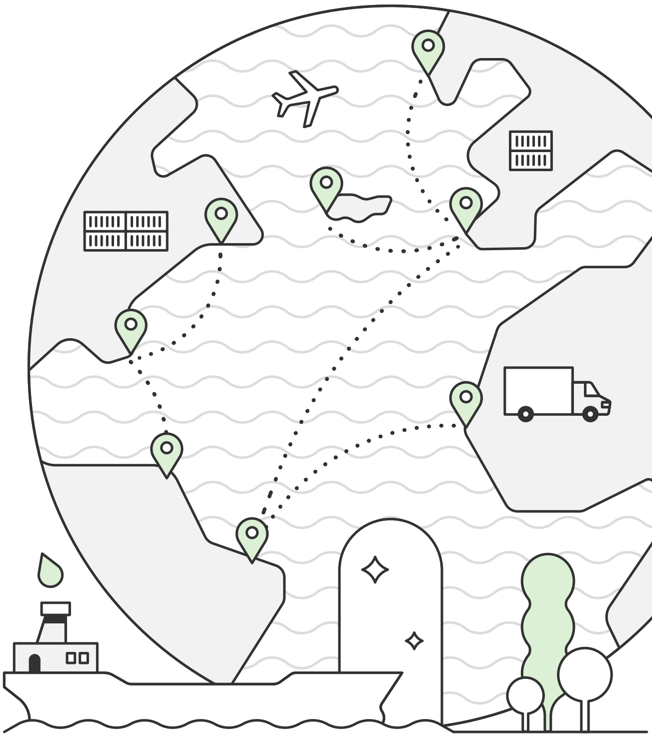
Mapping the adoption process for new drop-in fuels

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Table of Contents



01 Introduction

To support decarbonization, the maritime industry is increasingly assessing low-emissions drop-in fuels, which can be blended with conventional fuels and used in existing engines. These fuels offer a practical option to reduce emissions across the current fleet without requiring major retrofits, infrastructure changes, or early vessel retirement.

However, drop-in fuels alone cannot meet long-term decarbonization goals. To overcome supply limitations and achieve deeper emissions reductions, the sector will likely rely on a combination of drop-in fuels and alternative fuels such as low-emissions methane, methanol, ethanol, and ammonia. These fuels typically require dedicated newbuilds or retrofitted vessels equipped to meet safety and operability requirements. Even on such vessels, low-emissions drop-in fuels can play an important supporting role as decarbonized pilot fuels needed for ignition of alternative low-emissions fuels.

To support the testing and broader uptake of low-emissions drop-in fuels, this paper provides an overview of the processes that may be required for a new drop-in fuel to be evaluated and potentially adopted by the market. While this paper outlines a single, overarching adoption process, real-world pathways often diverge, and not all stakeholders are involved at every stage. The sequence, duration, and level of engagement vary depending on the fuel, vessel, engine configuration, and the operational experience of the parties involved.

1.1 Scarcity of mature drop-in fuels

Established drop-in fuels for maritime use are fatty acid methyl esters (FAME, also known as biodiesel) and hydrotreated vegetable oils (HVO). Both FAME and HVO are produced from edible vegetable oils like palm, soybean, and rapeseed oil; or from waste fats, oils, and greases (FOGs), which include used cooking oils, animal fats, palm oil mill effluent, and other residual or waste oils. The International Energy Agency (IEA) foresees that production of FAME and HVO may increase to a combined ~68 million tonnes of oil equivalent (MTOE) by 2030, limited by nature conservation and food security concerns.[1,2]

Ultimately, this supply falls significantly short of the anticipated demand across multiple global industries. Shipping alone today consumes 210–230 MTOE,[3] far outstripping the projected availability of FAME and HVO and necessitating the development of additional drop-in alternatives. These alternatives include biomass-derived fuels like pyrolysis oil, hydrothermal liquefaction oil, and cashew nutshell liquid (CNSL). These fuels are not currently covered by the International Organization for Standardization (ISO) standard ISO 8217:2024, which applies to conventional fuels, FAME, HVO, and their blends. For the purpose of this report, fuels falling outside the scope of ISO 8217:2024 are categorized as “new fuels.”

