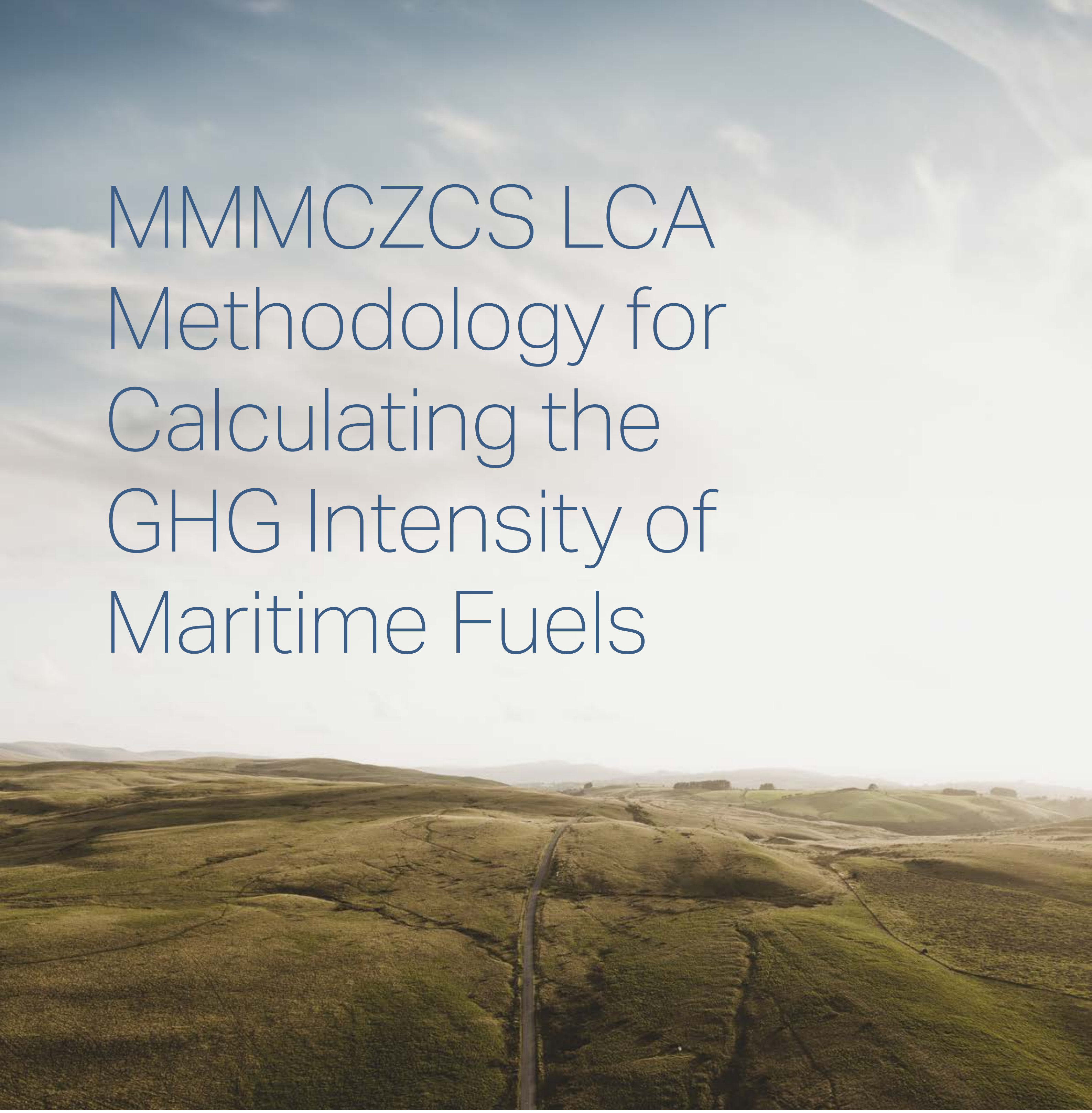


MMMCZCS LCA Methodology for Calculating the GHG Intensity of Maritime Fuels

Policy brief

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Table of Contents

Executive summary

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) presents an initiative within our 'Life Cycle Approach for Policymaking' project. This document serves as the first installment in a two-part series detailing the MMMCZCS life cycle assessment (LCA) methodology developed by the Center. The primary focus of this paper is to give an overview of the fundamental principles for the accounting of greenhouse gas (GHG) emissions considered in the methodology.

In the maritime industry, the need for a standardized approach to assess the GHG intensity of alternative marine fuels has become increasingly clear. This necessity arises from the complexity of the current regulatory landscape, where different countries and regions adopt different methodologies for evaluating fuel life cycles and their effects on climate change. This disparity creates uncertainty about the actual climate impact of alternative marine fuels, leading to uncertainty, delays, and indecision on investments necessary to steer the decarbonization process.

At its core, the MMMCZCS LCA methodology aims to provide a solution by offering a consistent framework to calculate the GHG intensity of marine fuels. This standardized approach aligns with the groundwork established by existing guidelines and standards acknowledged in Section 1.1 of this document. The accompanying in-depth technical document delves deeper into LCA principles to standardize our approach and guide LCA practitioners to carry out life cycle emissions assessment of alternative marine fuels.

The International Maritime Organization (IMO) has responded to the pressing need for standardization by building the Draft Guidelines on the Life Cycle GHG Intensity of Marine Fuels. Through its comprehensive and global structure, the MMMCZCS LCA methodology aims to make a reference for fully assessing the GHG intensity of maritime fuels. The MMMCZCS methodology not only adds details to the existing foundation laid by the IMO but also aligns different aspects, paving the way for a unified approach. Our methodology provides a supplementary approach to consider not only the specificities of new marine fuels, but also to allow the various actors in the well-to-wake chain to identify the sources of emissions and thus enable them to improve their processes.

In conclusion, the MMMCZCS LCA methodology is a pivotal tool in the pursuit of sustainable maritime practices. By offering clear and standardized principles for calculating GHG emissions, it navigates the complex waters of varied regulatory methods. This methodology can encourage more informed decisions, catalyze investments, and help propel the global maritime community towards a greener future.

1. Introduction

Greenhouse gases (GHGs) play a major role in climate change by accelerating global warming. Therefore, accounting for the GHG emissions associated with alternative marine fuels is vital to ensure that the shipping industry meets climate targets. GHG emissions accounting enables the maritime industry to select fuels with transparent and sound climate credentials, thereby ensuring greater certainty on the GHG emissions reductions needed for our climate goals.

To support the shipping industry on its journey to decarbonization, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) has developed an independent standardized life cycle assessment (LCA) methodology that provides guidance for calculating the well-to-wake (WTW) fuel life cycle GHG emissions of maritime fuels.

To serve the right audience, we have created two documents to explain the MMMCZCS LCA methodology: the current policy document and an accompanying technical document stage.[1] This policy document provides an overview of the guiding principles that form the foundation of the methodology. It gives high-level insight on what is critical in the alternative fuels value chain, what kinds of emissions and credits arise at various stages, and how to calculate these emissions to understand the climate performance of alternative marine fuels.

The policy document begins by explaining the scope of the MMMCZCS LCA methodology, including the five key life cycle stages for marine fuels, what is included in the system boundaries, and what kind of data should be collected to apply the methodology *(Section 2)*. We then outline how climate impact *(Section 3)* and GHG emissions intensity *(Section 4)* are calculated in the methodology, before moving to an overview of the well-to-tank (WTT) emissions inventory details for three main alternative fuel categories: biofuels *(Section 5)*, electro- or e-fuels *(Section 6)*, and blue fuels *(Section 7)*. These emissions inventory sections explain the activities and the sources of emissions and credits that should be included when applying the methodology. Next, the document describes the tank-to-wake (TTW) emissions inventory: that is, the activities, emissions, and possible credits associated with fuel use on board vessels *(Section 8)*. We then provide specific guidance on handling emissions and credits from carbon capture and storage (CCS) or use of biogenic CO_2, which may be relevant for a variety of fuel pathways *(Section 9)*. Finally, the document summarizes some guidelines on the interpretation of results generated using the methodology *(Section 10)* and reporting requirements *(Section 11)*.

The aim of this document is to support policymakers to make informed decisions by providing a clear understanding of the life cycle emissions of alternative marine fuels to promote, regulate, or invest in to achieve industry sustainability targets and reduce GHG emissions. The document will also help diverse stakeholders to formulate effective strategies for transition towards cleaner energy sources, as an understanding of the emissions associated with alternative fuels allows prioritization of specific fuels that align with regional energy needs, available resources, and technological capabilities. Since the alternative fuels have varied emissions profiles, the principles laid out in this document will aid in navigating the complexities, setting robust emission standards, incentivizing cleaner fuel options, and creating a level playing field for industry participants. In essence, the policy document lays the foundation for informed decisions, strategic planning, and a sustainable energy future within the maritime sector.

Why do we need a standardized life cycle methodology?

Over the past decade, many countries and regions have developed policy frameworks and regulations to steer the transport sector toward reducing global warming.[2–9] However, the MMMCZCS has identified a lack of standardization and consistency in the adoption of LCA methodologies for calculating GHG emissions from fuels.[10] This inconsistency poses a range of complex issues that hinder effective progress towards maritime decarbonization.

A primary challenge is the significant divergence in LCA methodologies among different fuel applications, regions, and countries. This divergence hampers the creation of coherent and harmonized policies to promote alternative marine fuels. The resulting inconsistencies generate confusion among stakeholders and undermine the establishment of unified regulations and incentives that are crucial for driving the adoption of cleaner fuels.

Furthermore, the absence of standardized LCA methodologies in fuel regulations compromises the reliability of comparative analysis for assessing the environmental performance of various alternative marine fuels. Such inconsistent assessments can lead to misguided policy choices as the basis for decision-making becomes unclear. Consequently, market distortions can emerge, favoring certain fuels over others due to variations in emissions calculations. This imbalance might prevent the intended goal of achieving global GHG emissions reduction, as well as challenging the credibility and transparency of fuels' GHG intensity assessments.

With ships traversing international waters, international collaboration is needed to effectively reduce GHG emissions across the shipping industry. However, a lack of harmony in LCA methodologies hinders effective collaboration across national borders. Without a common understanding of emissions impacts, cooperative initiatives are challenged, and progress toward global sustainability goals is inhibited.
The development and widespread adoption of a harmonized LCA methodology for alternative marine fuels emerges as a solution to these issues. By addressing these challenges collectively, policymakers can foster more effective decision-making, ensure accurate and transparent environmental assessments, and pave the way for a smooth transition toward cleaner maritime transportation, supporting both regional and global sustainability goals.

As the International Maritime Organization (IMO) continues its work to develop draft guidelines for assessing the life cycle GHG emissions intensity of alternative marine fuels, it is crucial for the maritime industry to be well prepared for these guidelines' implementation. The methodology proposed by the MMMCZCS aligns with the IMO's approach, focusing on the entire life cycle of emissions and aiming to standardize the methodology for consistent global use. This preparation is vital to ensure a smooth and efficient adoption of emissions intensity calculations throughout the industry.

