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Original Paper

Towards methodological harmonization of life cycle assessment for marine fuels: A framework for informed policy decision-making

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Abstract: To address the escalating pressure to decarbonize international shipping, establishing a standardized Life Cycle Assessment (LCA) methodology is essential for evaluating the environmental integrity of alternative marine fuels. This paper critically examines the methodological consistency required for a global regulatory framework by analyzing preceding maritime LCA studies and established policies in the aviation and road transport sectors. Through a comprehensive technical analysis, this study identifies significant methodological ambiguities—such as inconsistent functional units, divergent GWP horizons, and varied allocation methods—that obstruct the reliable quantification of GHG emissions. The findings underscore the necessity of a harmonized regulatory roadmap, specifically recommending the adoption of GWP100 with IPCC AR6 values, the gCO_2 eq/MJ_LHV functional unit for regulatory integration, and a prioritized Attributional LCA (A-LCA) approach. By providing these strategic solutions, this research offers a methodological foundation to resolve uncertainties in maritime emission accounting, ensuring a stable and transparent transition toward a net-zero future for the global shipping industry.

Keywords: Life cycle assessment (LCA), IMO policy, Maritime decarbonization, Alternative marine fuels, Greenhouse gas (GHG), Regulatory harmonization

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1. Introduction

1.1 Background on Life Cycle Assessment Framework for Marine Fuel

The shipping sector is responsible for approximately 3% of global annual anthropogenic greenhouse gas (GHG) emissions, a figure comparable to the emissions of Germany, the world's 7th largest emitter **[1]**. Under business-as-usual scenarios where global trade doubles, these emissions are projected to increase by up to 250% by 2050. However, achieving the 1.5–2 °C climate target necessitates net-zero GHG emissions across all economic sectors, including international shipping **[2]**. In response, the International Maritime Organization (IMO) established an initial GHG strategy to reduce CO_2 intensity by 40% by 2030 and total GHG emissions by at least 50% by 2050 compared to 2008 levels **[3]**. Furthermore, following COP 26 in Glasgow, there is intensifying pressure to raise these targets to 100% to fully align with the 1.5 °C Paris Agreement goal **[4]**. It is projected that over 60% of these reduction efforts must be driven by the adoption of alternative low- and zero-carbon fuels **[5]**.

To improve ship energy efficiency, the IMO has implemented mandatory instruments under MARPOL Annex VI, such as EEDI, EEXI, and CII **[6][7]**. However, these indicators are limited in scope as they primarily account for Tank-to-Wake (TtW) emissions from on-board combustion, neglecting the significant upstream emissions associated with fuel production and distribution (Well-to-Tank, WtT). Such a restricted focus poses a regulatory risk: using a CO_2 conversion factor of "0" for fuels like hydrogen could inadvertently encourage the uptake of alternative fuels that may actually emit more GHGs over their entire lifecycle than conventional fossil fuels.

Recognizing this gap, the IMO initiated the development of "robust lifecycle GHG/carbon intensity guidelines for marine fuels" to encompass both upstream and downstream emissions **[3]**. As illustrated in **Figure 1**, Life Cycle Assessment (LCA) for marine fuels evaluates emissions from production to end-use (Well-to-Wake). While the importance of a Well-to-Wake (WtW) approach is internationally recognized, the development of robust default emission values and verification procedures remains hampered by a lack of unified and harmonized LCA methodologies.

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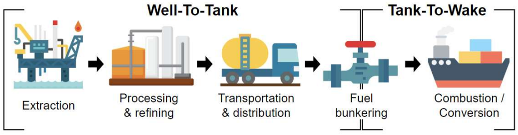

Figure 1: Generic Well-to-Wake supply chain

For the purposes of this paper, Well-to-Tank (WtT) refers to upstream emissions associated with feedstock extraction, fuel production, and distribution, Tank-to-Wake (TtW) refers to emissions from onboard fuel combustion or conversion during ship operation, and Well-to-Wake (WtW) refers to the combined emissions across the full fuel life cycle.

1.2 Problem Statement: Methodological Divergence and Policy

LCA is a systematic methodology for quantifying environmental impacts across a product's lifecycle **[8]**. Despite its well-established four-phase framework—goal and scope definition, inventory analysis, impact assessment, and interpretation (**Figure 2**)—each phase is subject to significant uncertainties **[9]**. Crucially, ISO standards do not prescribe specific methodologies for estimating these impacts, allowing for a high degree of flexibility that complicates direct comparisons between studies **[10]**.

In the context of maritime policy, this methodological divergence creates "regulatory gray areas." Divergent choices in functional units, global warming potential (GWP) horizons, and allocation methods lead to inconsistent appraisal of alternative fuels. Such uncertainty not only complicates the establishment of default values but also hinders long-term investment and the effective transition to sustainable fuels. Although the global shipping industry is increasingly exploring alternative energy sources **[11]**, the scarcity of research based on harmonized LCA methodologies often leads to an underestimation of the comprehensive environmental impacts of these fuels.

1.3 Objectives and Structure of the Study

This paper addresses the critical need for methodological consistency as a prerequisite for informed policy decision-making. Rather than merely offering suggestions for a specific regulatory body, the study aims to identify the key methodological determinants that should be harmonized to support a unified LCA framework for marine fuels and to provide a stable foundation for international maritime regulation. By critically reviewing the existing literature on marine fuel LCA and comparing relevant policy approaches adopted in other transport sectors, this paper seeks to provide pragmatic insights into how a standardized LCA framework can reduce regulatory ambiguity and industry-wide uncertainty.

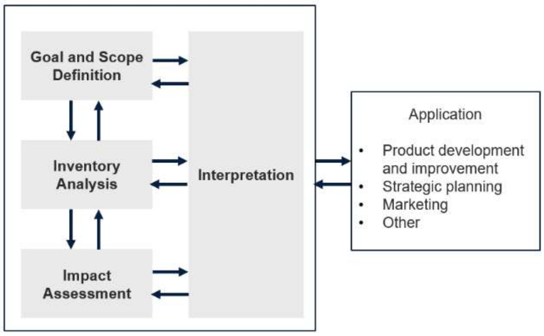

Figure 2: Main stages of lifecycle assessment framework

Unlike previous studies, which mainly compare specific fuel pathways or report LCA results under varying assumptions, this review focuses on the methodological issues that shape regulatory consistency. Specifically, it contributes by: (1) synthesizing the principal sources of methodological divergence in marine fuel LCA studies; (2) comparing these issues with established policy approaches in other transport sectors; and (3) proposing a policy-oriented framework to support informed decision-making for maritime fuel regulation.