1.2 The challenging process of new drop-in fuel adoption

The process for adopting new fuels is unclear, fragmented, and time-consuming, involving many parties whose roles are often poorly defined and sometimes driven by diverging priorities. This complexity is compounded by a lack of harmonization across the regulatory bases, which often sit at the intersection of multiple national and international frameworks, with conflicting requirements and occasionally insufficiently specific regulatory language.

Without a clear mapping of the process and practical guidance, stakeholders interested in testing, supplying, or purchasing new drop-in fuels lack a starting point. Those unfamiliar with the landscape struggle to identify the critical steps and risks, and to assess the associated costs and timelines, while new entrants in the value chain frequently underestimate the process’s complexity. Against this backdrop, this project was launched to identify key stakeholders, map the current approval process for new fuels, identify key challenges, and highlight areas for improvement.

02 About this project

To capture industry perspectives on the drop-in fuel adoption process, we conducted a survey and a series of interviews with stakeholders from across the maritime value chain, including: ABS, Alfa Laval, Bernhard Schulte, Bunker Holding, Cargill, the Danish Maritime Authority, Equinor, Everllence, FincoEnergies, FVTR, Gard, GreenfuelHub, Lloyd's Register, Maersk, MASH Makes, the Maritime and Port Authority of Singapore (MPA), NORDEN, NorthStandard, Skuld, Stolt Tankers, TotalEnergies, VeriFuel, V.Group, Wärtsilä, and WinGD.

In addition, we held two multi-stakeholder workshops to validate the findings, share practical experiences, identify key hurdles in the adoption process, and discuss potential solutions for streamlining implementation.

The project further draws on contributions from NORDEN and TotalEnergies, whose recent vessel trials offer practical insight into how the adoption process works in practice and the challenges encountered along the way.

NORDEN TotalEnergies

03 Key stakeholder groups in the process

Stakeholders in the adoption of new drop-in fuels vary in their levels of involvement and authority, ranging from those who approve bunkering and onboard use to consultative actors and the wider ecosystem (Figure 1).

Figure 1: Stakeholders involved when approving new drop-in fuels, grouped according to their level of authority.

Ecosystem overview

Who approves and who is consulted across the stakeholder landscape

Onboard use
Secondary stakeholders
Bunkering
To be consulted

Approves

1. Onboard use

Insurers
Need information from: OEMs, classification societies
- Provide H&M and P&I risk coverage, a requirement from flag state and for port entry
- May have own sustainability targets

Flag states
Need information from: Insurers, classification societies, OEMs
- Responsible for compliance with international conventions and national regulations
- Oversee safety for crew, operations, and third-party assets, as well as environmental protection
- Typically requires proper insurance

Ship operators
Interact with: Classification societies, OEMs, shipowners, insurers, cargo owners
- May be the same as the shipowner
- Aims to preserve voyage profitability and minimize decarbonization costs
- May have own sustainability targets
- May assume the shipowner's emissions reduction obligations depending on the charterparty

Shipowners
Interact with: Flag states, insurers, classification societies, OEMs
- Is the obligated party under EU ETS and IMO NZF
- May have own sustainability targets
- Aim to maximize asset value and minimize decarbonization costs

2. Bunkering

Port authorities
Need information from: OEMs, classification societies
- Grant bunkering permission to port terminal
- Permission is subject to review of terminal's facilities, safety procedures, and regulatory compliance
- May have own sustainability targets

Connects to

Terminal operators
- Manage infrastructure & operational processes to supply bunkers to ships

Bunker physical suppliers
- Own or manage the physical transfer of fuel to vessel
- Provide the Bunker Delivery Note

National and international regulations
- Establish the frameworks for safety, environmental compliance and labour rights at port

Secondary stakeholders

Technical managers
- Responsible for ship operations, (maintenance, regulatory compliance, budgeting, and coordinating with crew and stakeholders)
- Is the obligated party under FuelEU Maritime

Crew
- Operates the ship (navigation, maintenance and repair, safety, fuel efficiency, cargo handling)

Fuel traders
- Secure fuel supply and sells to shipowner or operator.