The MMMCZCS LCA methodology is a blueprint to build upon as the industry embarks on its decarbonization journey. The methodology is voluntary in nature, and its application aims to ensure greater consistency and harmonization of GHG emissions accounting practices. Our methodology is intended to assist policymakers, shipping industry stakeholders, technology providers, and fuel producers, as detailed in Table 1.

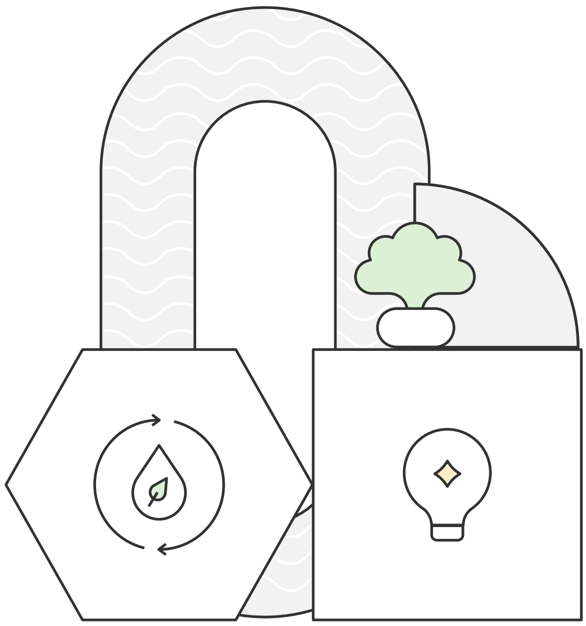


Table 1: How the MMMCZCS LCA methodology supports different stakeholders across the shipping industry to advance decarbonization.

Stakeholder group	Role	How the MMMCZCS LCA methodology helps
Policymakers	Regulate the use of alternative marine fuels	The methodology quantifies the life cycle GHG intensity of various maritime fuels to help inform regulatory decisions that will best support decarbonization
Industry stakeholders e.g., ship owners	Purchase and use marine fuels	The methodology helps stakeholders to document climate performance of their chosen fuels and to identify suitable alternative fuels to support their decarbonization
Technology providers	Develop technological solutions to support decarbonization, e.g., GHG abatement technologies	The methodology helps identify sources of both GHG emissions and avoided emissions throughout the fuel life cycle, with specific attention to production pathways of alternative maritime fuels (e.g., byproducts, CCS, renewable power)
Fuel producers	Produce fuels and document their climate performance	The methodology provides a framework for documenting the life cycle GHG intensity of marine fuels, which is a major part of the fuels' climate performance

LCA = life cycle assessment, GHG = greenhouse gas, CCS = carbon capture and storage.

The MMMCZCS LCA methodology is based on the following established guidelines and product accounting standards:

- **2006 Intergovernmental Panel on Climate Change** (IPCC) Guidelines for National Greenhouse Gas Inventories[9]
- **ISO14040:2006** – Environmental management – Life cycle assessment, principles, and framework[11,12]
- **ISO14044:2006** – Environmental management – Life cycle assessment – Requirements and guidelines[13–15]
- **ISO14067:2018** Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification[16]
- **GHG Protocol** Product Life Cycle Accounting and Reporting Standard[17]

In this context, the fuel used by a ship represents the 'product'. We consulted scientific literature to guide methodological choices when these references needed further clarification.

2. Scope

This section gives an overview of the scope of the methodology and most important elements that the users must consider while assessing the various alternative marine fuel pathways to understand their environmental impact.

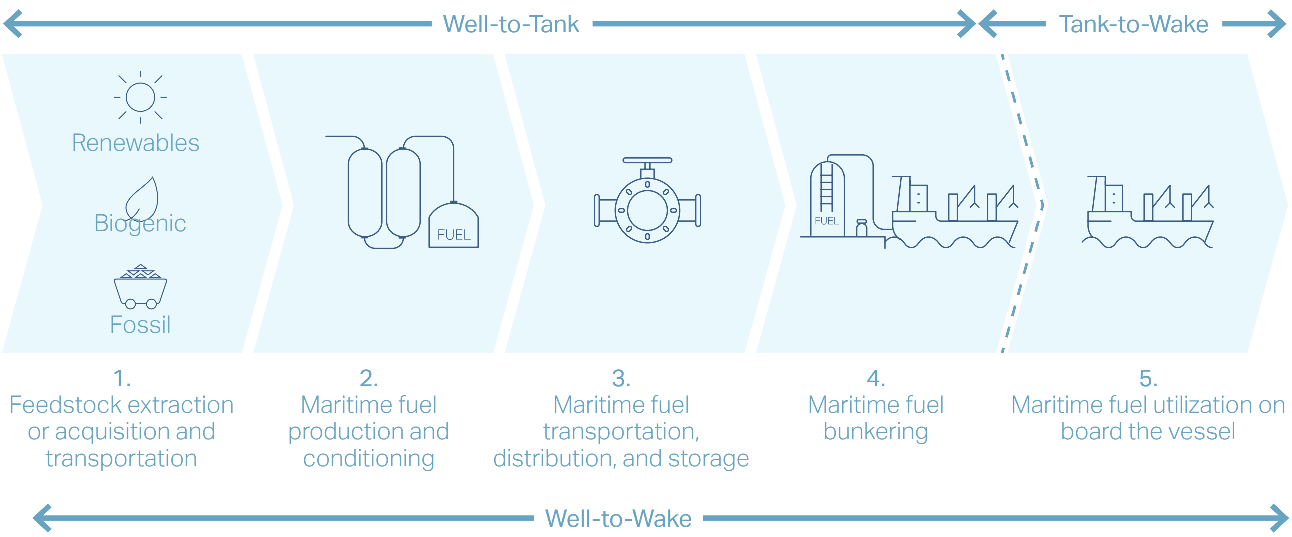
2.1. System boundary

A system boundary defines the scope and limits of the analysis for assessing the environmental impacts of a product, process, or activity throughout its entire life cycle. The system boundary outlines what processes and activities will be included in the assessment and what will be excluded. It helps to establish the extent to which the life cycle stages will be considered, and it aids in deciding which inputs, outputs, and environmental impacts will be accounted for. The system boundary of the use of fuel on vessels must consist of five life cycle stages:

- **Stage 1**: Feedstock extraction or acquisition and transportation
- **Stage 2**: Maritime fuel production and conditioning
- **Stage 3**: Maritime fuel transportation, distribution, and storage
- **Stage 4**: Maritime fuel bunkering
- **Stage 5**: Maritime fuel utilization on board the vessel

The methodology covers the entire life cycle of the fuel, from the well up to fuel utilization on board the vessel, expressed as fuel utilized in fuel converter (wake). The system boundary is outlined in Figure 1.

Figure 1: Fuel life cycle stages (well-to-tank, tank-to-wake, and well-to-wake) of maritime fuels.



Co-products* generated during the different fuel life cycle stages must be included in the system boundaries. They must be handled by system expansion and substitution (see Section 2.3 and more detailed explanation in the technical document), in compliance with ISO 14040:2006 and ISO 14044:2006 standards. Although both standards provide hierarchy steps to avoid allocation, the methodology requires the users to follow them to ensure consistency. This principle applies to all potential co-products, such as digestate, exacess electricity injected into the grid, excess heat, or captured CO_2 used or sequestered. The embodied emissions, or emissions from infrastructure arising from construction, manufacturing, and infrastructure decommissioning, are not included within the system boundary. The rationale for this

* Co-products are defined as any of two or more products coming from the same unit process or product system.

simplification is that such infrastructure is outside the system boundary of most of the fuel life cycle methodologies used in energy policy and regulations. However, the impact of these aspects should be evaluated separately, and evaluated for inclusion in later versions of the method, as these so-called embodied emissions can be significant.

2.1.1. Stage 1: Feedstock extraction or acquisition and transport

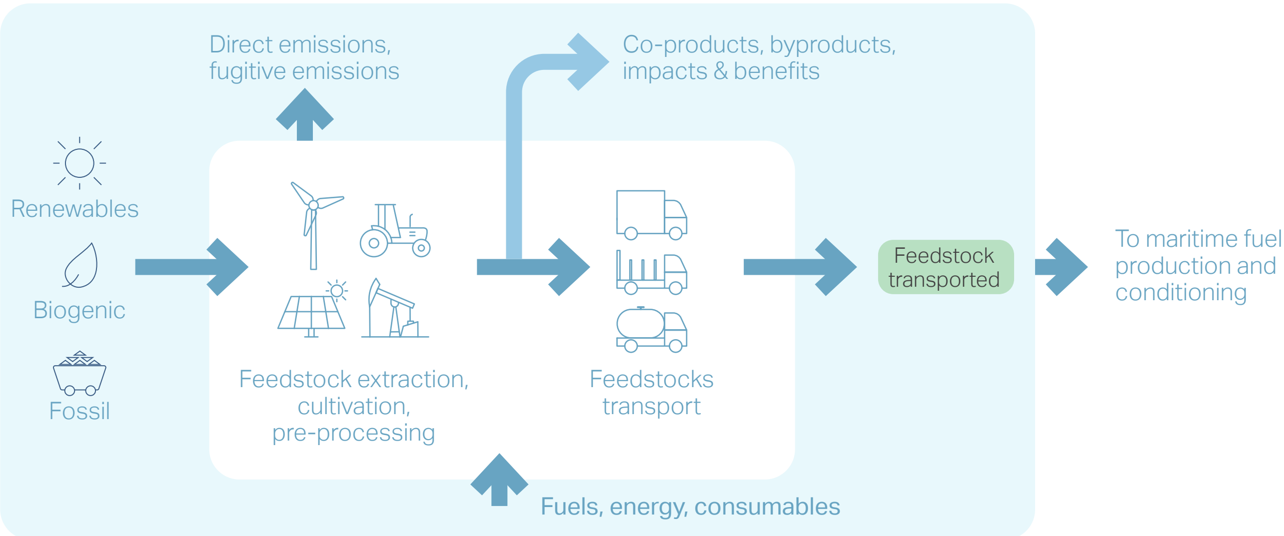
This first life cycle stage refers to the extraction of primary resources from the environment. It includes, but is not limited to, activities such as natural resource extraction, biomass cultivation, collection of wastes, capturing biogenic carbon, and harvesting renewable energies such as wind and solar.

This stage also includes feedstock pre-processing, if needed, and the transportation of the feedstock itself to the point of fuel production (Figure 2).

Users of the methodology must include agricultural operations and consumables such as fertilizer in the case of biomass cultivation, as well as direct land use change (dLUC)† impacts.

Sources of emissions at this life cycle stage include venting, flaring, fugitive emissions‡, fuel use, consumable use, purchased electricity and heat, and use of heat and electricity produced on site. Modification in carbon land stocks generated by dLUC and GHG emissions from soil, such as N_2O emissions associated with biomass feedstocks, must also be included.

Figure 2: System boundary description of feedstock extraction or acquisition and transportation stage (life cycle stage 1).



