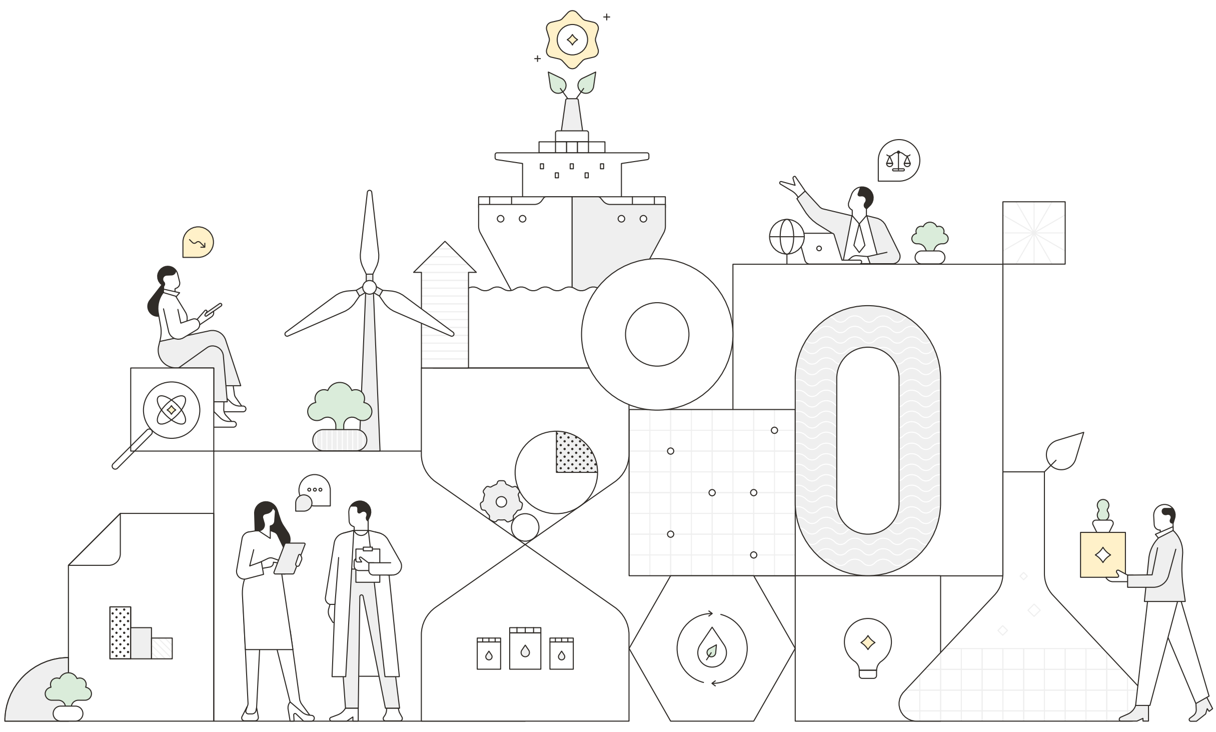
Biogas as a Source of Biofuels for Shipping

Well-to-Wake Greenhouse Gas Emissions from Biogas-Based Bio-methane and Bio-methanol

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Contents



Executive Summary

Successful decarbonization of the shipping industry is set to require adoption of a diverse array of marine fuels. Rather than waiting for one fuel to emerge as the 'winner' to replace fossil fuels, the industry must embrace a multi-fuel approach to successfully achieve the targets set by the International Maritime Organization (IMO) and attain net-zero emissions. Various factors determine which fuels are suitable to support this transition, including the availability of feedstocks, the influence of policies and regulations, production costs, and the potential for reducing greenhouse gas (GHG) emissions. Taking all these factors into account is crucial when selecting the most effective fuels to decarbonize the maritime sector.

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) which 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). These biofuel pathways are summarized in Figure 1.

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

To evaluate the environmental impact of these biofuel options, we present an in-depth report that includes feedstock displacement analysis, a sustainability criteria study, and well-to-wake (WTW) GHG emissions intensity analysis for various LBM and bio-methanol production pathways.

More specifically, our displacement analysis provides valuable insights into the risks associated with using biomass-based feedstocks for biofuel production. We find that some feedstocks including manure carry a low displacement risk. Others, such as certain types of fruit and vegetable residues, carry a higher risk. This type of assessment is crucial to avoid unintended negative impacts, such as competition with existing uses or disruption of established supply chains in other sectors. The consideration of displacement risks helps to ensure that the utilization of biomass-based feedstocks for biofuel production in the maritime sector is responsible and sustainable.

Next, our report highlights the importance of sustainability criteria in the production of biofuels, encompassing both environmental and socio-economic factors. Environmental criteria include assessing greenhouse gas (GHG) emissions savings, land-use change, sustainable forest management, and other relevant aspects. Socio-economic criteria, on the other hand, focus on worker rights, land rights, food security, and similar considerations. We review the inclusion of these criteria in various policies and schemes within the European Union (EU) and the United States (US) that incorporate these sustainability criteria as part of the certification process. These policies provide a regulatory framework and guidelines for biofuel producers to follow, promoting transparency and accountability in the industry.

Finally, our WTW analysis examines GHG emissions intensity across the full life cycle of our selected biofuels, from feedstock extraction to fuel production to onboard use. The document's detailed explanation of the WTW methodology provides insights into the calculation and evaluation of GHG emissions throughout the selected biofuel production pathways. We also examine four specific parameters that could contribute to further emissions reductions in these biofuel pathways: electricity source, feedstock displacement, fugitive methane emissions, and avoided landfill emissions. We analyze the sensitivity of the pathways' emissions intensity according to these parameters. Through this analysis, our study improves understanding of these biofuels' potential in achieving sustainable maritime decarbonization. Our results also allow stakeholders to identify areas where further improvements or optimizations can be made to enhance the overall effectiveness of the selected biofuel pathways in achieving maritime decarbonization goals.

Based on our analyses, we make the following conclusions and recommendations:

Feedstock displacement

- Some feedstocks carry a higher risk of displacement depending on their nutritional value, market value, market demand and consequences of displacement on other sectors.
- Moving forward, further research and collaboration are crucial to continuously evaluate and optimize feedstock selection and utilization in biofuel production.

Sustainability criteria

- Incorporation of these criteria ensures that biofuel production and utilization align with broader sustainability goals, such as reducing GHG emissions, promoting responsible land use, protecting biodiversity, and respecting human rights.
- By fulfilling these criteria, biofuel producers demonstrate their commitment to sustainable practices and contribute to the overall decarbonization efforts of the maritime industry.
- Sustainability criteria should be strengthened and harmonized across jurisdictions and regulatory frameworks to ensure consistency in assessing the sustainability of biofuels.
- Collaboration between governments, industry stakeholders, and certification bodies can facilitate the development of unified sustainability standards for biofuels in the maritime sector.
- Implementing robust certification and verification mechanisms can ensure that sustainability criteria are being met and consumers and stakeholders are able to make informed choices.

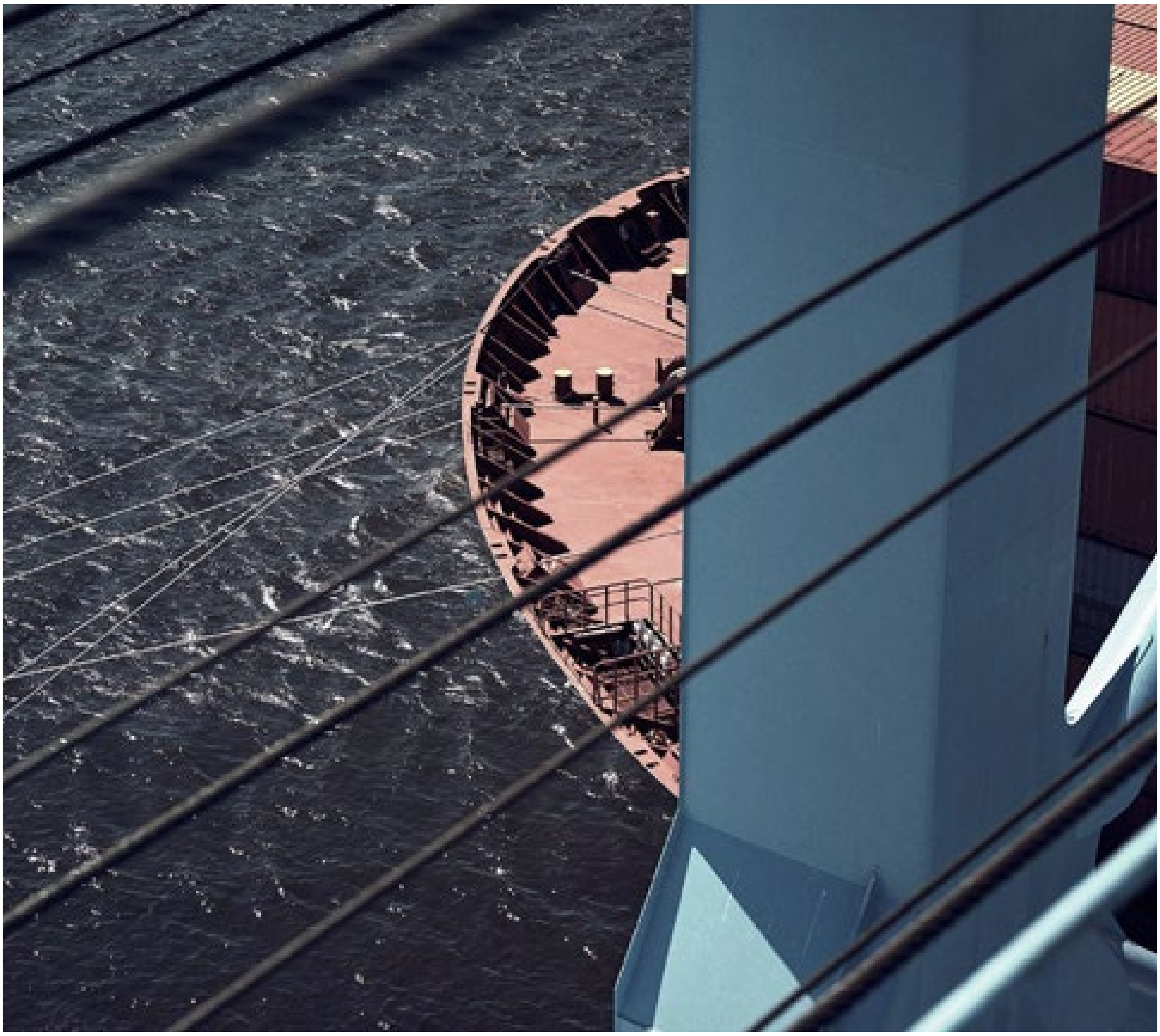
WTW GHG intensity and sensitivity parameters

- Using renewable electricity sources throughout the supply chain achieves high emissions reductions.
- Replacing 100% of the agricultural and industrial residue used for biofuel production with a biomass feedstock that is already used elsewhere (feedstock displacement) leads to poor GHG emissions performance for all production pathways.

