MMMCZCS LCA Methodology for Calculating the GHG Intensity of Maritime Fuels

Technical guidance for applying the methodology

Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping

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1. Introduction

Replacing conventional fossil fuels with alternative fuels is expected to play a central role in decarbonizing the maritime industry, thanks to these fuels' enhanced environmental performance. Although using alternative fuels is expected to significantly reduce the industry's greenhouse gas (GHG) emissions, no alternative fuel is free from environmental impacts. However, understanding the potential impacts of alternative fuel production is not straightforward, as these fuels use varied feedstocks, complex production processes, and may produce new co-products. As a result, we need a global life cycle assessment (LCA) methodology that can assess the GHG emissions reduction potential of various alternative marine fuels.

LCA entails many important methodological decisions and requires accurate datasets to deliver robust and exploitable results, especially to analyze and compare GHG emissions from different fuel options. Various frameworks are available to standardize LCAs and ensure an acceptable quality level, and the majority are aligned with the International Organization for Standardization ISO 14040 series or the International Life Cycle Data (ILCD) system. In a recent paper, we analyzed the existing and upcoming fuel life cycle methodologies for determining climate impact.[1] This analysis found notable differences across the methodologies and supported the need to harmonize the approaches in a global well-to-wake (WTW) methodology.

Following our earlier analysis, we have developed this LCA methodology to provide a standardized approach for calculating the GHG intensity of marine fuels and a framework to enable the shipping sector to understand which life cycle stages contribute more significantly to fuels' GHG emissions. We hope this will allow shipping companies to select fuels with transparent and sound climate credentials, ensuring greater certainty on their GHG emission reductions. With this methodology, we also aim to support the ongoing development of the International Maritime Organization's Draft Guidelines on the Life Cycle GHG Intensity of Marine Fuels[2] by providing a globalized LCA methodological approach for assessing alternative fuel pathways.

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) has developed a detailed LCA methodology[3] to help industrial actors over the whole fuel life cycle to quantify the GHG intensity of maritime fuels. Our ambition is to not only quantify the Global Warming Potential (GWP) benefits of alternative maritime fuels but also to help the actors identify the source of emission and to improve these sustainable pathways.

This detailed document describes how LCA practitioners can calculate the GHG emissions at each life cycle stage for alternative fuels used in the maritime industry by applying our methodology. Our methodological choices were based on following ISO 14040 standards [4–10] and other key documentation,[11–13] assessing existing fuel LCA methodologies, collecting input through open consultations with MMMCZCS partners, consulting the scientific literature and existing policies, and conducting internal and external peer review processes.

This document is a part of a two-part series of publications describing the MMMCZCS LCA methodology. The accompanying policy briefing document provides a higher-level overview of the motivation for the methodology and of the different stages of fuel life cycles and their associated GHG emissions. In contrast, this technical document provides a more detailed, step-by-step guide to implementing the MMMCZCS LCA methodology.

This technical guidance is structured according to ISO 14040 standards and covers the following:

- Goal and scope (Sections 3 and 4)
- Life cycle inventory (Section 5)
- Life cycle impact assessment (currently restricted to GWP – see Section 6)
- Results and interpretation (Section 7)

These sections describe the requirements to calculate or estimate GHG emissions, which can be converted into GWP (see Section 6). Additional technical guidance is provided for every specific fuel pathway in Section 9. Case studies in the appendices illustrate how this methodology should be applied in maritime fuel supply chains.

The MMMCZCS LCA methodology is intended to be a living product. We will continue to maintain, update, and expand this technical documentation as needed to support the transition and keep up-to-date with emerging science.

2. Key definitions

This section describes the main definitions of key concepts in this report. These definitions aim to help LCA practitioners to better understand the structure of the different life cycle stages and to identify the best information required to assess GHG intensity of maritime fuels.

Allocation (multifunctionality)	Also called "partitioning", allocation solves multifunctionality by splitting up the amounts of the individual inputs and outputs between the co-functions according to some allocation criteria, being a property of the co-functions (e.g., energy content, mass, market price).[11]
Biofuels	Biofuels are liquid or gaseous fuels produced from a biological source of feedstock. Examples: bio-oils, bio-diesels, bio-methanol, or bio-methane.
Blue fuels	Liquid or gaseous maritime fuels produced from fossil sources of hydrogen combined with CO_2 capture, transport, and storage. Examples: blue hydrogen and blue ammonia.
Bunkering	The process of refueling a ship, including movement of the fuel from the storage facility in the port to the ship.[14]
Byproduct	A substance or object resulting from a production process the primary aim of which is not the production of that item.[15]
Co-product	Any of two or more products coming from the same unit process or product system.[7]
Direct GHG emissions	Any GHG emissions (CO_2, CH_4, or N_2O) arising in any life cycle which is released directly to the atmosphere.
Direct land-use change (dLUC) emissions	Emissions (primarily from carbon stock losses) due to recent (previous 20 years or more) land conversion directly on the area of land that a company owns or controls or on specific lands in the company's value chain.[16]
e-fuels	All fuels in gas or liquid form that are produced from renewable (solar or wind power, for example) or decarbonized sources of electricity (power-to-gas or power-to-liquid). Examples: e-ammonia and e-methanol.
Electricity supply	Any electricity imported to the system boundaries for use in operations at every life cycle stage.
Fuel slip (most commonly used for methane as "methane slip")	Fuel that escapes unburnt from marine engines.
Fuel supply	Liquid, solid, or gaseous fuels imported to the system boundaries for use in operations at every life cycle stage.
Fugitive emissions	The European Environment Agency utilizes the California Air Resources Board definition for fugitive emissions as "Emissions not caught by a capture system, which are often due to equipment leaks, evaporative processes and windblown disturbances." These fugitive emissions can contribute to GHG emissions and may occur at every stage of the fuel life cycle due to the accidental release of GHGs through leakages.[17]
Indirect land-use change (iLUC) emissions	Emissions (primarily from carbon stock losses) due to land conversion on lands not owned or controlled by the company, or in its value chain, induced by change in demand for (or supply of) products produced or sourced by the company.[16]
Instantaneous CO_2 leakages	Event where large quantities of CO_2 may escape suddenly from a leakage pathway either during injection under inadequate injection conditions or poor storage management.

Material and consumable inputs	Material inputs include but are not limited to chemicals, water, oxygen, and solvents. In the context of this methodology, fuel feedstocks (e.g., biomass, renewable hydrogen, or natural gas) are not considered material inputs and are not subject to the requirements described in section 8.1.3.
Multifunctionality	Multifunctionality refers to processes or systems delivering more than one product or services, here called co-products (even if some of these are considered residues or byproducts). Impacts from such a process shall be assigned to the different co-products using the ISO hierarchy: 1) Subdivision or system expansion, 2) Allocation based on physical relationship, 3) Allocation based on other relationship than physical.
Seepage of CO_2	The gradual migration of CO_2 into caprock or potentially adjacent reservoirs. This will depend on the geological formation, therefore data used shall be specific to store type.
Steam and heat supply	Any heat or steam imported into the system boundaries for use in operations in every life cycle stage.
Subdivision (multifunctionality)	"Subdivision" of multifunctional processes refers to the collection of data individually for mono-functional processes that relate to the analyzed system and are contained in the multifunctional process. In this way, the required processes are cut free and the multifunctionality problem is solved – unless any of the included single-operation unit processes are still multifunctional. Subdivision is often but not always possible to avoid allocation for black-box unit processes.[11]
System expansion or substitution (multifunctionality)	"System expansion" and its variant "substitution" are LCA approaches that consider the environmental impact as a consequence of an activity in a more global system, to avoid allocation between the product that is assessed and its co-products in multifunctional systems. This approach involves identifying the reference products that are substituted by the co-product(s) and quantifying the environmental impacts associated with those reference products. These impacts can then be credited to the product that is assessed, because the co-products can substitute these reference products. The system boundaries are expanded ("expansion") until access is reached to the market for the co-products to substitute the optional or unnecessary function with an alternative reference product ("substitution").[11]
Transport, distribution, and storage	Any material or energy inputs and outputs associated with the transport, distribution or storage of feedstocks, intermediary, and final fuel products.
Waste streams	Any substance (or object) which the holder discards or intends or is required to discard.[15]

3. Defining the goal of an LCA

Goal definition is the first stage of any LCA. The clarity of the goal established at the beginning of any LCA will impact all following stages, including the interpretation of results. Therefore, it is important to ensure the goal is properly defined. According to the ILCD, LCA practitioners should address the following areas when defining the goal of an LCA:

- **Description of the intended application(s) of the results**

LCA practitioners should describe the intended application as precisely as possible. The ILCD handbook provides several examples of intended applications, including identifying key environmental performance indicators throughout the supply chain, benchmarking a specific product against the product group's average, or developing an Environmental Product Declaration (EPD).

- **Description of the limitations due to the method, assumptions, and impact coverage**

Important limitations include, for instance, the reduction to one impact category such as GWP (i.e., GHG emissions) or any restriction regarding the geographic or temporal scope of an LCA, e.g., if implemented over a very specific geographic, market, or technological context, limiting the usability or comparability of results beyond this context.

- **Description of the reasons for carrying out the study and the decision context**

In line with the intended application, LCA practitioners must precisely define the reasons for conducting an LCA and the type of decisions it could trigger. This could, for instance, impact the scope, data sources, and certain methodological choices, such as the approach to dealing with multifunctionality or specific assumptions.

- **Definition of the target audience of the results**

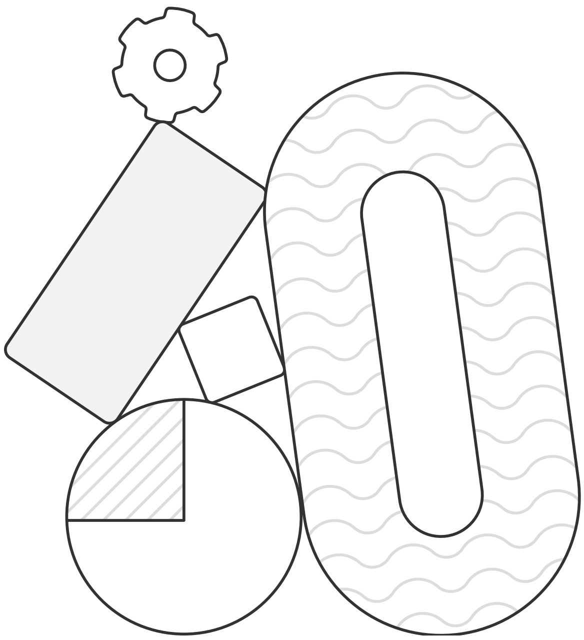
Defining the target audience (e.g., public vs. internal or technical vs. non-technical) is important for setting the level of detail and technical depth of the LCA report. Furthermore, it determines whether a critical review (see Section 4.10) is required.

- **Does the LCA involve comparing technologies or products, and are results intended to be disclosed to the public?**

The LCA goal(s) should clearly state whether the LCA includes comparisons of technologies or products and whether results are intended to be published. If this is the case, a critical review is required, and greater depth and transparency are expected, especially regarding data sources and the interpretation of results.

- **Who is the commissioner of the study and other influential actors?**

This provision aims to identify the potential influence the commissioner of the LCA and other involved experts may have on the design, execution, or interpretation of the LCA, including potential conflicts of interest.



4. Defining the scope of an LCA

This section describes the different stages of scope definition for a maritime fuel LCA, following ISO 14040/44 recommendations. The scope outlined in this methodology follows an attributional LCA with consequential elements, such as system expansion and substitution. In line with the definition of goals, the scope of an LCA is fundamental, as it defines the product or function being analyzed, the system boundaries, and key material or energy flows.

4.1 Product system

The methodology described in this document can be applied to any maritime fuel, both fossil and renewable. However, the document provides specific guidance for three categories of alternative maritime fuels (biofuels, e-fuels, and blue fuels), as defined under the Key definitions section. The guidelines provided here describe the process for assessing the environmental impacts of all fuel categories over the whole WTW life cycle: from feedstock extraction or cultivation ("well") through to final fuel use on board a shipping vessel ("wake"). However, LCA practitioners can also use these guidelines over a reduced scope, e.g., well-to-tank (WTT) or tank-to-wake (TTW) (see system boundaries description in Section 4.4).

4.2 Function and functional unit

The MMMCZCS LCA methodology aims to allow the potential climate impact comparison of different fuels used in the maritime sector. It is, therefore, important to ensure maritime fuels are compared using a common functional unit.

The functional unit represents a quantitative description of the functions provided by the system or product being analyzed. ISO 14040 and ISO 14044 standards specify that the functional unit must be consistent with the study's goal and with all system functions.

The function of maritime fuels is to be used in the engines of maritime vessels for auxiliary power generation and propeller power generation via the main engine or powertrain. Therefore, the functional unit used in this methodology is:

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

The functional unit used in the MMMCZCS LCA methodology must be expressed as 1 MJ of fuel using the lower heating value (LHV) of the fuel. LCA practitioners using this technical document over a reduced scope may adapt the functional unit accordingly, e.g., 1 MJ of fuel distributed to maritime vessels (WTT).

4.3 Reference flow

The reference flow reflects the physical product required to deliver the functional unit and will vary for each fuel type based on its physical characteristics, such as energy density. Example: to deliver 1 MJ of fuel A, x liters or y tonnes (t) of fuel A is required.

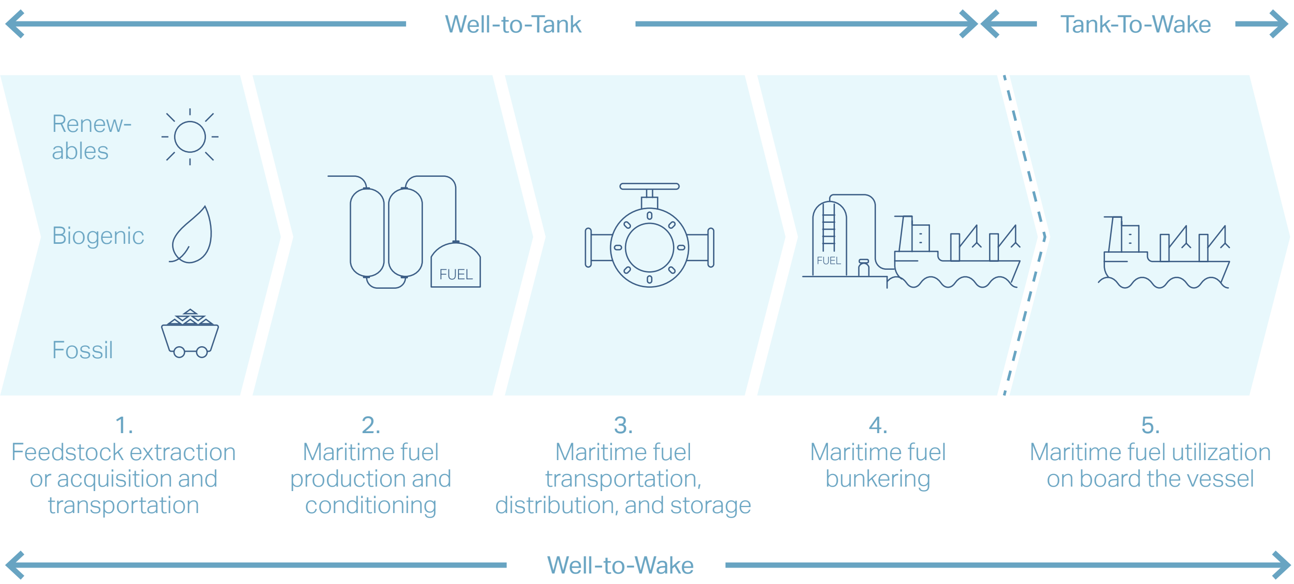
The reference flow shall be described based on the stages defined in Section 4.4.

It is common to conduct the fuel LCA calculations using the reference flow, converting to MJ at the end. This requires knowledge of the fuel's LHV. Default LHV values for various fuel pathways are listed in Appendix G (Table 12).

4.4 System boundary

By default, the system boundary covers the whole life cycle of the fuel, from the feedstock extraction or cultivation ("well") through to utilization of the fuel on board maritime vessels in the fuel converter ("wake"). The system boundary of the WTW utilization of fuels on maritime vessels should consist of five life cycle stages, further described in Figure 1, that bring together activities and processes of the WTT and TTW stages.

Figure 1. Maritime fuel life cycle stages included in the MMMCZCS LCA methodology.



Stages 1 to 4 cover the WTT steps of the fuel life cycle, while Stage 5 represents the TTW stage. The total WTW emissions are calculated using Equation 1.

Equation 1.

$$E_{WTW} = E_{WTT} + E_{TTW}, \text{ with:}$$
$$E_{WTT} = E_{Stage\ 1} + E_{Stage\ 2} + E_{Stage\ 3} + E_{Stage\ 4}, \text{ and}$$
$$E_{TTW} = E_{Stage\ 5}$$

Where:

E_{WTW}	WTW emissions of maritime fuels
E_{WTT}	WTT emissions of maritime fuels
E_{TTW}	TTW emissions of maritime fuels
$E_{Stage\ 1}$	Emissions from feedstock extraction or acquisition and transport life cycle stage
$E_{Stage\ 2}$	Emissions from fuel production and conditioning life cycle stage
$E_{Stage\ 3}$	Emissions from fuel transport, distribution and storage life cycle stage
$E_{Stage\ 4}$	Emissions from fuel bunkering life cycle stage
$E_{Stage\ 5}$	Emissions from fuel use on board the vessel life cycle stage

The MMMCZCS LCA methodology is specific to evaluating the GHG emissions of maritime fuels. E_{WTW} is, therefore, the WTW GHG emissions of maritime fuels, expressed in gCO_2eq/MJ_{fuel}. All emission factors in Equation 1 must be calculated based on the functional unit defined in Section 4.2.

The following subsections provide further details of the components and GHG emissions sources of each life cycle stage considered in this methodology. GHG emissions are calculated for these five stages as the sum of GHG emissions induced by the processes involved in each stage minus the applicable emissions credits.

4.4.1 Stage 1: Feedstock extraction or acquisition and transportation

Stage 1 covers the extraction of primary resources that will eventually constitute the energy content of final maritime fuels. It includes, but is not limited to, activities such as extraction of fossil fuels (oil, coal, and natural gas), biomass cultivation, collection of residues or wastes, capture of biogenic and fossil carbon (in combination with renewable hydrogen), and harvesting of renewable energy such as wind, solar, or hydro power to produce hydrogen via an electrolyzer, for example.

Environmental impacts from feedstock extraction or acquisition primarily stem from using energy (e.g., electricity, fuels, heat) and material inputs or outputs such as chemicals and water. Other impacts include:

- Land-use change (LUC) and agricultural management (relevant for biofuels)
- Agricultural operations and consumables such as fertilizer in the case of biomass cultivation
- Leakage, venting, or flaring of natural gas
- Feedstock pre-processing (e.g., cleaning, drying, baling)
- Transport stage to the fuel processing facility

As such, the emissions associated with Stage 1 can be described by Equation 2.

Equation 2.

$$E_{stage1} = e_l + e_{fecu} + e_{1,t} + e_{1,p} + e_{1,fug} - e_{sca} - e_{1,c} + (e_{ccsp} - e_{ccs})_1 + (e_{cpm} - e_{cpc})_1$$

Where:

e_l	Emissions from carbon stock change caused by dLUC
e_{fecu}	Emissions associated with the processes involved in feedstock extraction or cultivation
$e_{1,t}$	Emissions associated with feedstock transportation
e_{sca}	Emissions credit from improved agricultural management and improved soil carbon content
$e_{1,p}$	Emissions associated with feedstock pre-processing
$e_{1,fug}$	Fugitive emissions associated with feedstock extraction or acquisition and transportation
$e_{1,c}$	Emissions credit for CO_2 air emissions of biogenic carbon origin arising during feedstock extraction, acquisition, and transportation
$(e_{ccsp} - e_{ccs})_1$	Emissions e_{ccsp} and credits e_{ccs} associated with the CO_2 captured during feedstock extraction, acquisition, and transportation phase, as detailed in Section 8.4
$(e_{cpm} - e_{cpc})_1$	Emissions e_{cpm} and credits e_{cpm} associated with the system expansion/substitution from co-products generated during feedstock extraction or acquisition and transportation phase, as detailed in Section 8.3

Additional guidance on the calculation of emissions from feedstock extraction or acquisition and transportation is provided in Section 8.