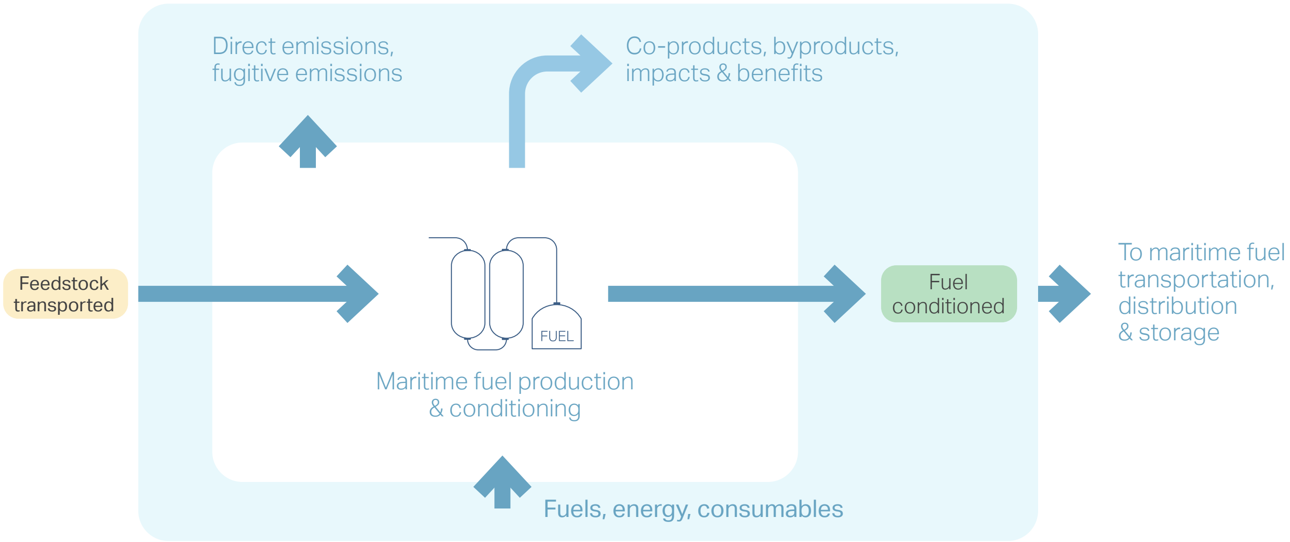
2.1.2. Stage 2: Maritime fuel production and conditioning

The maritime fuel production life cycle stage includes activities relating to converting feedstocks into fuels for maritime application and conditioning for further transport. These activities involve fuel synthesis, transport of interim fuel inputs, including CO_2 capture and storage or usage, liquefaction, and compression. Sources of emissions at this life cycle stage include venting, flaring, fugitive emissions, fuel use, consumable use, purchased electricity and heat, on-site produced electricity, heat, and steam; and carbon capture value chains, including CO_2, transport, storage, or usage (Figure 3).

† Direct land use change (dLUC) refers to the conversion of a piece of land, often due to activities like deforestation, urbanization, or agriculture expansion, which leads to the release of GHGs that have accumulated in the soil over a long period of time.

‡ Fugitive emissions refer to the various unintended or accidental release of gases, vapors, or particles into the atmosphere within a process or a system.

Figure 3: System boundary description for fuel production and conditioning stage (life cycle stage 2).

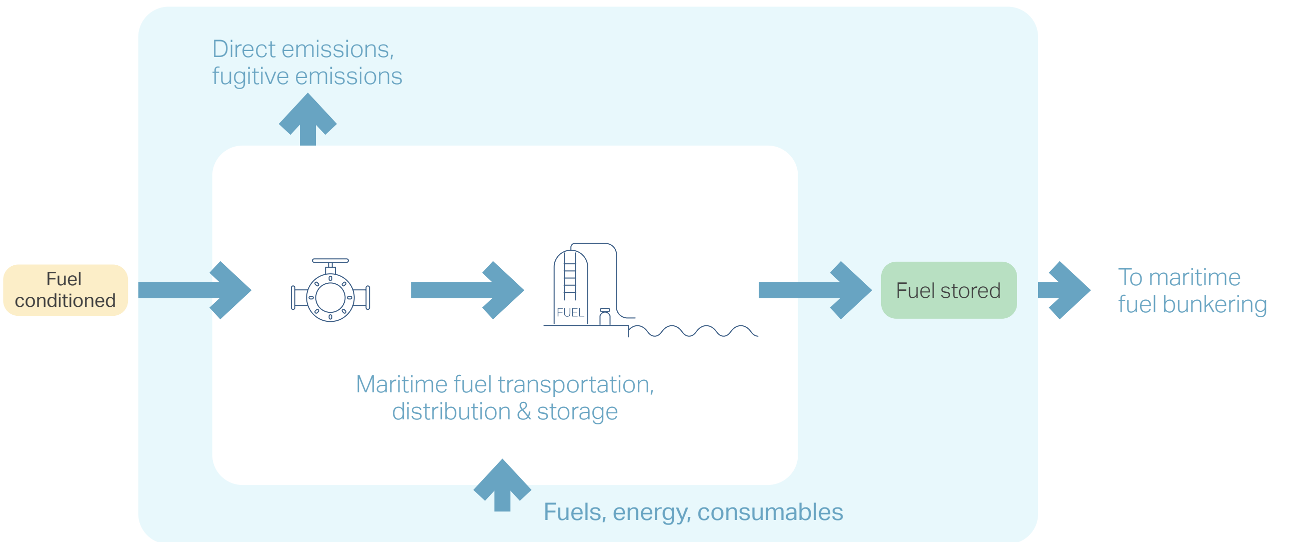


2.1.3. Stage 3: Maritime fuel transportation, distribution & storage

Maritime fuel transport and distribution activities include, but are not restricted to, pipeline transfer, road or marine transport of finished fuels, and storage of finished fuels.

Sources of emissions include fugitive emissions; fuel use; and heat and power consumption for transport, distribution, and storage (Figure 4).

Figure 4: System boundary description of fuel transportation, distribution, and storage stage (life cycle stage 3).

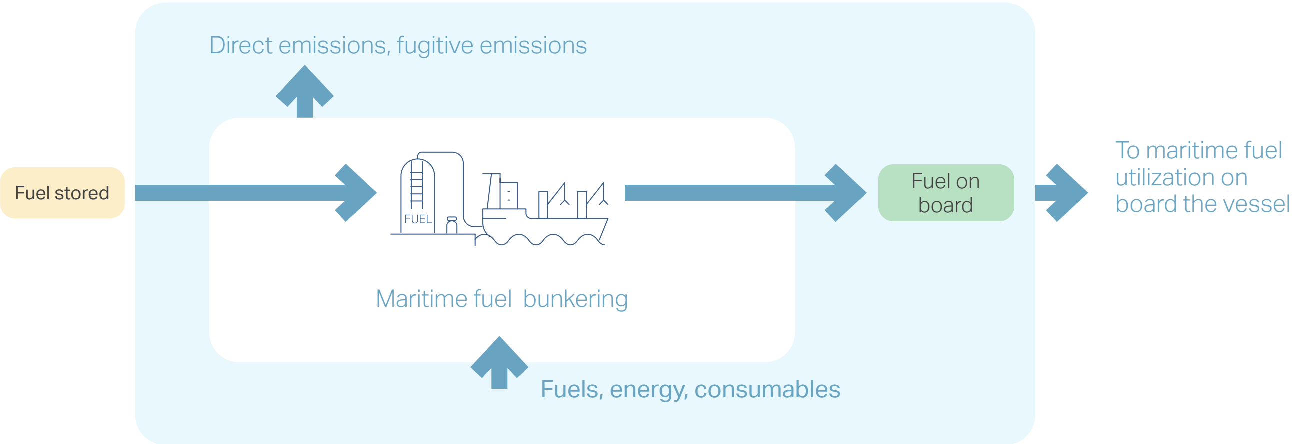


2.1.4 Stage 4: Maritime fuel bunkering

Maritime fuel bunkering activities include all logistics of loading and distributing the fuel among vessel fuel tanks.

Sources of emissions include fugitive emissions, maritime fuel use, and heat and power consumption for bunkering activities (Figure 5).

Figure 5: System boundary description of fuel bunkering stage (life cycle stage 4).

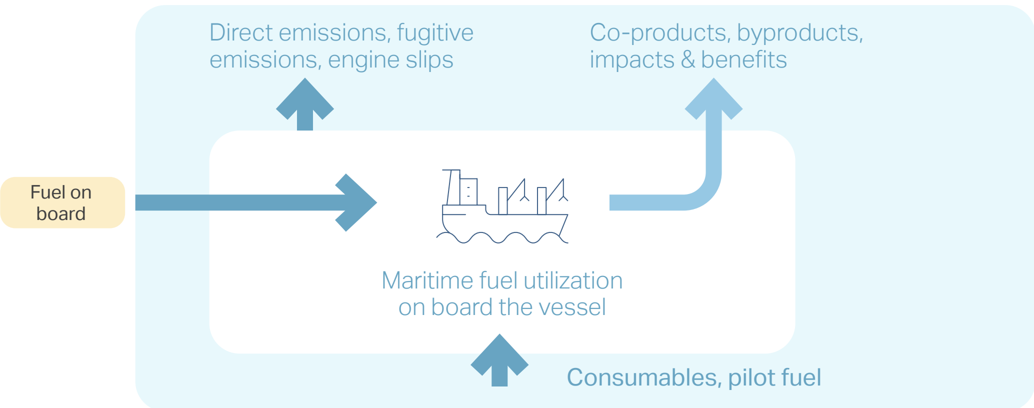


2.1.5. Stage 5: Maritime fuel utilization on board the vessel

This stage involves the utilization of maritime fuel by the vessel, fuel storage, use of consumables such as pilot fuel,[§] shore power use, and GHG emissions abatement technologies.

Sources of emissions include fugitive emissions, maritime fuel converter slips, purchased electricity when in port, consumable use, and maritime fuel utilization (Figure 6).

Figure 6: System boundary description of fuel utilization on board the vessel (life cycle stage 5).



[§] The methodology considers emissions related to consumables and pilot fuels in terms of their complete life cycle – e.g., pilot fuel emissions are based on the WTW emissions of that fuel.

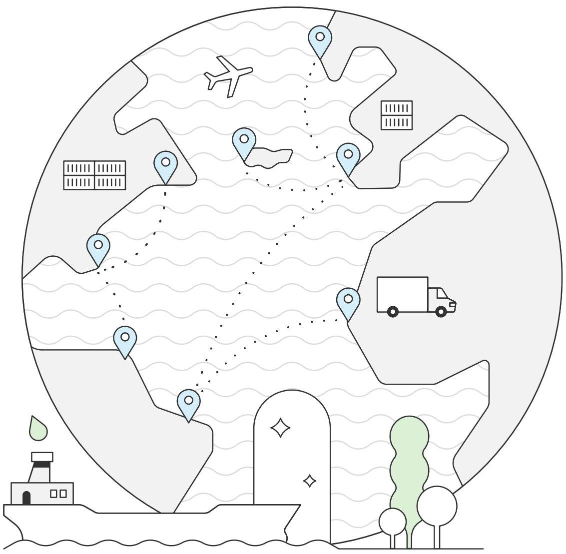
2.2. Selected cut-off criteria

Cut-off criteria are predefined limits or thresholds that help determine which processes, materials, or stages of a product's life cycle have a significant or negligible environmental impact, and consequently whether to include these factors in the analysis.