- Reducing methane fugitive emissions by 80% with respect to the baseline scenario allows all fuel pathways to achieve negative emissions intensity.
- By diverting the biomass that usually ends up in a landfill for biofuel production, all production pathways can achieve very high negative emissions.

General

- The key factors that contributed to high emissions intensities for the production pathways were fugitive methane emissions, the use of high-risk feedstocks, and the grid electricity mix.
- Measures such as improved manure management, mitigation of fugitive emissions, renewable energy use, excess heat recovery, and carbon capture and storage (CCS) technology also have high emissions reduction potential for the assessed biofuel pathways.
- Factors such as biomass availability, technological advancements, location, infrastructure requirements, and legislation can also influence the emissions reduction potential of LBM and bio-methanol production from biogas.
- Therefore, when deciding which biofuel one might invest in, a thorough investigation should be performed to assess all the factors that affect the feasibility of biofuel production with collaborative efforts between various stakeholders, including researchers, industry experts, and policymakers.



1. Introduction

Decarbonization of the maritime industry requires the exploration of novel alternative marine fuels that are both technologically and economically feasible while successfully reducing the sector's climate impact. To this end, it is essential to understand the climate performance of these fuels compared to conventional fossil-based fuels. 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 biomethane (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, insights into the value chain.

In this study, we aimed to evaluate the greenhouse gas (GHG) emissions associated with biogas-based LBM and bio-methanol and to identify opportunities to reduce these emissions throughout the supply chain. We conducted a well-to-wake (WTW) analysis encompassing the entire supply chain from feedstock production to fuel production (well-to-tank, WTT) and subsequent emissions when the fuel is used on board a ship (tank-to-wake, TTW). Following the life cycle assessment (LCA) methodology defined by ISO 14040 and ISO 14044 standards, we evaluated the GHG emissions intensity associated with several specific production pathways for biogas-based LBM and bio-methanol. The specific processes involved in these fuel production pathways are described in our accompanying report on energy demand for emissions reduction compliance.

The primary objective of this report is to conduct a comparative assessment of the climate burden associated with the production of LBM and bio-methanol from biogas, also considering their subsequent use on board ships. We compared the GHG emissions intensity — measured in grams of CO_2 equivalent per megajoule of fuel (gCO_2eq/MJ) — of specific LBM and bio-methanol production pathways. For the purposes of this analysis, we have emphasized climate impact and excluded other environmental impact categories. Our results can enable informed recommendations regarding the selection of optimal biogas-based biofuel options based on emissions intensity.

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. The project was carried out by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) in collaboration with a team representing commercial companies with experience and interests in this supply chain. The team consisted of Boston Consulting Group, Cargill, Maersk, Norden, Novonesis, Topsoe, and TotalEnergies. The project has further benefited from the experience of several additional companies. A full list of project participants is in Section 7.

This report is part of a series on 'Biogas as a source of biofuels for shipping'. Other reports in this series deal with insights into the value chain, methane emissions, energy demand for emissions reduction compliance, techno-economic trends, and biomass availability.

Our project partners

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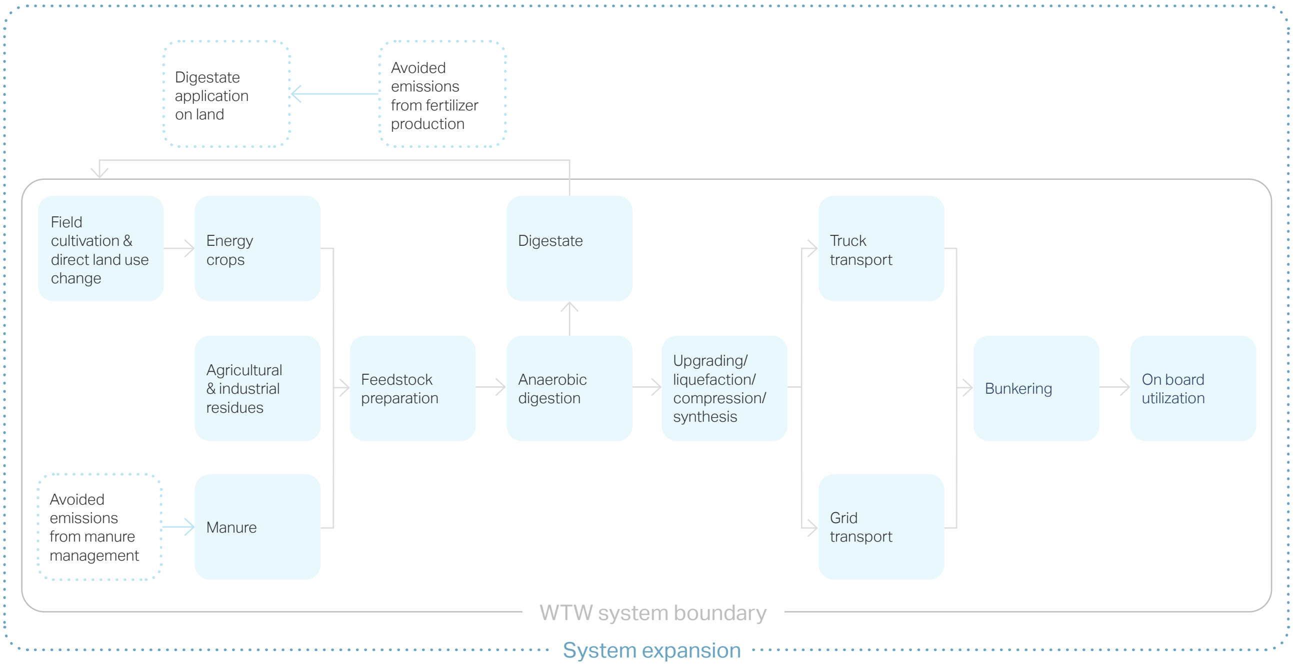
2. Well-to-wake system boundary

Following established LCA practice, we begin by defining the system boundary for our analysis. Our system boundary (Figure 2) encompasses various stages of biofuel production pathways, including feedstock production, collection, conditioning, storage, and transportation, as well as fuel production, conditioning, storage, and transportation. The system boundary also considers the combustion of the fuel on board the ship. We also considered an expanded system boundary to incorporate the use of digestate, a byproduct of the biogas production process, as a replacement for fertilizers during crop cultivation.

Figure 2: WTW system boundary with system expansion and substitution.



Further details on the assumptions and limitations for our WTW assessment are outlined in Appendix A.

3. Displacement analysis

Displacement analysis due to the diversion of biomass-based feedstock involves evaluating the consequences of redirecting biomass resources from one application or industry to another. This analysis is particularly relevant in the context of biomass feedstocks used for various purposes such as bioenergy, bioproducts, or other applications. Diverting biomass feedstock from one use to another can have significant economic, environmental, and social implications. Low-displacement-risk scenarios involve a smooth redirection of biomass, often due to its versatility. In contrast, high-displacement-risk situations might arise when the diversion leads to challenges such as increased competition for resources, changes in land use, or negative environmental impacts. This analysis is particularly relevant in the context of biomass feedstocks used for various purposes such as bioenergy, bioproducts, or other applications.

This portion of our assessment aims to evaluate the potential risks of using different types of waste feedstock for biogas production. The reference biogas plant used for this study is the Biovilleneuvois plant (BioV), described in our companion publication on energy demand for emissions reduction compliance. BioV is fed with livestock manure, agricultural residues, and food waste in roughly equal amounts. In this study, we considered manure, maize silage, retentate from disposed and landfilled solid waste, grape marc, onion residues, and fruit and vegetable residues as feedstocks. These feedstocks were chosen based on their utilization in biogas plants in France and Denmark for which statistical data could be found. The majority of the feedstock mix in both countries consists of waste materials — particularly manure, slurry, and deep litter, which account for 70% of the feedstock mix in Denmark and 56% in France. Danish plants also utilize maize silage as an energy crop feedstock, constituting 8% of the mix. Table 1 shows the displacement risk associated with the major feedstock types considered in our assessment and their current use.

Table 1: Displacement risk for the major feedstock types considered in this report.

Feedstock	Current use	Percentage*	Displacement risk
Any type of manure/ slurry/ litter	Reapplied to soil	90% [1]	Low
Landfill's retentate (or filtrate)	Disposed and landfilled	Unknown	Low
Grape marc[2]	Alcohol distillation; compost or direct soil application; feed. Small cosmetics; food and pharmaceutical use.	Unknown	High
Grinding press juice	Animal feed	50% - 80% of total discard[3]	High
Onion residues	Disposed and landfilled	Unknown	Low
Fruit and vegetable residues	Animal feed	50% - 80% of total discard	High

* 'Percentage' here refers to the percentage of total generated waste/residue feedstock that is already currently in use.

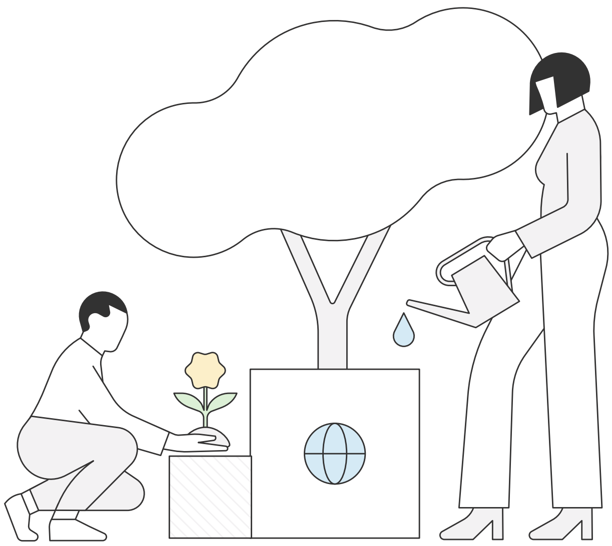
Based on this assessment, we conclude that manure is a low displacement risk feedstock. Manure has a high nutrient content, which allows it to be effectively used as fertilizer without causing significant market changes or displacing other products. Diverting manure for biogas production can potentially lead to a displacement effect, resulting in increased production and application of artificial fertilizers. However, the waste stream from anaerobic digestion, known as digestate, can also be applied to the soil, eliminating the need for additional fertilizer production.[4] In the case of specific applications, a more detailed analysis considering the bioavailability of nutrients in manure and digestate is recommended.

We also identified landfill's retentate/filtrate and onion peels as low displacement risk feedstocks since they are not currently used as feed or food and are typically discarded after the production process. Diverting these waste streams for biogas production can be seen as a beneficial utilization of these waste types. On the other hand, grape marc is considered a high displacement risk feedstock due to its high market value for alcoholic beverages and cosmetics immediately after winemaking, which can lead to displacement effects if the grape marc is used for biogas production. However, the spent grape marc, which is a waste from subsequent uses, can have a lower displacement effect. Waste feedstock from grinding pressed juices and fruit and vegetable residues also have a higher displacement risk because they are already used as animal feed.