4.4.2 Stage 2: Maritime fuel production and conditioning

The maritime fuel production and conditioning life cycle stage includes activities relating to converting feedstocks into fuels for maritime applications and conditioning for their transport. These activities involve fuel production, feedstock processing to intermediary products, transportation of interim fuel inputs (including CO_2 capture, storage, or usage during fuel production), liquefaction, and compression.

Sources of emissions at this life cycle stage include venting, flaring, and 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.

Equation 3 shows how to calculate the emissions associated with Stage 2.

Equation 3.

$$E_{stage2} = e_{2,p} + e_{2,fug} - e_{2,c} + (e_{ccsp} - e_{ccs})_2 + (e_{cpm} - e_{cpc})_2$$

Where:

$e_{2,p}$	Emissions associated with maritime fuel production and conditioning
$e_{2,fug}$	Fugitive emissions associated with maritime fuel production and conditioning
$e_{2,c}$	Emissions credit for CO_2 air emissions of biogenic carbon origin arising during maritime fuel production and conditioning
$(e_{ccsp} - e_{ccs})_2$	Emissions e_{ccsp} and credits e_{ccs} associated with the CO_2 captured during maritime fuel production and conditioning, as detailed in Section 8.4
$(e_{cpm} - e_{cpc})_2$	Emissions e_{cpm} and credits e_{cpc} associated with the system expansion or substitution from co-products generated during maritime fuel production and conditioning, as detailed in Section 8.3

Details on how these terms should be calculated are described in Section 9.

4.4.3 Stage 3: Maritime fuel transportation, distribution, and storage

In this methodology, emissions from the transportation, storage, and distribution of maritime fuels include emissions from the energy (primarily electricity, fuel, and heat or steam) used to transport, distribute, and store the final fuel. All impacts associated with fuel and electricity supply and use must be considered. Fugitive emissions must also be included.

This stage does not cover emissions associated with transporting feedstocks or intermediate products, which are covered in Stage 1. In addition, it does not cover bunkering operations or storage on board the vessel.

Equation 4 describes how to calculate emissions from Stage 3.

Equation 4.

$$E_{stage3} = e_{3,t} + e_{3,p} + e_{3,fug} - e_{3,c}$$

Where:

$e_{3,t}$	Emissions associated with maritime fuel transportation and distribution
$e_{3,p}$	Emissions associated with maritime fuel storage
$e_{3,fug}$	Fugitive emissions from transport, storage, and distribution of maritime fuel
$e_{3,c}$	Emissions credit for CO_2 air emissions of biogenic carbon origin arising during transport, storage, and distribution of maritime fuel

Section 8.2.1 provides details on calculating emissions from fuel transport, distribution, and storage.

4.4.4 Stage 4: Maritime fuel bunkering

Fuel bunkering activities include all logistics of loading and distributing the fuel to vessel fuel tanks. It does not include storage on board the vessel. Sources of emissions include energy (electricity, fuels, and heat or steam) and fugitive emissions occurring during the distribution of the maritime fuel to fuel tanks.

Equation 5 describes how to calculate emissions from Stage 4.

Equation 5.

$$E_{stage4} = e_{4,p} + e_{4,fug} - e_{4,c}$$

Where:

$e_{4,p}$	Emissions associated with the bunkering of maritime fuel
$e_{4,fug}$	Fugitive emissions from bunkering of maritime fuel
$e_{4,c}$	Emissions credit for CO_2 air emissions of biogenic carbon origin arising during the bunkering of maritime fuel

Sections 8.2.2 and 8.2.3 provide details on calculating emissions from bunkering (energy supply) and fugitive emissions.

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

This stage covers the utilization of fuel on board the vessel by the maritime fuel converter. The stage includes maritime fuel storage, use of consumables such as pilot fuel, shore power use, and GHG emissions abatement technologies.

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

- Fugitive emissions (e.g., boil-off losses) occurring as a result of accidental releases during storage and transportation up to the fuel converter
- Maritime fuel converter slips
- GHG emissions from maritime fuel combustion in maritime fuel converter (carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)) – with separate cases for fuel cells and combustion engines where applicable
- Use of consumables such as pilot fuel, onshore 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 onboard captured CO_2
- Emissions credit from permanent sequestration of CO_2
- Emissions credit for CO_2 air emissions of biogenic carbon origin (e.g., associated with biogenic carbon sources in the maritime fuel)

Equation 6 describes how to calculate emissions from Stage 5 using the terms outlined above.

Equation 6

$$E_{stage5} = e_{slip} + e_{fc} + e_{fu} + e_{5,fug} - e_{5,c} + (e_{ccsp} - e_{ccs})_5 + (e_{cpm} - e_{cpc})_5$$

Where:

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 consumable use on board the vessel
$e_{5,fug}$	Fugitive emissions of maritime fuel during onboard storage
$e_{5,c}$	Emissions credit associated with biogenic carbon sources in fuel
$(e_{ccsp} - e_{ccs})_5$	Emissions e_{ccsp} and credits e_{ccs} associated with the CO_2 captured during fuel utilization in the fuel converter on board the vessel, as detailed in Section 8.4
$(e_{cpm} - e_{cpc})_5$	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, as detailed in Section 8.3

Additional guidance on calculating emissions during Stage 5 is provided in Section 10.

4.4.6. Excluded processes

Impacts associated with construction, manufacturing, and infrastructure decommissioning should not be included within the system boundary. However, the impact of these aspects should be evaluated separately and evaluated for inclusion in later versions of the methodology where these so-called embodied emissions can be significant.

4.4.7 Handling co-products and residues (multifunctionality)

Dealing with multifunctionality is necessary when a process provides multiple functions, i.e., delivering several goods and/or services (often called "co-products"). The GHG emissions must be divided appropriately among the different co-products or outputs.

According to the ISO 14044:2006 standard, addressing multifunctionality in product footprint should be conducted according to the following allocation hierarchy: 1) Subdivision or system expansion, 2) Allocation based on physical relationship (e.g., LHV as defined in Appendix G, energy content, or mass), 3) Allocation based on other relationship than physical (e.g., economic value).

The MMMCZCS LCA methodology stipulates that system expansion must be used when the following conditions are met:

- One main product is clearly identified in the life cycle stages considered and mainly drives the production process, and
- Some byproducts or residues are generated but in smaller amounts (for example, hydrogen is the main product of electrolysis, while oxygen is a residue), and
- Co-products have an identified market and are sold. The co-products must directly replace the original product(s) on the market, and data must be collected to demonstrate the reduced use of the original product(s).

When an output from a process has no economic value, it cannot be considered a co-product and is instead considered waste. In this case, or if there is no visibility over the fate of products (e.g., biochar), energy allocation may be the best approach.

System expansion cannot be performed when multiple co-products are generated, for products without alternatives or substitutes, when there is no visibility over the fate of products, or for waste (no economic value). Furthermore, uncertainty in the substitutability and displacement rate of the co-products can influence the results. In such cases, an allocation approach must be used.

Allocation should primarily be based on physical characteristics (mass or energy). It should be captured under ep (process emissions) by withdrawing a share of GHG emissions corresponding to the mass or energy ratio of co-products or residues to the main product. If the allocation cannot be based on physical characteristics, the allocation can be based on the relative economic value of co-products or residues compared to the main product.

Further guidance on system expansion and allocation is given in Section 8.3.

4.5 Cut-off criteria

When conducting an LCA, cut-off criteria are often applied to the inputs and outputs to and from a life cycle stage or process. The reason for doing so is to limit the resources expended on collecting and providing data and calculating the environmental flows associated with inputs or outputs with minor impacts on overall GHG emissions.

The cut-off criteria used in this methodology for including or excluding materials, energy, and emissions data apply to any system boundaries defined by LCA practitioners (e.g., one specific life cycle stage, WTT, WTW) and are as follows:

Mass – if a flow is less than **1% of the cumulative mass** of the model, it may be excluded, provided its environmental relevance is not a concern. Cumulative cut-offs shall not exceed 5% of the total mass flow.

Energy – if a flow is less than **1% of the cumulative energy** of the model, it may be excluded, provided its environmental relevance is not a concern. Cumulative cut-offs shall not exceed 5% of the total energy flow.

Environmental relevance – if a flow meets the above criteria but may have a significant environmental impact, it must be included. This judgment shall be made based on experience and documented as necessary.

Flows should typically not be cut off where data have been provided or sourced, regardless of whether these are below the abovementioned cut-off thresholds. In instances where a choice was made to exclude a flow that does not meet the stated study exclusions, the choice must be documented in the inventory analysis section of the LCA report.

4.6 Limitations

LCA practitioners implementing this methodology must list and disclose limitations concerning the goal and scope. For instance, if the scope of the LCA is reduced, this must be disclosed. Furthermore, if there are methodological limitations due to restrictions around location, data availability, or reliability, these must be disclosed. Finally, limitations related to the assumptions made in the study (e.g., the evolution of the GHG intensity of the grid) must be clearly stated (see Section 4.7).

LCA practitioners must also assess the risks of double counting GHG reductions from CO_2 capture. Whenever GHG reductions from CO_2 capture are utilized or claimed by economic operators controlling the processes generating CO_2 (e.g., cement or steel production) for regulatory compliance (e.g., European Union Emissions Trading System) or to generate carbon credits, no additional credits can be claimed by economic operators using captured CO_2 to produce maritime fuels (e.g., e-methanol).

4.7 Assumptions

The user shall define all key assumptions within the scope of the study. Below is a non-exhaustive list of assumptions that may be relevant in LCA studies:

- Assumptions relating to the origins of feedstocks and subsequent transportation to the processing plant if suppliers are not yet confirmed.
- Assumptions relating to downstream transportation and storage – for example, if the maritime fuel's final destination is unknown, LCA practitioners may assume the fuel is transported 500 km by truck from fuel production site to the port.
- Assumptions about grid electricity emissions if, for example, the plant will not be operating until 2030.
- Assumptions relating to the origins of consumables used in processing if suppliers are not yet confirmed.
- Assumptions about whether the fuel will be used in fuel cells or internal combustion engines.

4.8 Data quality requirements

The quality of data about the different life cycle stages must be assessed against the requirements defined in Table 1. These requirements are based on the ISO standards[5] on goal and scope definition and inventory analysis.

Table 1. Data quality requirements for the MMMCZCS LCA methodology.

Parameter	Description	Requirement
Time-related coverage	The desired age of data and the minimum length of time over which data should be collected.	Primary data should represent 12 consecutive months. All or part of the data must be collected within the last calendar year. For crop data, longer periods are required to account for variations associated with climate, pests, etc. Secondary data should be the most recent available. The datasets used should consider inter-annual and intra-annual variabilities. Inter-annual data captures long-term changes and trends that may influence the environmental performance of a product, process, or system, e.g., shifts in market demand, consumer preferences, or economic conditions. Intra-annual data capture seasonal or short-term fluctuations, e.g., fluctuations in resource availability, energy consumption, waste generation, or emissions due to changes in seasons or weather patterns.
Geographical coverage	The area from which data for unit processes should be collected.	Data should be representative of the known geographical locations of each process.
Technology coverage	Technology mix.	Data should be representative of the technology currently used in the known geographical locations of each process.
Precision	Measure of the variability of the data values for each data category expressed.	Specific and representative data should be used in the study. Where there is potential variability in the data, sensitivity analysis must be used to determine its significance.
Completeness	Assessment of whether all relevant input and output data are included for a certain dataset.	Specific datasets will be benchmarked with literature data and databases. Simple data validation checks (e.g., mass balances) must be performed.
Representativeness	The degree to which the data represent the identified time-related, geographical, and technological scope.	The data should fulfill the defined time-related, geographical, and technological scope.
Consistency	How consistently the study method has been applied to different analysis components.	The study method must be applied to all components of the analysis.

Reproducibility	Assessment of whether an independent practitioner would be able to reproduce the results.	The information about the method and the data values should allow an independent practitioner to reproduce the results reported in the study.
Sources of the data	Assessment of data sources used.	Data must be derived from credible sources and databases.
Uncertainty of information	Assessment of the influence of uncertainty due to data, modeling approach, methodological choices, and assumptions.	The most specific available data must be used. Any assumptions made must be conservative. Sensitivity analyses must be used to assess the influence of important methodological choices on the results.

Where specific data are unavailable, proxy data, estimates, or assumptions can be used; these must be clearly described and specified in the LCA report. Where proxy data, estimates, or assumptions significantly impact the overall environmental profile, their influence should be further investigated using a sensitivity analysis.

4.9 Type and format of the report required for the study

ISO 14067:2018[8] describes requirements for reporting the assessment, consistent with international standards on LCA. According to ISO 14067:2018, LCA reports must contain the following items:

- A description of the system boundary, including the type of inputs and outputs of the system as elementary flows.
- A 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 diagrams and descriptions of life cycle stages (WTW).
- The time period over which the data was collected.
- The geographical scope of the data.

4.10 Critical review

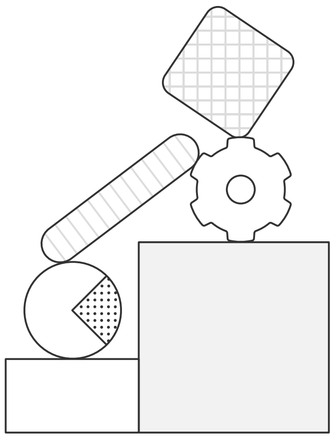
A critical review may be required to further enhance the robustness and accuracy of an LCA by ensuring conformity with ISO 14040:2006[4,10] and ISO 14044:2006.[5,7,9] The purpose of the critical review process is to ensure that:

- The methods used to carry out the LCA are consistent with ISO 14040/14044,
- The methods used to carry out the LCA are scientifically and technically valid,
- The data used are appropriate and reasonable in relation to the goal of the study,
- The interpretation reflects the limitations identified and the goal of the study, and
- The study report is transparent and consistent.

A critical review is only required in specific conditions, e.g., if an LCA aims to compare two competing technologies delivering the same function and if the results are expected to be public.

The International Reference Life Cycle Data System (ILCD) provides further guidance on the minimum review requirements of an LCA based on the stakeholder involvement and technical knowledge of the audience.[11]

The exact scope of the critical review must be defined and recorded during the scoping phase of the LCA. Further details on the types of review that may be required can be found in Appendix F.



5. Life cycle inventory

The qualitative and quantitative data required by this methodology must be collected for each unit process that is included within the system boundary. The collected data, whether measured, calculated, or estimated, are utilized to quantify the inputs and outputs of a unit process.

5.1 Data sources

In this methodology, practitioners may use primary or secondary data sources to derive the GHG intensity for a given life cycle stage. 'Primary data' includes quantified values of a process or activity obtained from direct measurements or calculations based on direct measurements. 'Secondary data' includes all data that do not fulfill the requirements for primary data, such as data from databases and published literature, default emissions factors from national inventories, calculated data, estimates, or other representative data validated by competent authorities. Proxy processes or estimates are also considered secondary data.

Site-specific data shall be used for key unit processes. Site-specific data includes direct GHG emissions (determined through direct monitoring, stoichiometry, mass balance, or similar methods), activity data (process inputs and outputs that result in GHG emissions or removals), and emissions factors. Fundamentally, site-specific data is primary data obtained within the product system.

5.1.1. Foreground data

Foreground data refers to all data concerning the energy and material flows under the control of the economic operators who own each life cycle stage. Examples include the amount and type of chemicals used for feedstock production, water used in fuel production, and energy sources and amounts consumed.

The ILCD defines the following principles for foreground data collection:

1. Avoiding black-box unit processes

To ensure data accuracy and avoid multifunctionality issues, collecting data specifically for the processes of interest within the system boundaries is crucial. The focus should be on the required processes (single-operation unit process) rather than combining them with other physically separate process steps that are not required (black-box unit process).* This can be done by either collecting data specifically for the required processes or, in some cases, by virtual subdivision of collected data. Virtual subdivision involves sufficiently and accurately splitting up the data from a multifunctional process and assigning the inventory items to the included unit processes.

2. Using specific data for the identified processes within system boundaries

Ideally, using the most accurate information to model a system's life cycle would involve producer-specific, operator-specific, or site-specific primary data, which can be obtained from the relevant operator in the supply chain, e.g., product or technology developer. Additionally, the information should include relevant secondary data from tier-one suppliers (where upstream or downstream processes cannot be replaced with, for example, technology or market average data), including waste service suppliers. When starting data collection, a lack of appropriate available data (appropriate generic or average secondary background data) may highlight the need for more representative or specific data. For processes that are not expected to be key for the system, estimations can provide an initial understanding of the process data.

3. Using generic or average data for the foreground system in attributional modeling

Generic or average data may be more appropriate if the quality of available site-specific data cannot be verified. It is important to note that the choice between site-specific and generic or average is not a matter of choice but is determined by the representativeness of the data. For foreground processes that make a minimal contribution to the overall environmental impact, generic or average background datasets can also be used.

* For example, for e-fuel production, it is preferable to separate the hydrogen electrolysis production from the methanation process to clearly identify the required process for the e-fuel production.

5.1.2 Background data

Background data refers to the environmental impact factors (e.g., GHG intensity) from different energy/material flows (foreground data). They are not within the control of the economic operators implementing the processes and operation.

The ILCD defines the following principles for background data collection:

1. Types of background data

For attributional modeling, the type of background data required is the market consumption mix of processes or systems.

2. Unit process, parameterized unit process, or life cycle inventory (LCI) results datasets for background use.

Background datasets can be unit processes, parameterized unit processes, or life cycle inventory results. Documenting and reviewing the background datasets is recommended, either through qualified and independent external review or through panel review, depending on the intended application.

In cases where fixed LCI results or unit process inventories are inappropriate due to specific operating conditions, parameterized unit process datasets or partly terminated system datasets may provide more flexibility. This is particularly relevant for transportation, flexible processing machines, waste management, etc.

3. Specific, average, or generic data

When no specific supplier is involved or data sets are further in the background, using country or market technology averages or generic background LCI sets is more appropriate. Regardless of choice, the data should still accurately represent the technology level by reflecting real market averages or worst- and best-case scenarios.

5.1.3 Hierarchy of data sources

At each stage of the maritime fuels value chain, the relevant operator is expected to collect primary data. However, if this is not possible, LCA practitioners must use trustworthy secondary data sources. LCA practitioners must implement the following hierarchy of data sources, which is partly based on guidance from the EU Innovation Fund:[18]

1. Stoichiometric combustion emissions for a wide range of fuels, as provided in Tables 2.2 and 2.3 of Vol.2 Energy of the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories.[19]

2. Data made available in the context of regulatory compliance via dedicated methodologies and/or tools, including but not limited to the EU Renewable Energy Directive (RED) II[13] in Europe and associated Implementing Regulations or Delegated Acts, as well as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET)/CA-GREET[20] in the United States (Renewable Fuel Standard or Low Carbon Fuel Standard).

3. Coherent data for a different range of inputs or products from JRC-EUCAR-Concawe (JEC)-WTW v.5, WTT Annexes[21] which shares the same input database as the calculations in Annex V of EU RED II.[13]

4. Calculations using input data from ecoinvent 3.9 (or more recent versions).[22] Calculations in ecoinvent should use the “cut-off system model.” An equivalent calculation may also be made in other proprietary software packages (e.g., Ganzheitliche Bilanzierung (GABI), open LCA) using the same input data. If the calculation calls for the allocation of emissions between multiple products, allocation by energy content (LHV) should be selected.

5. “Official” sources, such as the IPCC, the International Energy Agency (IEA), or governments (but note that most IPCC and IEA tables show combustion emissions, not life cycle emissions intensity).

6. Other reviewed data sources, such as the E3 databases.[23]

7. Peer-reviewed publications: the applicant should properly reference the source used so that the evaluator can check it but does not have to provide a review of the methodology of the chosen source.

8. Duly documented own estimates.

9. “Gray literature”: unreviewed sources, such as commercial literature and websites.

6. Life cycle impact assessment

The life cycle impact assessment (LCIA) is the step where the material and energy inputs and outputs (foreground data) collected for each stage in the life cycle are combined with the relevant environmental impact factors (background data) to quantify the overall life cycle impacts of fuels.