Every effort has been made to include all fuel life cycle activities and consumables that carry significant climate impact. We consulted scientific literature during the method development process to establish the climate significance of inputs.[5,18–21] The general cut-off principle applied in the methodology is:

Cut-off criteria =
Climate impact < **1% cumulative contribution**

Activities that meet this cut-off criterion may be excluded from the system boundary. Users of the methodology must use this criterion to determine which activities need to be included in the system boundary and which can be left out. However, the activities that are excluded must be recorded, and reported wherever applicable.



2.3. Handling co-products using system boundary expansion and substitution

Co-products are defined as any of two or more product outputs coming from the same production process or product system. They are the intentional outcomes of a production process, with relevant economic value.

Co-product handling (also referred to as multifunctionality)** must be dealt with using system expansion and substitution. This process ensures avoidance of allocation††, as preferred in ISO 14044:2006 norms, and allows the integration of the product system that is substituted using the co-product into the system boundary. For expansion and substitution to apply, the co-products must directly replace the original product on the market. Therefore, data needs to be collected to demonstrate the reduced use of the original product. Detailed steps for this process are provided in the accompanying technical document.[1]

2.4. Temporal coverage

Following the ISO 14067:2018 standard, the temporal coverage must be representative considering interannual and intra-annual variability in supply chain operations. Users of the methodology must provide evidence to support the temporal representativeness of their data selection.

** Multifunctionality refers to a situation where a product or process provides multiple outputs simultaneously.
†† Allocation refers to the process of distributing the environmental impacts of a product or process among different co-products or outputs that are generated because of a single process.

2.5. Functional unit

The MMMCZCS LCA methodology aims to allow comparison of different fuels used in the maritime sector. The overall function of marine fuels is to be used in the fuel converters or engines of the maritime vessel to generate power. This use must consider fuel converter exhaust emissions; fugitive emissions; use of consumables; and fuel converter slips, including the use of pilot fuel when required.

Based on the function of the fuels and the objective of the proposed methodology, a functional unit in our methodology is defined as follows, consistent with ISO 14040:2006 and ISO 14044:2006 standards:

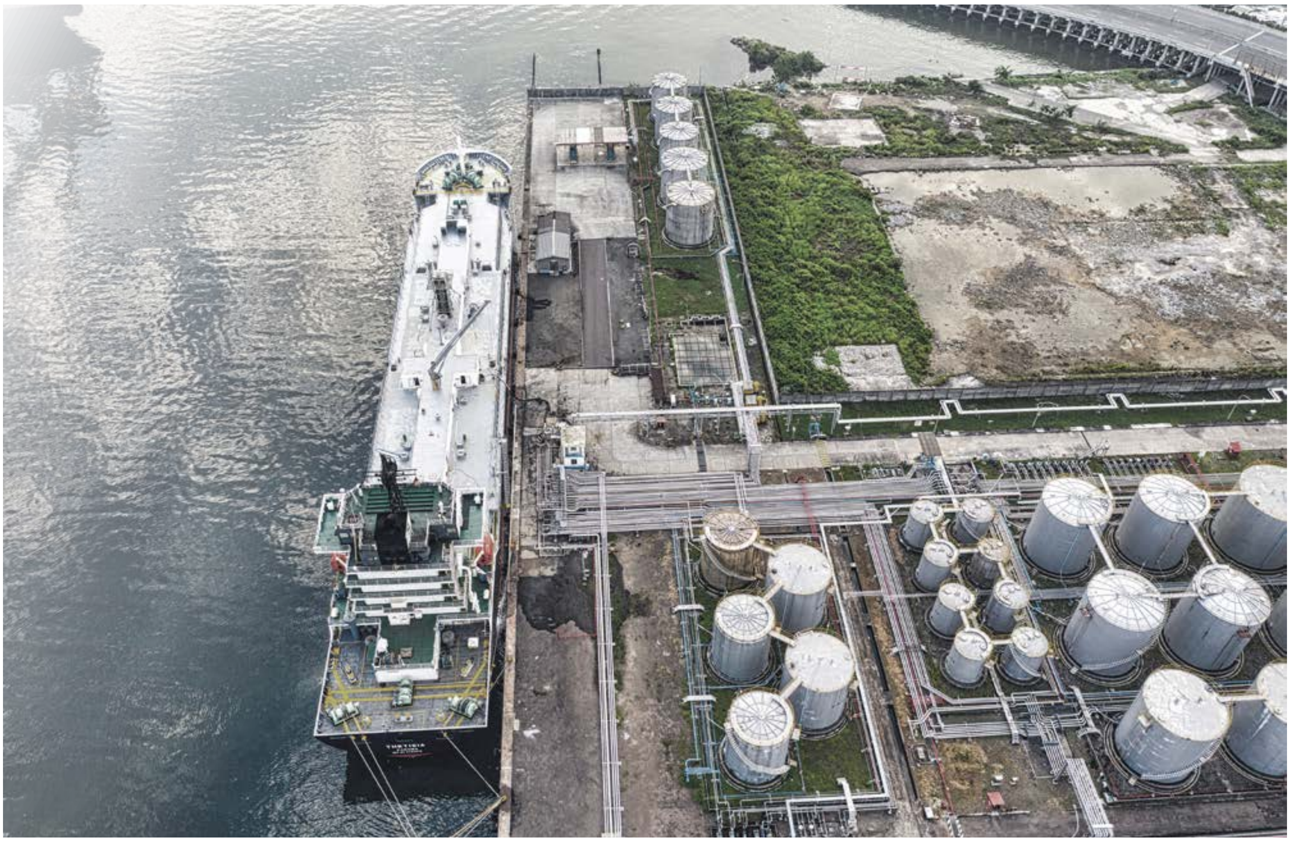
FU = 1 MJ of maritime fuel used in marine vessels by the marine fuel converter

The functional unit used in the methodology must be expressed as **1 MJ of maritime fuel using the lower heating value (LHV) of the fuel.**

2.6. Data collection and quality

The collected data used in the methodology should be primary data (measured or calculated data). Where these data sources are not feasible, users of the methodology may use secondary data. Secondary data is sourced from databases, scientific literature, or other sources. When used, these secondary data sources must be appropriately referenced and recorded.

In the case of primary data generated via measurements, details of the measurement technology must be reported, and calibration logs of the instrument maintained, to ensure adequate quality and validation of the measurements. Other primary data sources include meter readings and utility bills.



3. Impact characterization

This methodology aims to assess the global warming potential (GWP) of marine fuels. GHGs included in the methodology are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Emissions of these gases must be multiplied by the associated GWP conversion factors and must be expressed as carbon dioxide equivalent (CO_2eq). The individual gas components must be reported separately to allow for transparency on the contribution of short-term (CH_4) and long-term (CO_2 and N_2O) climate forcers.

The methodology uses a GWP time horizon of 100 years. This time horizon aligns with current international carbon accounting practices in climate-related regulations and UN Framework for Climate Change (UNFCC) guidelines. However, the methodology supports reporting climate impact for a 20-year time horizon for information purposes, which aligns with recommendations from the IPCC.[22]

Table 2 shows the GWP conversion factors for use in the methodology. These factors are as per the IPCC's Sixth Assessment Report (AR6).[22]

Table 2: AR6 GWP conversion factors for 100-year and 20-year time horizons, as gram CO_2eq per gram GHG.[22]

Greenhouse gas	GWP-100	GWP-20
Carbon dioxide (CO_2)	1	1
Carbon dioxide (CO_2), biogenic	1	1
Methane (CH_4)	29.8	82.5
Nitrous oxide (N_2O)	273	273

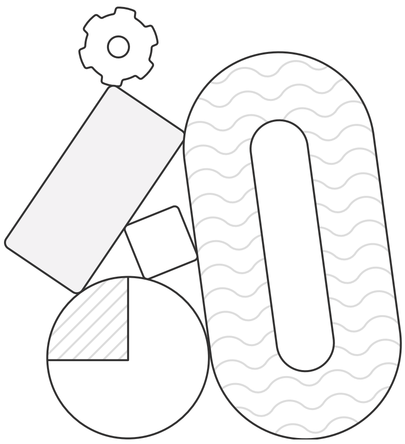
The following generalized formula calculates the GWP, based on burdens and avoided emissions assessment:

$$\text{Total life cycle GWP}= \sum_{i=1}^{n} \text{mass GHG}_i \times GWP_i - \sum_{j=1}^{m} \text{mass GHG}_{jv} \times GWP_j$$

Where:

mass GHG_i	total mass quantityof **GHGs emitted** during the life cycle of the fuel
GWP_i	global warming potential of GHG, per mass, as defined in Table 2
mass GHG_j	total mass quantity of **GHGs emission credit** during the life cycle of the fuel
GWP_j	global warming potential of GHG, per mass, as defined in Table 2

This GWP impact is expressed as grams CO_{2eq} per functional unit: **gCO_{2eq}/MJ fuel LHV.**



4. Assessing the GHG emissions intensity of fuel utilization in marine vessels

This section describes the GHG accounting principles in developing GHG emissions inventories for fuel pathways. In summary, the formula is as follows:

Total fuel life cycle GHG emissions intensity =
(Total fuel life cycle GHG emissions)/(1 MJ of fuel LHV)

Emissions associated with energy inputs, use of consumables, and land use change must be included in the total fuel life cycle GHG emissions calculation, including emissions credits. The analysis must be based on the life cycle emissions inventory prepared for each activity in the system boundary (see Figure 1).

Total fuel life cycle GHG emissions must be the sum of emissions releases, sinks (sequestration), and avoided emissions that occur over the entire fuel life cycle (WTW) as described in Equation 1.

Equation 1:

$$GHG_{WTW} = e_{fecu} + e_{l} - e_{sca} + \sum_{i=1}^{5} e_{i,t} + \sum_{i=1}^{5} e_{i,p} + \sum_{i=1}^{5} e_{i,fug} + e_{slip} + e_{fc} + e_{fu} - \sum_{i=1}^{5} e_{i,c} + \sum_{i=1}^{5} (e_{ccsp} - e_{ccs})_i + \sum_{i=1}^{5} (e_{cpm} - e_{cpc})_i$$

Where:

GHG_{WTW}	GHG emissions associated with the well-to-wake (WTW) life cycle stages
i	life cycle stages described in Section 2
e_{fecu}	emissions associated with the processes involved in feedstock extraction or cultivation
e_{l}	emissions from carbon stock change caused by direct land use change (dLUC)
e_{sca}	emissions credit from improved agricultural management
$e_{i,t}$	emissions associated with the transport involved in the different life cycle stages i
$e_{i,p}$	emissions associated with the processes involved in the different life cycle stages i
$e_{i,fug}$	fugitive emissions occurring during the different life cycle stages i
e_{slip}	fuel converter slip emissions during fuel utilization on board vessel
e_{fc}	emissions associated with fuel utilization in vessel fuel converter on board
e_{fu}	emissions from consumables use associated with fuel utilization in fuel converter on board vessel
$e_{i,c}$	emissions credit associated with carbon origin in CO_2 air emissions at the different life cycle stages i (see Section 9.2)
$(e_{ccsp} - e_{ccs})_i$	emissions e_{ccsp} and credits e_{ccs} associated with the CO_2 captured during the different life cycle stages i (see Section 9.1)
$(e_{cpm} - e_{cpc})_i$	emissions e_{cpm} and credits e_{cpc} associated with the system expansion/substitution from co-products generated during the different life cycle stages i

Details of GHG emissions inventories for specific fuel pathways are described in the accompanying technical document.[1] All emissions associated with the utilization of consumables, fuels (other than the considered maritime fuel), or energy sources during the well-to-tank (WTT) or tank-to-wake (TTW) life cycle stages must be attributed to their respective life cycle.