In summary, the displacement risks associated with different feedstock types for biogas production are not the same. To some extent, the risks are local because they depend on local demand for a given feedstock. Nevertheless, it is generally advisable to prioritize the following feedstock categories for biofuels manufacturing:

- feedstocks with lower nutritional value
- feedstocks with antinutritional qualities, like onion residues
- feedstocks that are too concentrated to be safely used in other applications

The absence of competition for these feedstocks also makes them cheaper and therefore more attractive. For the purposes of our analysis in this report, we have assumed that the process feedstocks had no alternative use, and we did not include any displacement effects of waste feedstocks. However, to avoid unintended consequences, we recommend conducting a comprehensive analysis to understand the displacement effects of feedstocks used in any real-world biogas production.



4. Sustainability criteria for biofuels

Sustainability criteria are the standards that a product and its production process must meet to be considered sustainable and receive certification as such. These criteria relate to environmental, economic, and social dimensions of sustainability and are used to evaluate the benefits and risks associated with biofuels. We conducted a literature review to explore the different sustainability criteria related to biofuels and their incorporation into policies and programs at national and regional levels in the United States and Europe.[5,6]

Table 2 shows the inclusion of various sustainability criteria in Renewable Energy Directive (RED I, RED II), national legislation, and voluntary schemes for liquid biofuels and solid biomass. "All" stands for all types of feedstocks, "F" stands for forestry residues, "W" stands for waste and residues, and "Ec" stands for energy crops. A ⬢ indicates that the sustainability criterion is included in the scheme but does not specify the strictness level. Relevant sustainability criteria are further explained in this section and in Appendix B.[7] Our definitions of the criteria are based on a 2010 report published by the World Bioenergy Council's biofuels task force.[8]

Table 2: Sustainability criteria in RED I, RED II, national legislation, and voluntary schemes for liquid biofuels and solid biomass.

		Policies and schemes	Feed-stock Coverage	Sectoral Relevance	Enviromental Criteria							Socio-economic Criteria			
					GHG Emissions Savings	SFM	Carbon Stock Preservation	High Biodiversity Protection	Protection of water resources, air & soil	ILUC	LULUCF	Worker Rights	Land Rights	Food-Price & Security	Resource efficiency
Liquid Biofuels	1	REDI	Ec&W	T	◆		◆	◆							
	2	RED II	ALL	T,H,E	◆	◆	◆	◆			◆				
	3	UKRTFO	ALL	T	◆		◆	◆	◆			◆	◆		
	4	ISCC	ALL	T,H,E	◆	◆	◆	◆	◆			◆	◆	◆	
	5	Bonsucro	Ec	T	◆		◆	◆	◆			◆	◆		
	6	RTRS	Ec	T	◆		◆	◆	◆			◆	◆		
	7	RSB	ALL	T,H,E	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	
	8	2BSvs	Ec&W	T	◆		◆	◆	◆			◆			
	9	Red tractor	Ec	T			◆	◆							
	10	SQC	Ec	T			◆	◆							
	11	REDcert	ALL	T	◆		◆		◆			◆		◆	
	12	Better biomass	ALL	T	◆		◆	◆	◆	◆		◆	◆	◆	◆
	13	RSPO	Ec	T	◆		◆	◆							
	14	Biograce I,II	All	T,H,E	◆										
	15	HVO	Ec&W	T	◆		◆	◆							
	16	Gafta	Ec	T			◆	◆							
	17	KZRING System	Ec&W	T	◆		◆	◆							
	18	TASCC	Ec	T	◆		◆	◆							
	19	UFAS	Ec	T	◆		◆	◆							
	20	RFS2	ALL	T	◆										
	21	CARB-LCFS	All	T	◆										
	22	CORSIA	ALL	T	◆					◆					
	23	CFS	ALL	T	◆										
	24	LCFS-BC	ALL	T	◆										
Solid Biomass	25	REDII	ALL	T,H,E	◆	◆	◆	◆			◆				
	26	UKRO	F&W	H&E	◆	◆	◆	◆							
	27	SDE+	F.Ec&W	H&E	◆	◆	◆	◆	◆	◆	◆				
	28	FSC	F	T,H,E		◆	◆	◆	◆	◆	◆	◆	◆	◆	
	29	PEFC	F	T,H,E		◆		◆	◆		◆	◆	◆	◆	
	30	SBP	F	H&E	◆	◆		◆	◆		◆	◆	◆	◆	

Note: Full forms of the policies and certification schemes can be found in Appendix B.
Appendix B contains details regarding the sustainability criteria as followed in this report.

4.1 Greenhouse gas emissions savings

Biofuel production must adhere to current legislation regarding GHG emissions savings throughout the entire life cycle of the product. Over time, there should be continuous improvement in the savings achieved from producing biomass for energy and other purposes. The accounting of GHG emissions associated with biomass production should therefore follow a life cycle approach, considering the system boundaries defined by the relevant legislation in the specific territory, if applicable. In Europe, there are six tools available for calculating GHG emissions, namely BioGrace I and BioGrace II, International Sustainability and Carbon Certification (ISCC), Roundtable on Sustainable Biofuels (RSB), UK Biofuels Carbon Calculator, and Solid and Gaseous Biomass Carbon Calculator.

4.2 Environmental criteria

The environmental sustainability of any project related to biomass is crucial for the development of sustainability standards and is particularly important during the compliance phase with the principles and criteria outlined in those standards. Environmental sustainability encompasses a range of concerns, including but not limited to sustainable forest management (SFM); preservation of high carbon stock (HCS); biodiversity protection; protection of air, soil and water; indirect land-use change (ILUC); and land use, and land-use change and forestry (LULUCF). More detailed descriptions of relevant environmental criteria are available in Appendix B.

4.3 Socio-economic criteria

Social sustainability criteria refers to the effects that biomass production for energy, particularly in transportation, have on local progress. It strives to uphold human and land rights, as well as land-use rights, while addressing concerns such as labor and safety standards.

Economic sustainability is essential for the sustainable cultivation of biomass for energy purposes, including transportation. Local development matters are significant not only in terms of social sustainability but also from an economic sustainability standpoint. Furthermore, it is crucial to guarantee the economic feasibility of individual operators, worker rights, land rights, food security, resource efficiency, and economic criteria.

More detailed descriptions of relevant socio-economic criteria are available in Appendix B.

4.4 Implications and recommendations

In today's world, the pursuit of sustainability is a priority for many regions and countries. However, the specific requirements and criteria to achieve sustainability can differ significantly in different contexts. Some criteria are compulsory and must be met by all parties involved, while others are optional, allowing for flexibility in their implementation. Moreover, even among mandatory criteria, there can be variations in the strictness of the standards and the specific requirements that need to be fulfilled.

These variations in sustainability policies and schemes can be observed at different levels, including international, national, and regional. At the international level, organizations and agreements may establish broad guidelines or goals for sustainability, but the specific methods and approaches to achieve them can differ between countries. This can be due to variations in methodology, differing interpretations of sustainability, and discrepancies in the economic, social, and environmental contexts of each region.

Similarly, governments and governing bodies may develop their policies and regulations to address sustainability challenges at the national and regional levels. These policies can be influenced by factors such as prevailing agricultural practices, the level of technological infrastructure available, and the socio-economic priorities of the region. As a result, the requirements for sustainability can vary significantly from one jurisdiction to another.

This variation in sustainability criteria and policies poses challenges to global collaboration and the adoption of standardized sustainability practices. It makes it difficult to establish a universal set of guidelines and regulations that can be uniformly implemented worldwide. Discrepancies in requirements and standards can create trade barriers, hinder the transfer of technology and best practices, and lead to inconsistencies in sustainability reporting and evaluation.

To create legislation for bioenergy sustainability, policymakers must engage in extensive discussions to establish shared definitions and measurements of sustainability criteria. These discussions should aim to prevent issues such as emissions impacts on biodiversity and ecosystems, socio-economic conflicts, and trade barriers. Policymakers can collaborate with voluntary scheme officers and the scientific community to ensure a higher level of assurance for bioenergy sustainability. This collaboration will help address pending sustainability concerns and promote the transparent and consistent establishment and implementation of sustainability criteria.

It is important to avoid establishing binding sustainability criteria exclusively for the bioenergy sector while neglecting other sectors that use the same feedstocks, as this could lead to trade-offs between sectors as well as debates on the meaningfulness of sustainability performance. The stakeholders involved must agree on the sustainability aspects that need to be considered to ensure sustainability compliance across different sectors. For instance, discussions may be required to determine how multifunctionality should be addressed in bio-refineries that utilize biomass feedstocks and produce multiple outputs, including bioenergy. Increased collaboration between stakeholders from various sectors is essential for exchanging information and sharing lessons learned in demonstrating sustainability performance.

5. Well-to-wake greenhouse gas emissions assessment

5.1 Methodology for WTW GHG emissions assessment

For the purposes of this report, WTW GHG emissions from biogas-based biofuels are expressed in **gCO_2eq/MJ of fuel**. Similarly, emissions from raw materials and intermediate products are measured in gCO_2eq/MJ or in gCO_2eq/tonne of dry feedstock or intermediate product. Emissions from the manufacturing of machinery and equipment are not considered in these calculations.

When assessing the emissions associated with biogas-based biofuels, biogenic CO_2 emissions throughout the supply chain are assumed to be zero. However, emissions of non-CO_2 GHGs like N_2O and methane are accounted for. We calculate the WTW emissions for the biofuels of interest (i.e., LBM and bio-methanol from biogas) using the following formula:*

$$E_{total}(WtW)=$$
$$e_{ec}+e_{l}+e_{p}+e_{td}+e_{u}+e_{fugitive}-e_{sca}-e_{ccs}-e_{cpc}-e_{avb}$$
$$e_{sca}=e_{manure}+e_{fertilizer}$$

* Equation modified from Directive (EU) 2018/2001.

Where:

$E_{total}(WtW)$	total emissions associated with the complete biofuel supply chain
e_{ec}	emissions associated with feedstock acquisition and pre-processing, especially during cultivation and harvesting of biomass
e_{l}	annualized emissions associated with land-use change (specific to first-generation energy crops)
e_{p}	emissions associated with fuel production and processing (synthesis, upgrading, liquefaction, etc.)
e_{td}	emissions associated with transportation, distribution, and storage
e_{u}	emissions associated with fuel utilization on board the vessel
$e_{fugitive}$	emissions associated with fugitive emissions and slip emissions
e_{sca}	emissions savings from soil carbon accumulation via improved agricultural management
e_{ccs}	emissions savings from carbon capture and storage
e_{cpc}	emissions credits associated with the processes involved in the original synthetic product on the market when the co-product directly replaces an original synthetic product on the market
e_{manure}	emissions savings from avoidance of methane emissions during manure management (if relevant)
$e_{fertilizer}$	emissions savings from avoidance of fertilizer production and use due to digestate application
e_{avb}	emissions savings from avoidance of methane emissions from biowaste ending up in landfill

Additional specific details on the terms in this equation are available in Appendix C.

We highlight that, at the MMMCZCS, we believe that **certain emissions credits considered in this study have a time limit and may become invalid after 15-20 years** due to the relevant activities becoming common practice.