The overall objective is to establish a robust basis for the consistent appraisal of the greenhouse gas (GHG) emissions and sustainability performance of alternative marine fuels. Such harmonization is indispensable for providing a clear, unequivocal signal to both regulators and the shipping industry, thereby enabling a proactive and effective transition to net-zero shipping.

The remainder of this paper is organized as follows: Section 2 reviews previous literature on marine fuel LCA and compares policies in other transport sectors. Section 3 identifies technical requirements for improving the LCA framework within maritime instruments. Finally, Section 4 elaborates on the conclusion and broader policy implications.

2. Literature Review

2.1 LCA Application for Policy in Other Transport Sectors

Before analyzing specific studies on marine fuels, this section examines how LCA-based policies have been integrated into other transport sectors. The successful implementation of LCA-based regulations, such as Low Carbon Fuel Standards (LCFS), demonstrates that LCA is no longer just a research tool but a fundamental pillar for evaluating and enforcing environmental policies **[12]**.

Table 1: List of policies with LCA approach in other transport sectors

Scheme	Description	Fuels	Region	Scope
British Columbia Low Carbon Fuel Standard (BC-LCFS)	Requirements on annual goals for fuel suppliers to reduce the average carbon intensity of fossil fuels	Fossil fuels	Canada (British Columbia)	WtW
California Low Carbon Fuel Standard (CA-LCFS)	Standard designed to reduce the carbon intensity of California's transportation fuel pool and promote the use of an variety of low-carbon and renewable alternatives fuel	Low-carbon and renewable alternatives fuel	USA	WtW
Clean Fuel Standard	Standard for fuel suppliers (producers and importers) to reduce the lifecycle carbon intensity of fuels	Fossil fuels	Canada	WtW
Renewable Energy Directive II (RED II)	Setting a common target for the promotion and use of energy from renewable sources within the EU	Biofuels and bioliquids	EU	WtW
Renewable Fuel Standard	Standard for fuel refiners or importers to achieve compliance by blending renewable fuels into transportation fuel(or by obtaining credits)	Renewable fuels including biofuels	USA	WtW
Renewable Transport Fuel Obligation	Detailed regulation for biofuels used for transport and non-road mobile machinery	Biofuel	UK	WtT
ICAO CORSIA	Requirements on a CORSIA eligible fuel	Fossil fuels and renewable or waste-derived fuels	International aviation	WtW

As shown in **Table 1**, LCA-based approaches are already deeply embedded in various regional and international regulatory frameworks. These policies rely on the accurate determination of a fuel's Carbon Intensity (CI) across its entire lifecycle—from feedstock extraction and production to distribution and end-use. For example, under many of these regimes, fuel providers are required to achieve specific lifecycle GHG reduction targets (e.g., gCO$_2$eq/MJ), creating a market-based mechanism where compliance is directly tied to the rigor of the LCA methodology **[13]**.
A critical analysis of these existing frameworks reveals several key insights for the maritime sector:

- Regulatory Precedents: Standards like California's LCFS and the EU's RED II have established that a Well-to-Wake (WtW) perspective is essential for preventing "carbon leakage" across the supply chain.
- Safeguarding Sustainability: RED II and CORSIA have pioneered the integration of sustainability
- criteria beyond carbon, such as preventing the use of biomass from land with high carbon stocks [14, 15].
- Cross-Sectoral Alignment: ICAO's CORSIA provides a particularly relevant template for the IMO, as it addresses international emissions through an agreed-upon LCA method that includes Induced Land Use Change (ILUC) and rigorous certification practices **[16][17]**.

These established policies should be viewed as benchmarks for methodological harmonization. The shipping sector can leverage these precedents to reduce the "learning curve" in policy development and ensure cross-sectoral regulatory consisten

2.2. Review of Existing LCA Research on Marine Fuels

While the transport sector as a whole is moving toward LCA-based regulation, a review of specific literature on marine fuels reveals a significant lack of methodological consistency. **Table 2** summarizes the diversity of approaches adopted across the 22 studies reviewed and highlights substantial divergence in key LCA parameters:

- Divergent Functional Units: The use of diverse functional units (g/MJ, g/kWh, tkm) hinders direct cross-pathway comparisons of environmental performance for policymakers
- Inconsistent GWP Horizons: While most studies use GWP 100, several include GWP 20 or even GWP 500 [18], leading to vastly different appraisals of fuels with high methane or ammonia slip.