This methodology is currently restricted to estimating life cycle impacts in terms of GWP. Total life cycle GWP is estimated using the life cycle emissions of different GHGs (including but not limited to CO_2, CH_4, and N_2O) calculated by applying Equation 1 combined with the corresponding GWP over 100 years (GWP100) extracted from the IPCC Sixth Assessment Report[24] (shown in Table 2) or a subsequent IPCC assessment report, as described in Equation 7. This allows practitioners to report total aggregated emissions for all GHGs expressed as CO_2 equivalents (CO_2eq).

Life cycle impact as GWP over a 20-year horizon (GWP20) may also be calculated separately if desired and subject to data availability for GWP20 emissions factors. However, the impacts of biogenic CO_2 must be reported separately under both GWP100 and GWP20.

As only GWP is to be calculated in the current version of this technical document, no normalization or weighting is required.

Equation 7.

$$\text{Total life cycle GWP} = \sum_{i=1}^{n} \text{mass } GHG_i \times GWP_i - \sum_{j=1}^{m} \text{mass } GHG_j \times GWP_j$$

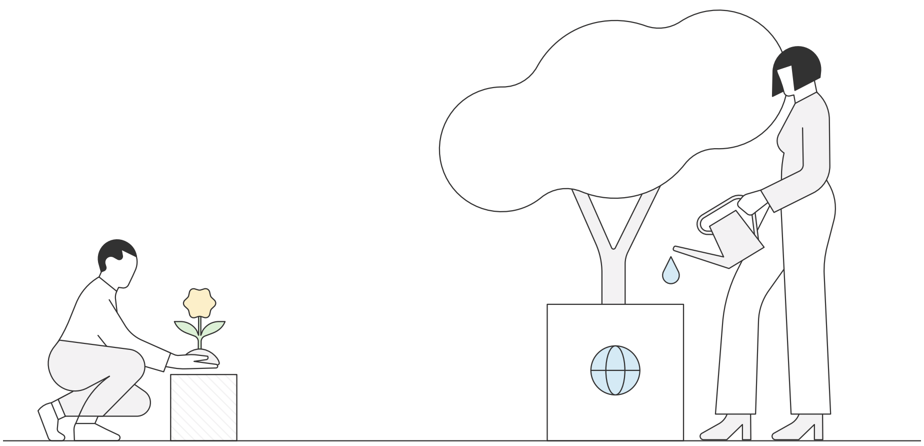
Where:

mass GHG_i	The total mass quantity of greenhouse gases emitted during the life cycle of the fuel
GWP_i	The global warming potential of GHG_i, as defined in Table 2
mass GHG_j	The total mass quantity of greenhouse gases emissions credit during the life cycle of the fuel
GWP_j	The global warming potential of GHG_j, as defined in Table 2

The GWP impact is expressed as grams CO_2eq per functional unit: GWP_{fuel}=gCO_2eq/MJ fuel LHV.

Table 2. GWP conversion factors for 100-year and 20-year time horizons.[24]

Greenhouse gas	GWP100 (gCO_2eq/gGHG)	GWP20 (gCO_2eq/gGHG)
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



7. Interpretation of results

The MMMCZCS LCA methodology aims to help LCA practitioners identify optimized fuel pathways for climate warming reduction by determining the most significant GHG emitters across the five life cycle stages. To meet that aim, the following elements must be completed and recorded during the life cycle interpretation phase:

- Quantification of the fuel WTW GWP impact and the relative distribution of emissions across the fuel life cycle stages.

- Identification of "hotspots" that are significant GHG emitter sources and issues.

- Limitations of the methodology concerning the fuel production system and the implications for the results.

- Data quality (as per the requirements set out in Section 4.8), e.g., reliance on secondary data.

- Data completeness: While the cut-off criteria are set to 1%, due to the novelty of many alternative fuel pathways, a lack of data may be a limiting factor for quantifying impact. If this is the case, these limitations must be clearly documented.

- Where relevant, comparisons between fuel pathways may also be made.

8. Technical guidance for fuel pathways (GHG emissions)

8.1 General guidance

This section provides general guidance applicable across all fuel pathways. Fuel-specific guidance is provided in more detail in Sections 8 and 9, followed by specific guidance on TTW emissions in Section 10.

8.1.1 Processing material inputs and outputs

Processing materials inputs and outputs are the emissions from material and energy flows entering or exiting the system boundaries at every stage defined in Section 4.4, including direct and indirect GHG emissions. Some material and energy flows may also be generated and consumed or treated within the system, e.g., excess heat or process residues fed back to the system as process inputs.

The GHG emissions associated with each material input and output should be calculated by multiplying the amount (mass/volume/energy) of material flow by its corresponding emissions factors, using Equation 8.

Equation 8.

$$E_i = C_i \times EF_i$$

Where:

E_i	GHG emissions of material input or output *i*, calculated in gCO_2eq/MJ fuel
C_i	Unit of material *i* flow, which may be on a mass or energy basis, e.g., t/MJ final fuel or kWh/MJ final fuel
EF_i	Emissions factor of material input or output *i*, expressed in gCO_2eq/unit of material flow

In some cases, C_i and EF_i may be split into the constituent GWPs for CO_2, CH_4, and N_2O. In such cases, the individual contributions must be summed.

GHG emissions from intermediary steps may not be expressed in gCO_2eq/MJ of fuel but as a unit of time (e.g., hours, year) or on another basis, e.g., per t dry feedstock. LCA practitioners aggregating GHG emissions from intermediary steps into WTT or WTW emissions must use the reference flow to convert life cycle emissions into terms of MJ fuel.

8.1.2 Direct GHG emissions

In line with the IPCC's sixth assessment report,[24] both biogenic and fossil GHG emissions must be included in WTW emissions calculations with their GWP impact as defined in Table 2.

The user must calculate direct CH_4, N_2O, and CO_2 emissions from operations (e.g., fuel combustion or intentional venting or flaring) based on plant operational data or, when plant data has not been fully quantified, using stoichiometric principles based on energy supply.

Note: For fuel use in transportation, emissions factors may be provided on a tonne-kilometer (t.km) basis, whereby emissions associated with fuel combustion are already accounted for, from raw material extraction to fuel utilization in transportation. If only the fuel supply is reported, the WTT impact of the considered fuel as well as direct CO_2eq emissions from fuel utilization must be captured separately.

8.1.3 Material and consumable inputs

Only imported materials (i.e., that cross the system boundaries) can contribute to the WTW GHG emissions related in Equation 1. Imported materials must enter the system boundaries with a GHG burden corresponding to their production, transport, and storage. Material inputs generated within the system (e.g., processing residues used for heat production) do not carry any GHG burden.

Note: Using processing residues or excess heat or electricity within the system boundaries reduces the need for imported materials or energy, thus reducing embedded emissions from imported materials or energy.

The GHG burden of material inputs must be represented by an emissions factor (EF_i) per unit of imported material. Material suppliers must provide emissions factors when possible. Where this is not possible, emissions factors must be sought from external sources, following the data hierarchy described in Section 5.1.3.

Negative GHG burdens for material inputs (e.g., if carbon capture and storage (CCS) is used in biogenic material production) are not allowed under this methodology due to the risk of double counting GHG abatement benefits (by both the producer and the user of material inputs). In such cases, the GHG emissions factor must be considered zero.

8.1.4 Electricity supply

The impact associated with electricity supply to any life cycle step must include impacts arising from the production and distribution of the electricity used in operations, including electricity imported from the grid, external facilities, or produced within the system boundaries.

GHG emissions from electricity supply are calculated as shown in Equation 8: by multiplying the amount of electricity consumed (expressed in MJ or kWh) per functional unit and an emissions factor describing GHG emissions per unit of electricity consumed (expressed in CO_2eq/MJ or CO_2eq/kWh).

Table 3 provides guidance on determining which emissions factor to consider when assessing the impact of electricity supply. If using grid electricity with or without renewable power purchase agreements, **consider the residual electricity mix** (share of renewables and fossil sources), which will influence the grid emissions factor.[25] If directly connected to a renewable electricity production plant, considering the capacity and availability of renewable energy in the local region can help assess the environmental benefits and potential emissions reductions.

Table 3. Characteristics of electricity emissions factors.

Source of electricity	Emissions factor characteristics and sources
Grid-imported electricity	Includes production, transmission, and distribution losses. Reflects geographic and temporal characteristics of residual electricity mix: recent local or regional emission factors are preferred over national or continental-level emission factors.
Imported renewable electricity (direct connection, power purchase agreements, Renewable Energy Certificates (RECs), etc.)	Imported renewable electricity (direct connection, power purchase agreements, RECs, etc.)
On-site electricity generation (renewable or non-renewable)	On-site electricity generation (renewable or non-renewable)

8.1.5 Steam and heat supply

Emissions factors for imported steam and heat must be based on supplier data or estimated based on the sources listed in Section 5.1. The emissions factor for imported steam and heat from neighboring industries must be based on an energy allocation, assigning a share of the GHG emissions from the process generating steam or heat.

Emissions factors for steam and heat generated within the system boundaries for operational purposes must be calculated or estimated based on the external sources listed in Section 5.1.2.

Excess steam and heat generated within the system boundaries and fed back to other processes within the system boundaries do not carry any GHG burden.

8.1.6 Fuel supply

Any fuel entering the system must carry a GHG burden corresponding to its production, transport, and storage (the fuel WTT emissions factor). This includes any fuels used in the processing stage, including (but not limited to) natural gas, diesel, bio-methane, and biomass. For fuel use in transportation, emissions factors may be provided on a t.km basis, where emissions associated with fuel combustion are already accounted for.

In addition, GHG emissions from the combustion of these fuels on site must be counted under direct emissions (see Section 8.1.2).

8.1.7 Waste streams

Following the cut-off approach, impacts associated with waste treatment and/or disposal must be captured, regardless of whether treatment occurs within or outside system boundaries. For example, if wastewater is sent to an off-site wastewater facility, the emissions factor associated with the wastewater should encompass the off-site treatment. Emissions from waste or wastewater treatments may be calculated based on operational data from treatment operators or estimated using external sources, as listed in Section 5.1.3.

8.2 Stage-specific guidance

This section provides additional guidance for specific life cycle stages and GHG emissions covered in this methodology, including transport, distribution, and storage; bunkering; fugitive emissions; emissions credits from co-products; emissions credits from conditioning, transport, and permanent storage of CO_2; and credits for biogenic CO_2 emissions.

8.2.1.Transport, distribution, and storage

Emissions from transporting, distributing, and storing feedstocks, intermediates, and final fuels are included in Stage 1 (see Equation 2) and Stage 3 (see Equation 4).

Transport can include various modes, including but not limited to pipeline, truck, rail, and ship, or a combination of different modes of transportation. GHG emissions from transport ($e_{i,t}$) must be calculated by multiplying the distance traveled (round trip) for each transport mode (e.g., 50 km local truck transport, followed by 3,000 km overseas shipping, followed by 25 km local truck transport, etc.) by the emissions factor corresponding to each transport mode. The emissions associated with distribution must also be incorporated into the term ($e_{i,t}$).

GHG emissions from fuel storage in Stage 3 ($e_{3,p}$) must be calculated by multiplying the amount of electricity, heat, and/or steam required per functional unit by the corresponding emissions factors.

Fugitive emissions occurring during transport, distribution, and storage are further explained in Section 8.2.3.

Emissions from bunkering should not be included under transport, distribution, and storage.

8.2.2. Bunkering

Key GHG emissions from bunkering ($e_{4,p}$) must be calculated by multiplying the amount of electricity, heat, and/or steam required per functional unit by the corresponding emissions factor, which must be obtained from bunkering operators or external sources listed in Section 5.1.3.

8.2.3 Guidance on handling fugitive emissions

Fugitive emissions $e_{i,fug}$ must be calculated by users through recorded or estimated leakage rates based on the best available mass balance data or changes in stock levels of the relevant substances as measured throughout the relevant consignment period.

Fugitive emissions must cover both CO_2 and non-CO_2 emissions, including CH_4 and N_2O. Below is a (non-exhaustive) list of possible sources of fugitive emissions that LCA practitioners must consider in this assessment:

- Unburnt fuels – fugitive CH_4 or N_2O emissions from incomplete combustion
- Seals – fugitive emissions permeated through seals, e.g., valves or flange gaskets
- Storage – cryogenic liquid fuel storage may result in fugitive emissions from liquid boil-off of compressed gas in cylinders susceptible to leaks
- Leaks (e.g., during transport)
- Accidental releases or spills (e.g., during bunkering)

Fugitive emissions should not include direct emissions from fuel combustion or intentional flaring or venting of gases.

8.3 Guidance on handling emissions and credits from co-products

As discussed in Section 4.4.7, the preferred approach for treating co-products within the system is through substitution or system expansion. However, in some circumstances, system expansion may not be suitable. In this case, allocation on an LHV energy basis should be used instead. Table 4 summarizes the intended approach for co-products, residues, and wastes.

Table 4. Definition of co-products, residues, and waste.

Type	Definition	Proposed treatment
Products or co-products	The primary product of a production process Significant economic value (relative to the whole revenue stream)	WTT GHG emissions are assigned following the ISO hierarchy (i.e., substitution or system expansion, then allocation).
Residues (byproducts)	Not the primary product of a process Limited economic value	WTT GHG emissions are assigned following the ISO hierarchy (i.e., substitution or system expansion, then allocation).
Waste	Would normally be discarded No economic value	No GHG emissions are assigned up to the first point of collection. GHG emissions are then assigned following the ISO hierarchy (i.e., substitution or system expansion, then allocation). Biogenic waste: Combustion emissions = 0 Non-biogenic waste: Combustion emissions = fossil C content

The following subsection provides more details about system expansion and allocation, including application for common co-products in alternative fuel pathways.

8.3.1 System expansion

System expansion can be a means of avoiding allocation. The process involves expanding the product system to include additional functions related to the co-products. In practice, the co-products are compared to other substitutable products, and the environmental burdens associated with the substituted product(s) are subtracted from the product system under study.

In system expansion, co-products generated in a process are assumed to displace existing product(s) within the market. The life cycle impacts corresponding to the displaced products are then subtracted from the total life cycle impact. In this regard, the boundaries of the product system are expanded such that it is credited for the avoided environmental impacts.

Equation 9 describes the calculation of $E_{i,co\text{-}products}$, representing the GHG emissions and credits (if any) from co-products via system expansion. It can be integrated under any of the Stage 1-5 equations.

Equation 9.

$$E_{i,co\text{-}products} = (e_{cpm} - e_{cpc})_i$$

Where:

e_{cpm}	Emissions associated with the processes involved in co-product conditioning and transport to market, conversion, and utilization when the co-product directly replaces an original synthetic product on the market
e_{cpc}	Emissions credit associated with using a reference synthetic product on the market when the co-product produced directly replaces the original synthetic product on the market

In this way, the user shall quantify emissions associated with the co-product downstream of where the co-product is produced to ensure that the functionality of the displaced product is equivalent.

Within system expansion, there are several considerations about the displaced product:

- **Market considerations:** These involve analyzing the dynamics of the market in which the product is being assessed, which can include understanding the supply and demand dynamics, market share of different products, and potential changes in consumer preference. By considering the market context, evaluating the impact of a product's introduction on the displacement of existing products or materials becomes possible.
- **Geographic considerations:** These take into account regional or country-specific variations in environmental impacts. This involves recognizing that different regions have varying energy mixes, resource availability, infrastructure, and regulatory frameworks. By considering these factors, the assessment can capture the specific environmental burdens associated with the displaced product in different geographic areas.
- **Temporal considerations:** These address changes in the market and technology landscape over time. In this way, the analysis recognizes that the environmental impacts associated with products can evolve as markets change, technology improves, and regulations are updated.

Table 5 provides a non-comprehensive list of practical examples for treating co-products and residues.

Table 5. Practical examples of co-product and residue treatment.

Co-product or residue	Application	Emissions credit
Digestate from anaerobic digestion	Application of digestate to land	Avoided emissions from substituted synthetic fertilizers (based on nitrogen content) applied to Stage 1 Note: Emissions credits from avoided CH_4 emissions due to improved manure management (bio-methane production via anaerobic digestion of manure and biogas upgrading) are already included in e_{sca} (See Section 9.1.5)
Excess electricity, heat, or steam	Provision of excess electricity to the grid or excess heat or steam to local residential heating or industries	Emissions credits applied to Stage 2 based on avoided power/heat/steam production and national or local (if available) electricity emissions factor or emissions factor for natural gas-based heat or steam

8.3.2 Impact allocation

System expansion and substitution is the preferred approach to be applied in the MMMCZCS LCA methodology. However, if at stage i, system expansion and substitution cannot be applied to the co-product(s) and where an allocation approach is adopted, the $E_{i,co\text{-}products}$ term in the overarching equations must be zero.

An allocation factor (AF) should then be calculated instead and applied to each term of the emission $E_{Stage\ i}$ within the equation, up to and including the point at which the co-product leaves the system.

Equation 10 should be modified and applied, depending on the type of allocation, to calculate the AF.

Equation 10.

$$AF_j = \frac{C_j \text{ in product } j}{C_{Total}}$$

Where:

C_j *in product j*	is the energy content within the product j (MJ, LHV basis)
C_{Total}	is the total energy content of all products generated in the stage considered

For non-energy products, a mass or an economic allocation may be used, where C_j is the dry mass (kg or t) and the economic value (USD/kg or USD/tonne) is based on actual selling prices or on geographically and temporally accurate official commodity prices.

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

CO_2 capture allows reduction of direct GHG emissions and may be implemented at various stages of the fuel life cycle. For example, CO_2 can be captured during the fuel production process (Stage 2), hydrogen production from steam methane reforming (SMR) for blue fuels (Stage 1), or on board the vessel consuming the fuel (Stage 5).

If the CO_2 that is captured at stage i is placed in permanent storage, the system can receive a credit, $e_{i,ccs}$. This credit is equivalent to the amount of CO_2 resulting from capture processes applied at the life cycle stage and permanently stored. All emissions e_{ccs} related to the compression, transport, injection, and storage of CO_2, as well as fugitive emissions sequestration, must also be considered (see Equation 11).

Equation 11.

$$(e_{ccsp} - e_{ccs})_i = (e_{i,ccsp} - e_{i,ccs})$$

Where:

$e_{i,ccsp}$	Emissions associated with conditioning (e.g., compression, liquefaction), temporary storage, transportation, and injection in permanent CO_2 storage sites of the CO_2 captured at stage i and not accounted for in $e_{i,p}$
$e_{i,ccs}$	Emissions credit associated with permanent storage of CO_2 captured at stage i that has not already been accounted for in e_{fecu} , $e_{i,p}$, or e_{fc}

Note: All emissions associated with the capture of CO_2 at stage i must be covered within $e_{i,p}$ (processing) terms.

8.4.1 Accounting of emissions associated with the management of captured CO_2

The emissions associated with CO_2 capture itself should be covered within $e_{i,p}$. Therefore, these emissions shall only be included in $e_{i,ccsp}$ if they have been omitted from the processing step.

Equation 12 shows the relevant terms for calculating $e_{i,ccsp}$.

Equation 12.

$$e_{i,ccsp} = (e_{i,ccs,cs} + e_{i,fug,ccs,cs}) + (e_{i,ccs,t} + e_{i,fug,ccs,t}) + (e_{i,ccs,inj} + e_{i,fug,ccs,inj}) + e_{i,fug,ccs,seq} - e_{i,ccs,c}$$

Where:

$e_{i,fug,ccs,cs}$	Fugitive CO_2 emissions occurring during conditioning (e.g., compression, liquefaction) and temporary storage of the CO_2 captured at stage i
$e_{i,ccs,cs}$	Emissions associated with conditioning and temporary storage of the CO_2 captured at stage i
$e_{i,fug,ccs,t}$	Fugitive CO_2 emissions occurring during the transport to permanent CO_2 storage site of the CO_2 captured at stage i
$e_{i,ccs,t}$	Emissions associated with the transport to permanent CO_2 storage site of the CO_2 captured at stage i
$e_{i,fug,ccs,inj}$	Fugitive CO_2 emissions occurring during the injection in permanent CO_2 storage site of the CO_2 captured at stage i
$e_{i,ccs,inj}$	Emissions associated with the injection in permanent CO_2 storage site of the CO_2 captured at stage i
$e_{i,fug,ccs,seq}$	Fugitive CO_2 emissions occurring during the permanent storage of the CO_2 captured at stage i
$e_{i,ccs,c}$	Emissions credits associated with carbon origin in CO_2 air emissions during the conditioning, transport, and storage of the captured CO_2, and with carbon origin in CO_2 permanently stored, at stage i , as described in Section 8.4.2.