5.2 Sensitivity cases

Our assessment of WTW GHG emissions examines four different sensitivity cases for the specific biogas-based biofuel pathways described in our companion report on energy demand for emissions reduction compliance. Each case is evaluated based on specific parameters outlined in Table 3 and described in more detail in this section, and each sensitivity case is tested on the baseline scenario.

Baseline scenario

The baseline scenario involves evaluating different factors for all fuel pathways, and then testing these factors for their sensitivity. The results of these tests are illustrated in Section 5.3. In this scenario, we assume that the electricity used in the fuel pathways is sourced from the French electricity mix. If the anaerobic digestion process produces digestate that can be used as a substitute for fertilizers, credit is given. Additionally, if heat recovered during the process replaces the need for an external heat supply, this is also credited. Credits are also awarded for reducing emissions through improved manure management and the rehabilitation of degraded land. Carbon capture and storage (CCS) is incorporated into the system wherever possible to prevent CO_2 emissions. Furthermore, all emissions released throughout the supply chain, including fugitive emissions, are considered in the baseline scenario.

Table 3: Overview of the four sensitivity cases: electricity use, fugitive methane emissions, feedstock displacement, and avoided landfill emissions.

Sensitivity parameters	Sensitivities				Case
	Baseline scenario	Scenario 2	Scenario 3	Scenario 4	
Electricity use	FR mix	100% renewable w/ zero emissions	100% renewable w/ O&M emissions	EU mix	1
Feedstock displacement	No feedstock displacement	10% feedstock displacement	100% feedstock displacement	-	2
Fugitive methane emissions	Typical	80% fugitive emission reduction	No fugitive emissions	-	3
Avoided landfill waste	No avoided landfill waste	10% of landfill waste avoided	100% landfill waste avoided	-	4

FR = French, EU = European Union, O&M = Operational and Maintenance.

Case 1: Electricity source

Case 1 examines the baseline scenario while introducing four distinct electricity sources and their effects on WTW GHG emissions. The first electricity source is the French grid electricity mix, which represents the typical electricity generation mix in France. The second source is the EU grid electricity mix, representing the average electricity generation mix across the European Union.

Moving towards renewable energy, the third source is a 100% renewable electricity mix that includes operational and maintenance (O&M) emissions. This mix signifies electricity generated solely from renewable sources such as solar, wind, hydro, and biomass. However, it still considers emissions associated with the ongoing operation and maintenance of renewable energy infrastructure.

The fourth source is also a 100% renewable electricity mix but with zero emissions. This implies electricity generation exclusively from renewable sources without considering any emissions resulting from the operation and maintenance of the renewable energy infrastructure. This represents a scenario where renewable energy systems have reached a level of efficiency and sustainability that eliminates additional emissions beyond the initial construction phase.

In Case 1, we investigate how each of these electricity sources influences WTW GHG emissions, providing valuable insights into the environmental impact of different energy generation approaches and their implications for our fuel pathways of interest. By analyzing these scenarios, we can assess the potential benefits and trade-offs associated with various electricity sources in terms of emissions reduction throughout the fuel supply chain.

Case 2: Feedstock displacement

Case 2 investigates the effects of using feedstock derived from agricultural and industrial residues that would otherwise be used for alternative purposes, resulting in displacement. This case explores three different situations regarding feedstock displacement: no displacement, 10% displacement, and 100% displacement.

In the baseline scenario, no feedstock displacement occurs. This means that the feedstock used in the fuel pathways is obtained without affecting or displacing any other intended uses. It allows for an assessment of the emissions and sustainability implications of using feedstock that does not interfere with existing agricultural or industrial processes.

The second scenario considers a 10% feedstock displacement, implying that only a small portion of the available agricultural and industrial residues is redirected towards fuel production, causing a limited impact on other potential uses. This scenario helps evaluate the emissions and sustainability outcomes when a partial displacement of feedstock occurs.

The third scenario assumes 100% feedstock displacement, meaning that all the agricultural and industrial residues that could have been used for other purposes are now used exclusively for fuel production. This scenario examines the most significant potential impact on other sectors or industries that rely on the same feedstock, providing insights into the trade-offs and environmental consequences of a complete diversion of resources towards fuel pathways.

By analyzing these three scenarios, Case 2 allows for an understanding of the effects of feedstock displacement on emissions, resource allocation, and the overall sustainability of the different biofuel pathways. This understanding can help policymakers and other stakeholders assess the balance between utilizing available residues for fuel production and ensuring the preservation of other essential uses of these residues within the agricultural and industrial sectors.

Case 3: Fugitive methane emissions

Case 3 focuses on assessing the environmental implications of fugitive methane emissions in our selected biofuel pathways. It examines three distinct scenarios related to these fugitive emissions: no fugitive emissions, typical fugitive emissions, and an 80% reduction in typical fugitive emissions.

In the third scenario for this sensitivity case, no fugitive emissions are considered. This means that the fuel pathways are evaluated without accounting for any unintentional methane releases during the production, transportation, or utilization of fuels. This includes emissions from extraction, processing, storage, and distribution of feedstock and fuels as well as fuel utilisation on the vessel.

The baseline scenario reflects typical fugitive emissions, considering the average or expected level of unintentional methane releases that occur throughout the fuel supply chain. This includes emissions from extraction, processing, storage, and distribution of feedstock and fuels as well as fuel utilisation on the vessel. The values for typical methane emissions are derived from our companion report on methane emissions. By incorporating these typical fugitive emissions, the scenario provides insights into the overall environmental impact of fuel pathways under realistic operating conditions.

The second scenario explores the effect of an 80% reduction in typical fugitive emissions. In doing so, we can investigate the potential benefits of implementing measures and technologies to minimize methane leaks throughout the fuel supply chain. This reduction signifies efforts to improve operational practices, enhance infrastructure integrity, or adopt advanced leak detection and repair techniques. This scenario therefore evaluates the environmental performance of the selected fuel pathways when substantial progress is made in mitigating fugitive methane emissions.

Through the examination of these three scenarios, Case 3 allows for a comprehensive analysis of how fugitive methane emissions influence the environmental sustainability of our biofuel pathways of interest. It highlights the importance of addressing and reducing these emissions to minimize the overall GHG footprint and enhance the environmental performance of the fuel production and utilization processes.

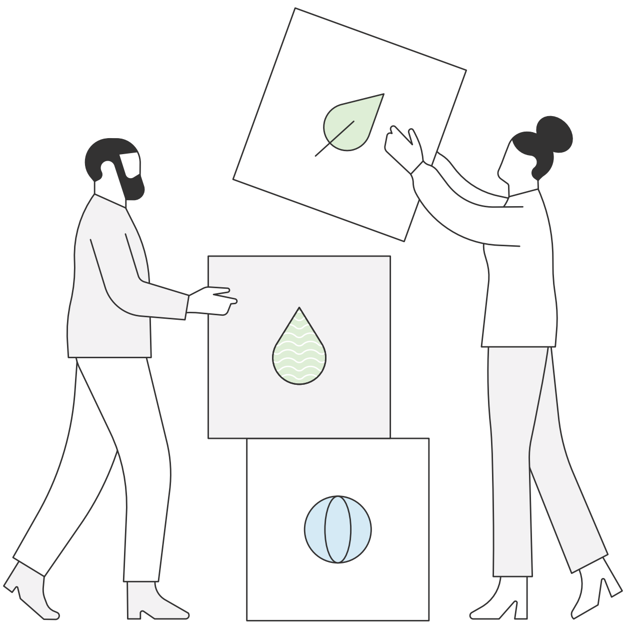
Case 4: Avoided landfill waste

Finally, Case 4 examines the utilization of waste feedstock for fuel production, preventing its disposal in landfills and consequently avoiding associated GHG emissions. This case explores three specific situations: no waste going to landfill being used as feedstock, a 10% reduction in waste sent to landfill, and complete avoidance of waste sent to landfill by utilizing this waste for fuel production.

In the baseline scenario, no waste directed to landfills is used as feedstock for fuel production. Instead, all waste materials that could potentially be used as feedstock for fuel production end up in landfill.

The second scenario involves a 10% reduction in waste sent to landfills. This means that a portion of the waste feedstock is recovered and utilized for fuel production, resulting in a reduction in waste disposal. This scenario allows for an assessment of the emissions reduction and resource recovery achieved when some waste is diverted from landfills to fuel pathways.

The third scenario represents a complete avoidance of waste disposal in landfills, where 100% of the waste feedstock is utilized for fuel production. By redirecting all waste materials towards fuel pathways, emissions associated with landfilling are entirely prevented. This scenario explores the maximum potential for emissions reduction and resource recovery through the utilization of waste feedstock for biofuel production.



5.3 WTW GHG assessment results and discussion

Figure 3-6 summarize the WTW GHG emissions associated with nine pathways for production of LBM and bio-methanol from biogas. Details on these fuel pathways and their specific characteristics can be found in our accompanying report on energy demand for emissions reduction compliance.

In brief, moving from left to right across the figures' horizontal axis, there are four production pathways for LBM from biogas (Pathways 1a, 1b, 2, and 3): these comprise, respectively, a 'standard' pathway using commercially available technology (Pathway 1a), this standard pathway with the addition of CCS (Pathway 1b), and two pathways that boost methane production by converting CO_2 in biogas to synthetic natural gas (SNG) (Pathways 2 and 3). The five pathways for bio-methanol production from biogas (Pathways 4, 5, 6a, 6b, and 7) include two pathways for producing fuel-grade bio-methanol (Pathways 4 and 5), and three pathways for producing AA-grade (high-purity) bio-methanol (Pathways 6a, 6b, and 7). For each methanol grade, we include options that use traditional steam methane reforming (Pathways 4 and 6) and electric steam methane reforming (Pathways 5 and 7) to boost fuel production by converting CO_2 that would otherwise be emitted into more methanol. Finally, one pathway for AA-grade bio-methanol production also incorporates CCS of residual CO_2 with traditional reforming (Pathway 6b). The key features of all nine pathways are also summarized in Table 4.

Table 4: 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.

The four upcoming figures highlight the impact of four parameters (electricity source, feedstock displacement, fugitive emissions, and avoided landfill waste) on the overall GHG emissions of our selected fuel pathways. The WTW GHG emissions intensity of the various fuel pathways, measured in terms of grams of CO_2 equivalent emitted per megajoule (gCO_2eq/MJ) of fuel, is scaled on the vertical axis of the figures. The exact WTW GHG emissions intensity value in the baseline scenario for each pathway is also represented as a number over the relevant column. The contributions of different sources of emissions and credits to the emissions intensity for each pathway are represented as stacked bars in various colors.

It is important to note that the baseline scenarios presented in the figures do not account for reductions in fugitive emissions, emissions resulting from feedstock displacement, or emissions avoided through the use of landfill waste. Additionally, the baseline scenario assumes the use of the French grid mix and does not assume zero emissions from the use of renewable electricity sources.