Table 2: Comparative analysis of LCA Studies on marine fuels

Ref.	Type of fuels	GHG emission Scope	Global warming potential	Sustainability criteria except for GHG	Functional Unit	Life cycle inventory database/tool
[19]	Methanol, Biomethanol, LNG, Hydrogen in Solid Oxide Fuel Cells (SOFC)	CO_2, CH_4, N_2O	GWP 100	ODP, POCP, AP, EP	kg CO_2eq per kWh (electricity)	SimaPro
[20]	HFO, MGO, LNG, GTL(gas-to-liquid)	CO_2, CH_4, N_2O	GWP 100	AP, EP	t CO_2eq per 1 t cargo transported 1 km with a ro–ro vessel	ELCD, JEC
[21]	HFO, MGO, Rapeseed methyl ester (RME), Synthetic bio-diesel (BTL), LNG, Bio-LNG	CO_2, CH_4, N_2O	GWP100	AP, EP, Agricultural land use, Primary energy use, and PM	g CO_2eq /MJ fuel: emission factors for the engines on the ro-pax ferries based on the yearly fuel consumption corresponding to energy content	ELCD, JEC
[22]	HFO, LNG, Methanol, bio-LNG, Biomethanol	CO_2, CH_4, N_2O	GWP100	PM, POCP, AP, EP	1 t cargo transported 1 km with a ro-ro vessel (g CO_2eq/t km)	ELCD, JEC
[18]	HFO, Hydrogen, Ammonia	CO_2, CH_4, N_2O	GWP 500	ADP, AP, ODP Ecotoxicity Potentials	g CO_2eq emission per tonne-kilometre cruise travel where the functional unit is 1 tonne-kilometre.	GREET
[23]	HFO, MDO, LNG, Hydrogen, Methanol, Bio-LNG, Biodiesel	CO_2, CH_4, N_2O	GWP 100	Air quality (NOx, SOx, PM)	g CO_2eq emission/kWh delivered to the shaft	Ecoinvent, ELCD
[24]	HFO, MGO, LNG	CO_2, CH_4, N_2O	GWP100 & GWP 20	(GWP only)	g CO_2eq per 1 kWh of energy transferred to the ship propeller	Oil Production Greenhouse Gas Emissions Estimator (OPGEE), GREET
[25]	HFO, MGO, LNG	CO_2, CH_4, N_2O	GWP100	AP, PM, POCP, EP	g CO_2eq emission per the supply and consumption of LHV(MJ) of fuel	Gabi
[26]	HFO, LSFO, MGO, LNG	CO_2, CH_4, N_2O	GWP20 & GWP 100	Air quality (NOx, SOx, PM)	g CO_2eq emission per 1 kWh brake power specific unit (g CO_2eq/kWh)	GREET
[27]	HFO, LNG	CO_2, CH_4, N_2O	GWP 100	Air quality (NOx, SOx)	g CO_2 emissions per kWh engine output	GREET
[28]	MDO, Methanol, LNG	CO_2, CH_4, N_2O	GWP 20 & GWP 100	Air quality (NOx, SOx, PM)	mass per energy units (e.g., g/MJ) with engine efficiency	GREET /TEAMS

Ref.	Type of fuels	GHG emission Scope	Global warming potential	Sustainability criteria except for GHG	Functional Unit	Life cycle inventory database/tool
[12]	HFO, LSFO, MGO, LNG	CO_2, CH_4, N_2O	GWP 20 & GWP 100	(GWP only)	g CO_2eq emissions per kWh as a function of fuel and engine	Gabi, GREET, JRC
[29]	Methanol, Dimethyl ether, LNG, Hydrogen, Biodiesel, Electricity	CO_2, CH_4, N_2O	GWP 100	(GWP only)	tons of CO_2eq.	GREET
[30]	MDO, LNG, Bio-LNG	CO_2, CH_4, N_2O	GWP 100	AP, EP, PM, human health	g CO_2eq /MJ fuel with engine efficiency	Literature review
[31]	HFO, LNG	CO_2, CH_4, N_2O	GWP 100	(GWP only)	g CO_2eq emission per “1 t of cargo transported for 1 km (1 tkm)” and “1 passenger transported for 1 km (1 pkm)”	ELCD, Ecoinvent
[32]	HFO, LSFO, MGO, LNG	CO_2, CH_4, N_2O	GWP 20 & GWP 100	(GWP only)	g CO_2eq emission per shaft work produced by the engine (g/kWh)	GREET
[33]	LNG	CO_2, CH_4, N_2O	GWP 100	(GWP only)	-	GREET, GHGenius
[34]	HFO, LNG	CO_2, CH_4, N_2O	GWP 100	AP, EP	g CO_2eq emission per unit of fuel energy (g/MJ fuel)	Literature review
[35]	HFO, LSFO, MGO, LNG	CO_2, CH_4, N_2O and Black carbon	GWP 20 & GWP 100	(GWP only)	g CO_2eq emission per the mass of fuel the ship consumed	GREET
[36]	Biogas, Dimethyl ether, Ethanol, LNG, LPG, Methanol, Ammonia, Biodiesel	CO_2, CH_4, N_2O	GWP 20, GWP 100, GWP 1000	human health, ecosystem, resource utilization, emission inventory	g CO_2eq emission per 1 ton or the equivalent volume of fuel	SimaPro
[37]	Bio-methanol, Fossil methanol, Electro-methanol (eMeOH), MGO	CO_2, CH_4, N_2O	GWP 20, GWP 100	AP, EP, POCP, PM, terrestrial eutrophication	g CO_2eq emission per a voyage with a RoPax vessel travelling	ELCD
[38]	Hydrogen	CO_2, CH_4,N_2O	GWP 100	HTP,POCP,AP,ADP,ODP ,EP, Ecotoxicity Potentials	g CO_2eq emission per 1 kWh of energy obtained from the PEMFC and the ICEs systems	Gabi

Abbreviations: GWP (global warming potential), AP (acidification potential), EP (eutrophication potential), PM (particulate matter), POCP (photochemical ozone creation potential), HTP (human toxicity potential), ADP (abiotic depletion potential), and ODP (ozone depletion potential).

- Varied LCI Databases: The use of different databases (GREET, Ecoinvent, GaBi, ELCD) introduces underlying data uncertainties that can obscure the true climate impact of alternative fuels.

These findings underscore the core premise of this paper: the current body of research, while technically rigorous, is too fragmented to provide a stable foundation for international maritime policy. The methodological "gray areas" identified in this review—ranging from functional unit selection to sustainability criteria—necessitate a move toward a unified and harmonized LCA framework to support informed and unequivocal policy decision-making.

3. Key Determinants for a harmonized LCA Framework in Shipping

Previous studies have extensively investigated alternative marine fuels using diverse LCA methodologies. As analyzed in Section 2, the broad variance in outcomes stems from inconsistencies in methodological criteria, such as GHG emission scope, Global Warming Potential (GWP) horizons, functional units, and inventory databases. To establish a robust and consistent framework for policy decision-making, the following factors must be harmonized.