This equation accounts for two categories of emissions within $e_{i,ccsp}$, as also illustrated in Figure 2:

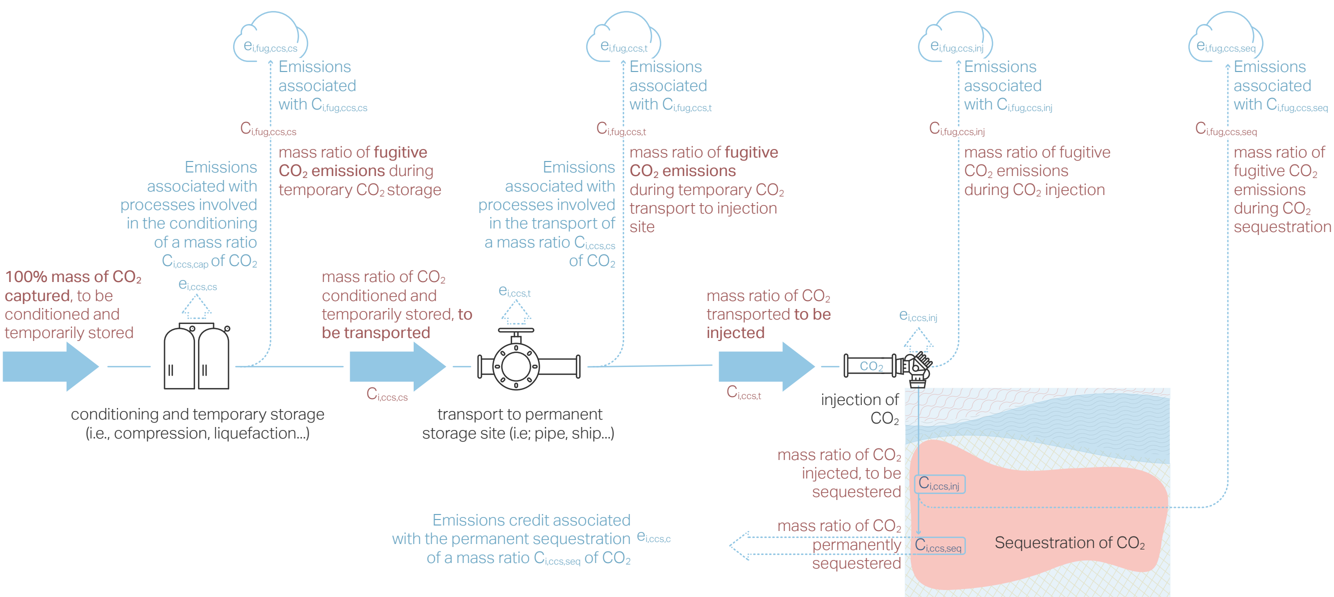
1) GHG emissions associated with conditioning, transport, storage, and injection of the captured CO_2. These emissions may arise from energy inputs, e.g., electricity for injection, diesel for transporting the CO_2 to the storage site, and any consumables that may be required. LCA practitioners should refer to the general guidance in Section 8.1.

2) Fugitive CO_2 emissions occurring during the conditioning, transport, storage, and sequestration of captured CO_2. Fugitive CO_2 emissions associated with conditioning, temporary storage, and transport depend on the physical state of the CO_2 (e.g., liquid, supercritical, compressed), the type of storage (e.g., cryogenic or gas canisters), and the type of transport (e.g., pipeline, trucks, ships). Fugitive emissions from injection and permanent storage can arise in two ways:

- Instantaneous CO_2 leakages: Events where large quantities of CO_2 escape suddenly from leakage pathways either during injection from inadequate injection conditions or due to poor storage management.

- Seepage of CO_2: The gradual migration of CO_2 into caprock or potentially adjacent reservoirs. This will depend on the geological formation. Therefore, data used must be specific to the CO_2 storage type.

Figure 2. Illustration of the mass balance distribution and related emissions associated with the carbon capture and storage (CCS) chain at a life cycle stage i frontier.



Emissions from instantaneous CO_2 leakages and seepage must be calculated through direct measurements or estimated using the best available data (see case studies in the appendices for concrete examples).

The sum of all fugitive emissions associated with the conditioning, transport, and injection of CO_2 and the total CO_2 sequestered should equal 100% of the CO_2 captured in the processing step, as described in Equation 13 (expressed as CO_2 mass balance ratio), where $C_{i,ccs,cap}$ accounts for 100% of the quantity of CO_2 captured at stage i.

Equation 13

$$C_{i,ccs,cap} = 100\% = C_{i,fug,ccs,cs} + C_{i,fug,ccs,t} + C_{i,fug,ccs,inj} + C_{i,fug,ccs,seq} + C_{i,ccs,seq}$$

Where:

$C_{i,ccs,cap}$	accounts for 100% of the quantity of CO_2 captured at stage i
$C_{i,fug,ccs,cs}$	accounts for fugitive emission losses of CO_2 captured at stage i, occurring during temporary storage of CO_2, expressed as a mass ratio (%) of the quantity of CO_2 captured at stage i, and source of GHG emission $e_{i,fug,ccs,cs}$
$C_{i,fug,ccs,t}$	accounts for fugitive emission losses of CO_2 captured at stage i, occurring during transport of CO_2 to the permanent storage site, expressed as a mass ratio (%) of the quantity of CO_2 captured at stage i and source of GHG emission $e_{i,fug,ccs,t}$
$C_{i,fug,ccs,inj}$	accounts for fugitive emission losses of CO_2 captured at stage i, occurring during CO_2 injection at the permanent storage site, expressed as a mass ratio (%) of the quantity of CO_2 captured at stage i, and source of GHG emission $e_{i,fug,ccs,inj}$
$C_{i,fug,ccs,seq}$	accounts for fugitive emission losses of CO_2 captured at stage i, occurring during the permanent sequestration of CO_2, expressed as a mass ratio (%) of the quantity of CO_2 captured at stage i, and source of GHG emission $e_{i,fug,ccs,seq}$
$C_{i,ccs,seq}$	accounts for the ratio of the CO_2 captured at stage i , that is permanently sequestered of CO_2, expressed as a mass ratio (%) of the quantity of CO_2 captured at stage i, and source of CO_2 emission credit $e_{i,ccs,c}$

Emissions associated with CCS should be based on actual data or best available mass balance estimates where necessary.

Note: Credits ($e_{i,ccs}$) applied must only represent CO_2 permanently (i.e., for 100 years or more) sequestered, ($e_{i,ccs,seq}$) and must not include any fugitive emissions, if they have not already been accounted for e_{fecu}, $e_{i,p}$ or $e_{f,c}$ to avoid double counting in the specific life cycle stage.

8.4.2 Accounting of credits from carbon origin in CO_2 emissions and CO_2 permanently stored in the CCS chain

When the biogenic origin of the CO_2 captured at stage i is proven, emissions credits $e_{i,ccs,c}$ associated with the fugitive CO_2 air emissions during the conditioning, transport, and storage of the captured CO_2, and with CO_2 permanently stored, must be accounted for. This emissions credit can be divided into two parts, as described in Equation 14.

Equation 14.

$$e_{i,ccs,c} = e_{i,ccs,ctis,c} + e_{i,ccs,seq,c}$$

Where:

$e_{i,ccs,ctis,c}$	Emissions credits associated with biogenic carbon origin in fugitive CO_2 air emissions during the conditioning, transport, injection, and storage of the CO_2 captured at stage i
$e_{i,ccs,seq,c}$	Emissions credits associated with biogenic carbon origin in CO_2 captured at stage i and permanently stored

Emissions credits $e_{i,ccs,ctis,c}$ must be calculated on the basis of guidance described in Section 8.5.

Emissions credits associated with biogenic carbon origin in CO_2 captured at stage i and permanently stored must be calculated as:

$$e_{i,ccs,seq,c} = 1 \text{ kg } CO_2eq / \text{kg } CO_2 \text{ from biogenic C origin permanently stored}$$

8.5 Guidance on handling credits for biogenic CO_2 emissions

No credits should be associated with atmospheric CO_2 storage in biomass during biomass growth of biological feedstocks in Stage 1. Any CO_2 emissions must be assigned an emissions burden of 1 gCO_2eq/gCO_2, irrespective of their biogenic or non-biogenic origin, as listed in Table 2.

When calculating all WTW emissions, an emissions credit ($e_{i,c}$) must be applied to account for the release of biogenic CO_2 at each life cycle stage (through fugitive or direct emissions), thus considering biogenic CO_2 emissions as net-zero over the whole life cycle. This applies to both biomass feedstocks for biofuels and biomass used within the process, e.g., bio-methane for heat.

LCA practitioners must apply accurate accounting and transparent traceability of biogenic carbon in fuels utilized and in the sources of CO_2 emissions.

An emissions credit $e_{i,c}$ must be applied when any CO_2 emission resulting from fugitive emissions or fuel combustion is 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 emission = 1 kg CO_2eq / kg CO_2 from biogenic C origin

This emissions credit must be included when the carbon in the CO_2 is proven to be of biogenic origin in all stages of the WTW cycle, including but not limited to:

- Fugitive emissions of CO_2
- Process CO_2 emissions, such as CO_2 venting resulting from upgrading biogas into bio-methane
- Emissions from using fuels of biogenic origin as energy sources for extraction, cultivation, conversion processes, transport, distribution, and storage

When biofuel is used as source of energy for processes involved in the life cycle stages, the emissions credit from CO_2 emissions resulting from the oxidation of biogenic carbon in fuel in the marine fuel converter can be calculated as:

Emissions credit from CO_2 air emission from biofuel combustion = 3.6641 kg CO_2eq / kg biogenic C in fuel

Pending further methodological refinement of the emissions credit, $e_{i,c}$ should be considered zero when the carbon in the fuel arises from a carbon capture and utilization pathway, i.e., for e-fuels.

This $e_{i,c}$ must be applied only at the stage where the CO_2 emissions from biogenic carbon origin appear.

9. Guidance for WTT fuel pathways

9.1 Guidance for biofuels: feedstock production or collection

GHG emissions from biofuels primarily depend on biomass feedstock production or collection. In the specific context of biomass production, emissions in Stage 1 must be calculated as described in Equation 1. In the case of biomass production, the emissions factor e_{fecu} must be calculated as described in Equation 15.

Equation 15.

$$e_{fecu} = e_{onsite\_fuel} + e_{field}$$

Where:

e_{onsite_fuel}	Emissions associated with the on-site use of energy (e.g., sowing, harvesting, baling, etc.)
e_{field}	Field emissions (N_2O and soil organic carbon)

9.1.1 Guidance on calculating LUC GHG emissions from carbon stock change caused by dLUC (e_l)

According to the GHG Protocol,[26] emissions e_l include:

1. Biogenic CO_2 emissions due to carbon stock decreases occurring as a result of land conversion within or between land-use categories

2. Biogenic and non-biogenic CO_2, N_2O, and CH_4 emissions resulting from the preparation of converted land, such as biomass burning or liming

Emissions from dLUC occurring 20 years before the operations being assessed should not be taken into account (i.e., $e_l = 0$). Changes in crop types or cropping patterns are not considered LUC.

9.1.2 Calculating direct LUC emissions

Calculation of dLUC emissions must be based on the stock-difference approach implemented in EU RED II, as shown in Equation 16. This methodology is based on the 2006 IPCC Guidelines for Tier 1 calculation of land carbon stocks.

Equation 16.

$$e_l = (CS_R - CS_A) \times 3.664 \times (1/n) \times (1/P) - e_B$$

Where:

e_l	Annualized GHG emissions from carbon stock change due to LUC, measured as mass (grams) of CO_2eq per unit of biofuel or bioliquid energy (MJ).
CS_R	The carbon stock per unit area associated with the reference land-use (measured as mass (t) of carbon per unit area, including soil and vegetation). The reference land-use must be 20 years before the raw material was obtained (emissions from land-use changes older than 20 years should be considered zero).
CS_A	The carbon stock per unit area associated with the actual land-use (measured as mass (t) of carbon per unit area, including soil and vegetation). In cases where the carbon stock accumulates over more than one year, the value attributed to CS_A should be the estimated stock per unit area after 20 years or when the crop reaches maturity, whichever is earlier.
3.664	Quotient obtained by dividing the molar weight of CO_2 (44.011g/mol) by the molar weight of carbon (12.011g/mol) in gCO_2eq/g carbon.
n	The period (in years) of the cultivation of the crop considered with average of 20 years recommended.
P	The productivity of the crop (measured as biofuel or bioliquid energy per unit area per year).
e_B	Bonus of 29 gCO_2eq/MJ biofuel or bioliquid if biomass is obtained from restored degraded land, if evidence is provided that the land: (a) was not in use for agriculture or any other activity at the beginning of biomass cultivation operations; and (b) is severely degraded land, including such land that was formerly in agricultural use. The bonus of 29 gCO_2eq/MJ shall apply for up to 20 years from the date of conversion of the land to agricultural use, provided that a steady increase in carbon stocks and a sizable reduction in erosion phenomena for land falling under (b) are ensured.

The above CS_R and CS_A parameters have to be determined by means of direct measurements of soil carbon stocks, or calculated, as described in Paragraph 3 of the Guidelines for the calculation of land carbon stocks[27] published by the European Commission and described in Appendix I.

9.1.3 iLUC considerations

iLUC emissions should not be included in the calculation of GHG emissions. However, high-iLUC-risk feedstocks should be avoided, unless low-risk feedstock cultivation practices are implemented.

High-iLUC-risk feedstocks are defined as feedstocks with a global LUC risk of 0.10 hectares (ha)/tonne or higher (see Table 13 in Appendix H).

Low-risk feedstock cultivation practices include:

- The production of additional biomass from existing agricultural land: for example, through rotations, cover crops, or other yield improvement measures
- Biomass production on unused, abandoned, or severely degraded land
- Smallholder production

Chapter V of the Commission Implementing Regulation (EU) on rules to verify sustainability and GHG emissions saving criteria and low-iLUC-risk criteria (European Commission, 2022) provides additional guidance and details regarding low-iLUC-risk practices.[18]

9.1.4 Guidance on calculating emissions associated with on-site energy use (e_{onsite_fuel})

Agricultural and forestry operations consume energy (primarily fuels and electricity) in vehicles and machines used in land preparation, sowing, maintenance operations, harvesting, and on-site pre-processing.

On-site electricity or fuel consumption (e.g., diesel) must be recorded on an annual or crop-cycle basis, per hectare (ha) basis, or per output (harvested material) basis. Whenever possible, total fuel and electricity consumption shall be converted on a 'per MJ of final fuel' basis.

Total fuel and electricity consumption must be combined with relevant emissions factors to calculate on-site energy use emissions. GHG emissions factors e_{onsite_fuel} may be calculated through direct measurements or by using data from approved sources (see Section 5.1.3).

9.1.5 Guidance on calculating emissions savings from soil carbon accumulation via improved agricultural management (e_{sca})

Calculation of emissions savings must be based on the soil carbon stock-difference approach generated by the improvement of agricultural practices. Improved agricultural management includes reducing tillage, improving crop rotation, and using cover crops, crop residue management, or organic soil improver (e.g., compost, manure digestate from anaerobic digestion). Based on guidance provided by the European Commission (2022), e_{sca} must be calculated according to Equation 17.

Equation 17.

$$e_{sca} = (CS_A - CS_R) \times 3.664 \times 10^6 \times (1/n) \times (1/P) - e_f$$

Where:

e_{sca}	Avoided emissions from soil carbon accumulation via improved agricultural management
CS_A	Mass of soil carbon stock per unit area associated with the reference crop management practice in megagrams (Mg) of carbon per ha
CS_R	Mass of soil estimated carbon stock per unit area associated with the actual crop management practices after at least ten years of application in Mg of carbon per ha
3.664	Quotient obtained by dividing the molar weight of CO_2 (44.011g/mol) by the molar weight of carbon (12.011g/molC) in gCO_2eq/gC
n	Period (in years) of the cultivation of the crop considered
P	Productivity of the crop (measured as biofuel or bioliquid energy per unit area per year)
e_f	Emissions from increased fertilizer or herbicide use

The above CS_R and CS_A parameters have to be determined by means of direct measurements of soil carbon stocks, or calculated, as described in Paragraph 3 of the Guidelines for the calculation of land carbon stocks[27] published by the European Commission and described in Appendix I.

Where manure is used as feedstock for bio-methane production (anaerobic digestion and biogas upgrading), the default value of e_{sca} shall be 45 gCO_2eq/MJ to account for improved agricultural management through the application of digestate and improved manure management (avoided CH_4 emissions).

9.2 Guidance for e-fuels: feedstock production or collection

For e-fuels, the emissions resulting from Stage 1 in Equation 2 can be simplified as shown in Equation 18.

Equation 18.

$$E_{stage\ 1} = e_{fecu} + e_{1,t} + e_{1,fug} - e_{1,c} + (e_{ccsp} - e_{ccs})_1 + (e_{cpm} - e_{cpc})_1$$

For e-fuels, e_{fecu} encompasses the emissions associated with the extraction and acquisition of feedstocks required to produce the e-fuel: for example, the nitrogen (e.g., capturing in an air separation unit) or CO_2 feedstock (e.g., capturing and transporting industrial CO_2) and the production of hydrogen via electrolysis (including energy, water purification, catalysts, etc.). Nitrogen input must be accounted for like any other material input, following the guidance described in Section 8.1.3.

9.2.1 Electricity

GHG emissions from electricity must be calculated using the guidance set out in Section 8.1.4.

9.2.2. CO_2 source as feedstock

Some e-fuels (e.g., e-methanol or e-methane) are produced by combining hydrogen with CO_2 from four CO_2 sources:

1. Atmospheric CO_2 obtained using direct air capture (DAC)

2. Collection of naturally-occurring geothermal CO_2

3. Capture of point-source fossil CO_2

4. Capture of point-source biogenic CO_2

For cases (1) and (2), CO_2 is considered to have zero life cycle GHG emissions up to the point of capture or collection.

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.

Intentionally produced CO_2 must be accounted for like any other material input, following the guidance described in Section 8.1.3.

If the producer of the CO_2 is claiming a reduction in their GHG emissions, these emissions must be assigned to the waste CO_2 used to produce the e-fuel and must, therefore, be captured under E_{stage1} within the term e_{fecu}.

Note: GHG emissions associated with material and energy inputs or outputs required to capture CO_2 must be included within E_{stage1}. For example, the electricity required to capture atmospheric CO_2 via DAC and the heat and amine solvent needed to capture CO_2 from an industrial flue gas stream must be included in E_{stage1}.

9.3 Guidance for blue fuels: feedstock production or collection

Blue fuels have two defining features: feedstocks of fossil origin (e.g., natural gas) and the use of CCS to decarbonize the conversion of these feedstocks to fuel. The application of CCS for blue fuels must follow the guidance specified in Section 8. The use of fossil feedstocks means that Equation 2 can be simplified as described in Equation 19.

Equation 19.

$$E_{stage\ 1} = e_{fecu} + e_{1,t} + e_{1,p} - e_{1,fug} + (e_{ccsp} - e_{ccs})_1 + (e_{cpm} - e_{cpc})_1$$

The key terms in E_{stage1} for blue fuels are e_{fecu} (fossil feedstock extraction or production), $e_{1,p}$ (transportation to a processing facility), and $e_{1,fug}$ (fugitive emissions).

The emissions intensity of extracting or producing fossil feedstocks varies depending on the nature and type of the fossil resource, location, extraction technologies, and practices (well type, flaring, etc.). Therefore, the user must endeavor to obtain data directly from the fossil feedstock supplier.

CH_4 fugitive emissions (leakages) can occur when extracting, producing, and transporting natural gas. The rate of leakage varies by location, technology, and practices. Where possible, data should be obtained from the supplier of natural gas. Otherwise, default fugitive emissions factors can be taken from literature sources, such as the following:

- IEA Greenhouse Gas R&D Programme, 'IEAGHG Low-Carbon Hydrogen from Natural Gas: Global Roadmap', August 2022[28]
- Sustainable Gas Institute and Imperial College, 'Methane and CO_2 emissions from the natural gas supply chain: an evidence assessment'[29]
- Oil and Gas Climate Initiative performance annual data reports[30]

When the methodology user cannot quantify feedstock emissions using actual data, the user must use proxy data that most closely represents the natural gas used in the process. For example, if conventional natural gas from the Middle East is used, the user should not report the emissions from unconventional natural gas (shale gas) in North America.