Figure 3 illustrates how the source of electricity used in the fuel production pathways influences the overall associated GHG emissions. Fuel pathways that use 100% renewable electricity assumed to have zero emissions (represented by the red dashed line) exhibit the best GHG emissions performance. Using renewable electricity with O&M emissions (dark yellow dashed line), we notice a small increase in the WTW emission intensities of these biofuel pathways. Fuel pathways relying on the EU electricity mix (represented by the blue dashed line) have the poorest performance, with Pathways 3-7 performing worse than the others due to their high electricity consumption and the higher emissions factor associated with the EU grid mix. When using the French electricity mix (baseline scenario, black line), significantly negative emissions are only achieved in Pathways 1b and 6b, due to their integration of CCS. When using renewable electricity with O&M emissions, we notice a small increase in the WTW emission intensities of these biofuel pathways.

Figure 3: Sensitivity analysis of electricity use and its impact on the WTW performance of selected LBM and bio-methanol production pathways. Numbers show the WTW GHG emissions intensity in the baseline scenario for each pathway.

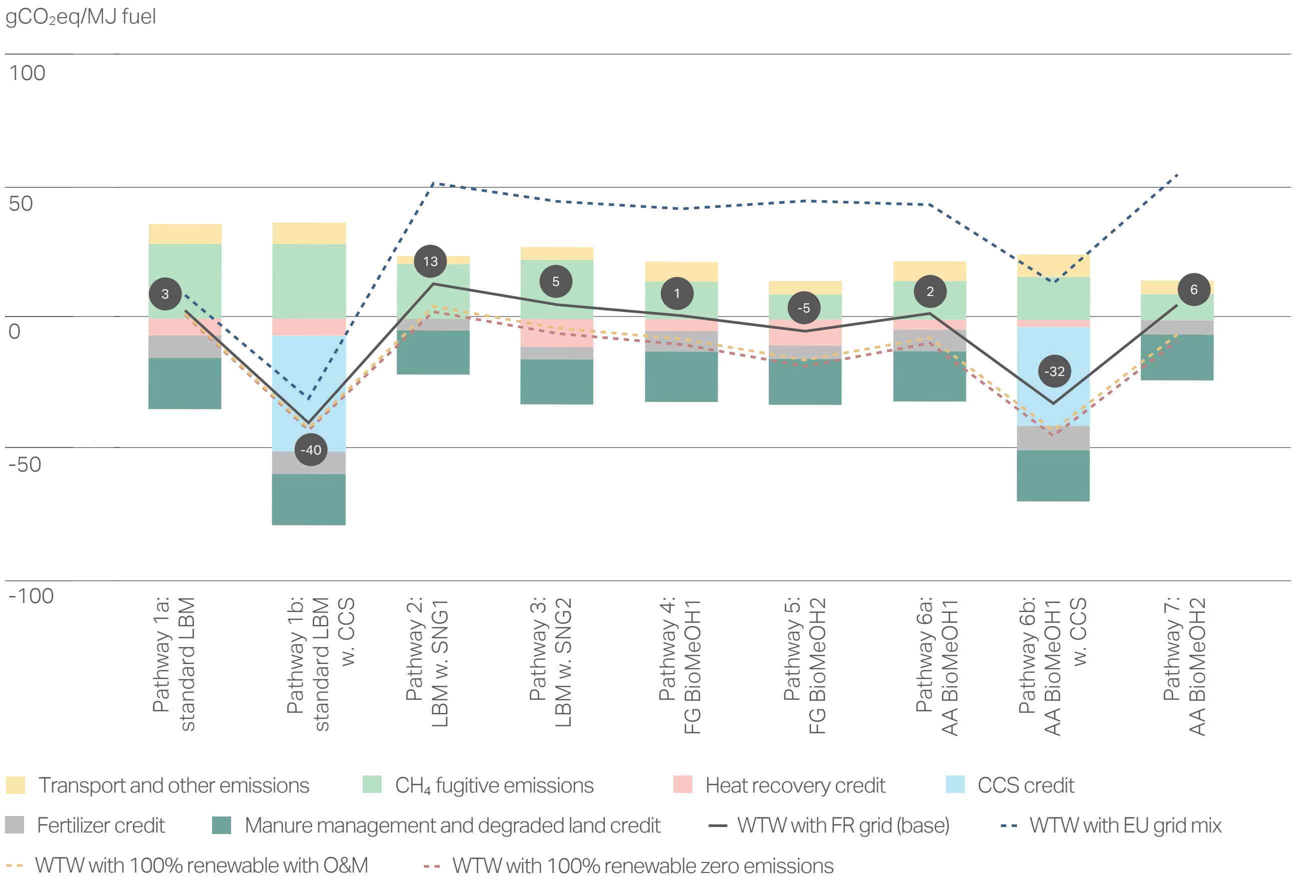


Figure 4 illustrates the influence of utilizing biomass feedstock that is currently employed for other purposes to produce biofuels. When 100% of the applicable agricultural and industrial biomass is diverted from its existing use case, the resulting biofuels consistently exhibit high GHG emissions intensity (dark yellow dashed line). This is primarily due to the increased demand for biomass caused by its diversion from its original purpose. Importantly, use of CCS technology in Pathway 6b does not offset the negative impact caused by diverting biomass from its previous uses, although Pathway 1b still has slightly negative emissions in this scenario. This finding highlights the importance of carefully considering the source and sustainability of biomass feedstock when producing biofuels to avoid negative environmental outcomes.

Figure 4: Sensitivity analysis of feedstock displacement and its impact on the WTW performance of selected LBM and bio-methanol production pathways. Numbers show the WTW GHG emissions intensity in the baseline scenario for each pathway.

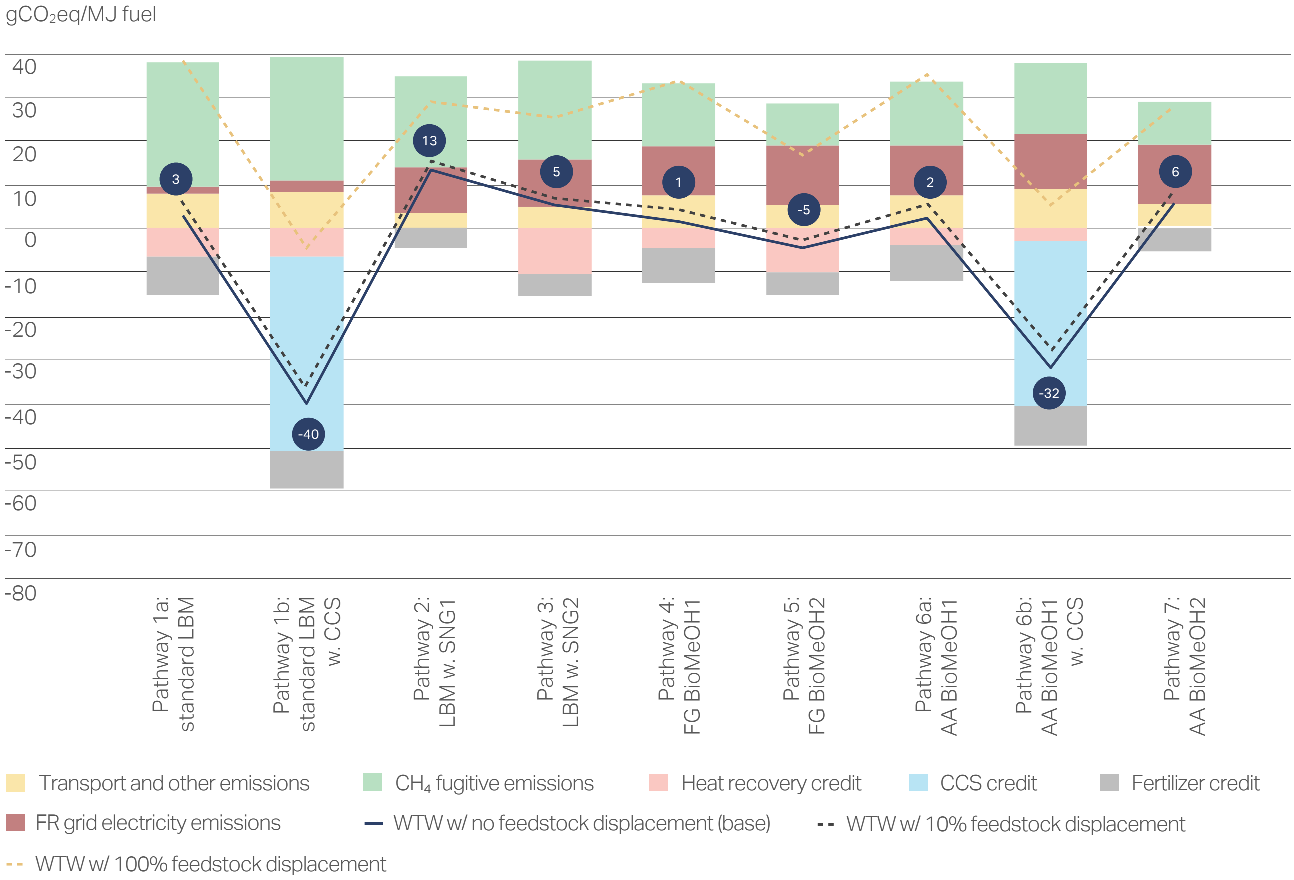
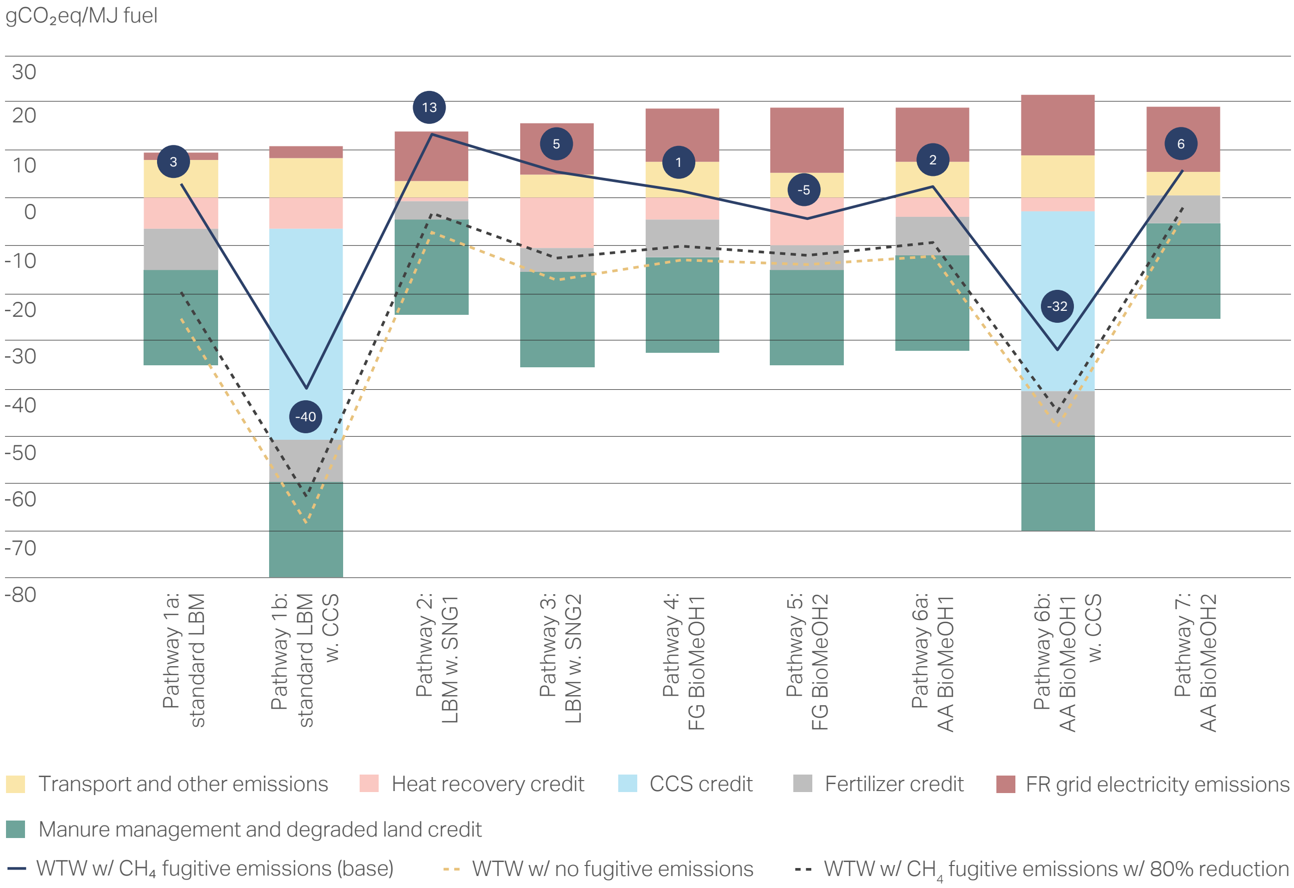