To more clearly position the contribution of this study within the maritime regulatory context, **Table 3** identifies selected methodological gaps in the current IMO framework for marine fuel assessment and links them to the harmonization measures proposed in this paper. By juxtaposing these gaps with the corresponding measures, the table highlights the practical relevance of the proposed framework for improving consistency in marine fuel LCA. It also demonstrates that harmonization is not merely a methodological issue, but a necessary condition for credible regulatory implementation, predictable compliance, and greater policy certainty.

3.1 GHG Emissions Scope

The UNFCCC identifies six primary greenhouse gases, yet existing mandatory IMO instruments—EEDI, EEXI, and CII—exclusively address CO_2 emissions **[7][39]**. While the Fourth IMO GHG Study provided estimates for CO_2, CH_4, N_2O, and Black Carbon (BC), most previous LCA research has omitted BC from its scope **[5]**.

BC is a potent non-gaseous climate forcer with a warming impact second only to CO_2 in the maritime sector, possessing a GWP of approximately 900 **[40]**. Its inclusion would theoretically raise shipping's contribution to global CO_2-equivalent emissions from 3% to approximately 7% **[1]**. Its impact is particularly critical in the Arctic, where BC deposits accelerate ice melting by reducing the albedo effect **[41]**.

Despite its significance, this paper suggests that the immediate regulatory framework should prioritize the three main GHGs (CO_2, CH_4, N_2O) to ensure alignment with other transport sectors and international reporting standards. Due to the current lack of standardized measurement protocols for BC, a phased-in

Table 3: Illustrative gap analysis between the current IMO approach to marine fuel assessment and the proposed harmonized LCA framework

Current gaps in the IMO framework for marine fuel assessment	Why it matters	Proposed response in this paper
Predominant reliance on Tank-to-Wake (TtW) or CO_2-focused metrics in operational instruments	Upstream emissions and non-CO_2 greenhouse gases may be insufficiently reflected in fuel policy	Expand the framework toward a Well-to-Wake (WtW) approach covering CO_2, CH_4, and N_2O
Absence of a fully harmonized LCA methodology for marine fuels	Results vary significantly across studies, reducing transparency and policy certainty	Harmonize key methodological determinants, including GHG scope, GWP horizon, functional unit, allocation method, and modelling approach
Limited recognition of pathway-specific certified actual values	Supply-chain improvements may not be adequately reflected in regulatory assessment	Introduce certification-based use of actual values alongside transparent default values
Incomplete treatment of sustainability criteria beyond GHG emissions	Fuel switching may create burden-shifting across environmental or social dimensions	Apply phased sustainability criteria supported by certification schemes
Unclear treatment of indirect effects such as ILUC	Biofuel pathways may be evaluated inconsistently across regulatory contexts	Use A-LCA as the default approach while allowing targeted use of C-LCA for specific indirect effects

approach is recommended. This allows for immediate policy action on gaseous emissions while continuing the technical development required to accurately reflect the industry's full climatic impact in the future.

3.2 Global Warming Potential

GWP measures a gas's heat-trapping ability relative to CO_2 over a specific timeframe. While a 20-year horizon (GWP20) is frequently used in sensitivity analyses to highlight the near-term impact of methane slip **[28][35]**, the international regulatory consensus—including CORSIA and EU RED II—favors a 100-year horizon (GWP100) **[42]**.

To ensure cross-sectoral comparability and alignment with the Paris Agreement's long-term goals, this paper recommends the adoption of GWP100 as the primary metric for the IMO LCA framework. Crucially, the framework must utilize updated values from the IPCC Sixth Assessment Report (AR6) (e.g., CH_4: 29.8, N_2O: 273). Moving away from the outdated AR5 values prevalent in older studies is a prerequisite for ensuring that maritime policies remain scientifically synchronized with UNFCCC reporting standards.

3.3 Functional Unit : Bridging fuel intensity and regulatory Compliance

The functional unit is the reference basis for quantifying environmental impacts and ensuring comparability between different fuel technologies **[8][43]**. Applying inconsistent functional units to identical fuels leads to incomparable results, creating significant hurdles for policymakers **[44]**.

Currently, other transport sectors have normalized their frameworks based on gCO_2eq/MJ_fuel. For the maritime sector, selecting an appropriate unit requires distinguishing between fuel production (WtT) and on-board consumption (TtW). Possible functional units can be categorized into three primary options, as evaluated in **Table 4**.

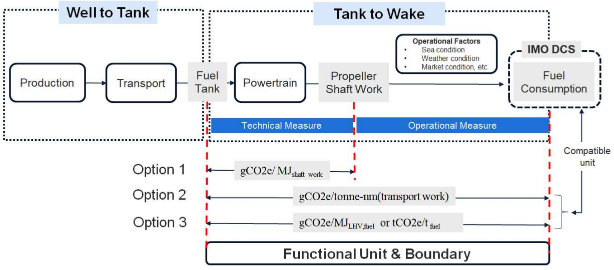

Figure 3: Diagram of possible functional units for IMO LCA Frameworks

Table 4: Evaluation of functional units

Option	Functional Unit	Purpose
1	$gCO_2eq/MJ_{\text{shaft work}}$ or $gCO_2eq/kWh_{\text{engine output}}$.	This unit can rank order or prioritise specific propulsion systems with specific fuel
2	$t\ CO_2eq$/tonne-nm	This unit with transport work (tonne-nm) can rank order or evaluate the performance of specific vessels or operators
3	tCO_2eq/t_{fuel} or $gCO_2eq/MJ_{LHV,\text{fuel}}$	This unit is multiplied by fuel quantities to evaluate total lifecycle emissions

While Option 1 (gCO_2eq/kWh) effectively captures engine efficiency, it fails to account for broader vessel-specific or operational factors. Option 2 (gCO_2eq/tonne-nm) is useful for monitoring individual vessel performance **[45]** but is influenced by complex variables like speed, weather, and cargo load, making it unsuitable for isolating the GHG intensity of the fuel itself **[46]**.

To align with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, this paper proposes that $gCO_2eq/MJ_{LHV,\text{fuel}}$ is the most appropriate functional unit for the following reasons:

- DCS Integration: This unit can be directly multiplied by fuel quantities reported to the IMO Data Collection System (DCS), facilitating seamless and transparent regulatory enforcement.
- Cross-Sectoral Harmony: It aligns with established global standards in aviation (CORSIA), road transport, and the EU's FuelEU Maritime regulation.
- Technological Neutrality: While the fuel-based unit does not inherently account for energy converter differences (e.g., Internal Combustion Engines vs. Fuel Cells), these variations can be addressed through differentiated TtW emission factors **[47]**.