Fuel producers
- Ensure availability, sustainability, and reliability of supply
- Supply sustainability documentation and ensure fuel quality

Analysis laboratories
- Provide independent third-party analysis of fuel properties and quality

Engine test centers
- Provide independent third-party analysis and tests new fuels in small-scale engine test rigs

Sustainable fuels certification schemes
- Certify the GHG emissions intensity, sustainability metrics and traceability requirements for compliant fuel supply chains

International Organization for Standardization (ISO)
- Establish standard methods of analysis and reference values for marine fuels

IMO, national, or regional decarbonization frameworks
- Establish decarbonization targets, consequences for non-compliance, sustainability criteria, and LCA methodologies

To be consulted

OEMs
Need information from: Fuel traders, fuel producers
- Assess operational risks associated with new fuels
- May issue a support letter to stakeholders who need confidence that the fuel presents low operational risk
- May have own sustainability targets

Classification societies
Need information from: Fuel traders, fuel producers
- Establish and maintains technical standards for design, construction, and operation of ships
- Perform statutory tasks on behalf of the flag state to ensure regulatory compliance
- Can be contracted by the shipowners or operators, flag states, insurers

Cargo owners (voluntary market)
- Influence sustainability requirements when bearing the cost of the trial

Cargo owners are influenced by

Citizens
- Consumers
- Influence political decisions

Shareholders
- Focused on earnings, ethical conduct, corporate image, and long-term value protection

Civil society
- Independently assess sustainability and advocate for higher environmental standards
- Holds industry accountable and influences brand value

EU ETS = European Union Emissions Trading Scheme, GHG = greenhouse gas, H&M = hull and machinery, IMO = International Maritime Organization, LCA = life cycle analysis, NGO = non-governmental organization, NZF = Net-Zero Framework, OEM = original equipment manufacturer, P&I = protection and indemnity

3.1 Approving entities

Usage approval for bunkering and onboard operations follows stakeholder-specific processes and responsibilities. This approval typically involves five stakeholder categories: shipowners, ship operators, the flag state, insurers, and port authorities. Their support for low-emissions fuels may be driven by regulatory, sustainability, business, or operational considerations.

3.1.1 For onboard use

A. Shipowners

Shipowners ultimately decide whether to trial new drop-in fuels, as they carry the associated commercial and operational risks. They are the obligated party under the European Union Emissions Trading System (EU ETS) and potentially the International Maritime Organization (IMO) Net-Zero Framework (NZF).* Shipowners may also have voluntary sustainability targets that encourage the use of low-emissions fuels, or wish to expand their drop-in fuel portfolio and build supplier partnerships. Nonetheless, concerns over asset protection from the uncertainties associated with unproven technologies continue to limit uptake of new drop-in fuels.

B. Ship operators

When the charterparty assigns emissions-reductions obligations to the operator rather than the shipowner, operators are more likely to support low-emissions fuels to meet those duties. The incentive may be reinforced by the operator's own sustainability targets, cargo owners' climate commitments, and in some cases, the transfer of FuelEU Maritime compliance costs from the technical manager. However, an operator's primary focus on voyage or charter profitability, safety, and on minimizing operational uncertainty can limit their willingness to adopt fuels perceived as risky.

C. Flag states

The flag state must ensure ship security and the safety of crew, operations, and third-party assets, as well as environmental protection in compliance with national and international conventions (including the IMO NZF, if adopted, and international sanctions). Therefore, to give approval, the flag state requires a strict risk assessment and a thorough risk-mitigation plan. Flag states also typically require vessels to maintain valid insurance as a condition of registration.

D. Insurers

Vessel insurance is almost always legally mandatory for ship registration. It may also be required for ship financing, i.e., hull and machinery (H&M) insurance for port entry (coverage under protection and indemnity (P&I)), and for protection against third-party liabilities such as pollution, injury to crew and passengers, and damage to cargo and structures. As they are liable for remediation costs in case of incidents, insurers also require a strict risk assessment and thorough risk-mitigation plans to give approval.

3.1.2 For bunkering

E. Port authorities

Port authority approval is mandatory for bunkering operations to ensure compliance with national safety and environmental regulations. Beyond that, port authorities may have their own sustainability targets that can further incentivize efforts to facilitate access to low-emissions fuels.