Figure 5 demonstrates the influence of fugitive methane emissions on the emissions intensity of the fuel pathways. In the baseline scenario (represented by the blue line), which includes typical methane emissions, only Pathways 1b and 6b achieve significant negative emissions. This can be attributed to the incorporation of CCS technology in these pathways, which helps offset the emissions. However, if fugitive methane emissions can be reduced by 80% through effective mitigation techniques (blue dashed line), then all the pathways have the potential to achieve highly negative emissions. The figure illustrates that if fugitive methane emissions are not controlled, then the emissions intensity of these biofuels cannot be reduced to the point where these fuels can help us decarbonize the maritime industry.

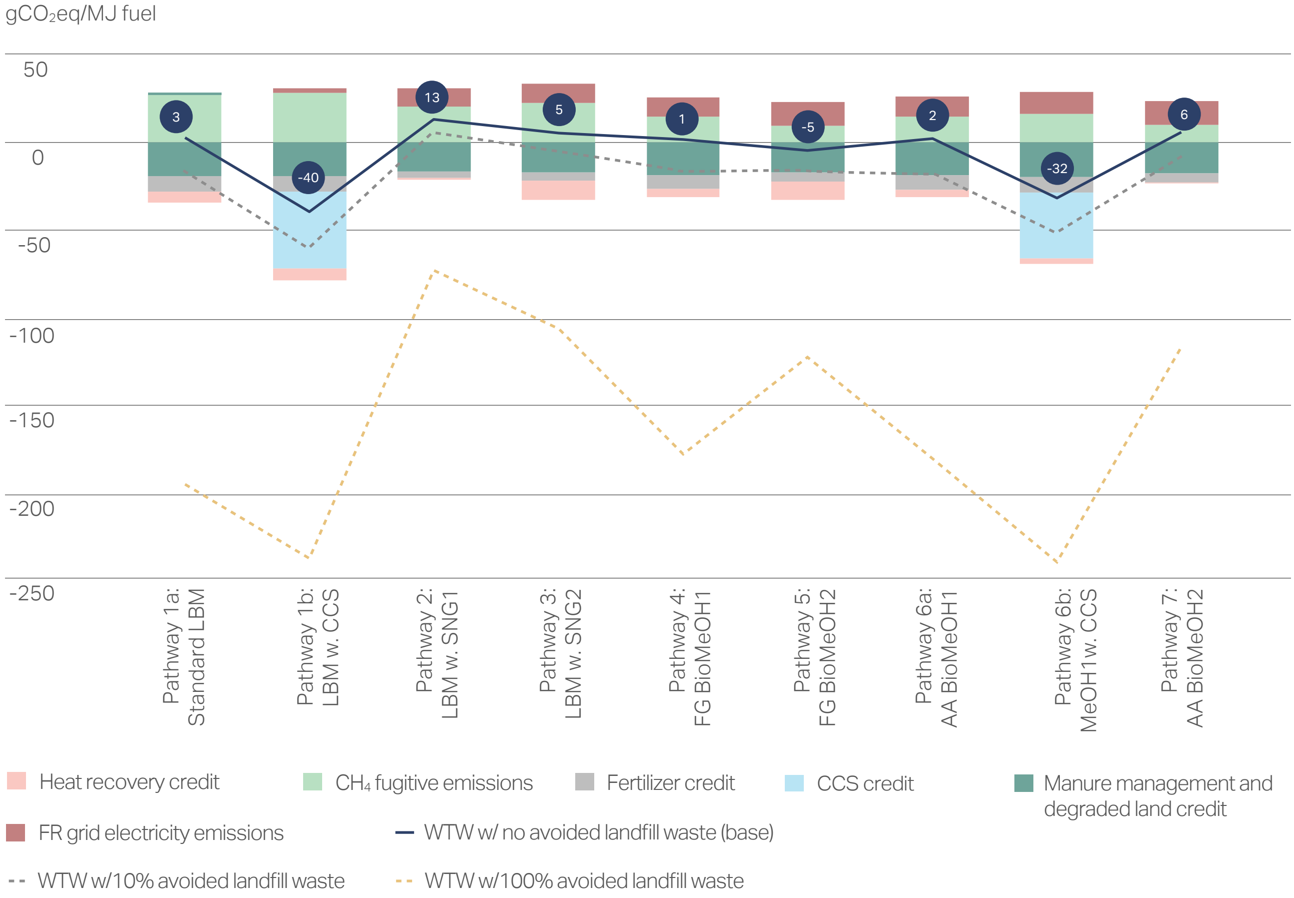
Figure 5 : Sensitivity analysis of fugitive methane emissions and their impact on the WTW performance of selected LBM and bio-methanol production pathways. Numbers show the WTW GHG emissions intensity in the baseline scenario for each pathway.



Finally, Figure 6 examines the impact of utilizing industrial biomass waste that would otherwise be disposed of in landfill for biofuel production. Diverting biomass waste from landfill can lead to negative emissions in most of the studied fuel pathways. Even when only 10% of the industrial biomass feedstock used in fuel production is replaced by biomass waste from landfills (represented by the grey dashed line), nearly all the fuel pathways exhibit negative emissions. This substitution allows for the avoidance of emissions that would arise from the decomposition of biomass in landfills, which releases methane into the atmosphere.

Furthermore, if 100% of the industrial biomass feedstock used in fuel production is replaced by biomass waste from landfills (represented by the dark yellow dashed line), then the emissions can become even more strongly negative. This suggests that fully utilizing biomass waste from landfills in fuel production has the potential to significantly reduce GHG emissions. This result underscores the importance of utilizing biomass waste as a sustainable resource and mitigating emissions from landfill through proper waste management practices.

Figure 6: Sensitivity analysis of avoided landfill waste and its impact on the WTW performance of selected LBM and bio-methanol fuel production pathways. Numbers show the WTW GHG emissions intensity in the baseline scenario for each pathway.



6. Conclusion

This report centers on the WTW performance, in terms of GHG emissions intensity, of different fuel production pathways for biogas-based LBM and bio-methanol — two biofuels of increasing interest to the global shipping industry. Our analysis highlights key factors contributing to emissions intensity, including fugitive emissions of methane and the use of grid electricity mix. It also underscores the potential for emissions reductions through measures such as improved manure management, mitigation of fugitive emissions, renewable energy use, process heat recovery, and CCS technology. Under the assumptions of this study, we do not find a major difference between the emissions intensity of LBM and bio-methanol per se. Rather, the study highlights the complex interplay of different factors — such as process-specific emissions, energy sources, and mitigation measures — which influence emissions intensity.

This complexity makes it crucial to understand the context and feasibility of the potential emissions reduction measures applicable to the production of these biofuels. Each region or facility may have unique circumstances and constraints that impact the applicability and effectiveness of emissions reduction strategies. Factors such as biomass availability, infrastructure requirements, and local regulations can also significantly influence feasibility and cost-effectiveness. Therefore, when considering the adoption of emissions reduction strategies, it is essential to conduct a comprehensive analysis that considers the specific characteristics and limitations of the given context. This analysis should encompass factors such as biomass availability, existing infrastructure, policy support, and technological advancements to determine the most appropriate and feasible measures for achieving emissions reductions in LBM and bio-methanol production.

Importantly, we encourage readers to keep in mind that emissions credits earned from activities like manure management or fertilizer displacement using digestate have a time limit. These credits can only be applied to reduce WTW fuel emissions for around 15 to 20 years. After that period, they could be considered invalid as these activities become a common practice in the industry. This perspective should be considered when assessing options for longer-term investment in the adoption of biofuels.

Our findings also support the importance of collaboration between various stakeholders, including researchers, industry experts, and policymakers. Collaborative efforts make it possible to develop and implement effective strategies and policies that promote the adoption of low-emissions biofuel production pathways. By carefully considering the factors that affect GHG emissions intensity and tailoring strategies to local conditions, stakeholders can work towards maximizing the emissions reduction potential of biofuel pathways while ensuring their practicality and long-term sustainability.

In conclusion, the results presented in this report highlight the challenges and opportunities in reducing emissions intensity in LBM and bio-methanol production from biogas. By implementing mitigation measures and adopting innovative technologies, it is possible to enhance the environmental performance of these biofuels and make significant strides towards a greener and more sustainable energy future for the shipping industry.

7. 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 asterix (*) were seconded to the MMMCZCS from partner organizations.

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For the knowledge contributed to this project, we would like to thank:
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), Magnus Folkelid (Rambøll), Frank Harteveld (Rambøll), and Wärtsilä Einar Gudmndsson (Rambøll).

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), and Josh Hawthorne (World Biogas Association).