In conclusion, utilizing $gCO_2eq/MJ_{LHV,\text{fuel}}$ provides a robust, concise, and stable basis for calculating Well-to-Wake emissions, enabling the IMO DCS to effectively reflect the life-cycle GHG intensity of the fuel pathway in a transparent and comparable manner. It should be noted, however, that this metric is intended to measure the fuel itself, rather than the specific operational performance of an individual ship or engine. Ship-level or engine-level performance may vary depending on vessel design, propulsion technology, engine configuration, and operating conditions, and therefore requires separate performance-based indicators.

3.4 LCA database / modelling tool

The selection of a Life Cycle Inventory (LCI) database is a primary factor contributing to the significant variability of results in marine fuel LCA studies. As analyzed in Section 2, the use of disparate data sources often leads to inconsistent emission factors for identical fuel pathways. To ensure the regulatory reliability of the IMO LCA framework and support informed policy decision-making, it is essential to understand the geographical coverage, methodological transparency, and process details of major databases and software tools.

3.4.1 Ecoinvent

Ecoinvent is one of the most comprehensive and widely recognized LCI databases globally. It provides consistent and transparent data based on industry-vetted averages across various sectors. The database is highly integrated into major LCA software like SimaPro and GaBi, predominantly utilizing a cradle-to-gate modeling approach. Its strengths lie in its extensive process documentation and broad category coverage, making it a reliable source for general industrial processes and energy backgrounds.

3.4.2 ELCD database

Developed by the Joint Research Centre (JRC) of the European Commission, the ELCD provides high-quality LCI data for core materials, energy carriers, transport, and waste management systems within the European context. It is designed to support the European Platform on Life Cycle Assessment and is accessible free of charge. While its data sets comply with ISO 14040/14444 standards, its scope is more focused on European industrial sectors and may require supplementation with other databases for broader applications

3.4.3 GaBi Database

The GaBi database, provided by Sphera (formerly PE International), is renowned for being one of the largest and most consistent LCI repositories on the market. It offers a vast array of processes, particularly in manufacturing and energy production, which are updated annually by technical experts. GaBi’s strengths include high methodological consistency and detailed inventory documentation, supporting a wide variety of life cycle impact assessment (LCIA) methods.

3.4.4 GREET

Developed by Argonne National Laboratory, GREET is specifically designed to evaluate the environmental impacts of transportation fuels and vehicle technologies. It consists of two submodels: the fuel-cycle (Well-to-Wheels) and the vehicle-cycle. Although its primary focus is on the North American context, it is extensively used in maritime studies due to its robust modeling of alternative fuel pathways and its ability to analyze criteria pollutants alongside greenhouse gases.

Table 5: Comparative characteristics of major LCA databases and tools

Database	Primary Region	Key Strengths	Marine Sector Coverage
Ecoinvent	Global	High transparency, broad industrial data	Partial
ELCD	Europe	European policy alignment, core materials	Limited
GaBi	Global	Large-scale industry data, annual updates	Moderate
GREET	North America	Specialized in transport fuels and WtW	High
SimaPro	Global	Tool flexibility, multiple database integration	High

3.4.5 SimaPro

SimaPro is a leading LCA software tool that integrates several LCI databases, including Ecoinvent and various industry-specific datasets. It is highly valued in the research community for its flexibility and ability to perform complex impact assessments using multiple global mainstream LCIA methods. The tool provides powerful graphical features, such as process tree diagrams, which aid in identifying carbon hotspots within the fuel supply chain.

The diversity of these tools underscores the challenge of establishing unified default emission values. For a harmonized regulatory framework, it is imperative that policymakers define standardized data selection criteria to prevent the "cherry-picking" of data that could artificially lower carbon intensity. Furthermore, the framework should mandate the use of databases that offer high methodological transparency to ensure that LCA results are auditable by third-party verifiers, thereby enhancing the policy robustness and global consistency of maritime regulations.

3.5 Sustainability Criteria and Certification Scheme

Table 6: Economic, environmental, and social criteria for evaluating alternative marine fuels **[46]**

Environmental	Economic	Social
• Life cycle GHG • Air pollutions • Ocean acidification • Ecosystem degradation • Depletion of natural resources • Land use change	• Capital expenditures • Operational expenditures • Fuel cost • Opportunity cost • Safety-related risk costs • Possible regulatory penalty	• Regulatory compliance • Social acceptability • Ethics and social responsibility • Public health impact •Occupational health and safety • Socio-economic development

To achieve a comprehensive evaluation of marine fuel sustainability, it is imperative to integrate environmental, social, and economic dimensions throughout the entire life cycle. As identified by Ashrafi *et al.* (2022) through a multi-stakeholder participatory approach **[46]**, 18 sustainability criteria provide a systematic framework for evaluating alternative fuels, ensuring that greenhouse gas (GHG) reductions do not come at the expense of other ecological or social assets (**Table 6**).

From a policy perspective, a life-cycle approach to sustainability is essential for informing strategic investment decisions and preventing "burden-shifting" between different environmental impact categories **[48]**. Several existing transport regulations, most notably ICAO's CORSIA and the EU's RED II, have already established robust sustainability criteria to define eligible fuels.

3.5.1 Lessons from Aviation: CORSIA’s Certification Framework

ICAO’s CORSIA framework provides a highly relevant precedent for the maritime sector. It distinguishes between Sustainable Aviation Fuels (SAF) and Lower Carbon Aviation Fuels (LCAF), mandating that these fuels achieve at least a 10% reduction in life-cycle GHG emissions compared to conventional fuels and are not produced from high carbon-stock land **[16]**. Crucially, compliance is managed through approved Sustainability Certification Schemes (SCS).