Note: It may not be possible to quantify each term within $E_{stage\ 1}$ individually, as some data sources may aggregate values. Example data sources include:

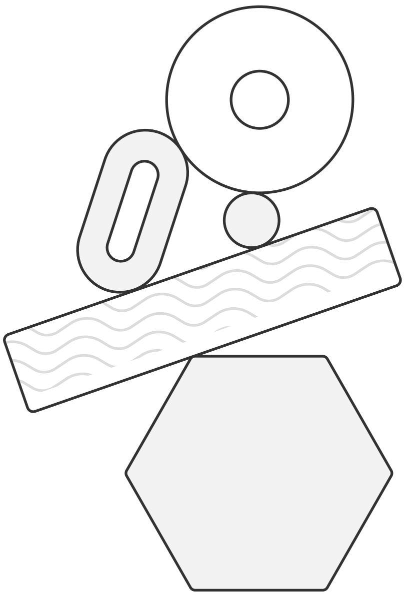
- JEC WTT v5 Study (2020): Appendix 1 provides life cycle inventory and aggregated emissions for a range of natural gas sources in the European context[21]
- GREET (2022): uses data from the US Environmental Protection Agency to model conventional and unconventional natural gas production in the US[31]

9.3.1 Electricity

GHG emissions from electricity must be calculated using the guidance set out in Section 8.1.4.

9.3.2. CO_2 capture processes

Emissions credits can be achieved through the permanent storage of CO_2 involved in blue-fuel production stages. To calculate emissions and emissions savings, the detailed approach described in Section 8.4 must be used.



10. Guidance on calculating TTW emissions (Stage 5)

Stage 5 covers the TTW emissions associated with maritime fuels. The equation describing the TTW emissions is introduced in Section 4.4.5 in Equation 6.

As fugitive emissions in the TTW stage can be low relative to a fuel's entire life-cycle impacts, it may be useful to keep the methodology's cut-off criteria (Section 4.5) in mind when analyzing this stage.

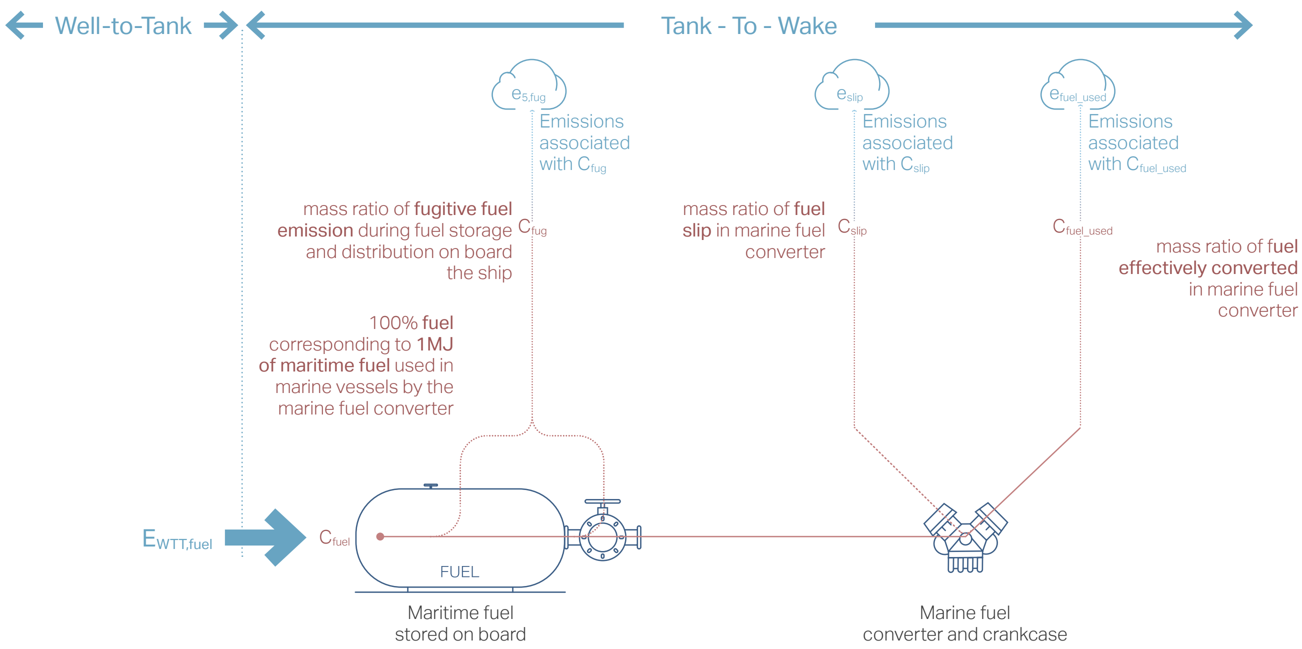
TTW GHG emissions must be split into:

a. emissions directly resulting from processes occurring on board the vessel ($e_{slip} + e_{fc} + e_{fu} + e_{5,fug}$), and

b. emissions not directly resulting from processes occurring on board the vessel, such as the emissions credit associated with carbon sources in the fuel [$e_{5,c} + (e_{ccsp} - e_{ccs})_5 + (e_{cpm} - e_{cpc})_5$].

For direct onboard emissions, tracing the fuel mass balance is important to ensure all emissions are accounted for. Figure 3 describes where maritime fuel losses might occur through the TTW stage. This mass ratio balance is equilibrated based on Equation 20.

Figure 3. Schematic of fuel mass balance and related emissions through the TTW stage.



Equation 20.

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

Where:

C_{fuel}	accounts for 100% of the 1MJ of maritime fuel used on board by the marine fuel converter
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 C_{fuel}, and source of GHG emission $e_{5,fug}$
C_{slip}	accounts for the slip emission of fuel in the energy converter and from crankcase, expressed as a mass ratio (%) of C_{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}

The following section provides guidance on calculating direct onboard emissions and emissions credits for biogenic CO_2. For $(e_{cpm}-e_{cpc})_5$ refer to Section 8.3 and for $(e_{ccsp}-e_{ccs})_5$ refer to Section 8.4.

10.1 Emissions from fuel utilization in the fuel converter (e_{fc})

Default GHG emissions factors per MJ of fuel combusted or oxidized – by fuel type – exist in the literature.[13,31] These emissions factors include combustion or oxidation of byproducts (e.g., trace amounts of CH_4 and N_2O from liquid fuel combustion) and incomplete combustion (e.g., release of CH_4 in the exhaust of an LNG-fueled vessel due to incomplete combustion). Emissions from incomplete fuel combustion should not include emissions from engine slip from other parts of the engine (e.g., from the crankcase), which are addressed in Section 10.1.

Whenever e_{fc} cannot be measured directly, it can be calculated using Equation 21.

Equation 21.

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

Where:

e_{fc}	emissions from maritime fuel utilization in the fuel converter on board the vessel, expressed as gCO_2eq/MJ_{fuel}
C_{fuel_used}	accounts for the mass ratio (%) of C_{fuel} effectively utilized and converted in the energy converter
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
LHV_{fuel}	is the LHV of the maritime fuel converted in the maritime fuel converter, expressed as MJ_{fuel}/g_{fuel}

The IPCC considers that all anthropogenic NOx emissions are potential sources of indirect N_2O emissions. We recommend performing a sensitivity assessment by applying indirect N_2O emission from NOx emission resulting from the maritime fuel utilization in the maritime fuel converter. For this sensitivity assessment, the methodology of the 2019 refinement of the IPCC Guidelines for National Greenhouse Gas Inventories Volume 1, Chapter 7, Section 7.3 must be applied to quantity indirect N_2O emission from NOx emission.[32] This indirect N_2O emission must be added to the C_{fc,N_2O} factor.

10.2 Emissions from fuel slip from the fuel converter (engine or fuel cell) (e_{slip})

Emissions from fuel slip occur when the maritime fuel leaks out of the marine fuel converter and crankcase before it is combusted or oxidized. They are characterized by the fugitive emission losses C_{slip} , as described in Equation 20, and generate an emissions term, e_{slip}, that is proportional to the GWP of this slipped fuel, GWP_{sf}. These emissions are therefore important when considering vessels using CH_4-based fuels, owing to the large GWP of CH_4.

Fuel slip GHG emissions from maritime fuel converters and crankcase must be included in the e_{slip} emissions factor in Equation 6. Fuel slips should be considered zero for fuels that are liquid at room temperature (bio-oils and methanol) and for fuels based on a mix of non-GHG components (i.e., for ammonia, since ammonia has a GWP of zero). Therefore, this subsection is mainly relevant to liquefied natural gas (LNG) and LBM, due to their CH_4-based composition. However, very similar approaches could be applied to other fuels in the future if the IPCC identifies their associated emissions as GHGs with scientifically proven GWP.

Onboard monitoring of the fuel entering the engine cannot distinguish between fuel that leaks and fuel that is combusted. Furthermore, leakage levels vary by engine type.

A weighted approach to assessing default slip emissions factors is preferred in the methodology. A slip emissions factor is specific to the maritime fuel converter and crankcase and the maritime fuel type. The assessment should be based on test cycles which capture characteristics of the engine design and associated operational patterns, engine speed, and engine load as used during the engine testbed certification.

Since these default emissions factors are expressed as gram of fuel leaked per kWh of mechanical energy supplied to the propellor, they enable a like-for-like comparison across powertrains and fuels. This result can be multiplied by the WTW GWP of the leaked fuel to obtain the CO_2eq emissions, as summarized in Equation 22.

Equation 22.

$$e_{slip} = \frac{C_{slip}}{100} \times \frac{GWP_{fuel}}{LHV_{fuel}}$$

Where:

e_{slip}	emissions from slips in the maritime fuel converter and from crankcase on board the vessel, expressed as gCO_2eq/MJ_{fuel}
C_{slip}	accounts for the slip emission of maritime fuel in the energy converter and from crankcase, expressed as a mass ratio (%) of C_{fuel}
GWP_{fuel}	is the GHG emission factor of the slipped maritime fuel and calculated as described in Equation 23, and expressed as gCO_2eq/g slipped fuel
LHV_{fuel}	is the LHV of the maritime fuel converted in the maritime fuel converter, expressed as MJ_{fuel}/g_{fuel}

Equation 23.

$$GWP_{fuel} = C_{f,CO_2} \times GWP_{CO_2} + C_{f,CH_4} \times GWP_{CH_4} + C_{f,N_2O} \times GWP_{N_2O}$$

Where:

C_{f,CO_2}	is the CO_2 emission factor of the slipped maritime fuel per mass unit of maritime fuel (gCO_2/g slipped fuel)
C_{f,CH_4}	is the CH_4 emission factor of the slipped maritime fuel per mass unit of maritime fuel (gCH_4/g slipped fuel)
C_{f,N_2O}	is the N_2O emission factor of the slipped maritime fuel per mass unit of maritime fuel (gN_2O/g slipped fuel)
GWP_{CO_2}	is the GWP of CO_2, as listed in Table 2
GWP_{CH_4}	is the GWP of CH_4, as listed in Table 2
GWP_{N_2O}	is the GWP of N_2O, as listed in Table 2

Note: C_{f,CO_2}, C_{f,CH_4} and C_{f,N_2O} can be determined on the basis of the slipped maritime fuels' respective CO_2, CH_4 and N_2O composition. For the majority of considered maritime fuels, C_{f,CO_2} and C_{f,N_2O} are zero, but this depends on the purity of the considered fuel.

Alternatively, LCA practitioners may calculate the absolute emissions from the amount of fuel delivered to the vessel (for example, from a bunker delivery note). The default emissions factor above can be expressed per gram of fuel using the vessel's specific fuel consumption. Default emissions factors may be found in the literature.[33–35]

10.3 Emissions from the use of consumables on board (e_{fu})

The emissions from consumables required for the utilization of the maritime fuel in the maritime fuel converter must be included in e_{fu} and should be calculated using Equation 24.

Equation 24.

$$e_{fu} = \sum_{k=1}^{n} C_{consumable,k} \times GWP_{consumable,k}$$

Where:

k	is the index corresponding to the consumable type utilized on board the ship for the use on 1MJ (LHV) maritime fuel on board the vessel in the maritime fuel converter
n	is the total number of consumables type utilized on board the ship for the use on 1MJ (LHV) maritime fuel on board the vessel in the maritime fuel converter
$C_{consumable,k}$	is the quantity of consumable k required for utilizing 1MJ LHV of maritime fuel in the maritime fuel converter (either using a default value or measured using flow meters)
$GWP_{consumable,k}$	is the WTW emissions factor of the consumable k , expressed as gCO_2eq per quantity unit of consumable k and calculated under the same methodology described in this document
LHV_{fuel}	is the LHV of the maritime fuel used in the maritime fuel converter

Pilot fuel is the most important consumable for using fuel in the maritime fuel converter on board. Pilot fuel is fuel used in small quantities to ignite the primary fuel. For example, heavy oil is used in compression ignition LNG engines since heavy oil and diesel ignite under compression, while LNG does not.

When the consumable k is a pilot fuel, LCA practitioners must apply the same methodology prescribed in this technical document to calculate the WTW emissions factor $GWP_{consumable,k} = GWP_{pilot\ fuel}$ of the pilot fuel as gCO_2eq/MJ LHV of pilot fuel and utilize $C_{consumable,k} = C_{pilot\ fuel}$ corresponding to the **energy fraction of pilot fuel required for the utilization of 1MJ** (LHV) of the considered maritime fuel in the maritime fuel converter.

10.4 Fugitive emissions from leakage of fuel from the vessel's fuel tank and distribution ($e_{5,fug}$)

Fugitive emissions of fuel occurring during fuel C_{fug} utilization on board the vessel must be included in the $e_{5,fug}$ emissions factor. This value should be calculated using recorded or estimated leakage rates based on the best available mass balance data, or based on changes in stock levels of the relevant substances as measured throughout the relevant consignment period. If meters on board the vessel measure both the flow to the engine and the amount of fuel on board the vessel (as is the case with LNG tankers), the amount of fuel leaked from the fuel tank, distribution pipes, and valves must be calculated using the difference between the flow to the engine and the amount of fuel on board.

GHG emissions $e_{5,fug}$, expressed as CO_2eq/MJ LHV of fuel used by the maritime fuel converter, can be calculated using Equation 25.

Equation 25.

$$e_{5,fug} = \frac{C_{fug}}{100} \times \frac{GWP_{fuel}}{LHV_{fuel}}$$

10.5 Emissions credit for biogenic CO_2 air emissions ($e_{5,c}$)

Where the fuel utilized in the maritime fuel converter has been derived from biogenic feedstocks, an emissions credit should be applied to the TTW term ($e_{5,c}$) to account for the biogenic nature of the carbon in the fuel, as described in Section 8.5. The emissions credit ($e_{5,c}$) is calculated using Equation 26.

Equation 26.

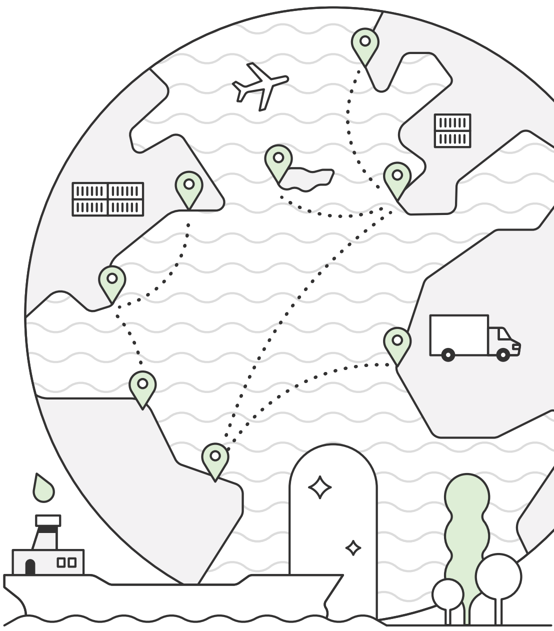
$$e_{5,c} = \frac{C_{fug\_used}}{100} \times \frac{(C_{fCO_2} + GWP_{CO_2})}{LHV_{fuel}}$$

10.6 Emissions and credit for onboard CO_2 capture (e_{ccsp} - e_{ccs})$_5$

When a vessel is equipped with onboard CO_2 capture capability, emissions and credits resulting from the capture, transport, and permanent sequestration of this CO_2 should be determined as described in Section 8.4.

10.7 Emissions and credit for co-products generated onboard (e_{cpm} - e_{cpc})$_5$

When a vessel is equipped with specific fuel or emissions management treatments that generate co-products that can substitute existing products within a market, emissions and credits associated with these co-products should be determined as described in Section 8.3.



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Abbreviations

Acronym	Definition
AD	Anaerobic digestion
AF	Allocation factor
AR	Assessment report
CCS	Carbon capture and storage
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
DAC	Direct air capture
dLUC	Direct land-use change
GABI	Ganzheitliche Bilanzierung (widely used LCA software tool developed by Sphera)
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global warming potential
ha	Hectare
HVO	Hydrotreated vegetable oil
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
ILCD	International Life Cycle Data
iLUC	Indirect land-use change
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization

Acronym	Definition
JEC	JRC-EUCAR-Concawe
JRC	EU Joint Research Centre
LBM	Liquefied bio-methane
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHV	Lower heating value
LNG	Liquefied natural gas
LUC	Land-use change
Mg	Megagram
MJ	Megajoule
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
Mt	Megatonne
N	Nitrogen
N_2O	Nitrous oxide
OGCI	Oil and Gas Climate Initiative
REC	Renewable energy certificates
RED	Renewable Energy Directive
SMR	Steam methane reforming
TTW	Tank-to-wake
WTT	Well-to-tank
WTW	Well-to-wake

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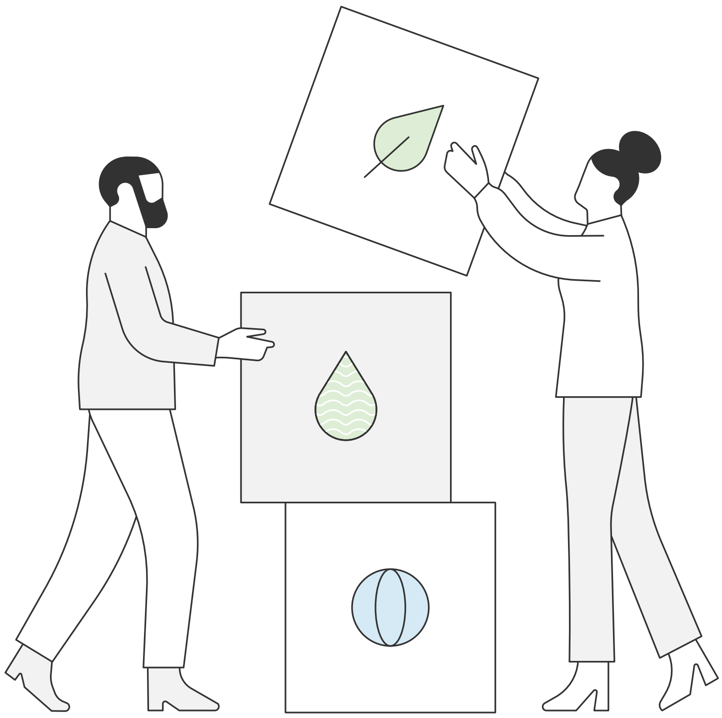
Appendices

The following case studies aim to provide additional guidance about existing fuel supplies to LCA practitioners implementing this methodology. Key guidance includes data sources, types of inputs and outputs in life cycle inventories, or multifunctionality. This guidance is not meant to be prescriptive; therefore, LCA practitioners may use alternative approaches if they align with the main body of this methodology.



Appendix A. Case study 1: Biofuel – soybean to HVO (hydrotreated vegetable oil)

Figure 4. Life cycle stages description of HVO biofuel pathway.

