimate that around 100 EJ/y of sustainable biomass can be available for industrial use. Our estimate includes a curtailed availability of energy crops, which are still accepted in some geographic regions, and of unconventional resources, such as biomass produced on low-producing land.

We apply lessons from other reports in this series to understand our estimated biomass availability in the context of biofuel production, by evaluating specific pathways for manufacturing bio-methane and bio-methanol from biogas. We find that converting all available sustainable biomass to biofuels using our selected manufacturing pathways can produce anywhere from approximately 50-120 EJ/y of LBM, or alternatively around 60-90 EJ/y of bio-methanol. For comparison, marine shipping currently consumes 11 EJ of energy per year.[1]

We also evaluated the biomass required to produce enough biofuel from biogas for the shipping industry to comply with specific emissions reduction targets or mandates, including FuelEU Maritime and the 2023 IMO GHG Strategy. For an interim target of up to 40% reduction in GHG emissions, LBM and bio-methanol from biogas can meet shipping's fuel mix needs using 5-10 EJ/year of biomass, depending on the carbon intensity of the manufacturing process. Biofuel production pathways with very low carbon intensity or very high energy utlization efficiency greatly reduce the volumes of biofuel required to meet the targets. In our assessment, biogas-based LBM and bio-methanol produced via pathways that boost the conversion of biomass to fuel using green hydrogen are the best options to minimize biomass consumption. However, these pathways rely on availability of renewable electricity, which may also be constrained.

Biofuels can provide an important source of energy in the world's low-emissions future. According to our estimates, the total energy that biomass may potentially supply is more than the needs of marine shipping but still only a fraction of the world's overall energy needs. Shipping, like other difficult-to-decarbonize industries, will need to apply multiple approaches to more sustainable energy consumption and look to incorporate biofuels strategically for the most critical and difficult energy applications. We recommend that shipping operators who see biofuels as a part of their decarbonization strategy should consider securing biofuels and biomass in long-term agreements.

6. The project team

This report was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners. Team members marked with an asterisk (*) were seconded to the MMMCZCS.

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Abbreviations

AA	Grade AA Methanol specifications
BioMeOH	Bio-methanol
BioMeOH1	Manufacturing of biomethanol based on traditional steam methane reforming
BioMeOH2	Manufacturing of biomethanol based on eREACT™
CCS	Carbon capture and sequestration
eREACT™	Electricity-driven steam methane reforming
FG	Fuel grade (methanol specification)
FuelEU	FuelEU Maritime initiative
GHG	Greenhouse gas
h	Hour
EJ	Exa (1x10^18) joule
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LBM	Liquified bio-methane (same as LBG: liquified biogas, or bio-LNG)
LNG	Liquified natural gas
MeOH	Methanol
MJ	Mega (1x10^6) joule
MCSC	MIT Climate and Sustainability Consortium
MIT	Massachusetts Institute of Technology
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
Mt	Million (or mega) tonnes
RED	Renewable Energy Directive of the European Union
SMR	Steam methane reforming
SNG	Synthetic natural gas: An almost pure stream of methane resulting from the catalytic or biological reaction of CO_2 with hydrogen
SNG1	SNG manufacture based on a catalytic process
SNG2	SNG manufacture based on a biological process
US EPA	United States Environmental Protection Agency
t	Tonnes, metric tons
WTW	Well-to-wake
y	Year

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