5. Emissions inventory details for biofuels

This section details the GHG accounting principles applied in developing the WTT GHG emissions inventories for liquid and gaseous biofuels, such as hydrothermal liquefaction oils (HTL oil), fatty acid methyl ester (FAME), hydrotreated vegetable oil (HVO), bio-oils, liquefied bio-methane (LBM), and bio-methanol.

The life cycle inventories for each main activity must cover the sub-activities listed in Table 3. The boundaries for each activity must include emissions that do notmeet the cut-off criteria. Emissions below the cut-off criteria must be reported for informational purposes.

Table 3: Well-to-tank activities associated with biofuels

Feedstock cultivation	Direct land use change (dLUC)	Feedstock collection and transport	Feedstock conditioning	Biofuel production	Fugitive emissions	Biofuel production emission credits	Biofuel distribution (transport, storage, and bunkering)
Fertilizer application Pesticide application Water irrigation Fuel use during harvesting, tillage Fuels and energy use during on-site feedstock storage Emissions from fertilizer application Biogenic CO_2 sequestration during plant growth	Emissions from carbon stock changes caused by a default 20-year transition period following conversion	Fuels and energy sources use during feedstock extraction/ collection Fuels and energy sources use during intermediate transport	Fuels and energy sources use during pre-processing	Energy sources use for biofuel production Consumable use for biofuel production, such as chemicals Fuel and energy sources use for biofuel temporary storage GHG emissions during biofuel production processes Emission of CO_2 due to incomplete CO_2 capture Emissions for biofuel conditioning for transportation (compression, liquefaction)	Unintentional or accidental releases of GHGs, such as CH_4 and CO_2 Unintentional or accidental GHG releases from biofuel during the WTT stages	Improved agricultural management Improved manure handling Application of digestate to land Biochar application to land Provision of excess electricity to the local grid CO_2 emissions from carbon biogenic origin* Permanent storage of captured CO_2	Fuels and energy source use for biofuel transport, distribution, and bunkering Fuels and energy sources use during biofuel storage Fugitive emissions during biofuel transport, distribution, and bunkering Boil-off emissions to air during liquefied fuel storage

* as described in Section 9.2.

Note: methodology users should select the activities relevant to their fuel production. For ease, this table summarizes potential activities to be listed in the inventory, but does not exclude other relevant activities.

Emissions factors must be sourced from suppliers as a first point. Sources such as ecoinvent[23] or GREET[24] data, scientific literature, and other sources recognized by the technical community as reliable can be used where primary data is unavailable and must be referenced in the final assessment.

Indirect land use change (iLUC) refers to the environmental impacts that happen when producing or using a product which causes changes in land use elsewhere: for example, if use of biomass for biofuel production causes deforestation elsewhere. These changes can result from the increased demand for that product, affecting ecosystems and emissions in distant places. Accounting for iLUC in GHG intensity merely adds uncertainty.[25–27] Therefore, a risk-based approach categorizing feedstocks into high and low iLUC risk categories based on the feedstock type and agricultural practices is considered in the methodology.[4]

When the **feedstock is a waste,** the MMMCZCS LCA methodology assumes zero climate burden until the point of feedstock collection. This approach assumes that the climate burden associated with waste has already been allocated to the products from which the waste has been produced.[28] All subsequent activities, such as waste transport, must receive the necessary GHG emissions allocations and emission credit depending on its carbon origin distribution (fossil or biogenic).

A **byproduct** is defined as a substance or object resulting from a production process of which the primary aim is not the production of that item. To meet this definition, byproducts must meet the following requirements:

- Further use of the substance or object is certain and proven, and
- The substance or object can be used directly without any further processing other than normal industrial practice, and
- The substance or object is produced as an integral part of a production process, and
- Further use is lawful, i.e., the substance or object fulfills all relevant product, environmental, and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.

We identified the following activities, resulting from byproducts, as having the potential for 'avoided emissions' credits during the WTT stages of a biofuel life cycle:

- Credit from application of digestate to land
- Credit from application of biochar to land
- Credit from adding excess electricity to the grid, based on substitution of local residual mix

In addition, specific credit can be applied from:

- Credit from improved manure handling
- Credit from permanent sequestration of CO_2 from capture processes
- Credit from biogenic origin of CO_2 emissions

This is a non-exhaustive list of potential GHG emissions credits. Where a fuel production system has the potential to achieve other environmental benefits, these should be assessed for inclusion as possible credit mechanisms.

5.1. Potential GHG emissions credits from application of digestate to land

Digestate is a byproduct of bio-methane production. When applied to land, digestate can displace the use of artificial fertilizer depending on its nutrient content, thereby creating a potential emissions credit based on the substitution approach. To claim this credit, methodology users must provide data to support the net climate benefit of fertilizer displacement. Such data must include:

- The GHG intensity of digestate storage and treatment
- Nutritional content of the digestate used in field
- Nutritional content of the reference artificial fertilizer
- Reduction in fertilizer use by the farmer relative to the baseline (annual fertilizer use before the use of digestate)

To calculate these GHG emissions savings, it is assumed that the availability of nutrients is the same, i.e., 1 kg nitrogen (N) in digestate can replace 1 kg N in synthetic fertilizer. The following formula can be used for a life cycle approach to calculate the $(ecpm - ecpc)_1$ from digestate:

GHG emission burdens and credits for 1 kg CO_2 captured during life cycle stage i and permanently stored

= {GHG emissions from additional energy required for the capture of CO_2, when not already accounted as credit in e_{fecu}, $e_{i,p}$ or e_{fc}}
+ {GHG emission from additional energy required for CO_2 compression}
+ {GHG emission from additional energy required for CO_2 transport}
+ {fugitive CO_2 emissions}
+ {GHG emission from additonal energy required for CO_2 injection}
-{1 kg CO_2 sequestered, when not already accounted as credit in e_{fecu}, $e_{i,p}$ or e_{fc}}

We recommended using the 'decision tree' from IPCC guidelines volume 4 to calculate direct N_2O emissions from synthetic fertilizer and digestate application at the global and regional scales.[29]

5.2. Potential GHG emissions credits from biochar applications

Pyrolysis, a process used to produce bio-oils, also produces biochar. Biochar is a carbon-rich material that can be used for soil conditioning in agriculture, carbon storage in soil, and in construction materials. Depending on the end use, biochar could achieve negative emissions credits due to its long-term CO_2 storage capabilities. Emissions credits are then based on carbon (C) content equivalent in biochar and must be characterized as:

***−3.6641 kg** atmospheric CO_2 / kg biogenic C stored in biochar*

5.3. Potential GHG emissions credits from provision of excess electricity to the grid

Where excess electricity is generated and exported to the grid to displace the electricity production using the residual local grid mix, a potential emissions credit per GHG savings mechanism can be achieved.

5.4. Potential GHG emissions credits from improved manure handling

The MMMCZCS LCA methodology assumes that agricultural manure for biofuel production comes with an emissions credit for reduced CH_4 emissions associated with improved handling.

The credit of **45 g CO_2 eq/MJ manure** is used for fuel production, as described in RED II.[2]

5.5. Potential GHG emissions credits from CO_2 capture and storage processes

Emissions credits can be achieved through the permanent storage of CO_2 involved in specific WTT stages of the biofuels life cycle. The approach described in Section 9.1 must be used to calculate these emissions savings.

5.6. Potential GHG emissions credits from CO_2 emissions from biogenic carbon

Emissions credits, accounted in $e_{i,c}$, can be achieved through the net-zero climate impact consideration of biogenic carbon from CO_2 emissions involved in specific WTT stages of the biofuels life cycle. The approach described in Section 9.2 must be used to calculate these emissions savings.

6. Emissions inventory details for e-fuels

Electro-fuels (e-fuels) are produced with hydrogen obtained using sustainable electricity. These fuels can be produced from a variety of different feedstocks combined with renewable sources of electricity via power-to-gas and power-to-liquid processes. In the case of e-methanol and e-ammonia, the hydrogen is obtained via water electrolysis and is combined with CO_2 and atmospheric nitrogen, respectively. e-fuel production can use various sources of power such as renewable electricity, grid electricity mix, and nuclear. Together, these aspects of the fuel life cycle, feedstock type, and electricity source make up most of the emissions associated with this fuel category.

The life cycle inventories for each main activity must cover the sub-activities listed in Table 4, which contribute to the overall GHG intensity of the fuel. The boundaries for each activity must include emissions that do not meet the cut-off criteria. Emissions below the cut-off criteria must be reported for information purposes.

Table 4: Well-to-tank activities associated with e-fuels

Feedstocks extraction/ production	Fugitive emissions during feedstocks extraction/ production	Feedstock collection and transport	e-fuel production	Fugitive emissions during e-fuel production	e-fuel production emission credits	e-fuel distribution (transport, storage, and bunkering)
GHG emissions from biogenic carbon feedstock for e-fuel production, same activities as listed in Table 3 GHG emissions from direct air capture (DAC) operations for e-fuel production GHG emissions from water extraction and processing for e-fuel production GHG emissions from nitrogen extraction and processing for e-fuel production Off-grid electricity production (emissions associated with the operational part of the life cycle) Use of consumables	Unintentional or accidental releases of GHGs relating to feedstocks extraction, production, and transport	Fuels and energy sources use during feedstocks pre-processing for transportation to e-fuel production site Fuels and energy sources use during feedstocks transport to e-fuel production site	Consumable use for e-fuel production, such as chemicals On-site e-hydrogen and nitrogen production Fuels and energy sources use for e-fuel production Fuels and energy sources use for e-fuel temporary storage e-fuel conditioning for transportation (compression, liquefaction)	Unintentional or accidental releases of GHGs, such as CH_4 and CO_2 Unintentional or accidental GHG releases from e-fuel during the WTT stages	Provision of excess electricity to the local grid Permanent storage of captured CO_2 CO_2 emissions from carbon of biogenic origin*	Fuels and energy sources use for e-fuel transport, distribution, and bunkering Fuels and energy sources use during e-fuel storage Fugitive emissions during e-fuel transport, distribution, and bunkering Boil-off emissions to air during liquefied fuel storage

* as described in Section 9.2.

Note: methodology users should select the activities relevant to their fuel production. For ease, this table summarizes potential activities to be listed in the inventory but does not exclude other relevant activities)

The MMMCZCS LCA methodology considers accounting zero life cycle GHG emissions up to the point of capture or collection of sources of CO_2 in the e-fuel WTT stages. However, users must account for the emissions associated with energy and consumable use needed to capture this CO_2. Using point-source captured CO_2 (fossil or biogenic) generates more complexity. When using these point-sources of CO_2 as feedstock for e-fuel production, we recommend that this CO_2 can only be considered to have zero life cycle GHG emissions up to the point of capture or collection if:

- Evidence can be provided that the CO_2 meets the definition of waste, AND
- The CO_2 would have otherwise been emitted into the atmosphere, AND
- The CO_2 producer does not claim a reduction in their emissions due to this use of waste CO_2.