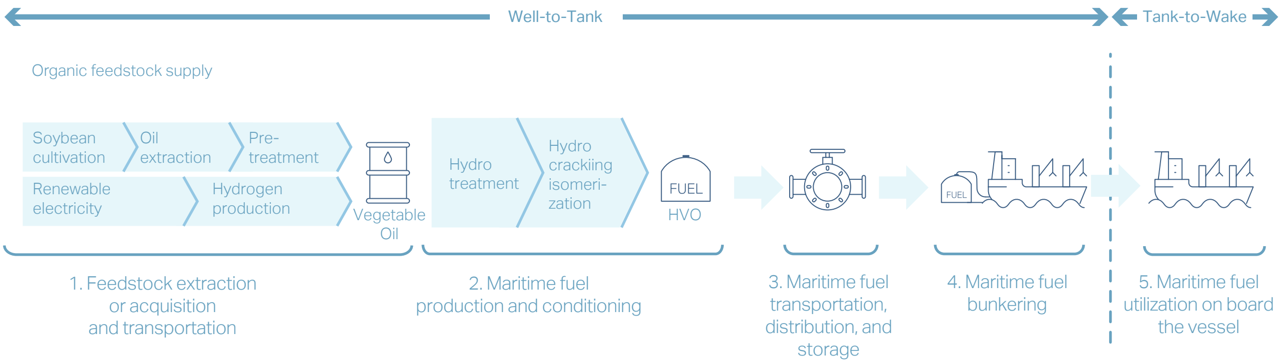


Table 6. Key data guidance for HVO biofuel.

<table>
<tr><th colspan="2">HVO maritime fuel life cycle stage and detail</th><th>GHG emission equation term</th><th>Key guidance</th></tr>
<tr><td rowspan="4">Stage 1</td><td rowspan="3">Soybean cultivation</td><td>e_{fecu}</td><td>• Data should be provided by soy oil supplier where possible.
• Secondary data sources include JRC default values (transport biofuels), IPCC, JEC-WTT, GREET, ecoinvent, etc.
• Geographical considerations, such as soil properties and climate conditions, can impact overall emissions in soybean cultivation for HVO production. Choosing cultivation areas with favorable soil conditions and suitable climates can optimize crop growth and reduce the need for excessive fertilizer and pesticide use, thereby minimizing associated emissions.
• Energy supply considerations: Fuel to power machinery for cultivation, harvesting, etc. This includes emissions from the combustion of the fuel used.
• Consumable and material considerations:
- Pesticides: Pesticide application for pest and weed control.
- Fertilizer: Application of fertilizers to enhance crop growth. This includes nutrient run-off and any subsequent contribution to water pollution and emissions.</td></tr>
<tr><td>e_{sca}</td><td>• If improved agricultural management has been evidenced, a credit could be applied.</td></tr>
<tr><td>e_l</td><td>• dLUC:
Emissions from dLUC from carbon stock changes occurring 20 years before the assessed operations should not be included (i.e., e_l = 0). Changes in crop types or cropping patterns are not considered as land-use changes.
Examples:
- Soybean production on land converted to agriculture in 1999 (i.e., 24 years before a GHG assessment in 2023) = No dLUC emissions.
- Soybean production on land used for corn production until 2020 (for a GHG assessment in 2023) = no dLUC emissions.
- Soybean production on land converted to agriculture in 2015 (for a GHG assessment in 2023) = dLUC emissions to be calculated over 12 years (between 2003 and 2015).
Calculating dLUC: Please see Section 9.1.2.
Estimating dLUC: Provide sources, e.g., IPCC, JEC-WTT, GREET, ecoinvent, etc.
• iLUC: emissions from iLUC should not be included in the GHG emission counting.</td></tr>
<tr><td>Hydrogen production, external supply</td><td>e_{fecu}</td><td>• Data should be provided by the hydrogen supplier where possible.
• Potential secondary data sources include EU Joint Research Centre (JRC) default values (biofuels used in transportation), IPCC, JEC-WTT, GREET, ecoinvent, etc.
• Energy supply considerations: The energy supply will vary depending on the hydrogen production pathway. Hydrogen can typically be produced from a range of sources, including fossil sources, e.g., natural gas, or renewable sources, e.g., renewable electricity. The source of energy used to produce hydrogen will have a direct impact on emissions.
• Consumable and material considerations: The type and quantity of consumables and materials used can affect total emissions. For example, the primary consumable in SMR with CCS (blue hydrogen) is the natural gas feedstock, whereas the primary consumable in electrolytic hydrogen is water, which undergoes desalination.</td></tr>
</table>

HVO maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 1	Vegetable oil extraction	$e_{1,p}$	• Energy supply: Energy sources used for pre-treatment can impact total emissions. For example, energy is required for heating and maintaining the temperature during pre-treatment. The type of energy source used, (e.g., natural gas or electricity) and its efficiency can influence the overall energy consumption and associated emissions. • Consumables and material use: The type and quantity of consumables and materials used in pre-treatment can affect total emissions. For example, chemicals and water used to remove impurities from soybean oil contribute to the total emissions of the process.
		$(e_{cpm} - e_{cpc})_1$	• Co-products: In soybean to HVO, system expansion may be applied as the co-product oil cake can displace other products on the market, such as animal feed or protein meal. For example, if the oil cake is used as animal feed, it can replace other products on the market, such as soybean meal. By displacing these alternative products, the environmental burdens associated with their production and use can be subtracted from the total emissions associated with the HVO production. • If system expansion cannot be applied due to uncertainties regarding the end market for the co-products, energy allocation may be more appropriate. This approach uses the lower heating value of the main product (HVO) and co-product (oil cake) to allocate the environmental burdens of the production process. This method can be implemented when comprehensive market data or suitable substitutes for system expansion are not readily available.
	Fugitive emissions	$e_{1,fug}$	• Fugitive losses during all feedstock stages are expected to be minimal.
	Vegetable oil and hydrogen transport	$e_{1,t}$	• Emissions associated with feedstock transportation to the HVO fuel processing facility should be considered
	Emission credits	$e_{1,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon arising during feedstock extraction, acquisition, and transport applies. It can be the case when bio-diesels are used to transport the feedstock, for example.
	MAIN STAGE OUTPUT		REFINED SOY OIL
Stage 2	Hydro-treatment and hydro-cracking	$e_{2,p}$	• Energy supply considerations: The hydrotreatment and hydrocracking isomerization processes require energy inputs for heating, pressurization, and other operations. The energy source (e.g., natural gas, electricity, or renewable energy) can impact the overall emissions and sustainability of the process. • Consumable and material considerations: The type and quantity of consumables and materials (e.g., catalysts, chemicals, and additives) used in fuel production and conditioning can affect total emissions. For example, using catalysts with higher activity and selectivity can increase process efficiency and reduce emissions. • Hydrogen supply: These processes require a source of hydrogen gas. The production or sourcing of hydrogen can affect emissions and energy consumption. This is accounted for in e_{fecu} in Stage 1 in this case study since the considered hydrogen supply is from an external source.
	Fugitive emissions	$e_{2,fug}$	• Fugitive losses are expected to be low as these processes are typically conducted in closed systems, reducing potential losses and production of a liquid fuel.
	Co-products	$(e_{cpm} - e_{cpc})_2$	• Co-products: Naphtha can be produced as a co-product in addition to HVO. System expansion is only suitable if the specific end use of naphtha is known and evidenced. If this is not possible, energy allocation (using LHV values) would be more appropriate.
	Emission credits	$e_{2,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon applies.
	MAIN STAGE OUTPUT		HVO MARITIME FUEL

HVO maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 3	Fuel transport and distribution	$e_{3,t}$	• Location: The emissions from this life cycle stage depend on the distance between the location of the fuel production plant and the bunkering site. If the plant is near the bunkering site, it can reduce the transportation distance and associated emissions. • Transportation modes: The choice of transport mode can have a significant impact on emissions. Different modes (e.g., road, rail, pipeline, or maritime shipping) have varying levels of fuel efficiency and associated GHG emissions. Often, a combination of transport modes may be employed to ensure efficient and reliable distribution of HVO fuel to end users. There may be intermediate storage before bunkering, such as storage at distribution terminals.[36] • Data sources for the transportation of HVO include Biograce[37] and JRC (2017).
	Fuel storage	$e_{3,p}$	• The energy supply required for HVO marine fuel storage will vary depending on the fuel storage location and must be considered in Stage 3 GHG emissions.
	Fugitive emissions	$e_{3,fug}$	• Fugitive losses during Stage 3 of HVO's life cycle are expected to be low. HVO is a stable and non-volatile liquid fuel with a low vapor pressure, so it does not escape during handling and transportation.
	Emission credits	$e_{3,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon applies. This can be the case when biofuels are used to transport the maritime HVO.
Stage 4	Bunkering operations	$e_{4,p}$	• Emissions associated with the supply and utilization of fuel and power sources required for HVO maritime fuel bunkering operation must be included.
	Fugitive emissions	$e_{4,fug}$	• To ensure greater accuracy, measurements of fuel bunkered should be used to establish the initial fuel quantity supplied to the vessel and any subsequent losses during HVO maritime fuel bunkering.
	Emission credits	$e_{4,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon could apply. This can be the case when bio-sourced fuels are used to generate the electricity which is used during HVO bunkering operations.
Stage 5	Fugitive emissions	$e_{5,fug}$	• Fugitive emissions from fuel tank boil-off are not relevant, as the fuel is a liquid at room temperature and pressure.
	Slips	e_{slip}	• Fuel slip in maritime fuel converter shall be considered in the e_{slip} emissions factor. This emissions factor is considered zero for HVO (including if it results from incomplete combustion), as it is a liquid at room temperature and pressure.
	Combustion emissions	e_{fc}	• Inconsequential trace amounts of N_2O and CH_4 are emitted during combustion, which can be estimated using conventional maritime oils as a proxy.[38]
	Consum-ables	e_{fu}	• Pilot fuel is not required for the utilization of HVO maritime fuel, so no emissions should be assigned to pilot fuel. But emissions from lubricity additives required for the utilization of HVO as maritime fuel must be considered in e_{fu}.
	Emission credits	e_{5c}	• Combustion emissions from fuel use in the engine are included in e_{fc}. However, as the carbon in HVO is of biogenic origin, a credit is applied equivalent to the fuel's biogenic carbon content, as defined in Section 8.5.

Appendix B. Case study 2: Biofuel – liquefied bio-methane (LBM) from anaerobic digestion and bio-methane liquefaction

Figure 5. Life cycle stages description of liquefied bio-methane (LBM) pathway from anaerobic digestion (AD) and bio-methane liquefaction.

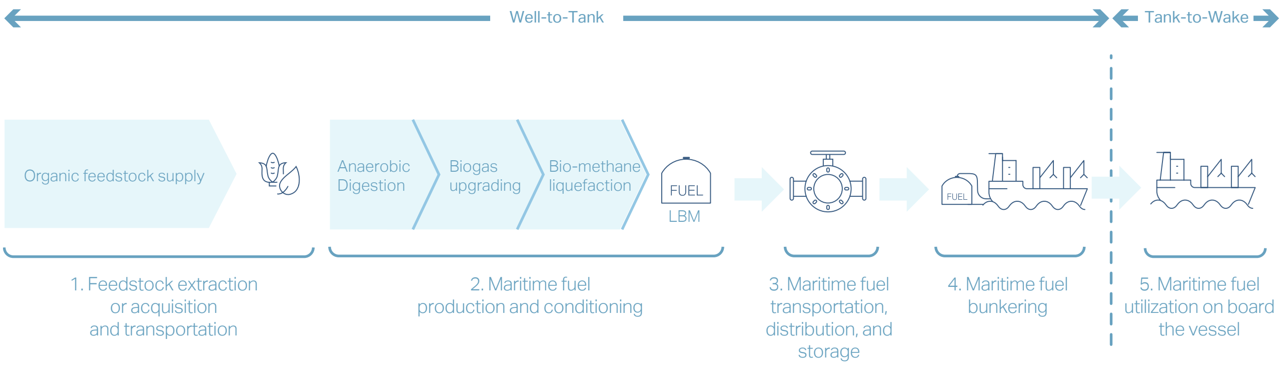
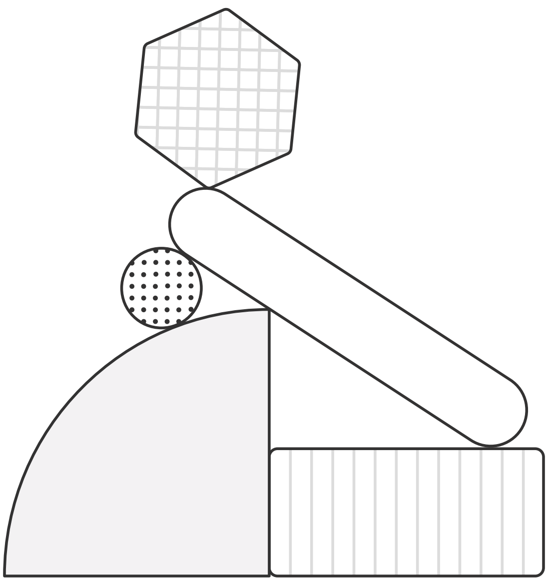


Table 7. Key data guidance for liquefied bio-methane from anaerobic digestion (AD) and bio-methane liquefaction.

LBM maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 1	Feedstock collection and transportation	e_{fecu}	• Feedstocks are typically wet biomass, such as manure and other organic matter, e.g., sewage sludge. Dry feedstocks can also be used, including food crops, feed crops, or lignocellulosic materials such as straw, wood, and energy crops. However, these typically require pre-treatment to improve the lignin, cellulose, and hemicellulose availability to the enzymes. • Data shall be provided by the feedstock supplier where possible. • Secondary data sources include JRC default values (biofuels used in transportation), IPCC, JEC-WTT, GREET, ecoinvent, etc. • Geographical considerations include local feedstock availability (limited resources of wet feedstocks suitable for anaerobic digestion in sufficient quantities in the same location) and proximity to feedstock sources.[36] These factors can contribute to a more efficient and environmentally sustainable feedstock preparation stage by reducing transportation-related emissions, improving feedstock availability, and enhancing the overall sustainability of the process. • Diesel use: Transporting feedstock to the digestion facility, e.g., via 40-t truck. This includes emissions from the combustion of the fuel.
		e_l	• dLUC: No direct LUC emissions should be included for waste feedstock.
		e_{sca}	• Avoided CH_4 emissions from manure feedstock qualify for a 45gCO_2eq/MJ credit.
	Feedstock pre-treatment	$e_{1,p}$	• Energy supply considerations: The energy source used for pre-treatment processes can impact total emissions. Energy is required for various pre-treatment processes such as thermal pre-treatment (sewage sludge), saponification (fatty residues), or delignification (lignocellulosic biomass).[36] The type of energy source used (e.g., natural gas or electricity) and its efficiency can influence the overall energy consumption and associated emissions. • Consumable and material considerations: The type and quantity of consumables and materials used in pre-treatment can affect total emissions. For example, chemicals and additives may aid the breakdown, separation, or conditioning of the feedstock.
	Fugitive emissions	$e_{1,fug}$	• Due to the nature of feedstock, fugitive losses are expected to be low during all feedstock stages.
	Feedstock transport	$e_{1,t}$	• Emissions associated with transporting feedstock to the fuel processing facility should be considered.
	Avoided emissions	$e_{1,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon arising during feedstock extraction, acquisition, or transport applies.
	MAIN STAGE OUTPUT		TRANSPORTED FEEDSTOCK (e.g., manure, pre-treated sludge)

LBM maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 2	Anaerobic digestion (AD)	$e_{2,p}$	• Energy supply considerations: The AD process requires energy inputs for maintaining optimal temperature, mixing tanks, biogas upgrading, and bio-methane compression. The energy source can impact the overall emissions and sustainability of the process. • Consumable and material considerations: The type and quantity of consumables/ materials used in the AD process, including chemicals such as ferric chloride and oxygen for desulfurization, can affect the total emissions.[39]
	Co-products	$(e_{cpm} - e_{cpc})_2$	• Co-products: The digestate remaining after the AD process can be considered a co-product when it is utilized as fertilizer. System expansion involves the co-product digestate displacing other products on the market, such as synthetic fertilizers or soil amendments. By displacing these alternative products, the environmental burdens associated with their production and use can be subtracted from the total emissions associated with the bio-methane production attributed to the digestate.
	Fugitive emissions	$e_{2,fug}$	• Fugitive CH_4 and CO_2 losses must be included and will vary between plants.[40] • Fugitive CH_4 emissions are estimated to be 1-3% of total produced CH_4 per biogas production plant.[41]
	Emission credits	$e_{2,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon applies.
	MAIN STAGE OUTPUT		BIOGAS
	Biogas upgrading and biomethane liquefaction	$e_{2,p}$	• Energy supply considerations: - Electricity is typically required to power equipment used to remove impurities in biogas and upgrade it. Using renewable electricity instead of fossil-fuel-based electricity can significantly reduce emissions. - Liquefaction also uses electricity to power compressors, coolers, and other equipment. • Consumables and material considerations: The type and quantity of consumables and materials used in biogas upgrading and bio-methane liquefaction can affect total emissions. Examples include amines, lubricants, and coolants (liquefaction).
	CO_2 capture	$(e_{ccsp} - e_{ccs})_2$	• Biogas upgrading is necessary to remove CO_2 and other unwanted components. This process presents an opportunity for negative CO_2 emissions. When biogas upgrading is combined with capturing and storing CO_2 separated during upgrading, the overall emissions can be reduced effectively, which can be reflected in the calculation.[42]
	Fugitive emissions	$e_{2,fug}$	• Fugitive losses of CH_4 can vary by facility. Facilities with adequate sealing and system maintenance can expect low fugitive losses.[41]
	Emission credits	$e_{2,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon applies.
	MAIN STAGE OUTPUT		LBM MARITIME FUEL
Stage 3	LBM fuel transport and distribution	$e_{3,t}$	• Location: The emissions from this life cycle stage depend on the distance between the location of the fuel production plant and the bunkering site. If the plant is near the bunkering site, it can reduce the transportation distance and associated emissions. • Transportation modes: The choice of transport mode can have a significant impact on emissions. Different modes (e.g., road, rail, pipeline, or maritime shipping) have varying levels of fuel efficiency and associated GHG emissions. Often, a combination of transport modes may be employed to ensure liquefied bio-methane fuel is distributed to end users in an efficient and reliable manner.
	LBM fuel storage	$e_{3,p}$	• The energy supply required for LBM marine fuel storage and boil-off gas management will vary depending on fuel storage location and must be considered in Stage 3 GHG emissions.
	Fugitive emissions	$e_{3,fug}$	• Fugitive losses of LBM are expected to be low because boil-off gas is managed to prevent methane leakage. LBM, like conventional LNG, is a liquefied gas and is typically transported and stored under controlled conditions to minimize any potential fugitive emissions leaks. The potential for fugitive emissions depends on various factors, including the quality of equipment, maintenance practices, operating procedures, etc.[36]
	Emission credits	$e_{3,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon applies. This can be the case when biofuels are used to transport the LBM maritime fuel.

LBM maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 4	Bunkering operations	$e_{4,p}$	• Emissions associated with the supply and utilization of fuel and power sources required for LBM maritime fuel bunkering operation must be included.
	Fugitive emissions	$e_{4,fug}$	• To ensure greater accuracy, measurements of LBM fuel bunkered should be used to establish the initial fuel quantity supplied to the vessel and any subsequent losses during LBM maritime fuel bunkering.
	Emission credits	$e_{4,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon could apply. This can be the case when bio-sourced fuels are used to generate electricity used during LBM bunkering operations.
Stage 5	Fugitive emissions	$e_{5,fug}$	• Fugitive emissions should be included. These can include small amounts of non-controlled methane boil-off.
	Slips	e_{slip}	• Fuel slip in maritime fuel converters must be considered in the e_{slip} emission factor. This is important to include, as LBM-fueled ships can have considerable CH_4 emissions.[43] Methane slip must be accounted as defined in Section 10.1.
	Combus-tion emissions	e_{fc}	• Combustion emissions from fuel use in the fuel converter are included.
	Consum-ables	e_{fu}	• Emissions from consumable use on board the vessel include emissions from pilot fuel required for the utilization of LBM maritime fuel, such as heavy fuel oil or marine diesel (bio-oil).
	Emission credits	$e_{5,c}$	• Combustion emissions from fuel use in the engine are included in e_{fc}. However, as the carbon in LBM is of biogenic origin, a credit is applied equivalent to the fuel's biogenic carbon content, as defined in Section 8.5. • Emission credits can be applied equivalent to the pilot fuel's biogenic carbon content, as defined in Section 8.5.