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Abbreviations

BioV	Biovilleneuvois biogas plant
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CH_4	Methane
EU	European Union
GHG	Greenhouse gas
GWP	Global warming potential
HCS	High carbon stock
ILO	International Labour Organization
IMO	International Maritime Organization
iLUC	Indirect land-use change
IPCC	Intergovernmental Panel on Climate Change
ISCC	International Sustainability and Carbon Certification
ISO	International Standardization Organization
LBM	Liquified bio-methane (also known as liquified biogas (LBG) or bio-LNG)
LCA	Life cycle assessment
LHV	Lower heating value
LNG	Liquified Natural Gas
LUC	Land-use change
LULUCF	Land use, land-use change and forestry
MFE	Mineral fertilizer equivalent
MJ	Megajoule
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
N_2O	Nitrous oxide
O&M	Operational and maintenance
RED	Renewable Energy Directive
RSB	Roundtable on Sustainable Biofuels
SFM	Sustainable forest management
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.
TTW	Tank-to-wake
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
WTT	Well-to-tank
WTW	Well-to-wake

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Appendix A: Assumptions and limitations for WTW GHG assessment

This appendix contains additional details on assumptions and limitations in our WTW GHG assessment presented in this report. For the purposes of this assessment (outlined in Sections 2 and 5), we made the following assumptions:

- Emissions associated with feedstock production are specific to energy crops‡ or first-generation fuel crops.§ Feedstocks classified as waste or residues are assumed to have zero climate burden at this stage, except when considering the impact of feedstock displacement in order to check the sensitivity of the analysis, as described in Section 5. The emissions associated with feedstocks, as outlined in the Renewable Energy Directive (RED) II (Annex V-C) guidelines, include factors such as the extraction or cultivation process; collection, drying and storage of raw materials; waste and leakages; and the production of chemicals or products used in extraction or cultivation. Inputs like fertilizers and pesticides are accounted for, while the capture of CO_2 during the cultivation or extraction of raw materials is excluded. For this exercise, we assumed all feedstock to be waste or residue, in line with the requirements of FuelEU Maritime. We also conducted a qualitative displacement analysis to evaluate the potential risks associated with utilizing waste feedstocks for biofuel production, which is discussed in Section 5 of the report.
- A feedstock's emissions may be negative if the feedstock is a waste that would otherwise be discarded without further treatment, releasing methane or nitrogen oxides in the process. The avoided emissions resulting from the management of manure are calculated based on the amount of feedstock manure processed annually. To ensure consistency, a negative emissions value (credit) of -26.28 kg CO_2/tonne of wet manure is adopted from RED II. Section 5.1 and Appendix C explain how these credits are calculated.
- The emissions associated with the transportation of feedstock, intermediate products, digestate, and final products are considered. Our companion report on energy demand for emissions reduction compliance provides details on the transport distances and the method used to account for fossil fuel consumption related to this activity.
- The emissions resulting from anaerobic digestion, upgrading, and compression of bio-methane are included in the analysis.
- During the storage phase, methane emissions from digestate are considered to be zero and are therefore not accounted for. We have also assumed the use of a closed digestate storage system, ensuring that all emissions, including any fugitive emissions, are captured and contained.
- Emissions resulting from the combustion of bio-methane on board the ship are included in the analysis, specifically for the tank-to-wake (TTW) phase.
- Fugitive methane emissions resulting from the loss of methane during almost all steps of the value chain (biogas transport, upgrading, liquefaction, chemical synthesis, biofuel transport) are also accounted for. These values are estimated in the companion study on methane emissions.

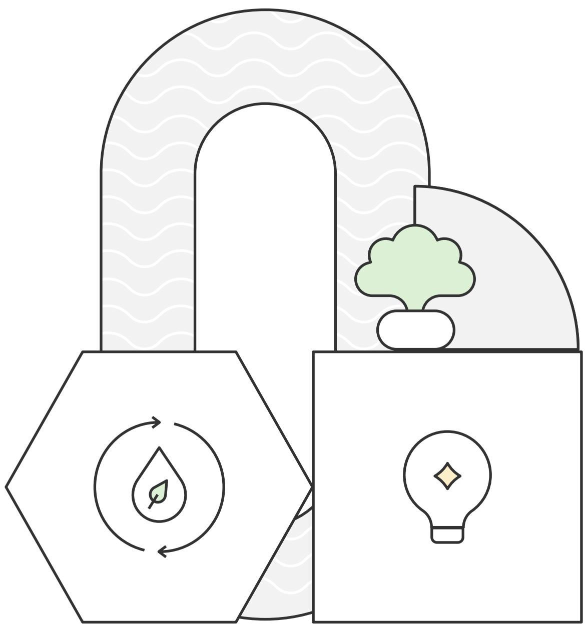
We also examined two different cases of system expansion to consider the emissions avoided through manure and digestate management:

- The first system expansion incorporates emissions savings from using or exporting excess heat generated in the biofuel production pathways and substituting the equivalent external heat supply, achieving avoided emissions and thereby credits.
- The second instance involves considering emissions savings due to the avoidance of conventional fertilizer production resulting from the application of digestate to the soil. In this case, the digestate is treated as raw, without separating its liquid and solid phases. This expansion allows for the estimation of emissions reductions achieved through the utilization of digestate as a fertilizer substitute.

‡ Energy crops are crops grown solely for renewable bioenergy production.
§First-generation fuel crops are crops which are usually grown for food but are also used for biofuel production.

Finally, we note the following limitations to our assessment:

- The GHG emissions resulting from the application of digestate to land are not included within the system boundary of this study. The application of raw digestate to agricultural fields can lead to the release of nitrous oxide (N_2O), a highly potent GHG. However, due to the lack of specific data on the chemical composition of the digestate, the use of average composition introduces uncertainty about the level of expected N_2O emissions. Considering the limitations in terms of certainty, time, and resources, these emissions are not included in the assessment.
- No fugitive methane emissions are considered during the bunkering step, due to insufficient information available for this specific phase.
- Comparison of a few public studies reveals a lack of consistent methodology for calculating fertilizer credits.[9,10,11,12] The approach adopted in this study should be regarded as a tier 1 approach,[13] which can be refined in the future to align with evolving best practices in the field. A detailed explanation of our relevant methodology is provided in Section 5.1 and Appendix C of this report.
- Wherever possible, we used data provided by project partners. In cases where no partner data was available, we sourced values from literature or published resources. While this may reduce the specificity of the analysis, the use of averaged or national values increases the applicability of our high-level conclusions to other plants or operators.



Appendix B: Details of sustainability criteria

This appendix contains additional supporting information relating to Section 4: Sustainability criteria for biofuels.

Table 5 provides the full names of policies, legislation, and certification schemes included in Table 2, which summarizes sustainability criteria and their inclusion in different schemes for biofuel and biomass sustainability.

Table 5: Abbreviations and full names of biofuel and biomass sustainability policies, legislation and certification schemes included in Table 2.

RED I, II	Renewable Energy Directive
UK RTFO	United Kingdom Renewable Transport Fuel Obligation
ISCC	International Sustainability and Carbon Certification
Bonsucro	Global Sustainability Platform for Sugarcane
RTRS	Round Table on Responsible Soy Association
RSB	Roundtable On Sustainable Biofuels
2BSvs	Biomass Biofuel Sustainability Voluntary Scheme
Red tractor	Red Tractor Farm Assurance Combinable Crops & Sugar Beet Scheme
SQC	Scottish Quality Farm Assured Combinable Crops
REDcert	Renewable Energy Directive Certification
Better Biomass	Better Biomass Certification Scheme
RSPO	Roundtable On Sustainable Palm Oil
Biograce III	Policy Framework
HVO	Hvo Verification Scheme
Gafta	Gafta Trade Assurance Scheme
KZR INIG System	Kzr Inig System
TASCC	Trade Assurance Scheme for Combinable Crops
UFAS	Universal Feed Assurance Scheme
RFS_2	Renewable Fuel Standard
CARB-LCFS	California Air Resources Board- Low Carbon Fuel Standard
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CFS	Clean Fuel Standard
LCFS-BC	Low Carbon Fuel Standard-British Columbia
UK RO	United Kingdom Renewable Obligation Order
SDE +	Dutch Stimulation of Sustainable Energy Production
FSC	Forest Stewardship Council
PEFC	Programme For the Endorsement of Forest Certification
SBP	Sustainable Biomass Program

The remainder of this appendix is devoted to further details and descriptions of various relevant environmental and socio-economic sustainability criteria considered in Section 4.

Environmental criteria

Sustainable forest management (SFM)

The SFM criterion encompasses several aspects, including the legal sourcing of forest products, sustaining forest productivity, conservation of ecosystems and nature, protection of biodiversity, and safeguarding air, soil, and water resources. This criterion also promotes the efficient utilization of various forest products and services to maximize environmental and socio-economic advantages. It may involve measures to protect endangered plant and animal species and enhance crucial ecological cycles. Furthermore, it may require the implementation of anti-corruption measures and the payment of relevant royalties and taxes.

Preservation of high carbon stock (HCS)

This criterion prohibits the use of land with high carbon stocks.** It includes strict measures such as implementing management practices to preserve, enhance, or restore carbon storage in forests, including forest protection and reduced-impact logging techniques for carbon conservation. Other considerations involve (1) assessing the positive impacts on the long-term carbon sequestration capacity of forest vegetation, (2) recognizing the protective role of forests in climate regulation and carbon sequestration for society, and (3) ensuring the maintenance and improvement of regulating or supporting ecosystem services.

Biodiversity protection

Biodiversity protection involves evaluating the relevant biodiversity, ecosystems, and protected areas without any prior information. Additionally, it is necessary to identify and assess endangered species and regions. Moreover, there should be a greater emphasis on safeguarding, conserving, and enhancing areas with high biodiversity value.††

Protection of air, soil, and water

This criterion mandates the use of practices that prioritize soil preservation and fertility while achieving balanced yields. Proper management of waste and byproducts should be implemented to maintain soil health and fertility. Compliance with water management regulations, water usage rights, and water availability considerations is also essential. Adequate water availability, both surface and groundwater, must be ensured. Additionally, efforts should be made to minimize pollution, responsibly manage generated waste, responsibly expand soil cultivation, and preserve or restore natural vegetation areas along watercourses. The criterion suggests implementing practices to reverse soil degradation, maintain soil health, and respect existing formal or customary water rights. Moreover, it prohibits the production of sustainable biofuels using raw materials obtained from lands where soil, water, and air have not been adequately protected. Special attention should be given to coastal areas, riverbanks, erosion-prone regions, and sloping landscapes to improve their conditions.

Indirect land-use change (iLUC)

According to this criterion, biofuels can only be certified as low-iLUC-risk fuels if they meet GHG emissions-saving criteria and are produced from additional feedstock obtained through specific measures. These measures include (1) increasing productivity on existing land, (2) cultivating crops on previously unused land, subject to overcoming financial barriers or the land being abandoned or severely degraded, or being cultivated by small farmers, and (3) providing strong evidence of meeting the requirements mentioned in (1) and (2).

Land use, land-use change, and forestry (LULUCF)

Regarding the criteria for land use, land-use change, and forestry (LULUCF), forest biomass must originate from a country that (1) is a party to the Paris Agreement, (2) has submitted a nationally determined contribution to the United Nations Framework Convention on Climate Change (UNFCCC), and (3) has national or sub-national laws in place under Article 5 of the Paris Agreement. Additionally, LULUCF criteria require that (1) biomass production does not lead to the destruction of carbon sinks or the accumulation of long-term carbon debt, (2) the forest management unit (FMU) maintains or increases carbon stocks in the medium or long term, and (3) biomass is not sourced from stumps except for reasons other than wood or biomass production.