Because of the function of fuel is to be combusted, no “negative emissions" are recognized for these sources of CO_2 as feedstocks in the WTT stages. Emissions credit may be considered in the TTW stage, based on the net-zero climate impact consideration of biogenic carbon.

When a proven renewable electricity source is used for production, the methodology considers the electricity to have zero climate burden. Any purchased electricity from the grid must be accounted for using the emissions factor associated with the local grid mix.

Activities with the potential for ‘avoided emissions’ credits during the WTT stages of the e-fuels life cycle include:

- Credit from permanent sequestration of captured CO_2
- Credits from biogenic origin of CO_2 emissions
- Credit from adding excess electricity to the grid, based on substitution of local residual mix

6.1. Potential GHG emissions credits from CO_2 capture and storage processes from e-fuel well-to-tank stages

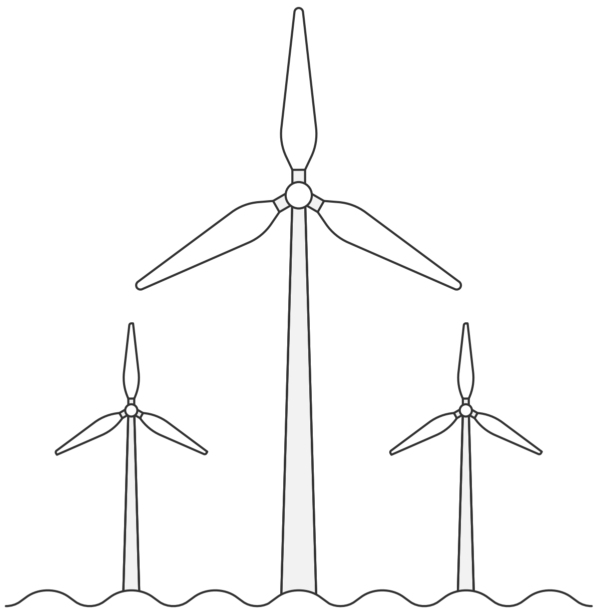
Emissions credits can be achieved through the permanent storage of CO_2 involved in specific WTT stages of the e-fuels life cycle. The approach described in Section 9.1 must be used to calculate these emissions savings.

6.2. Potential GHG emissions credits from CO_2 emissions from biogenic carbon origin involved in the e-fuels well-to-tank stages

Emissions credits can be achieved through the net-zero climate impact consideration of biogenic carbon from CO_2 emissions involved when biofuels are utilized for heat and power generation in the specific WTT stages of the e-fuels life cycle. The approach described in Section 9.2 must be used to calculate these emissions savings.

6.3. Potential GHG emissions credits from provision of excess electricity to the grid from e-fuel well-to-tank stages

Where excess electricity is generated and exported to the grid to displace the electricity production using the residual local grid mix, a potential emissions credit per GHG savings mechanism can be achieved.



7. Emissions inventory details for blue fuels

Blue fuels are characterized by the production of fuels from fossil feedstocks paired with CO_2 capture and permanent underground sequestration to produce a fuel with lower global warming impact.

Blue fuel production can be powered by various sources such as renewable energy, grid mix electricity, fossil fuels, and nuclear. Together, these aspects of the fuel life cycle, fossil feedstock type, and electricity source make up most of the emissions associated with this fuel category.

The life cycle inventories for each main activity must cover the sub-activities listed in Table 5, which contribute to the overall GHG intensity of the fuel. The boundaries for each activity must include emissions that do not meet the cut-off criteria. Emissions below the cut-off criteria must be reported for information purposes.

Table 5: Well-to-tank activities associated with blue fuels

Feedstocks extraction/ production	Fugitive emissions during feedstocks extraction/ production	Feedstock collection and transport	Blue fuel production	Fugitive emissions during blue fuel production	Blue fuel production emissions credit	Blue fuel distribution (transport, storage, and bunkering)
Natural gas Extraction, flaring, venting, processing, and transport Water and oxygen extraction and processing Off-grid electricity production (emissions associated with the operational part of the life cycle) Fuels and energy sources use Use of consumables Extraction, transport, preparation, processing	Unintentional or accidental releases of GHGs relating to feedstocks extraction, production, and transport	Fuels and energy sources use during feedstocks pre-processing for transportation to blue fuel production site Fuels and energy sources use during feedstocks transport to blue fuel production site	Energy use for blue fuel production Consumables use for blue fuel production, such as chemicals Emission from CO_2 capture, temporary storage, transport, and sequestration Emission of non-captured CO_2 due to incomplete CO_2 capture Fuel and energy sources use for blue fuel temporary storage Blue fuel conditioning for transportation (compression, liquefaction)	Unintentional or accidental releases of GHGs, such as CH_4 and CO_2 Unintentional or accidental GHG releases from blue fuel during the WTT stages Unintentional or accidental releases of GHG relating to captured CO_2 temporary storage, transport, and sequestration	Provision of excess electricity to the local grid Permanent storage of captured CO_2 CO_2 emissions from carbon of biogenic origin*	Fuels and energy sources use for blue fuel transport, distribution, and bunkering Energy sources use during blue fuel storage Fugitive emissions during blue fuel transport, distribution, and bunkering Boil-off emissions to air during liquefied fuel storage

* as described in Section 9.2.

Note: methodology users should select the activities relevant to their fuel production. For ease, this table summarizes potential activities to be listed in the inventory but does not exclude other relevant activities).

Activities with the potential for 'avoided emissions' credits during the WTT stages of the blue fuels life cycle include, but are not limited to:

- Credit from permanent sequestration of captured CO_2
- Credits from biogenic origin of CO_2 emissions
- Credit from adding excess electricity to the grid, based on substitution of local residual mix

7.1. Potential GHG emissions credits from CO_2 capture and storage processes from blue fuel well-to-tank stages

Emissions credits can be achieved through the permanent storage of CO_2 involved in specific WTT stages of the blue fuels life cycle. The approach described in Section 9.1 must be used to calculate these emissions savings.

7.2. Potential GHG emissions credits from provision of excess electricity to the grid from blue fuel well-to-tank stages

Where excess electricity is generated and exported to the grid to displace the electricity production using the residual local grid mix, a potential emissions credit per GHG savings mechanism can be achieved.

8. Tank-to-wake emissions inventory

The emissions inventory associated with the TTW part of the fuel life cycle must include the following sources of GHG emissions:

- Fugitive emissions caused by accidental releases during storage and up to the fuel converter
- Fuel converter slips
- GHG emissions from fuel combustion/oxidation (CO_2, CH_4, and N_2O)
- Use of consumables such as pilot fuel, shore power use, and GHG emissions abatement technologies on board
- Use of other consumables such as oils and lubricants
- Handling, treatment, and onboard storage of captured CO_2
- Fugitive emissions from onboard CO_2 capture and storage
- Onshore discharging, storage, transport, and deep geological storage of CO_2 captured on board
- Boil-off gas emissions to maintain liquefied fuels' storage tank pressure
- Emissions credit from onboard CO_2 capture, transport, and permanent sequestration
- Emissions credit from biogenic carbon source in fuel

TTW GHG emissions must be the sum of emissions releases, sinks (sequestration), and avoided emissions that occur during the TTW stage, as described in Equation 2.

Equation 2:

$$GHG_{TTW} = e_{slip} + e_{fc} + e_{fu} + e_{5,fug} - e_{5,c} + (e_{pccs} - e_{ccs})_5 + (e_{cpm} - e_{cpc})_5$$

Where:

GHG_{TTW}	GHG emissions associated with the tank-to-wake (TTW) life cycle stage
e_{slip}	emissions from slips in the maritime fuel converter and from crankcase on board the vessel
e_{fc}	emissions from maritime fuel utilization in the fuel converter on board the vessel
e_{fu}	emissions from consumables use on board vessel
$e_{5,fug}$	emissions from fugitive maritime fuel emissions during onboard storage
$e_{5,c}$	emissions credit associated with biogenic carbon sources in fuel
$(e_{pccs} - e_{ccs})_5$	emissions e_{pccs} and credits e_{ccs} associated with the CO_2 captured during fuel utilization in the fuel converter on board the vessel
$(e_{cpm} - e_{cpc})_5$	emissions e_{cpm} and credits e_{cpc} associated with system expansion or substitution from co-products generated during fuel utilization in the fuel converter on board the vessel

8.1. Accounting principles for GHG emissions e_{fc} from fuel utilization in the fuel converter

Whenever e_{fc} cannot be measured directly on board the vessel, it can be calculated using Equation 3 and Equation 4:

Equation 3:

$$C_{fug} + C_{slip} + C_{fuel\_used} = 100\%$$

Equation 4:

$$e_{fc} = \frac{C_{fuel\_used}}{100\%} \times \frac{(C_{fc,CO_2} \times GWP_{CO_2} + C_{fc,CH_4} \times GWP_{CH_4} + C_{fc,N_2O} \times GWP_{N_2O})}{LHV_{fuel}}$$

Where:

C_{fug}	accounts for fugitive emission losses of maritime fuel, occurring during storage and distribution of maritime fuel on board the vessel, expressed as a mass ratio (%) of maritime fuel, and source of GHG emission $e_{(5,fug)}$
C_{slip}	accounts for the slip emission of maritime fuel in the energy converter, expressed as a mass ratio (%) of maritime fuel, and source of GHG emission e_{slip}
C_{fuel_used}	accounts for the mass ratio (%) of C_{fuel} effectively utilized and converted in the energy converter, and source of GHG emission e_{fc}
C_{fc,CO_2}	accounts for the mass of CO_2 emissions resulting from the conversion of maritime fuel in the maritime fuel converter
C_{fc,CH_4}	accounts for the mass of CH_4 emissions resulting from the conversion of maritime fuel in the maritime fuel converter
C_{fc,N_2O}	accounts for the mass of N_2O emissions resulting from the conversion of maritime fuel in the maritime fuel converter
GWP_{CO_2}	is the GWP of CO_2 emissions, as defined in Table 2
GWP_{CH_4}	is the GWP of CH_4 emissions, as defined in Table 2
GWP_{N_2O}	is the GWP of N_2O emissions, as defined in Table 2
LHV_{fuel}	is the LHV of the maritime fuel converted in the maritime fuel converter

Principles of accounting for calculating emissions from slips, fugitive emissions, and consumable use are detailed in the accompanying technical document.[1]