Figure 4 illustrates the alignment between CORSIA and the International Sustainability and Carbon Certification (ISCC). This mechanism demonstrates how international regulatory bodies can utilize third-party certification to ensure that chemically identical fuels (e.g., bio-methanol vs. fossil-methanol) are distinguished based on their verified sustainability performance.

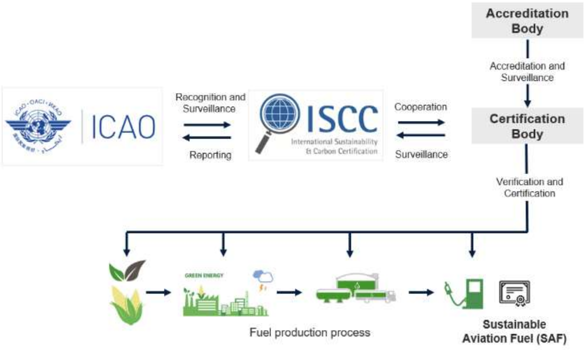

Figure 4: The processes and elements of sustainability certification: Alignment between CORSIA and ISCC

3.5.2 Proposed Methodological Approach for Maritime Policy

For the maritime sector to achieve a harmonized and enforceable regulatory framework, the recognition of certification schemes is essential. This allows for the use of "certified actual emission values," which provide more accurate data than conservative default values, incentivizing producers to optimize their supply chains.

In a regulatory context, default emission values should serve as transparent, comparable, and uniformly applicable benchmark values, particularly where pathway-specific data are unavailable or cannot be reliably verified. By contrast, certified actual values may be used to reflect geographically and operationally differentiated supply chains, provided that they are supported by robust certification systems, clearly defined data quality requirements, and independent third-party verification. A harmonized framework should therefore specify when default values apply, under what conditions actual values may be accepted, and how uncertainty arising from regional variability, data quality, and supply-chain differences should be managed. In this way, default values provide regulatory consistency, while actual values create incentives for verified improvements in supply-chain performance.

Considering the technical complexity of implementing global sustainability standards, this paper argues for a phased-in methodological approach to support stable policy transition:

- Phase 1: Fundamental Criteria. Focus on life-cycle GHG emission reductions and land-use safeguards (e.g., avoiding high carbon-stock land).
- Phase 2: Expanded Criteria. Incorporate broader sustainability dimensions, such as impacts on water

Table 7: Sustainability criteria and allocation choices in other transport policies **[17][49]**

Legislation	Region covered	Sustainability criteria	Allocation method
Renewable Transport Fuel Obligation (RTFO)	UK		System expansion (or substitution) approach whenever possible, if not allocation based on economic value
Renewable Energy Directive (RED II)	EU	Certification required (Third-party voluntary certification to ensure consistency with the land-use criteria and verify overall LCA emissions) GHG reduction eligibility threshold Sustainability criteria (Specific criteria applicable to biofuels to maintain soil quality and biodiversity and protect against deforestation	Energy based allocation, except for electricity co-production for which it is a system expansion (or substitution)
Low Carbon Fuel Standard (LCFS)	California	Certification needed GHG reduction eligibility threshold Sustainability criteria (Land carbon stock, water quality and availability, soil health, air quality, biodiversity conservation, waste and chemicals management, human labor, land use and water use rights, and food security)	System expansion (or substitution) approach whenever possible, if not allocation based on energy content
Renewable Fuel Standard (RFS)	US	Certification needed (LCA assumptions) Aggregate compliance (monitor nationwide LUC)	System expansion (or substitution) approach
CORSIA	International aviation sector	Certification needed GHG reduction eligibility threshold Sustainability criteria (Land carbon stock, water quality and availability, soil health, air quality, biodiversity conservation, waste and chemicals management, human labor, land use and water use rights, and food security)	Energy based allocation

- quality, soil health, and air pollution, as measurement protocols become standardized.

In conclusion, the analysis in Sections 3.6 to 3.8 indicates that the significant divergence in LCA outcomes is primarily driven by how studies handle functional units, sustainability criteria, co-product allocation, and modeling choices (A-LCA vs. C-LCA). Addressing these variances through a harmonized certification and criteria framework is a prerequisite for informed decision-making and the successful global uptake of low-carbon marine fuels.

3.6 Attributional (A-LCA) and consequential (C-LCA) modelling

The choice between attributional (A-LCA) and consequential (C-LCA) modelling—the latter also known as marginal modelling—is a fundamental decision in LCA methodology **[50]**. This selection is typically made during the goal and scope definition phase and determines how the system boundary is drawn and how impacts are quantified **[51]**.

- Attributional approach: A system modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.
- Consequential approach: A system modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.

Figure 5 provides a simple conceptual comparison between attributional LCA (A-LCA) and consequential LCA (C-LCA). A-LCA focuses on the environmental burdens directly associated

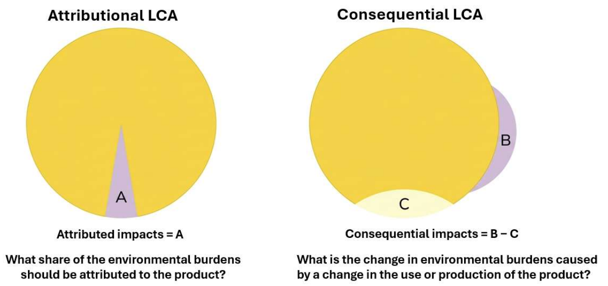

Figure 5: Conceptual comparison of attributional and consequential LCA. Adapted from National Academies of Sciences, Engineering, and Medicine **[68]**, originally based on Weidema **[67]**.

Table 8: Main differences between attributional and consequential modelling principles **[52]**

	Attributional approach	Consequential approach
Goal	Analysis of an average operation (e.g., on an annual basis)	Analysis of changes in operation (e.g., changes in demand)
Guiding question	For example, what are the potential environmental impacts of the average production of 1 ton of fuel (under different technical conditions)?	For example, what are the potential environmental impacts of a decrease in fossil fuel demand due to the increase in the use of alternative fuels in the transport sector?
Approach	Assigns elementary flows and potential environmental impacts to a specific product system typically as an account of the history of the product. Can use scenario analysis to project future technical situations	Studies of the environmental consequences of possible (future) changes within one or between multiple product systems

with a defined product or fuel pathway, whereas C-LCA considers how total environmental burdens change when production or use changes. In this sense, A-LCA asks what share of existing burdens should be assigned to the product, while C-LCA asks what additional or avoided burdens arise as a consequence of a change in demand or production.