Appendix C. Case study 3: e-fuel – e-ammonia

Figure 6. Life cycle stages description of e-ammonia pathway.

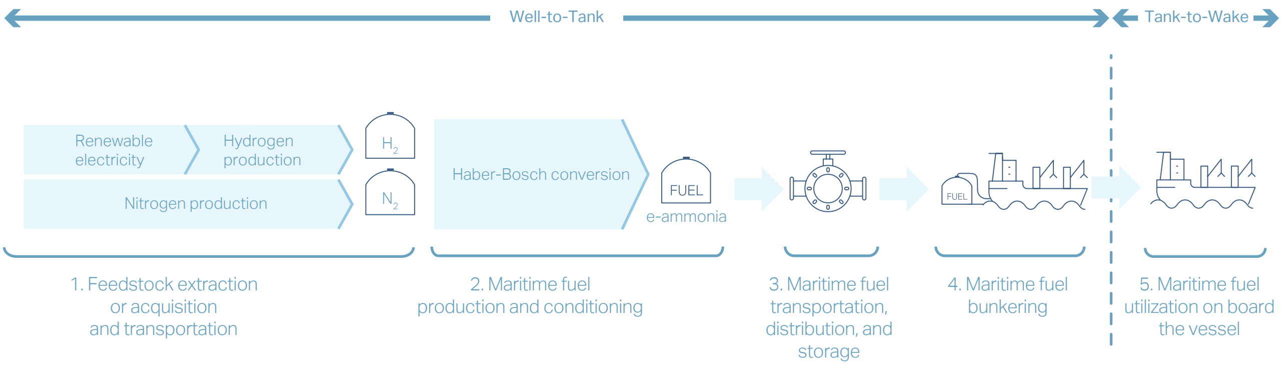
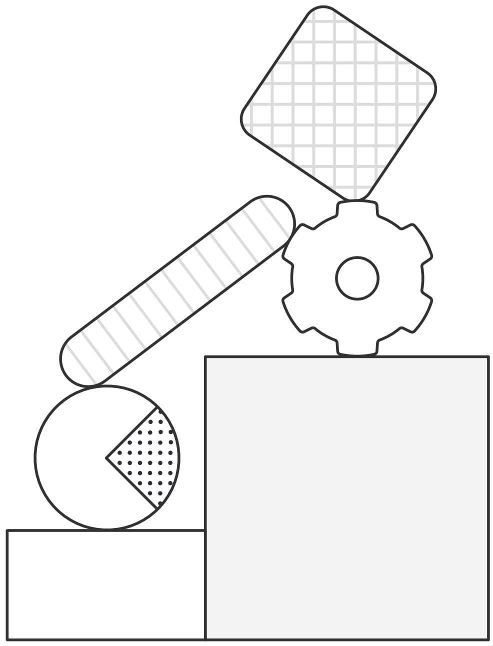


Table 8. Key data guidance for e-ammonia.

e-ammonia maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 1	Electricity and nitrogen production	e_{fecu}	• Data should be provided by the electricity and nitrogen supplier(s) where possible. • Secondary data sources include JRC default values (transport biofuels), IPCC, JEC-WTT, GREET, ecoinvent, etc. • Geographical considerations: If using grid electricity with or without renewable power purchase agreements, consider the residual electricity mix (share of renewables and fossil sources), which will influence the grid emissions factor. If directly connected to a renewable electricity production plant, then consider the capacity and availability of renewable energy in the local region to assess the environmental benefits and potential emissions reductions. • Energy supply considerations: Using renewable electricity instead of fossil-fuel-based electricity to separate nitrogen from the air can significantly reduce emissions. • Consumable and material considerations: The type and quantity of consumables and materials used can affect total emissions. For example, nitrogen obtained via an air separation unit requires cooling water to remove heat generated during the process. This water may come from a cooling tower or other cooling systems.[44]
		$e_{1,fug}$	• Fugitive nitrogen losses are expected to be low during nitrogen production, and are not releasing GHG, as nitrogen is chemically inert and non-reactive.
	MAIN INTERMEDIATE OUTPUT		ELECTRICITY AND NITROGEN
	Electrolysis	e_{fecu}	• Energy supply considerations: The electrolysis process requires electrical energy to produce hydrogen. Using renewable electricity can significantly reduce emissions compared to using fossil-fuel-based electricity. • Consumables and material considerations: The type and quantity of consumables and materials used can affect total emissions. For example, water purification (desalination) is typically required before electrolysis. In addition, catalysts may be used to enhance the efficiency of the process.
	Co-products	$(e_{cpm} - e_{cpc})_1$	• Co-products: Oxygen is produced as a byproduct during electrolysis (in addition to hydrogen) and can have potential value and various uses. System expansion is only suitable if the specific end use of oxygen is known and evidenced. If this is not possible, all electrolysis emissions should be allocated to the hydrogen product.
		$e_{1,fug}$	• Fugitive losses of hydrogen and oxygen are expected to be low, since the electrolysis process is designed to capture and collect the gases.
	MAIN INTERMEDIATE OUTPUT		HYDROGEN
	Feedstock transport	$e_{1,t}$	• Emissions associated with transporting the feedstock to the fuel processing facility should be considered.
	Emission credits	$e_{1,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon arising during feedstock extraction, acquisition, and transport applies. This can be the case when bio-diesels are used to transport the feedstock, for example.
	MAIN STAGE OUTPUT		NITROGEN AND HYDROGEN
Stage 2	Haber-Bosch	$e_{2,p}$	• Energy supply considerations: In certain configurations of the Haber-Bosch process, there may be auxiliary equipment or additional process steps where electricity is used. These may include pumps, compressors, separators, etc. Using renewable electricity instead of electricity from fossil fuel sources can reduce emissions. • Consumable and material considerations: The type and quantity of consumables and materials used in fuel production and conditioning can affect total emissions. This includes hydrogen and nitrogen, the main inputs to the Haber-Bosch process. In addition, using catalysts enhances the reaction rate and efficiency of the process, which can reduce the emissions produced by the process.
	Co-products	$(e_{cpm} - e_{cpc})_2$	• Co-products: Depending on the configuration, waste heat can be produced as a byproduct of the Haber-Bosch process. System expansion is only suitable if the specific end use of the waste heat is known and evidenced. If this is not possible, energy allocation (LHV) is more appropriate.

e-ammonia maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 2	Fugitive emissions	$e_{2,fug}$	• Fugitive losses typically include heat and hydrogen losses in the recycle purge. These losses can be offset through engineered solutions such as hydrogen recovery from the purge gas.[45] • When quantified, e-ammonia fugitive emissions should be considered as a sensitivity under the GHG emissions, as the resulting e-ammonia release could result in indirect N_2O emissions, by applying the indirect N_2O emission methodology of the 2019 refinement of the IPCC Guidelines for National Greenhouse Gas Inventories Volume 1, Chapter 7, Section 7.3.[32]
	Emission credits	$e_{2,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon applies. This can be the case when biofuels are used for the on-site heat generation required in the Haber-Bosch process.
	MAIN STAGE OUTPUT		e-AMMONIA MARITIME FUEL
Stage 3	Fuel transport and distribution	$e_{3,t}$	• Location: The emissions from this life cycle stage depend on the distance between the location of the fuel production plant and the bunkering site. If the plant is near the bunkering site, it can reduce the transportation distance and associated emissions. • Transportation modes: The choice of transport mode can have a significant impact on emissions. Different modes (e.g., road, rail, pipeline, or maritime shipping) have varying levels of fuel efficiency and associated GHG emissions. Often, a combination of transport modes may be employed to ensure e-ammonia fuel is distributed to end users in an efficient and reliable manner. There may be intermediate storage before bunkering, such as storage at distribution terminals.[36] • Energy supply required to maintain e-ammonia in its liquid form during its transport and distribution must be considered. • Data sources for ammonia transportation include Biograce JEC-WTT, GREET, ecoinvent, etc.
	Fuel storage	$e_{3,p}$	• The energy supply required for e-ammonia marine fuel storage will vary depending on fuel storage location and must be considered in Stage 3 GHG emissions. • Energy supply required to maintain ammonia in its liquid form during its storage must be considered.
	Fugitive emissions	$e_{3,fug}$	• Fugitive losses of e-ammonia are expected to be low. Ammonia is highly stable with a low vapor pressure under normal conditions. It is stored and transported in specialized containers or tanks designed to minimize leaks.
	Emission credits	$e_{3,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon applies. This can be the case when biofuels are used to transport the e-ammonia maritime fuel.
Stage 4	Bunkering operations	$e_{4,p}$	• Emissions associated with the supply and utilization of fuel and power sources required for e-ammonia maritime fuel bunkering operation must be included.
	Fugitive emissions	$e_{4,fug}$	• To ensure greater accuracy, measurements of fuel bunkered should be used to establish the initial fuel quantity supplied to the vessel and any subsequent losses during e-ammonia maritime fuel bunkering. Fugitive emissions are not relevant to GHG emission as ammonia has a GWP of zero. • However, when quantified, e-ammonia fugitive emissions should be considered as a sensitivity under the GHG emissions as the resulting ammonia release could result in indirect N_2O emissions, by applying the indirect N_2O emission methodology of the 2019 refinement of the IPCC Guidelines for National Greenhouse Gas Inventories Volume 1, Chapter 7, Section 7.3.[32]
	Emission credits	$e_{4,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon could apply. This can be the case when bio-sourced fuels are used to generate electricity used during e-ammonia bunkering operations.

e-ammonia maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 5	Fugitive emissions	$e_{5,fug}$	• E-ammonia fugitive emissions should not be included in the GHG emission, as ammonia has a GWP of zero. However, when quantified, e-ammonia fugitive emissions should be considered as a sensitivity under the GHG emissions as the resulting ammonia release could result in indirect N_2O emissions by applying the indirect N_2O emission methodology of the 2019 refinement of the IPCC Guidelines for National Greenhouse Gas Inventories Volume 1, Chapter 7, Section 7.3.[32]
	Slips	e_{slip}	• e-ammonia fuel slip in maritime fuel converter must be considered in the e_{slip} emission factor. Fuel slip must be accounted for as defined in Section 10.1. • e-ammonia slippage should not be included in the GHG emission, as ammonia has a GWP of zero. However, when quantified, e-ammonia slippage emissions should be considered as a sensitivity under the GHG emissions, as the resulting ammonia release could result in indirect N_2O emissions, by applying the indirect N_2O emission methodology of the 2019 refinement of the IPCC Guidelines for National Greenhouse Gas Inventories Volume 1, Chapter 7, Section 7.3.32.
	Combus-tion emissions	e_{fc}	• Fuel utilization emissions from the converter (fuel cell or internal combustion engine) must be included.
	Consum-ables	e_{fu}	• If using an internal combustion engine, emissions from consumables will include pilot fuel, such as marine gas oil.
	Emission credits	$e_{5,c}$	• Emission credits can be applied equivalent to the pilot fuel's carbon content, as defined in Section 8.5.



Appendix D. Case study 4: e-fuel – e-methanol from DAC

Figure 7. Life cycle stages description of e-methanol pathway.

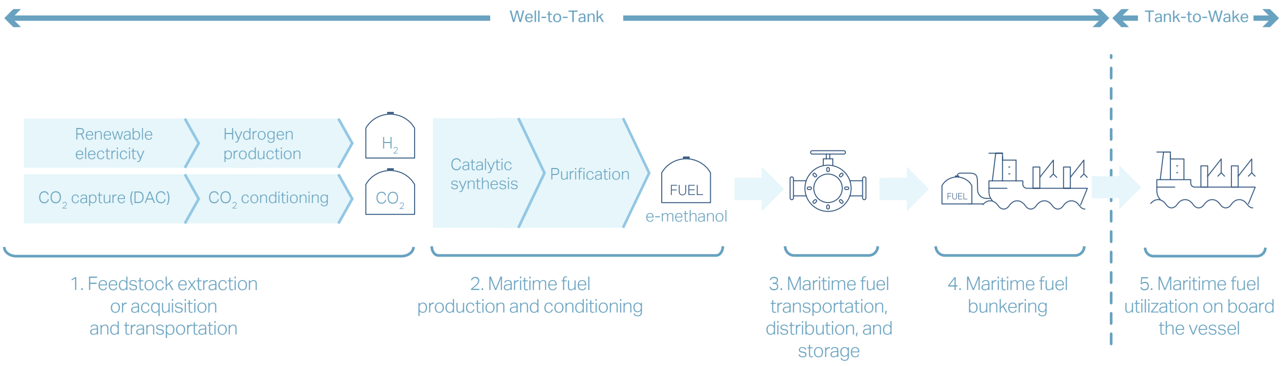


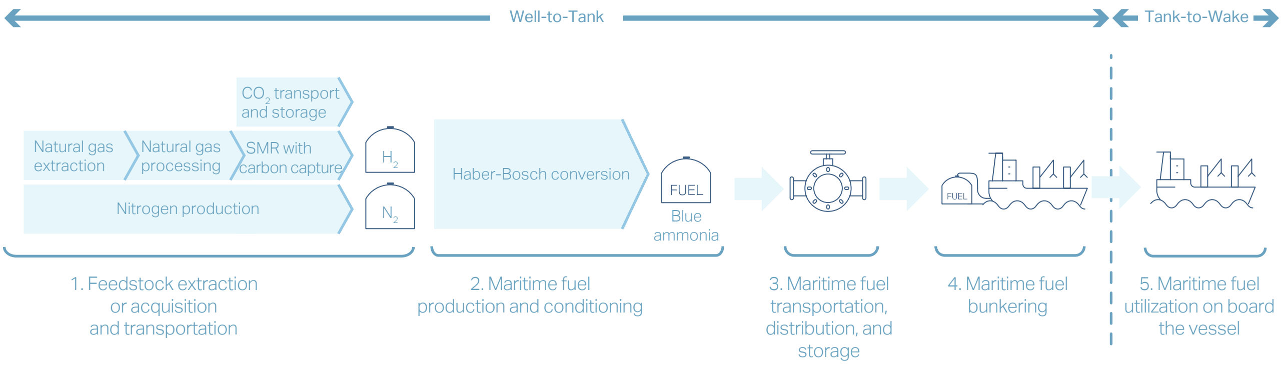
Table 9. Key data guidance for e-methanol.

e-methanol from DAC maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 1	Electricity production and CO_2 source	e_{fecu}	• Data should be provided by the electricity supplier(s) where possible. • Secondary data sources include JRC default values (transport biofuels), IPCC, JEC-WTT, GREET, ecoinvent, etc. • Geographical considerations: If using grid electricity with or without renewable power purchase agreements, consider the residual electricity mix (share of renewables and fossil sources), which will influence the grid emissions factor. If directly connected to a renewable electricity production plant, then consider the capacity and availability of renewable energy in the vicinity to assess the environmental benefits and potential emissions reductions. • Energy supply considerations: The type of energy required to capture CO_2 will vary depending on the source. For example, using renewable electricity for DAC can result in significantly lower emissions than using fossil-fuel-based electricity. • Consumable and material considerations: The type and quantity of consumables and materials used can affect total emissions and vary depending on the CO_2 source. This includes, for example, chemical sorbents or solvents in DAC systems and for CO_2 conditioning.
		$e_{1,fug}$	• Fugitive losses can vary depending on the specific process and equipment used. For example, fugitive losses in DAC systems are expected to be low, given that the capture process occurs in closed systems in controlled environments.
		$e_{1,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon arising during feedstock extraction, acquisition, and transport applies. This can apply in the case of biogenic fugitive emissions or when biofuels are used for on-site heat generation required in the DAC process.
	MAIN INTERMEDIATE OUTPUT		ELECTRICITY AND CO_2
	Electrolysis	e_{fecu}	• Energy supply considerations: The electrolysis process requires electrical energy to produce hydrogen. Using renewable electricity can significantly reduce emissions compared to fossil-fuel-based electricity. • Consumables and material considerations: The type and quantity of consumables and materials used can affect total emissions. For example, water purification (desalination) is typically required before electrolysis. In addition, catalysts may be used to enhance the efficiency of the process.
	Co-products	$(e_{cpm} - e_{cpc})_1$	• Co-products: Oxygen is produced as a byproduct during electrolysis (in addition to hydrogen) and can have potential value and various uses. System expansion is only suitable if the specific end use of oxygen is known and evidenced. If this is not possible, all electrolysis emissions should be allocated to the hydrogen product.
		$e_{1,fug}$	• Fugitive losses of hydrogen and oxygen are expected to be low, since the electrolysis process is designed to capture and collect the gases.
	MAIN INTERMEDIATE OUTPUT		HYDROGEN
	Feedstock transport	$e_{1,t}$	• Emissions associated with transporting feedstock to the fuel processing facility should be considered.
	Emission credits	$e_{1,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon arising during feedstock extraction, acquisition, and transport applies. This can be the case when bio-diesels are used to transport the feedstock, for example.
	MAIN STAGE OUTPUT		CO_2 AND HYDROGEN

e-methanol from DAC maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 2	Catalytic synthesis and purification	$e_{2,p}$	• Energy supply considerations: Heat energy is typically supplied from external sources. The purification stage typically uses electricity for operating equipment. The source used will impact emissions. • Consumable and material considerations: The type and quantity of consumables and materials used can affect total emissions. This includes catalysts used during synthesis and solvents or chemicals used in purification.
	Fugitive emissions	$e_{2,fug}$	• In both stages, fugitive losses of methanol do not emit GHG and can be excluded from the assessment.
	Emission credits	$e_{2,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon applies.
	MAIN STAGE OUTPUT		E-METHANOL FUEL
Stage 3	Fuel transport and distribution	$e_{3,t}$	• Location: The emissions from this life cycle stage depend on the distance between the location of the fuel production plant and the bunkering site. If the plant is near the bunkering site, it can reduce the transportation distance and associated emissions. • Transportation modes: The choice of transport mode can have a significant impact on emissions. Different modes (e.g., road, rail, pipeline, or maritime shipping) have varying levels of fuel efficiency and associated GHG emissions. Often, a combination of transport modes may be employed to ensure that e-methanol maritime fuel is distributed to end users in an efficient and reliable manner. There may be intermediate storage before bunkering, such as storage at distribution terminals.[36] • Data sources for methanol transportation include Biograce JEC-WTT, GREET, ecoinvent, etc.
	Fuel storage	$e_{3,p}$	• The energy supply required for e-methanol marine fuel storage will vary depending on fuel storage location and must be considered in Stage 3 GHG emissions.
	Fugitive emissions	$e_{3,fug}$	• Fugitive losses of e-methanol are expected to be low. Methanol's low volatility contributes to low fugitive losses during transport and distribution. The potential for fugitive emissions depends on various factors, including the quality of equipment, maintenance practices and operating procedures.
	Emission credits	$e_{3,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon applies. This can be the case when biofuels are used to transport the e-ammonia maritime fuel.
Stage 4	Bunkering operations	$e_{4,p}$	• Emissions associated with the supply and utilization of fuel and power sources required for e-methanol maritime fuel bunkering operation must be included.
	Fugitive emissions	$e_{4,fug}$	• To ensure greater accuracy, measurements of fuel bunkered should be used to establish the initial fuel quantity supplied to the vessel and any subsequent losses during e-methanol maritime fuel bunkering. Fugitive emissions are not relevant to GHG emissions as methanol has a GWP of zero.
	Emission credits	$e_{4,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon could apply. This can be the case when bio-sourced fuels are used to generate electricity used during e-methanol bunkering operations.
Stage 5	Fugitive emissions	$e_{5,fug}$	• Fugitive emissions from fuel tank boil-off are not relevant, as the fuel is a liquid at room temperature and pressure.
	Slips	e_{slip}	• e-methanol fuel slip C_{slip} in maritime fuel converter shall be quantified, as described in Section 10.1. However, the considered GHG emissions e_{slip} from e-methanol slip must be set to zero as methanol has a GWP of zero.
	Combus-tion emissions	e_{fc}	• Combustion emissions from e-methanol maritime fuel use in the fuel converter must be included.
	Consum-ables	e_{fu}	• As pilot fuel is required for the utilization of e-methanol maritime fuel, emissions from pilot fuel (such as marine gas oil) should be assigned.
	Emission credits	$e_{5,c}$	• Combustion emissions from fuel use in the engine are included in e_{fc}. However, when the carbon in e-methanol is of biogenic origin, a credit is applied equivalent to the fuel's biogenic carbon content, as defined in Section 8.5. • Emission credits can be applied equivalent to the pilot fuel's biogenic carbon content, as defined in Section 8.5.

Appendix E. Case study 5: Blue fuels – blue ammonia

Figure 6. Life cycle stages description of blue ammonia pathway. SMR = steam methane reforming.



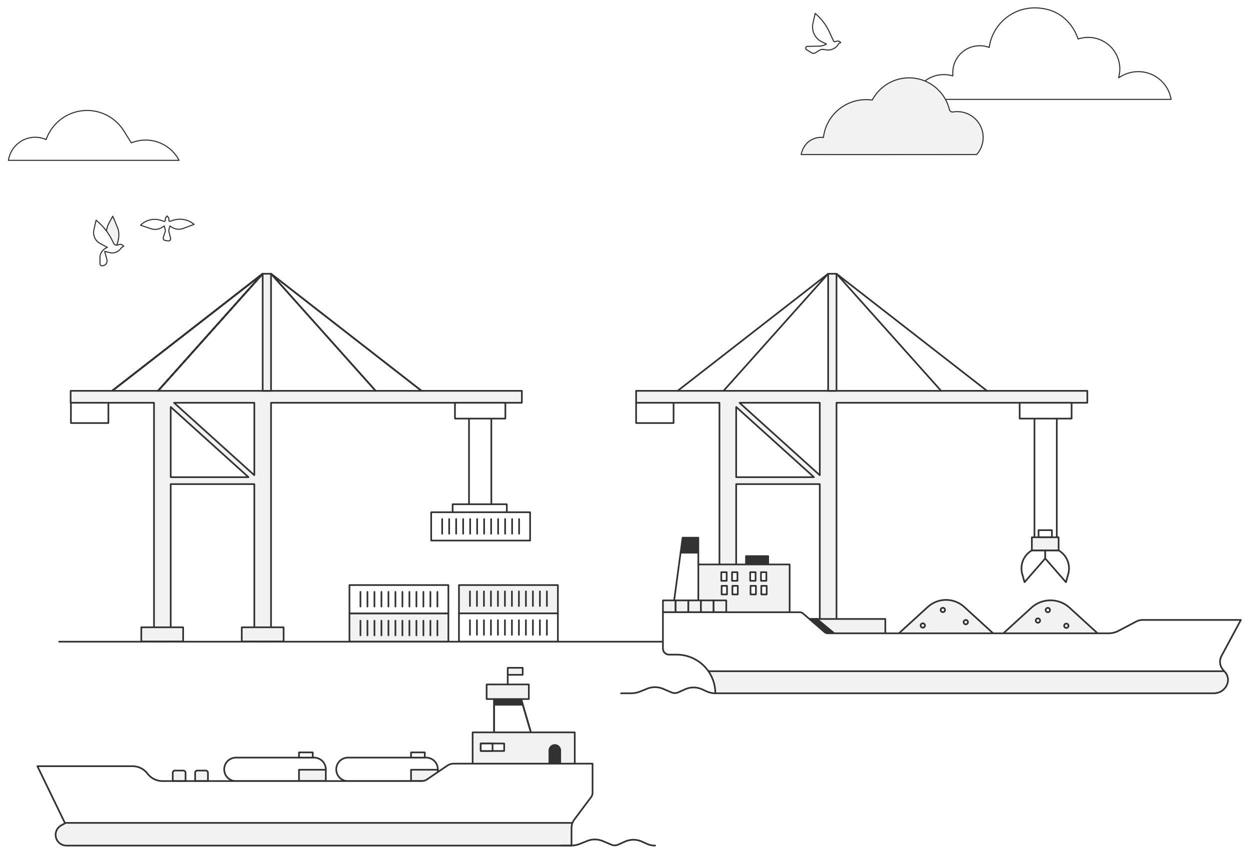


Table 10. Key data guidance for blue ammonia.

Blue ammonia maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 1	Natural gas extraction, production, and transport	e_{fecu}	• Data should be provided by the natural gas supplier where possible. • Secondary data sources include IEAGHG[28] and Sustainable Gas Institute (2015).[29] Proxy data sources include the JEC Well-to-Tank v5 Study[21] and GREET.[31] • Geographic considerations: The country of origin of the natural gas can affect overall emissions. For example, natural gas composition, including CH_4 content, impurities, etc., can vary by region. Factors such as the energy intensity of the natural gas extraction process can also affect emissions. For example, whether the extraction uses grid or renewable electricity will influence emissions. • Energy supply: Energy is required for drilling and extraction operations, typically using drilling rigs and equipment powered by diesel engines or electricity. Conditioning of natural gas (compression or liquefaction) for transport also requires different sources of energy, which much be considered in e_{fecu}. The use of renewable electricity would reduce emissions.
	Fugitive emissions	$e_{1,fug}$	• Fugitive CH_4 losses are expected in small leaks from valves and other equipment used in drilling, processing, and forwarding. CH_4 is also lost during venting or natural gas flaring (emitted as CO_2 and CH_4 from incomplete combustion), which may be required in certain situations for safety or other limitations.[46] • Fugitive CH_4 emissions in the production, process, and transport chain of natural gas are inescapable. Information from the OGCI can be used as reference for weighting these emissions.[30]
	CCS chain	$(e_{ccsp} - e_{ccs})_1$	• When natural gas extraction process involves CCS, emissions and credits associated with the CO_2 captured during feedstock extraction, acquisition, and transportation must be considered.
	Natural gas transport and distribution	$e_{1,t}$	• Emissions associated with natural gas transportation to the blue ammonia fuel processing facility should be considered when these feedstocks are not produced at the same location.
	Emission credits	$e_{1,c}$	• If evidenced, emissions credit for natural gas extraction, production, and transport applies. This can be the case when bio-diesels are used to transport the natural gas, for example.
	MAIN INTERMEDIATE OUTPUT		NATURAL GAS
	Electricity and nitrogen production	e_{fecu}	• Data should be provided by the electricity and nitrogen supplier(s) where possible. • Secondary data sources include JRC default values (transport biofuels), IPCC, JEC-WTT, GREET, ecoinvent, etc. • Geographical considerations: If using grid electricity with or without renewable power purchase agreements, consider the residual electricity mix (share of renewables and fossil sources), which will influence the grid emissions factor. If directly connected to a renewable electricity production plant, then consider the capacity and availability of renewable energy in the local region to assess the environmental benefits and potential emissions reductions. • Energy supply considerations: Using renewable electricity to separate nitrogen from the air can significantly reduce emissions compared to using fossil-fuel-based electricity. • Consumable and material considerations: The type and quantity of consumables and materials used can affect total emissions. For example, nitrogen obtained via an air separation unit requires cooling water to remove heat generated during the process. This water may come from a cooling tower or other cooling systems.[44]
	Fugitive emissions	$e_{1,fug}$	• Fugitive nitrogen losses are expected to be low during nitrogen production, and are not releasing GHG, as nitrogen is chemically inert and non-reactive.
	MAIN INTERMEDIATE OUTPUT		NITROGEN

Blue ammonia maritime fuel life cycle stage and detail		GHG emission equation term	Key guidance
Stage 1	SMR with CCS	e_{fecu}	• Energy supply considerations: Energy in the form of heat and electricity is required to produce steam and for the SMR process. Additionally, energy is needed for the carbon capture process. • Consumable and material considerations: The type and quantity of consumables and materials used can affect total emissions. The primary consumable is the natural gas feedstock, which undergoes reforming reactions with steam in the presence of a catalyst. Additionally, consumables include chemicals or solvents for capturing and separating CO_2 from the process stream.
	Fugitive emissions	$e_{1,fug}$	• Fugitive natural gas losses are expected to be low during the SMR process with well-maintained equipment, proper monitoring, and control measures. These practices aim to prevent leaks and minimize fugitive emissions during the reforming process. • Data sources for fugitive emissions during the storage of captured CO_2 include Deep Geological Storage of CO_2 on the UK Continental Shelf published by the UK Government (Department for Energy Security and Net Zero) and a numerical program on estimating geological CO_2 storage security to deliver on climate mitigation, developed by the University of Edinburgh and University of Barcelona.[47,48]
	CCS chain	$(e_{ccsp} - e_{ccs})_1$	• If the captured CO_2 is placed in permanent storage, such as a depleted oil reservoir in the North Sea, then the system can receive a credit equivalent to the amount of CO_2 stored once all emissions related to the compression, transport, injection, and storage of CO_2, as well as fugitive emissions sequestration, have been taken into account, as described in Section 8.4. Emissions from the capture of CO_2 must be considered in the e_{fecu} emission parameter.
	MAIN INTERMEDIATE OUTPUT		BLUE HYDROGEN
Stage 2	Haber-Bosch	$e_{2,p}$	• Energy supply considerations: In certain configurations of the Haber-Bosch process, there may be auxiliary equipment or additional process steps where electricity is used. These may include pumps, compressors, separators, etc. Using renewable electricity instead of fossil-fuel-based electricity can reduce emissions. • Consumable and material considerations: The type and quantity of consumables and materials used in fuel production and conditioning can affect total emissions. This includes hydrogen and nitrogen, the main inputs to the Haber-Bosch process. In addition, using catalysts enhances the reaction rate and efficiency of the process, which can reduce the resulting emissions.
	Co-products	$(e_{cpm} - e_{cpc})_2$	• Co-products: Depending on the configuration, waste heat can be produced as a byproduct of the Haber-Bosch process. System expansion is only suitable if the specific end use of the waste heat is known and evidenced. If this is not possible, energy allocation (LHV) is more appropriate.
	Fugitive emissions	$e_{2,fug}$	• Fugitive losses typically include heat and hydrogen losses in the recycle purge. These losses can be offset through engineered solutions such as hydrogen recovery from the purge gas.[45] • When quantified, blue ammonia fugitive emissions should be considered as a sensitivity under the GHG emissions, as the resulting ammonia release could result in indirect N_2O emissions, by applying the indirect N_2O emission methodology of the 2019 refinement of the IPCC Guidelines for National Greenhouse Gas Inventories Volume 1, Chapter 7, Section 7.3.[32]
	Emission credits	$e_{2,c}$	• If evidenced, emissions credit for CO_2 air emissions of biogenic carbon applies. This can be the case when biofuels are used for the on-site heat generation required in the Haber-Bosch process.
	MAIN STAGE OUTPUT		BLUE AMMONIA MARITIME FUEL
Stage 3			• Same terms and considerations as for e-ammonia
Stage 4			• Same terms and considerations as for e-ammonia
Stage 5			• Same terms and considerations as for e-ammonia

Appendix F. Supporting information for critical reviews

ILCD provides further guidance on the minimum review requirements of an LCA based on stakeholder involvement and technical knowledge of the audience.[49] We have summarized in Table 11 their guidance and adapted it to be applicable for LCA practitioners assessing maritime fuels using the MMMCZCS LCA Methodology laid out in this document.

Where an independent external review is required, at least one reviewer must be involved. Should a panel review be necessary, a minimum of three reviewers is needed. All reviewers shall not have been involved in the performance of the inventories and the assessment.

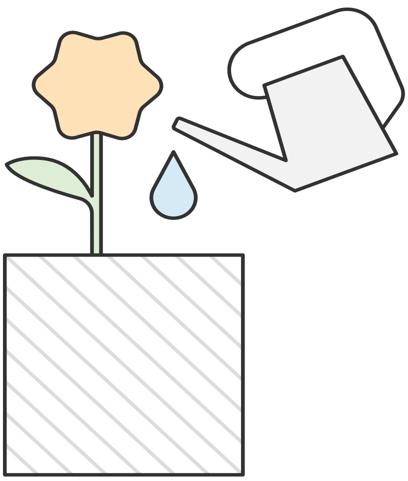
Table 11. Minimum LCA review requirements, adapted from Table 3 of the ILCD review scheme for life cycle assessment.

Knowledge of the audience		Required involvement of interested parties
Technical audience	Non-technical audience	
Independent external review • Micro-level LCI data sets • Life cycle impact assessment (LCIA) factors • Micro-level LCA studies and micro-level LCA-based monitoring indicators Independent panel review • LCIA models	Independent external review • Indirect aspects in Environmental Management Systems • Environmental Product Declarations for business-to-business	No
Independent external review • Comparative assertions disclosed to the public, e.g., comparing bio-methanol and e-methanol in a public report Independent panel review • Meso- or macro-level LCA studies	Independent external review • Environmental Product Declarations for business-to-business Independent panel review • Meso- or macro-level decision supporting LCA studies and meso- or macro-level life-cycle-based accounting indicator, e.g., comparison of maritime fuels to inform policymaking on fuel support	Yes (plus stakeholder panel)

Appendix G.
Default LHV

Table 12. Default lower heating values (LHVs) for various fuel pathways.

Fuel pathway	LHV (MJ/t)
e-hydrogen (liquefied)	120,000
e-hydrogen (compressed)	120,000
e-ammonia	18,800
e-methanol (DAC)	19,900
e-methanol (point source)	19,900
e-diesel (DAC)	42,700
e-diesel (point source)	42,700
e-methane (DAC)	50,000
e-methane (point source)	50,000
e-dimethyl ether (DAC)	25,000
e-dimethyl ether (point source)	25,000
Blue ammonia	18,800
Gray ammonia	18,800
Gray methanol	19,900
Low-sulfur fuel oil	41,200
Liquefied natural gas	48,000
Gray hydrogen (compressed)	120,000
Blue hydrogen (compressed)	120,000
Gray hydrogen (liquefied)	120,000
Blue hydrogen (liquefied)	120,000
Liquefied petroleum gas	46,000
Bio-methane	50,000
Bio-diesel (pyrolysis)	42,700
Bio-diesel (hydrothermal liquefaction)	42,700
Bio-methanol	19,900
Bio-diesel (pyrolysis blend)	34,280
Bio-diesel (hydrothermal liquefaction blend)	38,600
Lignin ethanol oil (LEO)	21,400



Appendix H.
Global LUC

Table 13. Global land-use change (LUC) from additional demand for biofuel from various feedstocks.[50,51]

Crop	Additional demand for feedstock (Mt)	Global total LUC (Mha)	Global LUC (ha/t)
Wheat	16.0	1.7	0.11
Maize	14.2	0.95	0.07
Barley	16.0	1.9	0.12
Sugar beet	58.0	0.32	0.01
Sugarcane	69.0	0.6	0.01
Maize silage	41.4	0.59	0.01
Sunflower oil	3.5	1.5	0.43
Palm oil	3.5	1.0	0.29
Rapeseed oil	3.5	1.9	0.54
Soybean oil	3.5	1.8	0.51
Perennial grasses	13.1	0.92	0.07
Short rotation coppice	13.1	1.2	0.09
Soy meal	15.6	1.0	0.06

Appendix I. Guidelines for calculating soil organic carbon stock

This appendix describes the methodology for calculation of the carbon stocks CS_R and CS_A, associated with the reference land-use and actual land-use respectively, to be used in this MMMCZCS LCA methodology.[27] We encourage the LCA practitioner to see the details in this reference.

This methodology is based on the 2006 IPCC Guidelines for Tier 1 calculation of land carbon stocks and may follow Equation 27.

Equation 27.

$$CS_i = A \times (C_{VEG} + SOC)$$

Where:

CS_i	The carbon stock per unit area associated with the reference land-use (i = R) or actual land-use (i = A)
A	Is a factor scaling to the area concerned (hectares per unit area)
C_{VEG}	The above- and below-ground vegetation carbon stock (measured as mass of carbon per hectare)
SOC	The soil organic carbon (measured as mass of carbon per hectare)

Calculation of soil organic carbon stock SOC

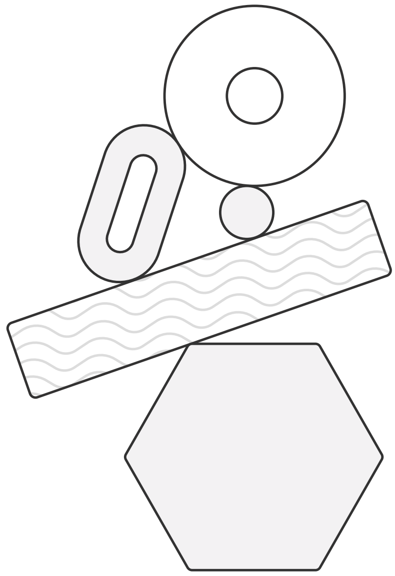
The calculation of SOC may follow Equation 28.

Equation 28.

$$SOC = SOC_{ST} \times F_{LU} \times F_{MG} \times F_I$$

Where:

SOC_{ST}	Is the standard soil organic carbon in the 0- to 30-centimeter topsoil layer (measured as mass of carbon per hectare)
F_{LU}	Is a land use factor reflecting the difference in soil organic carbon associated with the type of land use compared to the standard soil organic carbon
F_{MG}	Is a management factor reflecting the difference in soil organic carbon associated with the principles of management practice compared to the standard soil organic carbon
F_I	Is an input factor reflecting the difference in soil organic carbon associated with different levels of carbon input to soil compared to the standard soil organic carbon



Calculation of above- and below-ground vegetation carbon stock

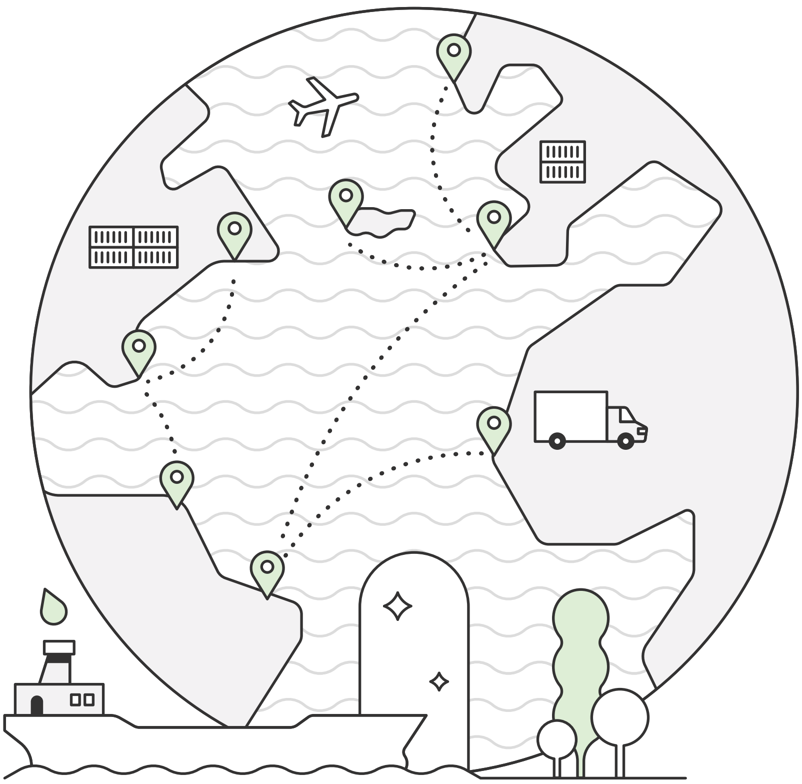
The calculation may follow Equation 29.

Equation 29.

$$C_{VEG} = (B_{AGB} \times CF_B) \times (1+R) + (DOM_{DW} \times CF_{DW}) + (DOM_{LI} \times CF_{LI})$$

Where:

B_{AGB}	Is the weight of above-ground living biomass (measured as mass of dry matter per hectare)
CF_B	Is the carbon fraction of dry matter in living biomass (measured as mass of carbon per mass of dry matter); a value of 0.47 may be used by default if the true value cannot be measured direcly, as recommended by the IPCC[52]
R	Is the ratio of below-ground carbon stock in living biomass to above-ground carbon stock in living biomass
DOM_{DW}	Is the weight of dead wood pool (measured as mass of dry matter per hectare)
CF_{DW}	Is the carbon fraction of dry matter in dead wood pool (measured as mass of carbon per mass of dry matter); a value of 0.5 may be used by default if the true value cannot be measured directly, as recommended by the IPCC[52]
DOM_{LI}	Is the weight of litter (measured as mass of dry matter per hectare)
CF_{LI}	Is the carbon fraction of dry matter in litter (measured as mass of carbon per mass of dry matter); a value of 0.4 may be used by default if the true value cannot be measured directly, as recommended by the IPCC.[52]



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