8.2. Accounting principles for emissions credit from onboard CO_2 capture

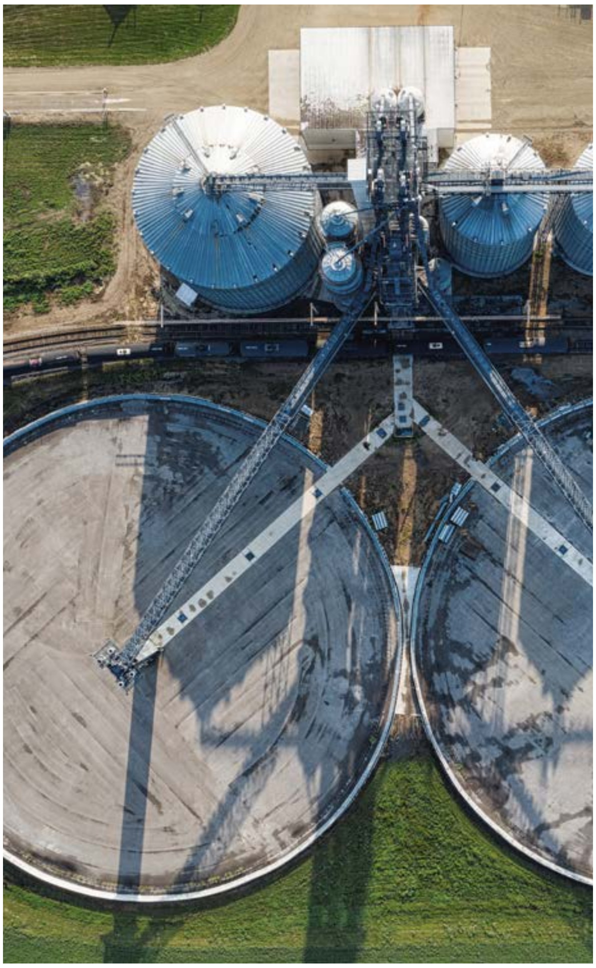
CO_2 captured on board a vessel must be defined as a co-product, assuming it has economic value and can be directly reused, while onboard-captured carbon that is permanently stored must be defined as waste. However, the applicable accounting principles will vary depending on the end use of the carbon, i.e., permanent storage, long-term uses such as building materials, or short-term uses such as fuel production. This methodology version describes the principles associated with CO_2 capture, transport, and storage. Further assessment is needed to identify how to distribute and handle the climate burden associated with reusing carbon.

Emissions credits can be achieved through the permanent storage of CO_2 involved in specific WTT stages for blue fuels. The approach described in Section 9.1 must be used to calculate these emissions savings.

8.3. Accounting principles for emissions credit from biogenic carbon cycle consideration

Emissions credits can be achieved through the net-zero climate impact consideration of biogenic carbon from CO_2 emissions (direct and fugitive) involved in the TTW stage. The approach described in Section 9.2 must be used to calculate these emissions savings.

9. Specific guidance on handling CO_2 emissions and credits from CCS chain and carbon of biogenic origin



9.1. Guidance on handling emissions and credits from conditioning, transport, and permanent storage of captured CO_2

Emission credits can be achieved through the permanent storage of CO_2 involved in any life cycle stage where CCS is implemented. Examples include, but are not limited to, production of blue fuels or implementation of carbon capture on board a ship.GHG emissions resulting from the CO_2 capture process must be applied to the process involved in the origins of these CO_2 emissions efecu, ei,p or efc. If not, these GHG emissions must be added to emission resulting from the CCS chain. To calculate these emissions burdens and savings, the following formula can be used for a life cycle approach to assess the (epccs − eccs)$_i$:

Carbon dioxide emission burdens and credits for 1 kg carbon dioxide captured during life cycle stage i and permanently stored =

{GHG emissions from additional energy required for 1kg CO_2 capture, when not already accounted as credit in e_{fecu}, $e_{i,p}$ or e_{fc}}
+ {GHG emissions from additional energy required for 1kg ***CO_2 compression****}*
+ {GHG emissions from additional energy required for 1kg ***CO_2 transport***
{-1 kg CO_2 sequestered*, when not already accounted as credit in e_{fecu}, $e_{i,p}$ or e_{fc}}}*
*+ {****fugitive*** *CO_2 emissions*}*
+ {GHG emissions from additional energy required for 1kg ***CO_2 injection****}*
- {GHG emissions credit associated with ***carbon origin in CO_2 air emission*****}*

9.2. Guidance on handling CO_2 emissions counting and credits for biogenic CO_2 emissions

During biomass growth, CO_2 in the atmosphere is incorporated in biomass as carbon via photosynthesis, creating a CO_2 sink (sequestration) in the considered biomass as:

3.6641 *kg atmospheric CO_2 sequestered in biomass / kg* ***biogenic C*** *in biomass*

When this CO_2 is released through biomass oxidation, anaerobic digestion, or during fuel combustion, it balances the carbon sequestration, creating a net-zero climate impact for this biogenic carbon (+3.6641-3.6641=0).

This principle currently excludes accounting for varying growth rates of different biomass types (temporal aspect). For example, annual crops have different growth dynamics from perennial crops, leading to delayed uptake of CO_2 from the atmosphere by the former. This challenges the assumption that biogenic CO_2 has a net-zero impact on climate and will be evaluated in greater detail in later versions of this methodology.

The MMMCZCS LCA methodology considers a GWP equal to 1 gCO_2eq/gCO_2 for any source of CO_2 emissions occurring at the different stages of the fuel life cycle (Table 2). To reflect the **net-zero biogenic CO_2 cycle**, the MMMCZCS LCA methodology considers an emissions credit from direct CO_2 emissions resulting from the oxidation of biogenic carbon during the fuel life cycle, when the biogenic source of the carbon is proven.

An emissions credit $e_{i,c}$ must be applied when any CO_2 emissions resulting from fugitive emissions or fuel combustion are generated by biogenic carbon contained in the CO_2. This emissions credit must be calculated as:

Emissions credit *associated with carbon origin in CO_2 air emissions =*
1 *kg CO_2 eq / kg CO_2 from* ***biogenic C*** *origin*

Biogenic carbon contained in intermediates and in biofuel is oxidized into CO_2 during, for example, the complete combustion of carbon-containing fuel. This carbon of biogenic origin must be characterized as a complete oxidation of the carbon as 3.6641 kg CO_2eq/kg $C_{biogenic}$ in fuel and emitted as CO_2 to the atmosphere.

For biofuels produced from biogenic feedstocks, the emissions credit from CO_2 emissions resulting from the oxidation of biogenic carbon in the marine fuel converter can be calculated as:

Emissions credit *from CO_2 air emissions from biofuel combustion =* ***3.6641*** *kg CO_2 eq / kg* ***biogenic C*** *in fuel*

For waste-derived fuels, the MMMCZCS LCA methodology considers applying recommendation claimed by the GHG Protocol[30] and recommends that CO_2 emissions from the fraction of waste-derived fuels of fossil origin should be accounted for, while the fraction of CO_2 emissions resulting from carbon of a biogenic origin should be estimated and reported separately. Then, this $e_{i,c}$ credit must be applied to this later CO_2 emissions only, for CO_2 emissions resulting from oxidation of fuels produced from wastes, at any stage of the life cycle.

This credit is also applied for the permanent storage of CO_2 from biogenic origin, when proven. These principles are a simplification to ensure consistency with existing international reporting schemes, such as national GHG inventories. We will update this approach in future versions of this methodology as we develop a better understanding of how to assess these waste-derived fuels.

When a fuel is produced from a CO_2 source obtained by DAC, the same principle of net-zero emissions is applied, based on the evidence that CO_2 obtained from DAC is generated from atmospheric CO_2. This emissions credit must be calculated using the same equation as the credit for carbon of biogenic origin.

10. Interpretation of results

Our proposed methodology has been consolidated to support the identification of the most significant GHG emissions sources in the five life cycle stages, with the ambition of helping users to identify optimized fuel pathways for climate warming reduction. During the LCA interpretation phase, the following elements must be considered and recorded:

- Identification of life cycle stage impact and relative distribution
- Identification of the significant GHG emissions sources and issues and evaluation of completeness
- Limitations of the methodology concerning the fuel production system, such as data quality, uncertainty in the information, and consistency

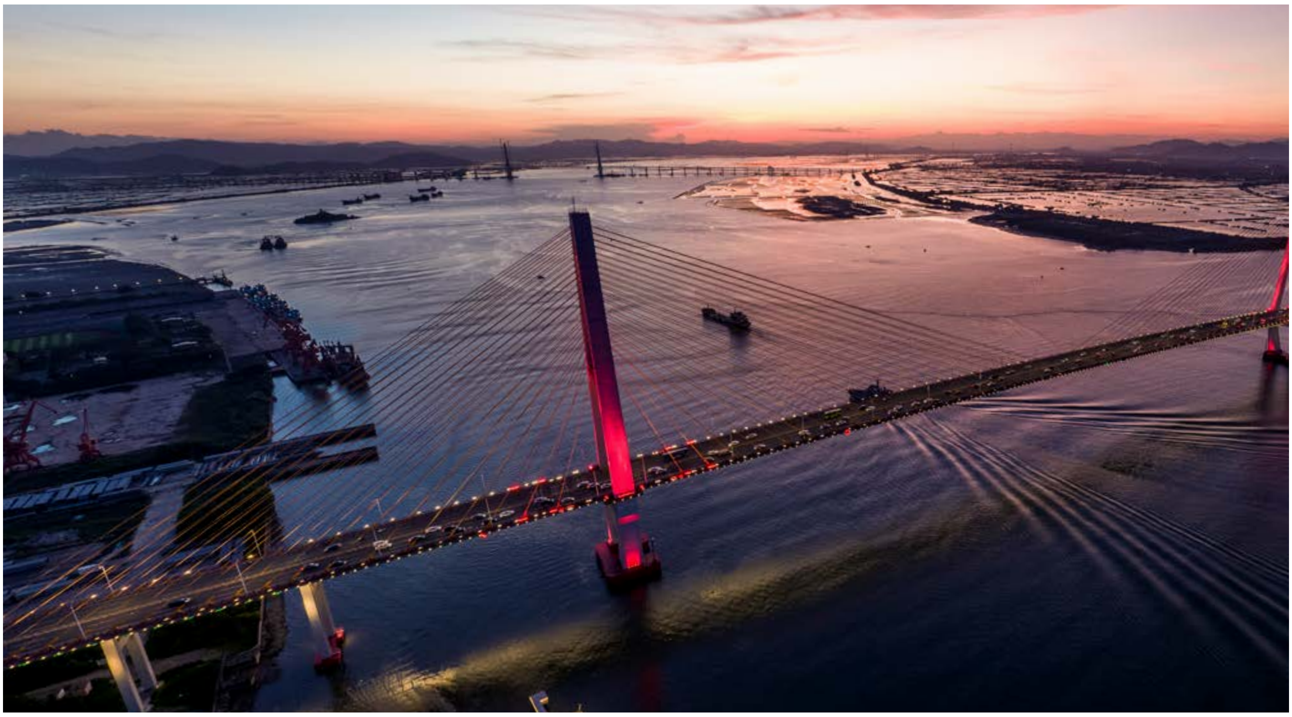
It is essential that users of the methodology, including the regulatory community, consider the relative nature of LCA in their interpretation of results, as these results indicate potential environmental effects and not actual impacts.

11. Reporting requirements

Users of this methodology should follow the reporting requirements described in the ISO 14067:2018 standard, consistent with international standards for LCA.[16] Specifically, the following information should be reported:

- System boundary, including the type of inputs and outputs of the system as elementary flows
- List of important unit processes
- Data collection information, including data sources, decisions concerning data, and quality assessment
- Biogenic GHG emissions and removals
- Fossil GHG emissions and removals
- Process flow diagram and description of WTW life cycle stages
- Time period from which the data was collected
- Geographic scope of the data

This methodology demands the same consistency as ISO 14067:2018 standard when it comes to reporting requirements.