**High carbon stock land is land that stores large amounts of carbon, such as wetlands and forests.
†† High biodiversity value means an area not subject to legal protection but recognized for important biodiversity features by a number of governmental and non-governmental organizations, including habitats that are a priority for conservation.

Socio-economic criteria

Worker rights

This criterion states that the fulfilment of the International Labour Organization (ILO) Convention No. 138 Indicator should be ensured to guarantee that the minimum age requirement for employment among the local Indigenous people is respected. The right to association of these individuals should also be protected under ILO Conventions No. 87 and No. 97. Additionally, promoting safety training, fair communication, employment opportunities, and the provision of goods and services to the local population is encouraged. Furthermore, efforts should be made to maintain or enhance the socio-economic well-being of workers.

Land rights

Land rights, as a crucial aspect of sustainability, involve safeguarding the land rights of Indigenous peoples and local communities. It is important that land-use rights are well-documented and do not clash with the claims of the local population. When using agricultural land for biomass cultivation for energy purposes, it is essential to ensure that this activity does not infringe upon the land and customary rights of the local community. Consultation with the local community is necessary for making decisions regarding land management. Efforts should be made to minimize any negative impacts of land management on the local community and maximize positive impacts. In cases of land rights conflicts, a resolution should be sought through the principle of free prior informed consent.

Food security

As defined by the Food and Agriculture Organization's approach, food security is a vital aspect of sustainability. It encompasses the idea that all individuals should have consistent access to an adequate supply of safe and nutritious food that caters to their dietary requirements and preferences, enabling them to lead active and healthy lives. Evaluating the risk to food security in the region and taking necessary measures to mitigate any adverse impacts caused by economic activities are also essential components of this criterion.

Resource efficiency

This sustainability criterion ensures that the feedstocks utilized for bioenergy production are efficient in terms of raw material usage. Compliance can be demonstrated by providing a description of the materials used and outlining the measures implemented to promote the efficient utilization of raw materials.

Economic criteria

According to this criterion, new initiatives such as constructing plants or cultivating crops should prioritize economic viability and contribute to the local development of the area. A thorough economic impact assessment of the business plan should be conducted, including an evaluation of the project's effect on the local community. Emphasis should be placed on highlighting the positive impacts of the project. It is important to ensure equitable profit-sharing among the owners, employees, and the local community. Compliance with national labor regulations, particularly in terms of minimum wages, should also be assessed. Ultimately, the goal is to foster improved local economic conditions over time.

Appendix C: Details of well-to-wake assessment methodology

This appendix contains additional details of our WTW assessment methodology. As previously outlined in Section 5, we used the following formula* to calculate WTW GHG emissions for this report:

$$E_{total}\,(WtW) = e_{ec} + e_l + e_p + e_{td} + e_u + e_{fugitive} - e_{sca} - e_{ccs} - e_{cpc} - e_{avb}$$

$$e_{sca} = e_{manure} + e_{fertilizer}$$

Where:	
E_{total} (WtW)	total emissions associated with the complete biofuel supply chain
e_{ec}	emissions associated with feedstock acquisition and pre-processing, especially during cultivation and harvesting of biomass
e_l	annualized emissions associated with land-use change (specific to first-generation energy crops)
e_p	emissions associated with fuel production and processing (synthesis, upgrading, liquefaction, etc.)
e_{td}	emissions associated with transportation, distribution, and storage
e_u	emissions associated with fuel utilization on board the vessel
$e_{fugitive}$	emissions associated with fugitive emissions and slip emissions
e_{sca}	emissions savings from soil carbon accumulation via improved agricultural management
e_{ccs}	emissions savings from carbon capture and storage
e_{cpc}	emissions credits associated with the processes involved in the original synthetic product on the market when the co-product directly replaces an original synthetic product on the market
e_{manure}	emissions savings from avoidance of methane emissions during manure management (if relevant)
$e_{fertilizer}$	emissions savings from avoidance of fertilizer production and use due to digestate application
e_{avb}	emissions savings from avoidance of methane emissions from biowaste ending up in landfill

*Equation modified from Directive (EU) 2018/2001.

More specifically:
e_{ec} encompasses the total emissions related to various stages such as growing, extracting, and preparing feedstock. Additionally, this factor considers emissions from machinery used during crop cultivation, as well as other farming activities like tillage. The e_{ec} for waste and residue feedstocks is considered zero and does not have any climate burden.

e_l includes the emissions connected to land-use change, particularly in relation to cultivating energy crops (also known as first-generation biomass). The emissions resulting from direct land-use change can be measured using the BioGrace GHG calculation tool, which is acknowledged as a voluntary program by the European Commission.[14] As this particular study does not consider the use of first-generation biomass for fuel production, e_l is regarded as zero.

e_p comprises the emissions linked to fuel production, including processes such as biomass processing, synthesis, upgrading, and liquefaction. It also considers emissions resulting from utilities and consumables, such as electricity, diesel, and catalysts. For our analysis described in Section 5, the emissions factors used for the French electricity mix for the typical case and the EU mix for our sensitivity assessment were reported by the European Environment Agency (EEA),[15] whereas the emissions factor for renewable electricity mix (wind and solar) for our sensitivity assessment was considered as zero when the emissions associated with operation and maintenance were excluded. It is important to note that fugitive emissions during fuel production are not included in e_p, but they are considered and accounted for separately in $e_{fugitive}$.

e_{td} encompasses the emissions that occur during transportation, distribution, and storage throughout the supply chain. These emissions are quantified by considering factors such as the type and quantity of fuel used for transportation, as well as the emissions factors associated with that fuel. This factor is calculated by multiplying the quantity of fuel used (e.g., truck diesel) by the emissions factor associated with that fuel's stoichiometric combustion.

e_u includes emissions during fuel utilization on board the vessel. The CO_2 from combustion of biofuels is considered to be biogenic and therefore does not carry any climate burden, meaning that the e_u from CO_2 is regarded as zero. However, we have assigned emissions factors to onboard methane and N_2O emissions based on the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5).[16]

$e_{fugitive}$ includes all fugitive, or unintentional, GHG emissions that occur throughout the fuel pathway. These emissions are unrelated to the final use of the fuel and can occur during various stages such as extraction, processing, transformation, and delivery of fuels until they reach their final point of use. Fugitive methane emissions are calculated by multiplying the quantity of methane emitted by the global warming potential value of methane over 100 years (GWP100), which is 28 based on the IPCC AR5 report. We have considered GWP100 instead of GWP20 for our assessment, as this metric is consistent with various established methodologies concerning emissions reduction.[17,18]

e_{sca} includes the emissions savings that occur through the process of soil carbon accumulation resulting from the adoption of improved agricultural practices. These practices focus on enhancing soil health and increasing the organic carbon content in agricultural soils. By implementing techniques such as conservation tillage, cover cropping, crop rotation, and organic amendments, carbon is sequestered in the soil over time. This sequestration process helps to mitigate GHG emissions by removing CO_2 from the atmosphere and storing it in the soil, thereby contributing to climate change mitigation efforts. The increased soil carbon levels also lead to improved soil fertility, water retention, and overall ecosystem health, further enhancing the sustainability and productivity of agricultural systems. We did not account for soil accumulation in this study as it requires comprehensive analysis of soil samples, entails variance due to the location, and comes with high uncertainty. e_{sca} also includes emissions avoided by using waste that would otherwise end up in landfill releasing methane as feedstock for fuel production.

e_{ccs} includes the emissions reductions achieved through the implementation of carbon capture and storage (CCS) practices at various stages of the supply chain. It includes not only the emissions associated with initial separation or capture but also the transportation, processing, and injection of CO_2 at the storage site.

e_{cpc} represents the reduction in emissions that can be accomplished through the substitution or replacement of existing products or processes. This includes actions such as adding excess electricity generated during fuel production to the local grid or utilizing surplus heat produced during the process to replace the need for heat from other sources. By implementing these strategies, emissions savings can be achieved while maintaining or improving the functionality and performance of the products or processes involved.

e_{manure} is determined by multiplying the total amount of manure (measured in tonnes) used as feedstock in the anaerobic digester at a biogas plant by the emissions factor associated with conventional manure management practices. Using manure for biogas production helps to avoid emissions from the manure, allowing these avoided emissions to be accounted for as a credit. The specific emissions factor used in this project is derived from RED II, which quantifies it as 45 gCO_2eq/MJ of manure used in anaerobic digestion. The project also considers the lower heating value (LHV) of dry manure, which is determined to be 12 MJ/kg.[19] The assumed total solid percentage in the manure is 5%, based on information provided by project partners. As a result, the final credit calculated for manure is 26.28 kg CO_2eq/tonne wet manure.

$e_{fertilizer}$ The digestate obtained from biogas production contains valuable nutrients such as nitrogen, phosphorus, and potassium (N, P, and K). These nutrients can fulfil the nutritional requirements of crops, thereby reducing the need for additional fertilizers. This reduction in fertilizer usage can result in avoided emissions, leading to potential credits. For this study, the key steps involved in establishing a value for this credit were:

- We aimed to determine the nutrient content of digestate, specifically N, P, and K. Due to the variability in digestate composition resulting from different feedstocks used in biogas plants, we derived an average composition from five samples collected from Danish biogas production plants for the purposes of this study.[20] Although this approach may not fully represent real-life variability, it provides a basis for analysis. The exact form of N, P, and K in the digestate is uncertain, but the total nitrogen and the nitrogen present in the digestate are identified.
- To assess the potential for substitution of mineral fertilizers with digestate, we identified the main fertilizers commonly used in France based on information provided by partners. This information is crucial because different fertilizers have varying GHG emissions factors. By understanding the commonly used fertilizer types in these regions, we can determine the appropriate fertilizer type that can potentially be replaced by digestate.
- The fertilizing value of organic residues, such as digestate, differs from that of mineral fertilizers due to the presence of nitrogen in both organic and mineral forms. Organic nitrogen requires mineralization by soil microorganisms before plants can assimilate it. To establish equivalence, we used the concept of mineral fertilizer equivalent (MFE). In this study, we assume that the available nitrogen in digestate is 100% available to plants and can replace nitrogen fertilizer. Similar assumptions of 100% availability are also made for the MFE of phosphorus and potassium.[21]

Based on these considerations, we adopted a one-to-one substitution principle, with the amount of avoided mineral N, P, and K fertilizer corresponding to the amount of MFE-N, -P, and -K present in the organic fertilizer at a 1:1 ratio. By applying this principle, the credit for avoided emissions resulting from reduced fertilizer usage can be quantified.

The principle can be described with the following equation:

$$e_{fertilizer} = -(AMF_x \text{ x } Fertilizer_x emission\ factor)$$

Where:
$AMF_x = MFE_x$

Where AMF_x is the amount of avoided mineral fertilizer containing the nutrient X (kg) and MFE_x is the amount of mineral fertilizer equivalent containing the nutrient X (kg).

e_{avb} encompasses emissions that can be prevented by using biowaste for fuel production instead of allowing the waste to end up in landfills and generate unwanted methane emissions. This additional factor is taken into account in this assessment to demonstrate an alternative method of reducing emissions and earning credits.

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