The primary differences between these two approaches, as identified by the European Council for Automotive R&D [52], are summarized in **Table 8**.

3.6.1 Methodological Divergence in Marine Ruel Research

Although the choice of modelling approach can significantly alter environmental impact results, many LCA studies on marine fuels do not explicitly state whether they employ A-LCA or C-LCA (see **Table 1**). This lack of transparency complicates the efforts of policymakers to harmonize default emission values.

Some researchers opt for C-LCA **[20]-[22]**, arguing it is more appropriate for supporting climate policy decisions by considering the systemic consequences of product avoidance **[53][54]**. Conversely, others select A-LCA **[23][24][26][37]**, contending it is better suited for national emission accounting and environmental taxation due to its focus on direct physical flows **[55]**.

Table 9: Suggested application of attributional and consequential LCA approaches in maritime fuel policy

Policy purpose or issue	Recommended approach	Reason
Setting default WtW emission values	A-LCA	Based on observable physical flows and suitable for stable regulatory accounting
Compliance assessment of fuel pathways	A-LCA	Supports transparency, comparability, and verification
Assessment of ILUC	C-LCA	Captures indirect market-mediated effects
Evaluation of broader indirect consequences	C-LCA	Useful for scenario-based policy analysis

3.6.2 Policy Alignment and Recommendations for Harmonization

From a regulatory perspective, the CORSIA framework provides a practical template for balancing these two models. It utilizes A-LCA to account for physical flows (mass and energy) along the upstream process, while applying C-LCA specifically to address Indirect Land Use Change (ILUC) emissions through complex economic models like GTAP-BIO and GLOBIOM **[16][17]**. To clarify when each modelling approach is most appropriately applied, **Table 9** summarizes the suggested use of A-LCA and C-LCA for different policy purposes in maritime fuel regulation.

To ensure regulatory clarity and methodological stability in the maritime sector, this paper proposes the following:

- Prioritization of A-LCA: For establishing robust targets and defining default Well-to-Wake (WtW) emission values, A-LCA should be prioritized. Its reliance on observable physical flows provides higher certainty and stability, which is essential for global regulatory compliance and fuel accounting.
- Targeted Use of C-LCA: A degree of flexibility should be maintained to incorporate consequential elements strictly when addressing complex feedstock-to-fuel pathways, such as ILUC associated with biofuels.

Table 10: Allocation choices in fuel policies **[17][49]**

Legislation	Region covered	Allocation method
Renewable Transport Fuel Obligation (RTFO)	UK	System expansion (or substitution) approach whenever possible, if not allocation based on economic value
Renewable Energy Directive (RED II)	EU	Energy based allocation, except for electricity co-production for which it is a system expansion (or substitution)
Low Carbon Fuel Standard (LCFS)	California	System expansion (or substitution) approach whenever possible, if not allocation based on energy content
Renewable Fuel Standard (RFS)	US	System expansion (or substitution) approach
CORSIA	International aviation sector	Energy based allocation

By establishing A-LCA as the standard while allowing C-LCA for specific sustainability criteria, the maritime regulatory framework can achieve a balance between scientific integrity and policy enforceability, providing a clear and stable signal for the shipping industry's energy transition.

3.7 Allocation method for co-products: Balancing theory and regulatory practicability

In fuel production processes that generate multiple co-products, environmental impacts must be accurately defined and assigned to each output. The methodology chosen for this assignment is critical, as it directly dictates the final carbon intensity value of the marine fuel. Two primary approaches are widely applied in LCA studies:

Proportional Allocation: This method partitions inputs and impacts based on physical or economic relationships, such as mass, energy content (Lower Heating Value), or market value.

System Expansion (Substitution Method): This approach expands the system boundaries to account for the environmental impacts of products displaced by the co-products, effectively "crediting" the main product for emissions avoided elsewhere.

While system expansion is often considered the preferred theoretical approach in LCA literature—particularly for consequential LCAs—and is recommended by ISO standards when feasible **[8]**, its application in a global regulatory context presents significant challenges.

3.7.1 Regional Divergence and the Need for Harmonization

As summarized in **Table 10**, existing regulations vary significantly in their handling of co-products, reflecting different legislative priorities.

This lack of international harmonization creates substantial uncertainty for marine fuel producers and the shipping industry. Research has demonstrated that the calculated emissions for a single fuel pathway can vary significantly depending on the chosen allocation method **[56]**, potentially leading to conflicting regulatory interpretations and market distortions.

3.7.2 Methodological Requirements for Policy Robustness

For a global regulatory framework like the IMO's to be effective, it must prioritize transparency, stability, and ease of verification. While system expansion may be theoretically robust, its reliance on complex assumptions about "displaced products" and market dynamics makes it difficult to implement and verify on a global scale.

In contrast, physical allocation (specifically energy-based) offers several advantages for international policy:

- Simplicity and Stability: Energy-based allocation is relatively straightforward to apply, and its results remain stable over time because the underlying physical data (e.g., LHV) is unambiguous and widely documented.
- Regulatory Alignment: Major international measures, including ICAO's CORSIA and the EU's RED II, have already moved toward energy-based allocation for fuel-related co-products.

To enhance the robustness and enforceability of maritime fuel policies, this paper argues that the maritime LCA framework should prioritize energy-based allocation for most fuels and their co-products. This approach provides a concise and transparent basis for calculating Well-to-Wake emissions, ensuring that the policy remains practical for regulators while providing clear, predictable signals for industry investment.

3.8 Indirect Emissions and Land Use Change

Indirect GHG emissions are defined as those occurring outside the immediate product system or supply chain as a result of the activities of the reporting entity, such as the international shipping sector. These emissions are often driven by market-mediated factors, including new sources of demand **[57]**. A prominent example is the relationship between biofuel demand and cropland expansion. The competition for agricultural land induced by biofuel production can result in direct land use changes (DLUC), as well as the expansion of crop acreage into native vegetation and forested areas **[58]**.

This expansion, in turn, increases carbon emissions and triggers indirect land use changes (ILUC) that contribute to overall GHG emissions while simultaneously causing a rise in global crop prices **[59]-[61]**.

3.8.1 DLUC and ILUC: Methodological Distinctions and Environmental Impacts

It is noteworthy that LCA studies evaluating biofuels in sectors other than shipping typically assess both DLUC and ILUC emissions associated with feedstock cultivation and fuel production.

- Direct Land Use Change (DLUC): Several studies have demonstrated that GHG emissions due to DLUC can be either positive or negative, depending on the type of land use prior to the implementation of energy crops **[62][63]**. For instance, if biofuel is produced on land with high carbon stocks—such as forests, peatlands, or pastures—it can have a significantly negative environmental impact due to immediate carbon release **[64]**.
- Indirect Land Use Change (ILUC): Studies addressing the expansion of cropland to meet growing biofuel demand emphasize severe concerns regarding ILUC. These effects result not only in increased GHG emissions but also in numerous other undesirable environmental and socio-economic impacts, such as biodiversity loss and food security issues **[65]**.

3.8.2 Regulatory Approaches and Policy Uncertainty

From a regulatory perspective, maritime policies should not overlook indirect emissions related to the production of alternative fuels. Currently, two primary regulatory philosophies exist among international frameworks:

- Explicit Accounting: Frameworks such as CORSIA, LCFS, RTFO, and RFS explicitly calculate and include GHG emissions induced by ILUC in the fuel's total carbon intensity score.
- Risk-Based Restriction: The EU's RED II adopts a different approach by restricting or capping the use of feedstocks that present a "high risk" of ILUC emissions **[66]**.

Despite its importance, it must be acknowledged that estimated ILUC emissions are subject to high levels of uncertainty. These values vary significantly depending on the type of biofuel, the feedstocks utilized, the specific geographical location of production, and the economic models employed **[17]**.

For the maritime sector to establish a harmonized and stable LCA framework, it is critical to determine whether to adopt an accounting-based approach (like CORSIA) or a restriction-based approach (like RED II). A unified methodology for addressing ILUC is essential to prevent regulatory fragmentation and to provide clear, long-term guidance for the production and certification of sustainable marine fuels.

4. Conclusion and policy implications

The global shipping industry is witnessing an unprecedented transition toward low- and zero-carbon fuels to achieve timely decarbonization. However, this transition is currently hampered by a significant lack of harmonized LCA methodologies, which are a prerequisite for informed policy decision-making and the identification of truly sustainable alternative fuels. By critically examining preceding LCA research and regional policies—including established frameworks in the aviation and road transport sectors—this study provides a strategic roadmap for the development of a robust maritime LCA framework.

The research findings indicate that current maritime instruments require substantial enhancement to effectively support the uptake of sustainable fuels. A harmonized LCA framework is not merely a technical tool; it is a regulatory necessity to ensure environmental integrity while minimizing unintended consequences such as market distortion or carbon leakage. In particular, the robustness of these guidelines is indispensable for the successful implementation of mid-term measures, such as the Goal-based Marine Fuel Standard (GFS).

Based on the comprehensive review and technical analysis, the key determinants for a unified and harmonized LCA framework are summarized as follows:

- GHG Scope: The regulatory scope should initially prioritize CO_2 , CH_4 , and N_2O. This focus ensures alignment with other transport sector standards and accounts for the vast majority of maritime GHG emissions while technical measurement protocols for non-gaseous forcers like Black Carbon are further matured.

- Global Warming Potential: To ensure consistency with the UNFCCC and facilitate cross-sectoral comparative assessments, GWP100 utilizing the latest IPCC AR6 values must be adopted. This ensures that maritime policies remain scientifically synchronized with global climate goals.
- Functional Unit: For seamless regulatory enforcement and fuel accounting, gCO_2 eq/MJ_LHV, fuel is the most appropriate unit. It enables direct integration with the IMO Data Collection System (DCS) and facilitates harmony with regional policies like FuelEU Maritime.
- Modeling Approach: Attributional LCA (A-LCA) should be prioritized for setting default emission values to ensure methodological stability and certainty. However, a degree of flexibility for Consequential LCA (C-LCA) is necessary to address specific complexities, such as Indirect Land Use Change (ILUC).
- Allocation Method: An energy-based allocation method is recommended for co-products. Its conciseness and transparency offer a stable basis for global policy, enhancing administrative feasibility and reducing data-related disputes.
- Phased Sustainability Criteria: A two-phased approach is proposed: Phase 1 focusing on immediate GHG reduction thresholds and high carbon-stock land safeguards, and Phase 2 expanding to broader ecological impacts, such as water, soil, and air quality.

As maritime GHG regulations become increasingly complex, the absence of a unified LCA methodology could exacerbate industry uncertainty and hinder long-term investment. The robustness of LCA policy serves as a critical signal to both shipowners and fuel producers, providing the legal and financial certainty required for a multi-decadal energy transition.

Future research should further refine the methodological foundations discussed in this review, particularly with regard to the inclusion of non-gaseous climate forcers such as black carbon, the treatment of indirect emissions and ILUC, the development of transparent and globally representative default emission factor datasets, and the verification of certified actual values through robust certification frameworks. Advancing these areas will be essential for improving both the scientific robustness and practical enforceability of maritime LCA regulation.

In conclusion, establishing unequivocal and harmonized LCA guidelines is indispensable to preclude a fragmented regulatory landscape. Given the urgency of the climate crisis, the proactive refinement of the maritime LCA framework is not just a technical task, but a strategic imperative to ensure that the global shipping industry's journey toward a net-zero future is built on a foundation of scientific rigor and policy consistency.

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Author Contributions

Conceptualization, S. M. Ha; Formal Analysis, S. M. Ha; Investigation, S. M. Ha; Data Curation, S. M. Ha; Writing-Original Draft Preparation, S. M. Ha.

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