12. Conclusion

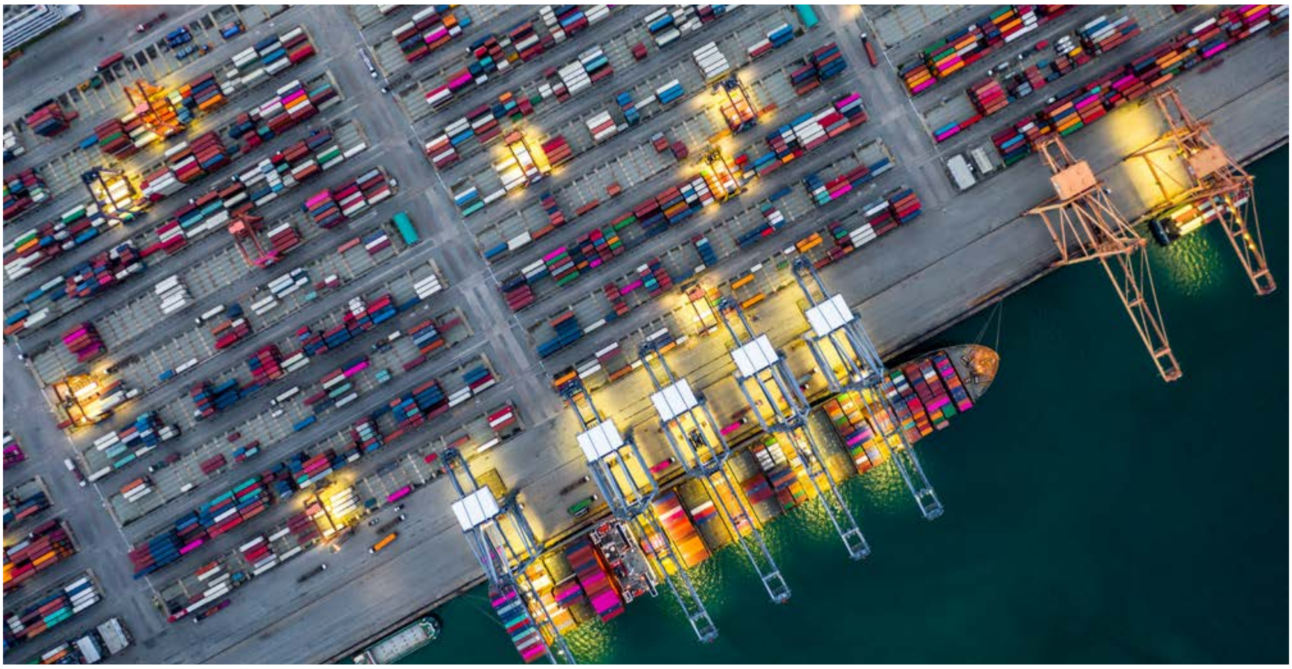
The current landscape of policies and regulations within the transportation sector lacks a unified approach to combating global warming. The absence of standardized LCA methodologies for calculating GHG emissions associated with marine fuels creates complex obstacles. Discrepancies among different regions hinder consistent policies that could support alternative marine fuels, leading to confusion and delay in achieving unified regulations and incentives. This inconsistency not only undermines the credibility of environmental assessments but also distorts markets and obstructs international cooperation to reduce emissions.

To address these challenges, international collaboration is imperative. The development and widespread adoption of a standardized LCA methodology for alternative marine fuels will help effective decision-making, enhance transparency, and ensure accurate environmental assessments.

To meet this need, the MMMCZCS has developed a global and comprehensive LCA methodology for use by the maritime community. The methodology is presented in the current policy document and an accompanying technical document.[1] The technical document provides a detailed, step-by-step guide for implementing the methodology, helping users calculate emissions intensity and identify major GHG emissions sources throughout the supply chain.

Conversely, this policy document offers a high-level overview suitable for policymakers and others involved in fuel regulations. It serves as a guiding beacon, highlighting the essential principles underpinning this methodology. The document walks readers through each stage of the supply chain, providing an understanding of the emissions that occur at different points. This understanding empowers decision-makers to endorse, regulate, and invest in alternative marine fuels that are pivotal in reducing the industry's carbon footprint. By providing policymakers with transparent insights into the emissions associated with alternative marine fuels, this document equips them to make informed decisions, advance sustainable industry benchmarks, and align with global efforts to curtail GHG emissions.

More broadly, this policy document can drive strategies for transitioning to cleaner energy sources across the shipping industry. Its guidance helps in navigating the complexities of diverse emissions profiles, advancing the establishment of emissions standards, encouraging the adoption of cleaner fuels, and fostering fair competition across the industry. Ultimately, this policy document sets the stage for a strategic, sustainable, and collaborative future within the maritime sector, where emissions reduction and environmental preservation drive decision-making.



Project team

This report was prepared by the MMMCZCS.

Lead authors
Ann O'Connor (MMMCZCS) and
Loïc Francke (MMMCZCS, seconded from TotalEnergies)

Contributing authors and project participants:
Harshil Desai (MMMCZCS)

This methodology was subject to a peer review performed from 10/03/2023 to 31/03/2023. The peer review panel was composed of:

- Dr Michael Wang, Director of the Systems Assessment Center, and interim director of the Energy Systems and Infrastructure Analysis division at Argonne National Laboratory, USA
- Prof. Michael Zwicky Hauschild, Department of Environmental and Resource Engineering, Technical University of Denmark, Denmark
- Dr Don O'Connor, CEO (S&T)2 Consultants Inc., Canada
- Dr Selma Brynolf, Researcher at Maritime Studies at Chalmers University of Technology, Sweden
- Dr Carl Vadenbo, project manager at ecoinvent Association, Switzerland

Steering committee
Torben Nørgaard (MMMCZCS) and
Louise Brix-Hansen (MMMCZCS)

Editing
Emily Nordvang (MMMCZCS) and
Matilda Handsley-Davis (MMMCZCS)

Design
Julia Garbowska,
Karoline Andersen (MMMCZCS) and
Tina Milosevic (By Milo)

Abbreviations

Abbreviation	Definition
C	carbon
CH_4	methane
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
DAC	direct air capture
dLUC	direct land use change
FAME	fatty acid methyl ester
g	gram
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	global warming potential
HTL	hydrothermal liquefaction
HVO	hydrotreated vegetable oil
iLUC	indirect land use change
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg	kilogram
LCA	life cycle assesment
LHV	lower heating value
MJ	megajoule
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
N	nitrogen
N_2O	nitrous oxide
RED	Renewable Energy Directive
TTW	tank-to-wake
UNFCCC	United Nations Framework Convention on Climate Change
WTT	well-to-tank
WTW	well-to-wake

References

1. Francke, L. & Desai, H. MMMCZCS LCA methodology for calculating the GHG intensity of alternative maritime fuels - Technical guidance for applying the Methodology. (2023).

2. European Commission. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. (2018).

3. European Commission. Supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin. (2023).

4. Roundtable on Sustainable Biomaterials, «RSB low iLUC risk biomass criteria and compliance indicators, Version 0.3. http://www.rsb.org/ (2015).

5. Wang, M. Life-cycle Analysis with the GREET Model. in (SwRI LCA for Transportation Symposium, 2021).

6. Prussi, M., Yugo, M., Padella, M. & Edwards, R. JEC Well-To-Wheels report v5 Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. https://ec.europa.eu/jrc (2020) doi:10.2760/100379.

7. Prussi, M. et al. CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels. Renewable and Sustainable Energy Reviews vol. 150 Preprint at https://doi.org/10.1016/j.rser.2021.111398 (2021).

8. Ministério de Minas e Energia/Agência Nacional do Petróleo Gás Natural e Biocombustíveis. Resolução ANP no 758/2018. (2018).

9. Intergovernmental Panel on Climate Change. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. (IGES, Japan, 2006).

10. O'Connor, A. Creating a Global Fuel Lifecycle Methodology - A qualitative assessment of existing methodologies and opportunities for the future. (2023).

11. ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework. https://www.iso.org/standard/37456.html (2006).

12. ISO 14040:2006/Amd 1:2020 Environmental management - Life cycle assessment - Principles and framework - Amendment 1. https://www.iso.org/standard/76121.html (2020).

13. ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines. https://www.iso.org/standard/38498.html (2006).

14. ISO 14044:2006/Amd 2:2020 Environmental management - Life cycle assessment - Requirements and guidelines - Amendment 2. https://www.iso.org/standard/76122.html (2020).

15. ISO 14044:2006/Amd 1:2017 Environmental management - Life cycle assessment - Requirements and guidelines - Amendment 1. https://www.iso.org/standard/72357.html (2017).

16. ISO 14067:2018 Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification. https://www.iso.org/standard/71206.html (2018).

17. Bhatia, P. et al. Product Life Cycle Accounting and Reporting Standard. (2011).

18. Svanberg, M., Ellis, J., Lundgren, J. & Landälv, I. Renewable methanol as a fuel for the shipping industry. Renewable and Sustainable Energy Reviews 94, 1217–1228 (2018).

19. Bilgili, L. Comparative assessment of alternative marine fuels in life cycle perspective. Renewable and Sustainable Energy Reviews 144, (2021).

20. Hwang, S. S., Gil, S. J., Lee, G. & Lee, J. W. Life Cycle Assessment of Alternative Ship Fuels for Coastal Ferry Operating in Republic of Korea. J Mar Sci Eng 8, 660–677 (2020).

21. Brynolf, S., Fridell, E. & Andersson, K. Environmental assessment of marine fuels: Liquefied natural gas, liquefied biogas, methanol and bio-methanol. J Clean Prod 74, 86–95 (2014).

22. Smith, C. et al. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/ (2021).

23. ecoinvent. ecoinvent database. https://ecoinvent.org/the-ecoinvent-database/ (2023).

24. Argonne National Laboratory. GREET model. https://greet.es.anl.gov/ (2023).

25. Brandão, M., Heijungs, R. & Cowie, A. R. On quantifying sources of uncertainty in the carbon footprint of biofuels: crop/feedstock, LCA modelling approach, land-use change, and GHG metrics. Biofuel Research Journal 9, 1608–1616 (2022).

26. Daioglou, V. et al. Progress and barriers in understanding and preventing indirect land-use change. Biofuels, Bioproducts and Biorefining 14, 924–934 (2020).

27. Malins, C. Considerations for addressing indirect land use change in Danish biofuel regulation. https://www.bike-biofuels.eu/wp-content/uploads/2022/08/chris_malins_rapport_-_conciderations_for_adressing_iluc_in_danish_biofuel_regulation.pdf (2021).

28. European Commission. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. (2008).

29. Intergovernmental Panel on Climate Change. 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Used by the National Greenhouse Gas Inventories Programme. (IGES, Japan, 2006).

30. Gillenwater, M. GHG Protocol guidance - Direct emissions from stationary combustion. (2005).

Visit our website for more
zerocarbonshipping.com

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping