Creating a Global Fuel Lifecycle Methodology

A qualitative assessment of existing methodologies and opportunities for the future

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Abbreviations

Acronym	Definition
Carb	California Air Resources Board
CCS	Carbon Capture and Storage
CORSIA	Carbon Offsetting and Reduction Scheme for International Avation
dLUC	Direct Land Use Change
GHG	Greenhouse Gas
GREET	Greenhouse Gasses, Regulated Emissions and Energy in Transportation
GWP	Global Warming Potential
HVO	Hydrotreated Vegetable Oil
ICAO	International Civil Avation Organization
iLUC	Indirect Land Use Change
IMO	International Mariime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardization Organization
JEC	Joint Research Center
LCA	Life Cycle Assessment
LNG	Liquified Natural Gas
LUC	Land Use Change
PEF	Product Environment Footprint
RED II	Renewable Energy Directive II
RFS	Renewable Fuel Standard
RSB	Roundtable for Sustainable Biofuels
RTFC	Renewable Transport Fuel Certificate
RTFO	Renewable Transport Fuel Obligation
SAF	Sustainable Advanced Fuels
TTW	Tank-to-wake
WTT	Well-to-tank
WTW	Well-to-wake

Executive Summary

The maritime industry wants to decarbonize. With these ambitions comes an increased interest in alternative marine fuels and their ability to deliver reductions in greenhouse gas (GHG) emissions. However, the regulatory landscape surrounding fuels is complex, with different regions of the world adopting different fuel lifecycle methodologies for determining the climate impacts of alternative fuels. These differences yield uncertainty about the actual GHG savings from alternative fuels and may impact crucial decisions as the industry continues to decarbonize.

Harmonizing existing and upcoming fuel lifecycle methodologies into a globally accepted standard for determining climate impact will provide increased certainty and enable ambitious decision-making. We conducted a qualitative assessment of seven existing fuel lifecycle methodologies to learn more about the landscape and harmonization opportunities. Methodologies were selected to reflect regional coverage and the important role they play in regulation and policy. The seven analyzed methodologies were:

- Roundtable on Sustainable Biomaterials (RSB)
- Renewable Transport Fuel Obligation (RTFO)
- Renewable Energy Directive II (RED II)
- Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)
- RenovaBio
- Greenhouse Gas, Regulated Emissions and Energy in Transport (GREET)
- JEC Well-to-Wheel study

We identified several key trends across the methodologies, including good coverage of biofuels, direct land use change (dLUC), and co-products. However, coverage of fugitive emissions is lacking. There are several notable differences across the methodologies, which must be harmonized in a global methodology. They relate to:

- Attributional or consequential approaches
- Handling of dLUC and indirect land use change (iLUC) aspects
- Co-product allocation
- Coverage of fugitive emissions.
- Coverage of marine fuels and system boundaries

The policies that promote alternative fuels mostly focus on the well-to-tank (WTT) part of the fuel lifecycle. From the reviewed studies, only GREET directly addresses alternative maritime fuels from a well-to-wake (WTW) perspective. The other methodologies are relevant to the WTT emissions of maritime fuels.
Most of the reviewed methods follow a core attributional approach, which assesses the direct environmental impact of fuels by accounting for resources and emissions directly related to fuel production and use. Attributional approaches are simpler than consequential approaches, which quantify how emissions change with decisions such as changes in the levels of fuel production.

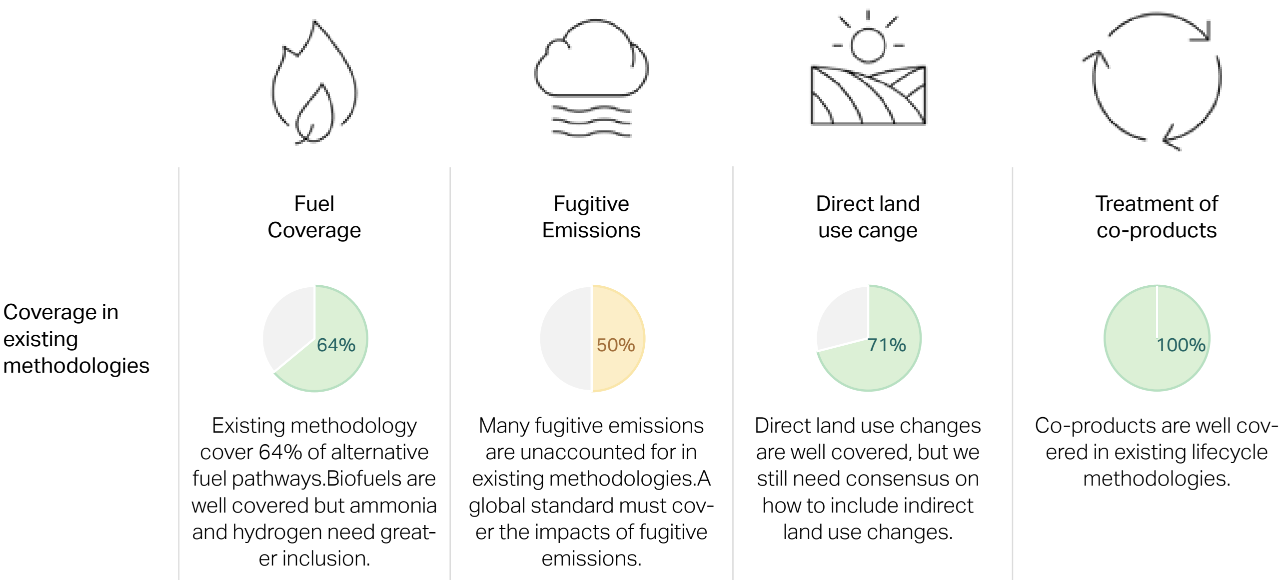
Few of the analyzed methodologies use consequential approaches. Still, they are largely considered by academic experts to be preferable for the treatment of emissions from co-products and land use change aspects. Core consequential approaches are likely better suited to supporting strategic decision-making rather than regulations due to the lack of accessible data and the immaturity of the approach.

A global fuel lifecycle methodology needs to balance climate ambitions (depth and breadth of the method) with delivering certainty to the industry. This may require a combination approach, which uses an attributional approach for emissions associated with feedstock, fuel production, and distribution, and a consequential approach for handling co-products.

This will deliver increased certainty on the main GHG emission activities while ensuring that consequential aspects are handled correctly.

A global fuel lifecycle GHG methodology, based on a combination approach similar to PEF and CARB, would provide confidence and certainty on the climate performance of alternative marine fuels. This could play a role in fuel certification and policy-making, unlocking the fuel production capacity needed to decarbonize.

Infographic: 4 key trends across the methodologies, including Fuel Coverage, Fugitive Emissions, Direct Land Use Change, and Treatment of co-products



01 The role of lifecycle methodologies in regulation

The maritime industry needs a standardized fuel lifecycle methodology

The marine industry wants to decarbonize. A major avenue for pursuing this goal is the decarbonization of marine fuels by adopting alternative fuels that deliver better climate performance than conventional fuels.

Incentivizing alternative fuels requires a lifecycle methodology to determine the climate impacts of different fuels. However, currently, there is no globally accepted methodology for calculating climate impacts. As a result, the regulatory landscape consists of many different methodological approaches across various transport sectors. This leads to uncertainty and a complex regulatory landscape. Without a globally accepted methodology, the climate performance of alternative fuels is unclear, presenting a barrier to enabling alternative marine fuels.

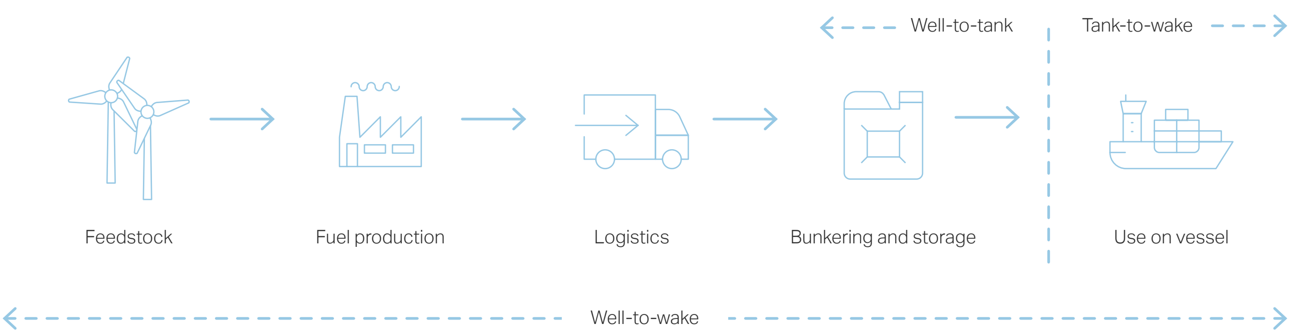
Currently, the International Maritime Organization (IMO) regulates the climate impact of fuel use from a tank-to-wake (TTW) perspective, omitting any upstream emissions relating to fuel production (Figure 1). In the case of conventional fuels, this approach could be deemed appropriate given that much of the climate impact occurs during fuel combustion. However, this is not the case for alternative marine fuels. Most of the climate burden and benefits of these emerging fuels originate from fuel production.

By continuing to regulate fuels from a TTW perspective, the industry risks burden transfer during the transition.

Burden shift can occur between environmental burdens (e.g., reducing greenhouse gas (GHG) emissions during fuel use while increasing land use change impact) and shifting between regions (e.g., reducing GHG emissions in shipping while increasing domestic emissions in fuel-producing countries). To enable the uptake of alternative fuels, the IMO must regulate the climate impact of fuels from a well-to-wake perspective, supported by a global lifecycle methodology for calculating well-to-tank emissions.

To develop a globally accepted lifecycle methodology, we must first understand the existing regulatory landscape. In this paper, we compare existing methodologies used in guidelines and regulations relating to alternative fuels. We assessed the following methodologies from across the transport sector: RSB Standard, Renewable Energy Directive II, GREET, International Civil Aviation Organization (ICAO)-CORSIA, JEC Well-to-Wheel report, and RenovaBio. Each method is described in more detail in Table 1 and the appendix. These methods were selected for their role in fuel policy development and to provide regional coverage.

Figure 1: Well-to-wake, well-to-tank, and tank-to-wake emissions from marine fuels.



To assess emerging trends in lifecycle methodologies and the elements that require harmonization, we evaluated how each methodology covers four key aspects:

- Fuel coverage: Coverage of the major alternative fuel pathways (hydrogen, ammonia, non-biological renewables, biofuels, electricity) and the system boundaries.
- Fugitive emissions (including engine slips): Coverage of unintentional WTT emissions and engine slip emissions during fuel combustion.
- Direct and indirect land use change: Coverage of change in the use or management of land by humans that impacts surface albedo, sources and sinks of GHG gases, and other properties of the climate system that increases radiative forcing (2).
- Co-product allocation: how input and output flows to the system boundary are partitioned between all products.

These aspects reflect the methodological issues currently being discussed in the context of fuels. Each lifecycle methodology was qualitatively assessed for coverage of each aspect and their impact on fuel GHG intensity assessments.

Table 1: Lifecycle methodologies used in our qualitative assessment of existing methodologies and emerging trends.

Lifecycle Methodology	Fuels	Implementation Coverage	Feedstock Methodology
RSB Standard Certification	All Transport Sectors	Global	Global
RFTO Regulation	All Transport Sectors	UK	UK
RED II Directive	All Transport Sectors	Europe	Europe
GREET Model	All Transport Sectors	North America	North America and Global
ICAO-CORSIA Certification	Aviation Fuels	EU 28 + 29 regions	Europe and Global
JEC Well-to-Wheel Study	All Transport Sectors	Europe-Global	Global
RenovaBio Regulation	All Transport Sectors	Brazil	Brazil

02 The lifecycle toolbox at a glance

Different tools lead to different outcomes

Currently, the lifecycle toolbox for assessing the climate impact of alternative marine fuels consists of LCA and well-to-wake (WTW), a subset tool of LCA. These tools bear many similarities; both are based on the lifecycle principles of ISO 14044;2006 (3) and follow the same steps. However, they use different methodologies, leading to differences in the measured climate performance of fuels. Furthermore, they differ in application.

LCA determines the potential environmental impact of a product throughout its' lifecycle. It is very comprehensive and analyses a wide range of potential environmental impacts. WTW is simpler than LCA, and its assessments focus on climate impacts related to the energy used to produce and use the fuel (4). Its simplicity means it is more suited to regulation than LCA, and it forms the basis of regulations such as Renewable Energy Directive II (1) and FuelEU Maritime (5).

Typically, WTW assessments follow an attributional approach for allocating emissions. Attributional approaches assess the direct environmental impact of fuels by accounting for resources and emissions directly related to fuel production and use. Attributional modeling is relatively easy to calculate, well-defined, uses a well-specified, easily accessible, and stable inventory, and is generally valid across the temporal and spatial scales covered by the legislation (8) Various applications of attributional approaches have already been included in European legislation with multiple purposes such as labeling (e.g., EU 2009b (9)), benchmarking products, and performing hotspot analyses such as EC 2013a (10)).

Attributional approaches are useful for comparing the emissions from the processes used to produce (and use and dispose of) different products. Furthermore, they are valuable for identifying opportunities for reducing emissions within the life cycle or supply chain (7). Across the transport industry, attributional approaches are common in lifecycle models supporting legislative instruments (6). However, they are less suitable for quantifying the total change in emissions resulting from changes in fuel production or other parts of the fuel lifecycle. This is because there may be indirect impacts that are outside the scope of an attributional assessment (9)(10).

In recent years, there has been discussion among some experts about whether coverage of indirect impacts is needed to understand the GHG intensity of fuels fully. Such a demand would require a consequential modeling approach. Consequential modeling quantifies the total change in emissions resulting from a change in the level of fuel production, for example. However, policymakers should be aware that consequential assessment results depend on descriptions of economic relationships embedded in models. Consequential models generally attempt to reflect economic cause and effect relationships by extrapolating historical trends in prices, consumption, and outputs, however, caution with the interpretation of such models is necessary as they are less well-defined than attributional methods and therefore allow a much higher degree of interpretation (7).

Given its uncertainty and complexity, implementing a consequential method in marine fuel regulations is difficult to anticipate. On the other hand, lifecycle methods that assess the impacts of strategic policy decisions may benefit from consequential modeling to provide a full overview of the climate impacts of policy decisions.

Another option to using either an attributional or consequential approach would be to use a combined approach. The Product Environmental Footprint (PEF) framework used in Europe provides an example of this approach. It allows for the use of average data consistent with the attributional approach while also encouraging the use of a consequential approach for handling co-products (11) A similar modeling setup is utilized under the California Air Resources Board (CARB).

03 Fuel coverage and system boundaries

Harmonized lifecycle methodologies must cover all fuel production pathways and technologies

The future fuel landscape is expected to utilize a range of fuels from various pathways. As a result, lifecycle methodologies must be capable of assessing the impacts of a wide range of alternative fuels and fuel pathways. We analyzed the fuel coverage of each lifecycle methodology, including which fuels and pathways they covered and their system boundaries. The results are summarized in Table 2.

Given the maturity of biofuels, it's no surprise that this fuel segment is well represented across all of the methods. However, hydrogen and ammonia fuels coverage is lagging (63% and 25%, respectively). At the time of this assessment, green ammonia fuel pathways were only covered in GREET.

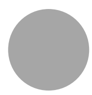
The methodologies we assessed showed variation in how they covered fuel pathways, with differences in the feedstocks and technologies considered for fuel production. For example, some methodologies consider bio-methanol produced via gasification, while others consider anaerobic digestion. These differences in coverage and system boundaries result in a lack of comparability across the methods, as fuels can be produced through various pathways, yielding different fuel GHG intensities.

GREET and the JEC report offer the greatest coverage of fuel pathways, covering over 100 and 250 fuel pathways, respectively, followed by RED II. Given the wide breadth of potential fuel pathways, it's important that any new global fuel lifecycle method can cover the diversity of fuel pathways. Alternatively, it could include fuel pathways according to commercial readiness, as in CORSIA.

All the analyzed methods followed an attributional approach for the core lifecycle impact. Furthermore, our assessment of the system boundaries reveals a clear trend toward WTT assessments. Only GREET considers a WTW approach. However, methodologies that cover WTT often assume the CO_2 emissions during combustion to be net zero. The assumption that biogenic CO_2 is considered net zero should be evaluated more closely as it is highly reliant on the temporal dynamics of biomass growth (sequestration) and CO_2 release to the atmosphere (combustion) (12).

The methodologies we analyzed focused on CO_2 emissions, omitting the impacts of other GHG such as CH_4 and N_2O. Future methodologies should expand include CH_4 and N_2O as they have high global warming potentials (11).

Table 2: Coverage of fuel pathways covered in the fuel lifecycle methodologies. Coverage is represented by the grey-shaded area (12).

Alternative Fuels	Coverage in (%)
Hydrogen	
Ammonia	
Renewabe fuels of non biological origin	
Biofuels	
Electricity	
System boundaries (WTT)	

04 Coverage of fugitive emissions

Coverage of fugitive emissions is an opportunity for improvement

Fugitive emissions are often defined as unintentional or accidental releases of GHGs. Fugitive emissions significantly impact the climate performance of alternative marine fuels. This is particularly true for methane-based fuels, as methane has a global warming potential more than 28 times higher than CO_2 over 100 years.

Fugitive emissions are inherent to feedstock production, fuel production, transportation, distribution, and use.

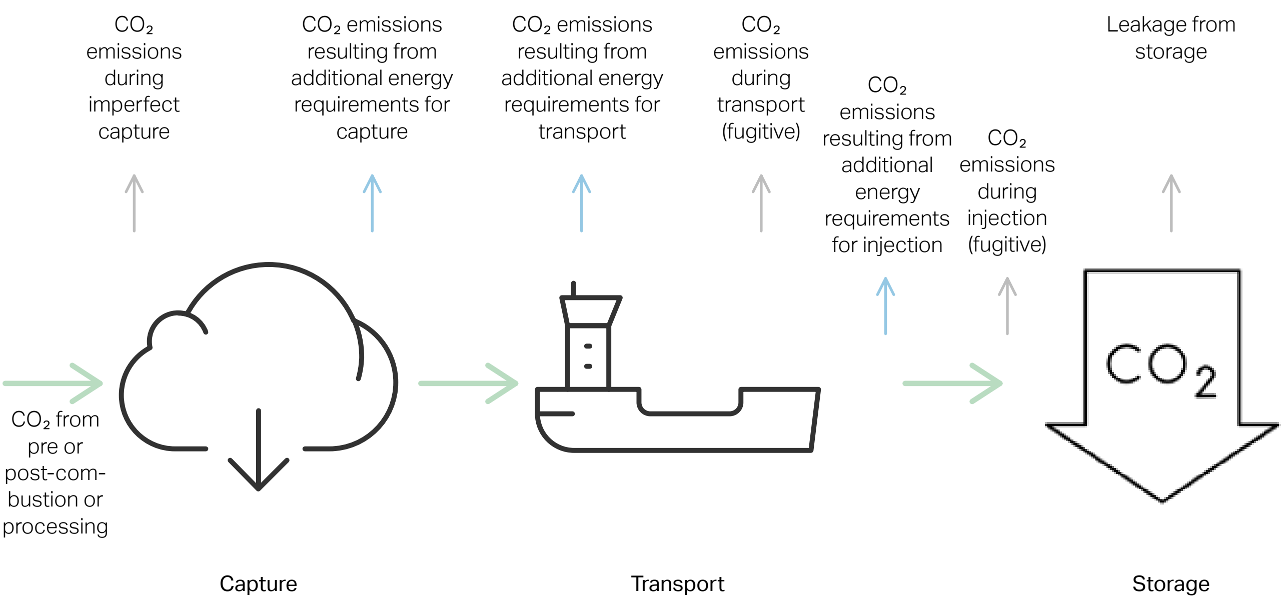
Fugitive emissions during feedstock production tend to be associated with natural gas extraction and transport in the case of blue fuels, as well as fertilizer application on land in the case of biomass production for biofuels.

Several activities relating to upstream natural gas production for LNG and blue fuels produce fugitive methane emissions. Sources include equipment leaks, evaporation and flashing losses, venting, flaring, and accidental releases. Fugitive methane and N_2O emissions are also inherent to biofuel production, distribution, and digestate storage. In addition, fugitive emissions can occur during the transportation and bunkering of fuels.

Releases of GHGs also occur during fuel combustion; these releases are referred to as engine slips and primarily result from gas emitted into the atmosphere due to incomplete combustion. See our Onboard Vessel Emission Reduction series for more information about onboard fugitive emissions and engine slip.

Another potential emerging source of fugitive emissions resides in the supply chain of captured carbon. The Intergovernmental Panel on Climate Change (IPCC) has reported that fugitive emissions from CCS systems can occur during the capture, compression, liquefaction, transportation, and injection of CO_2 into storage reservoirs (13). This is also true for CO_2 captured onboard the vessel. Figure 2 provides an overview of potential sources of emissions in CCS systems.

Figure 2: Simplified flow diagram of possible CO_2 emissions sources during CCS (Source: IPCC Special Report on Carbon dioxide Capture and Storage).

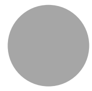
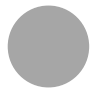
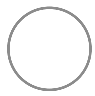


In general, fugitive emissions are covered to varying degrees across the methodologies. Table 3 shows that sources of fugitive emissions from well-established activities such as feedstock cultivation and fuel production are well covered. However, the same cannot be said for fuel distribution and CCS. Both categories are poorly covered in the methodologies and need further development.

However, many fuel production facilities do not have comprehensive measuring and monitoring schemes in place for quantifying fugitive emissions. Herein lies a degree of uncertainty in quantifying actual GHG emissions. To reduce uncertainty within this aspect, regulation is needed to stimulate the requirement for fugitive emissions monitoring. The US's Inflation Reduction Act (14) is an example of a legislative mechanism that required natural gas producers to measure and account for fugitive methane emissions.

Any fuel lifecycle methodology aims to ensure the fuel offers quantifiable climate benefits and emissions savings. Therefore, comprehensive accounting methodologies for fugitive emissions are critical. Any future global lifecycle methodology must cover activities such as fuel transport, CCS chain, and engine slips in a future global fuel lifecycle methodology. Evaluating the uncertainty of measuring fugitive emissions is outside the scope of this paper.

Table 3: Coverage of fugitive emissions across the analyzed fuel lifecycle methodologies. Coverage is represented by the grey-shaded area

Fugitive Emissions Categories	Coverage in (%)
Feedstock production	
Fuel production	
Fuel transport and distribution	
Fuel production (CCS)	
Fuel use (Onboard carbon capture storage)	
Engine slips	

05 Coverage of land use change and indirect land use change

iLUC requires the ability to work with uncertainty in quantitative modeling. This degree of uncertainty makes a risk-based approach an important alternative

Land use change refers to the change in the use or management of land by humans that impact surface albedo, sources, and sinks of GHG gases and other properties of the climate system that increases radiative forcing. Including these aspects in fuel lifecycle methodologies reduces the risk of GHG underestimation. However, the climate impact associated with direct land use change (dLUC) and indirect land use change (iLUC) is a relatively contentious aspect of lifecycle methodologies. Much of the debate rests in the models and tools used to quantify these impacts, with iLUC generating a particularly high degree of uncertainty.

Land use change impacts are typically associated with biofuel production as most biofuels are produced from land-based crops (except for waste to biofuel pathways and algae-derived biofuels). Increased demand for biofuels stimulates the climate risks associated with the conversion of land for the cultivation of bioenergy crops (dLUC) and the displacement effects associated with these conversions (iLUC). For example, land converted from food production to energy production (dLUC) could lead to land conversions elsewhere in the world to meet the food crop demand, thereby causing iLUC impacts. The dynamics of land conversions lead to changes in carbon stocks caused by modifications of the biomass and soil organic content. From a lifecycle methodology perspective, reducing carbon stocks should be counted as emissions, and increasing carbon stocks as negative emissions (removing CO_2 permanently from the atmosphere).

Table 4 shows a clear trend towards including dLUC. dLUC is covered in RED II as annualized emissions from carbon stock changes caused by land-use changes for feedstock and is included in the fuel system boundary. This method is also deployed in the RSB Standard. The impact of omitting this aspect could be an overestimation of GHG savings for biofuels (dLUC) and uncertainty around the impact of extended energy crop production on food security. Of the methodologies we analyzed, only GREET and CORISA include iLUC. Both CORSIA and GREET use different means of calculating iLUC, making it difficult to compare the associated GHG emission intensities. GREET uses the Carbon Calculator for Land Use and Land Management (CCLUB), which uses data from the Global Trade Analysis Project (GTAP). CORSIA, on the other hand, uses a hybrid approach with GLOBIOM (EU-centered) and GTAP-BIO (US-centered). Outputs from both are levelized mathematically to give a global value. The RSB standard handles iLUC impact via a risk-based approach. At the time of writing this paper, work is ongoing in the European Commission exploring handling iLUC similarly.

Like other consequential aspects, the knowledge derived from iLUC might be necessary to support strategic decisions by fuel producers, for example.

Table 4: Coverage of direct and indirect land use change across the analyzed fuel lifecycle methodologies. Coverage is represented by the grey-shaded area.

Land use change aspects	Coverage in (%)
Direct land use change	
Indirect land use change	

06 Coverage for treatment of co-products

Our assessment shows a clear trend toward using an attributional approach based on energy for co-product allocation

Fuel production processes often generate more than one product. For example, biofuel production generates biochar and digestate along with the desired fuel. Lifecycle methodologies must allow a complete description of input and output flows and allocate emissions across all products using lifecycle inventory analysis (LCIA). Lifecycle methodologies can use an attributional or a consequential approach to manage how emissions are allocated across different products.

In an attributional approach, the multifunctionality problem is addressed by allocating the burden of input and output flows by attributing shares to the products and co-products. The allocation can be based on the energy content, mass, or economic value of co-products. A consequential approach applies the so-called system expansion approach when quantifying co-product inventories in the fuel production process. In doing so, the approach estimates the impact of displacement effects derived from the co-product. An example would be the land application of digestate from biofuel production, displacing the need for mineral fertilizers, thereby creating a credit mechanism for the pathway.

Our assessment shows a clear trend towards using an attributional approach (Table 4) based on energy for co-product allocation, showing good harmonization across the methodologies. One potential reason for this trend is the ease of use, familiarity of the calculations, and access to data for an attributional approach.

Only RED II (for excess electricity from cogeneration), GREET, and CORSIA (iLUC) use a consequential approach. However, the outlook for this aspect is uncertain, with many LCA experts calling for a consequential approach to handling co-products in quantifying the core lifecycle GHG impact (WTT emissions). However, consequential approaches create greater uncertainty as assumptions are required on product displacement and market dynamics, which frequently change, making emission allocations uncertain. The impact of the methodological choices made during this step can produce different results; therefore, clarity is needed (12).

Table 5: Coverage for treatment of co-products across the analyzed fuel lifecycle methodologies.

Treatment of co-products	Coverage in (%)
Attributional	
Consequential	

07 Key trends

Our assessment of seven existing fuel lifecycle methodologies revealed several key trends, as shown in Figure 3. It also showed a clear trend toward WTT assessments and a preference for attributional approaches.Comparing the existing methodologies highlighted some areas of good harmonization, for example, for co-product treatment. However, our analysis identified core methodological differences in fuel lifecycle methodologies, resulting in variations in GHG emissions intensity estimates. Estimates varied with attributional and consequential methodologies, inclusion or exclusion of LUC aspects, co-product coverage and handling, and the system boundaries.

On closer inspection, many of these differences are more associated with biofuels, thereby, this fuel segment carries the greatest inherent uncertainty concerning potential GHG reduction potential.

All the analyzed methodologies used global warming potential (GWP) with a 100-year time horizon, consistent with the approach used by UNFCC. Only GREET offers users the ability to calculate for a 20-year time horizon.

The use of GWP is coming under increasing scrutiny for several reasons. One reason is the metric that may lead to insufficient policies to cut CO_2 emissions because cutting an equivalent amount of short-lived climate forcers (such as methane) may be easier/cheaper, but will not have the same effects on long-term warming (16). GWP* is an emerging metric developed by a team of climate scientists at the Oxford Martin School. GWP* considers the short-life time of methane in the atmosphere. Contrary to the GWP approach, GWP* uses temperature equivalence and is thus considered to better represent the temperature response towards methane emission (16).

Figure 3: Key trends in the coverage of methodological aspects across the analyzed methodologies.

		Further coverage is needed of fugitive emissions from fuel distribution, engine slips and carbon storage. Fugtive emissions from feedstock and fuel production are covered to varying degrees.		Treatment of co-products is well covered and largely focuses on biofuels. All treatment of co-products is handled via an attributional approach. Only GREET and JEC report offers a consequential approach as an option.
Technical aspect	Fuel Coverage	Fugitive Emissions	Direct land use change	Treatment of co-products
% Coverage	64%	50%	71%	100%
	Biofuels considered well represented across each of the methodologies. Expansion and improve-ment is needed to cover ammonia and hydrogen based fuels. There is also great disparity betweeen the fuel prodution tech-nologies and pathways in different methodologies.		Direct land use is covered in all methodologies with the excepion of JRC report and RenovaBio. ReovaBio implements land use change (LUC) as eleg-ibility criteria - outside the system boundary for life-cycle GHG qualifications. Indirect land use change (iLUC) is only covered in corisa and GREET	

Well covered
Aspect is mature and well covered in the methodologies. Only minor challenges outstanding.

Requires greater implementation
Aspect is not well covered in the methodologies. Median challenges remain.

Implementation lagging
Major challenges remaining for implementation. Clear guidance on how to implement is needed.

08 Recommendations for a global lifecycle methodology

International maritime policy currently focuses on the TTW impact of alternative maritime fuels. However, the WTT part of fuel production is a large contributor to the GHG emissions of alternative maritime fuels. This is an element that international maritime policy has not considered so far, as IMO's CII targets concern TTW CO_2 emissions per transport work. Furthermore, other GHG emissions (CH_4/N_2O) linked with alternative maritime fuel combustion are currently excluded.

To incentivize the uptake of alternative fuels, the IMO must regulate the climate impact of fuels from a WTW perspective, supported by a global fuel lifecycle methodology. Consistency across various lifecycle guidelines would enable the comparison of the impact of GHG emissions across fuels and thus further support policy. In addition, any future fuel lifecycle methodology should be able to account for a wide scope of fuel production pathways, provide extensive coverage of all fugitive emission sources (including engine slips), include LUC, and seek to find ways of handling the uncertainty for consequential aspects such as iLUC.

Including the WTT part of the production chain in emissions regulations has methodological implications. The lifecycle methods identified across the different regulatory schemes assessed in this report have differences in their methodological approaches, particularly on the treatment of co-products and the inclusion of dLUC/iLUC impact, leading to a variation in the GHG emission intensity of fuels. Most of the variations are identified upstream, which could potentially constitute an opportunity for the shipping sector to drive deep societal decarbonization by sending demand signals for low-climate-impact fuels.

When developing a methodology that aims to stimulate the enablement and scalability of alternative marine fuels, stakeholders (e.g., fuel suppliers) need a pragmatic approach to calculating their performance. Therefore, a straightforward, core attributional approach is preferable. However, a core consequential approach could be used to support the broader strategic decision needs of fuel producers.

Some aspects of the fuel lifecycle, such as iLUC and co-product allocation, are more suited to a core consequential approach. If iLUC is included in the attributional approach, it merely adds uncertainty. Therefore, a risk-based approach categorizing feedstocks into high and low iLUC risk categories based on the feedstock type and agricultural practices is preferable.

Coupling a core attributional approach for the input and output flows and consequential for handling co-products offers certainty on the core GHG-intensive activities while ensuring the benefits and burden of co-products are adequately captured. A global fuel lifecycle GHG methodology, based on a combination approach (similar to PEF and CARB applications), would provide confidence and certainty on the climate performance of alternative marine fuels. This could play a role in fuel certification and policy-making, unlocking the fuel production capacity needed to decarbonize.

09 About this project

This paper has been prepared as a part of the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping fuel lifecycle methodology development project. This project aims to understand the regulatory landscape for regulating fuel use in the transport industry and the subsequent impact of regulatory reform on the marine industry. Moreover, the project aims to determine how to support the industry in this transition by developing a lifecycle methodology. Our guidance on this topic will be published in 2023.

This qualitative regulatory landscape assessment will be accompanied by a quantitative assessment, which will also be published in 2023.

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12 Appendix

Roundtable of Sustainable Biomaterials (RSB)

RSB is an international sustainability standard and certification scheme following LCA guidelines, covering biofuels as a sustainable maritime fuel

The standard has identified 12 sustainability criteria for biofuels as maritime fuels, with the principle 3 defining the GHG lifecycle criteria minimum requirements. "Biofuels shall have on average 50% lower lifecycle GHG emissions relative to the fossil-fuel baseline (60% for new installations)."

The functional unit considered in RSB is gCO_2eq per MJ of finished biofuel (energy content determined by the lower heating value at 0% water as per the BioGrace standard values). For the feedstock processing part, the functional unit reported is kg CO_2eq/kg dry mass. The system boundaries considered are from cradle (fossil fuel feedstock extraction and biofuel feedstock production for fossil fuels and biofuels, respectively) up to, but not including the use of the fuel in an engine (i.e., well-to-tank). However, theoretical emissions from fuel combustion are included in calculating emissions from combustion.

The well-to-tank boundaries for GHG emissions include the impact of direct LUC, as well as above and below-ground carbon stock changes.

Attributional modeling is used for the LCI. Co-products from the production of biofuels are treated via the method of allocation of emissions. GHG emissions are divided between the fuel or its intermediate product and the co-products in proportion to their economic value (RSB Global Certification).

RSB uses REDII as a basis for the calculation of GHG emissions but also considers the additional carbon accumulation that could have happened if direct Land Use Change (LUC) to produce biofuels did not occur, the cutting and burning of plants (slash and burn), as well as N_2O emissions from the loss of soil organic carbon.

While agricultural crop residues were allocated zero emissions following a modification in March 2022, sustainability requirements now account for palm-based agricultural residues to prevent high deforestation risk feedstock from entering the supply chain for RSB certification without mitigation measures.

Allocation is based on energy content, whereby emissions are divided between products. The RSB follows RED II assumptions and default values for all other aspects. Coverage of fugitive emissions includes the following.

- Feedstock production
- Fuel production

TTW emissions from fuel combustion (i.e., use of final biofuel) are calculated based on the assumption that carbon is converted to CO_2. "Biogenic carbon emissions are assumed to be carbon neutral, as CO_2 was taken up from the atmosphere to grow the biogenic material. Therefore, biogenic carbon is not assigned any CO_2 emissions from fuel use; only fossil fuel is assigned CO_2 emissions." Emissions for CH_4 and N_2O, and other pollutants are not calculated, as emission factors of these GHG are highly dependent on engine efficiency. In addition, these emissions are found to be relatively low in comparison to lifecycle GHG emissions.

Renewable Energy Directive (RED II)

RED II provides LCA rules to limit the share of unsustainable crop-based biofuels and promote certain types of biofuels produced from a list of materials defined in its Annex IX. To qualify for RED II targets, biofuels must demonstrate compliance with the sustainability and GHG emission-saving criteria through national verification systems or European Commission-approved voluntary schemes. In addition to biofuels, Renewable Fuels of Non-biological origin (RFNBOs) are also considered eligible towards the 14% target.

The proposal for revising the REDII by EC in 2021 as part of the "Fit for 55" package and the expected Delegated Act on renewable fuels of non-biological origin (RFNBOs) is also relevant to maritime fuels. FuelEU Maritime indicates the emission factors of biofuels, biogas, RFNBOs, and recycled carbon fuels shall be determined according to the methodologies set out in Annex IX, part C of REDII. The FuelEU Maritime proposal further identifies the need for the EU to establish an

EU-wide methodology to certify maritime fuels on a WTW basis reflecting all GHG emissions by building upon existing practices such as the fuel import certification under REDII 6. Biofuels feedstock and production pathways covered are the same as RSB. For RFNBOs, e-diesel, e-methanol, e-LNG, e-hydrogen, and e-ammonia are considered. The functional unit is gCO_2eq/MJ of finished biofuel or e-fuel up to the fuel distribution, excluding combustion. Thus, the boundaries are determined on a WTT basis. For the TTW part, REDII assumes net zero tailpipe CO_2, CH_4, and N_2O for biofuels. Coverage of fugitive emissions includes the following.

- Feedstock production
- Fuel production

The agricultural residues are not considered for allocation as they are assumed to have zero GHG emissions.

Only direct LUC is accounted for in the GHG accounting. iLUC is not considered, and carbon capture and storage (CCS) is not included in the fuel production pathway. While the non-inclusion of agricultural residues and iLUC in the GHG emission accounting is argued that might create an incentive to increase the use of food-based first-generation biofuels to meet the 14% renewable share target in transport, the FuelEU Maritime Regulation recognizes the non-eligibility of food and feed crop-based fuels for the biofuel mandates in maritime 7 The EC adopted the Delegated Regulation (EU) 2019/807 setting out specific criteria for determining high iLUC risk feedstock (related to a significant expansion of the production area into land with high carbon stock observed) and certifying low iLUC risk biofuels- however iLUC is not accounted for in GHG accounting in REDII.

In addition, on May 20, 2022, the Commission published two Delegated Acts connected to RED II, aiming at providing a methodology for calculating the carbon intensity of the electricity used to produce RFNBOs. The approach to the additionality principle, e.g., whether the renewable electricity used to produce green hydrogen is excess electricity is important for capturing the realistic GHG emissions intensity reduction of e-fuels.

Greenhouse Gas, Regulated Emissions and Energy in Transportation (GREET)

GREET is an LCA model developed by Argonne National Laboratory – (U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy) evaluating energy and emission impacts of advanced and new transportation fuels, the fuel cycle from well to wheel, and the vehicle cycle through material recovery and vehicle disposal that need to be considered. The geographical coverage is North America; however, it is considered a flexible tool in assessing fuels globally. The model has been used in several US environmental policies; The US Environmental Protection Agency used GREET for the US Renewable Fuel Standards (RFS) covering US Biofuels standards and GHG standard developments in vehicles; CARB -Low Carbon Fuel Standard Compliance; The International Civil Aviation Organization (ICAO) used GREET to develop the carbon intensities of aviation fuel production pathways.

The model covers over 100 fuel pathways and was updated in 2021 to include five new maritime fuel pathways, namely, e-Methanol, conventional ammonia (grey ammonia from natural gas), low carbon ammonia (green ammonia – produced by H_2 + N_2 production via the Haber Bosch process), and finally by heavy fuel oil consumed in a scrubber retrofit vessel.

The boundaries of the GREET LCA were determined from cradle to gate for maritime fuel pathways, deriving from existing fuel pathways in GREET. The boundaries for the new maritime fuels introduced in 2021 go beyond the gate and include downstream maritime vessel operations and maritime fuel combustion on top of feedstock acquisition, processing, fuel conversion, and transportation. The downstream emission assessment considers specific fuel properties such as heating value, carbon content, sulfur content, the vessel's engine, and voyage-specific characteristics. Therefore, the functional unit can be expressed as gCO_2eq/ton mile, gCO_2eq/MJ, or other units such as per ton of biomass.

The modeling approach to co-products inventories assessment is the system expansion, while both energy and economic allocation are available as options. The allocation of impacts amongst co-products from the conversion processes are allocated based on energy, mass of fuel, and revenue depending on the production pathway. GREET accounts for both direct LUC and iLUC for certain biofuel production pathways, calculated with the Carbon Calculator for Land Use and Land Management (CCLUB). CCLUB uses global data for Land Use from the Global Trade Analysis Project (GTAP). Fugitive (methane) emissions from the production and distribution of the fuel are also accounted for. Fugitive emissions (methane leakage) from LNG distribution to storage and the bunkering stage are explicitly accounted for, contrary to the other reviewed studies. CCS is also accounted for.

JEC Well-to-Wheel Report and CORSIA

JEC Well-to-Wheel Report

The goal of the report is to provide a forward-looking assessment of future fuel and vehicle technology options from 2025 onwards. In this context, it assesses the impact that fuel and/or powertrain substitution in Europe has on the rest of the world's energy use and GHG emissions balance. The emissions quantification methodology is, therefore, consequential. The study does not directly address maritime fuels. However, certain alternative fuels, such as biofuels and synthetic fuels, may be relevant to the WTT boundary.

Well to Wheels - from feedstock collection, storage, transport, and processing to final distribution (WTT) and integration of the powertrain technology measuring emissions at the tailpipe (TTW), considering the engine's efficiency. The integration of WTW energy and GHG emission figures combines the WTT expended energy (i.e., excluding the energy content of the fuel itself) per unit energy content of the fuel – lower heating value basis measured in g CO_2eq/MJ final fuel. Including the TTW energy consumed by the vehicle, the g CO_2eq is expressed per unit of distance covered.

More than 250 pathways are modeled. Hydrotreated vegetable oil (HVO), Biodiesel FAME (from waste cooking oil), biomethane, synthetic diesel, and hydrogen are highly relevant for maritime usage. Emissions inventories are calculated based on the consequential methodology to co-products. For the WTT emissions measurement, results for alternative fuels that can be relevant for maritime fuel consumption showed that liquified bio-methane, electricity, and hydrogen can offer negative WTT emissions, as CH_4 and N_2O emissions are avoided when produced from biomass.

There is a big variability in upstream emissions for HVO, liquified biomethane, hydrogen and electricity production depending on the feedstock and conversion technology pathway.

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a voluntary carbon certification scheme that follows LCA for the GHG emissions of aviation fuels. The goal is to allow aircraft operators to offset carbon emissions by using eligible fuels, according to CORSIA, each year. It provides the default core life cycle GHG emissions of the different Sustainable Aviation Fuel (SAF) pathways, including all stages of the fuel supply chain. Boundaries extend from feedstock cultivation/collection to feedstock transportation, processing to jet fuel, transportation of jet fuel, and combustion in aircraft engines. While not covering maritime fuels, the WTT part of the boundary can be relevant for maritime biofuels. The geographical coverage of feedstock and processes is global for agricultural and forestry residue feedstock and animal fat and waste oil. In contrast, for the agricultural, forestry products and byproducts, such as sugarcane, corn grains, soybean oil, and the corresponding pathways, the coverage is regional to leading crops and agricultural byproducts producers (e.g., Brazil/USA for soybean oil, EU for rapeseed oil, Malaysia/Indonesia for palm oil).

The functional unit considered in CORSIA is in g CO_2eq per MJ of the biofuel or synthetic fuel produced and burnt in an aircraft engine (energy content determined by the lower heating value). The study is based on attributional LCA methodology for calculating GHG inventories. The residues, waste, and byproducts feedstock are not assigned upstream emissions before the feedstock collection, recovery, and extraction, and no ILUC is applicable for those feedstocks. iLUC applies only to agricultural feedstocks. The consequential approach is followed to estimate iLUC GHG emission values. The ILUC emission factor is derived from modeling exercises using GTAP-BIO and GLOBIOM models. Core LCA values are based on the attributional allocation of emissions on co-products when a production pathway leads to the production of multiple products based on their energy content. Core and iLUC GHG emission values are then summed up to final GHG

values.
Finally, emissions for transporting feedstock to the processing site from farms are measured according to distance, payload, and fuel consumption efficiency of the transport mode. The fuel conversion stage includes emissions from all inputs, including energy and chemical requirements and outputs. GHG emissions include CO_2, CH_4, and N_2O, except for the TTW emissions from fuel combustion, which only considers CO_2 emissions. The TTW GHG emissions from the combustion of biofuels produced from biomass are considered zero. CORSIA does not deploy a specific assessment tool.

RenovaBio and Renewable Transport Fuel Obligation (RTFO)

The National Biofuels Policy (RenovaBio)

Brazil has committed to reducing GHG emissions to 37% and 43% by 2025 and 2030, respectively, vs. 2005. The policy aims at reducing GHG emissions via commercializing the biofuel market with a focus on ethanol by creating biofuel decarbonization credits (CBIO). The program is voluntary for biofuel producers and importers but mandatory for fuel distributors with mandatory decarbonization goals based on their market share. In addition, the policy provides predictability of the transport fuel market over a 10-year period by setting national emissions reduction targets. The functional unit is expressed in g CO_2eq/MJ; The 2019 Brazilian fuel matrix carbon intensity value was 74.25 g CO_2eq/MJ, and in June 2018, a GHG reduction target of 10.1% by 2028 was set. The boundaries are expressed from cradle to grave; in the case of the program, the grave refers to the wheel.

The calculation of GHG inventories is done via the RenovaCalc tool. The methodology is based on energy allocation for co-products. Other input parameters quantified are the crop yield, the fertilizer application, and N_2O emission rate. Fuel and electricity and transport distance for domestic feedstock and biomass for energy generation are accounted for. Imported feedstock GHG emissions are also measured. The environmental criteria set by the RenovaBio initiative avoid the production of biofuel feedstock on lands converted from forest areas after December 2017 and limit the lands for sugarcane expansion within the demarked Agroecological Zoning.

However, LUC factors do not feed into the GHG emissions calculation. The traceability of soy and corn production is considered a challenge as several suppliers are involved. Thus, the estimation of the impact in terms of LUC/ deforestation may lack transparency.

Renewable Transport Fuel Obligation (RTFO)

RTFO is a regulation implemented in the UK to reduce GHG emissions from fuels supplied for road transport, non-road mobility machinery, and aviation and inland waterways by encouraging the use of renewable fuels. To serve its goal, it obliges fuel suppliers of road transport fuels trading more than 450,000 liters per annum to source a share of the fuel supplies from sustainable biofuels. Producers of sustainable biofuels are entitled to receive Renewable Transport Fuel Certificates (RTFCs) to comply with the target.

The RTFO order covers biofuels (e.g., ethanol, methanol, FAME, synthetic diesel, HVO, pure vegetable oil and dimethyl ether, biomethane) and RFNBOs (e.g., e-methane). The functional unit is expressed in units of g CO_2eq/MJ. The boundaries start from the cultivation of the feedstock through its processing and transportation of the fuel to the storage tank (excluding the fuel combustion stage), thus taking a WTW approach in GHG accounting. The GHG emissions methodology is attributional to co-products. The attributional method of assigning emissions is used based on the energy value. Crop residues are not taken into consideration when calculating carbon intensity. Waste and residues are attributed to zero GHG emissions up to the process of collection. The process of collection may involve the transportation of the material, and any emissions of this transport step are included in the calculation. LUC/iLUC: Only direct LUC is accounted for in the methodology. iLUC is not accounted for, although iLUC emission values are provided for reporting purposes. CCS savings are accounted for as well as feedstock production, fuel production, transport, and distribution.