*The obligated party under FuelEU Maritime is the Document of Compliance (DoC) Holder, under the International Safety Management Code. The Document of Compliance Holder is the ship's technical manager, who may be the shipowner but is often a separate entity. In practice, the costs of complying with FuelEU Maritime are frequently passed onto the shipowner or ship charterer through separate contracts.

3.2 To be consulted

Approving entities need technical support at various stages of the adoption process and typically seek the expert technical guidance of classification societies and original equipment manufacturers (OEMs).

F. Classification societies

Classification societies set and maintain technical standards for vessel design, construction, and operation. In the adoption process for new drop-in fuels, these societies carry out statutory tasks on behalf of flag states to verify regulatory compliance and provide the technical basis for approving the fuels' onboard use.

G. Original equipment manufacturers

OEMs assess the operational risks of new drop-in fuels associated with the fuel system, fuel injection components, or the engine. OEMs may issue a supporting letter for the trial after completing their fuel assessment, but remain cautious about providing a no-objection letter, which carries different commercial and reputational risks.

3.3 The broader ecosystem

Beyond the approving entities, fuel adoption relies on a complex network of producers, traders, cargo owners, technical managers, and superintendents. Analysis laboratories, engine test centers, and the onboard crew also have supporting roles in validation of fuel performance and safe implementation, but they do not typically participate directly in the fuel adoption decision.

H. Fuel producers and traders

Fuel adoption is often initiated by fuel producers or traders, who subsequently engage shipowners or operators to assess maritime suitability. Producers or traders require fuel analysis through accredited laboratories; if initial results are promising, they further arrange testing at engine test centers to evaluate performance under conditions representative of commercial equipment.

Furthermore, fuel producers and traders are also expected to hold certification under recognized voluntary sustainability schemes such as International Sustainability and Carbon Certification (ISCC), REDcert, and Roundtable on Sustainable Biomaterials (RSB). These schemes operationalize compliance with regional and international mandates by translating high-level sustainability and traceability rules into auditable standards; they further verify the decarbonization potential of the fuel through the rigorous application of prescribed life cycle assessment (LCA) methodologies.

I. Technical managers and superintendents

Technical managers and superintendents are responsible for the ship's physical integrity, maintenance, safe operation, regulatory compliance (including FuelEU Maritime), and budget oversight. In relation to the adoption of new fuels, they work closely with shipowners and operators to plan required retrofit, implement appropriate emissions monitoring, develop the Safety Management System, and ensure that the crew is appropriately trained to handle the new fuel on board.

J. Cargo owners

If they bear the costs of a trial, cargo owners may need to be involved in new fuel trials to assess the sustainability features of the fuel.

04 Mapping the adoption process

In this project, we have identified seven key steps when adopting new drop-in fuels for maritime use (Figure 2). While the overall process is presented linearly in Figure 2, it may be shorter or longer in practice, with ad hoc exceptions or lengthy iterations, with feedback loops, parallel activities, and repeated steps depending on fuel quality and readiness.

It is important to note that this framework does not represent a fixed or guaranteed pathway. Even when all steps are completed, final adoption may be derailed by technical, operational, or commercial uncertainties, and fuels that progress through the full process may still face discontinuation or negative results in practice.

Timelines and resource requirements vary significantly: early stages may involve short, desk-based studies, whereas vessel trials, particularly those assessing long-term effects, can be preparation-intensive and could extend over several years.

Time estimates

Although the process from initial market research to a vessel trial may take a couple of years, full standard development and product commercialization may take up to a decade.

Cost estimates

Trial costs vary widely, typically starting at 100,000 United States dollars (USD), depending primarily on the scope of the vessel trial. Extended main engine (M/E) trials are significantly more costly than limited-scope auxiliary engine (A/E) tests. Full commercialization of a new fuel may cost several million USD distributed across the industrial stakeholders involved.

This section of the report summarizes project insights into these seven steps. For each step, we outline stakeholder roles, describe the process and requirements with time and cost considerations, and identify challenges and opportunities for improvement.

Figure 2: The timeline and stakeholders involved in the seven steps to adopt new drop-in fuels.

Step duration	2-6 months	2-4 months	2-12 months	2-4 months	3-6 months	2-4 months	Years
	1 Market research on fuel availability & affordability	2 Fuel quality testing	3 Fuel handling and combustion test	4 Vessel selection, risk assessment and safety management	5 Operational preparation for vessel trial	6 Vessel trial	7 Commercialization & standardization
◆ Fuel producers / traders	◆	◆	◆	◆	◆	◆	◆
◆ Regulators	◆						◆
◆ Shipowners / Ship operators	◆	◆	◆	◆	◆	◆	◆
◆ Analysis laboratories		◆				◆	◆
◆ Engine test centers			◆				◆
◆ Technical managers				◆	◆	◆	◆
◆ Insurers				◆			◆
◆ Flag states				◆			◆
◆ Classification societies				◆			◆
◆ OEMs				◆		◆	◆
◆ Cargo owners				◆			◆
◆ Crew					◆	◆	◆
◆ Port authorities					◆		◆
◆ Terminal operators					◆		◆
◆ Bunker suppliers					◆		◆
◆ ISO/CIMAC work groups							◆

Typical interactions

CIMAC = Conseil International des Machines à Combustion, ISO = International Organization for Standardization,
OEM = Original Equipment Manufacturer

Step 1: Market research on fuel availability, sustainability, and affordability

2-6 months

Purpose:

As the initial step in the adoption process, market research establishes whether a new fuel is commercially viable by assessing its availability, sustainability, and affordability before deeper technical evaluations proceed.

Key tasks or activities:

- **Assess the fuel's availability:** this includes feedstock sources, competing demand across sectors, sustainability concerns or applicable sustainability regulations, and assumptions about scale-up of production capacity.

> The notion of "availability" is not univocal. While the overall supply of a potential new fuel may be limited, some shipping operators can secure volumes through long term offtake agreements, thereby ensuring availability for their own operations. This can lead to occasional friction within the value chain, as stakeholders may hold differing views on a fuel's relevance and on whether the effort required to qualify it is commercially justifiable.

- **Evaluate sustainability:** including trade-offs and synergies along the supply chain and across differing governing requirements. Beyond greenhouse gas (GHG) emissions, land-use change is a critical sustainability criterion. Other aspects—such as water use and eutrophication, soil health, and novel entities—may be only partially addressed by applicable regulatory frameworks, yet they can be material under voluntary sustainability commitments. To ensure that the fuel is eligible for emissions reduction credits, production sites must hold a valid certificate of compliance issued by a recognized voluntary sustainability scheme, such as ISCC, REDcert, or RSB.
- **Analyze affordability:** using metrics such as price per unit of energy, abatement cost (i.e., the cost of fuel per unit of avoided GHG emissions), potential retrofit needs, and business opportunities offered by overcompliance.

Stakeholder roles:

- **Fuel producers or traders** typically initiate this step to assess whether a new fuel is suitable for marine use.
- **Shipowners and ship operators** may also lead or commission market research to assess the business case viability, including financial and fuel requirements.
- Within the broader ecosystem, **regulators** set eligibility and sustainability criteria, decide LCA methodology, and shape market conditions through penalties and rewards.

Technical or operational requirements:

Assessing fuel sustainability requires understanding how definitions and GHG accounting differ across regulatory frameworks at international, regional, and national levels (see also 'Risks and challenges').

Time estimates

The market research step typically takes a few months

Cost estimates

The market research cost ranges from several thousand to tens of thousands USD, depending on case complexity.

Risks and challenges:

- Cross-sector competition for feedstocks and fuels: The pressure from the broader fuel market adds uncertainty when assessing both the availability of the drop-in fuels for shipping and their long-term pricing.

- Uncertainty from regulatory frameworks: New and existing global, regional, and national regulations affect pricing and affordability. Ongoing evolution of regulations and divergent national interpretations increase the risk of inconsistency over time.

- Varying sustainability definitions: These inconsistencies complicate comparability across fuels and overall availability assessments. While most frameworks focus on climate impacts, they differ in accounting scope (e.g., tank-to-wake versus well-to-wake) and in sustainability and eligibility criteria for fuels and feedstocks. Further complexity arises from differing approaches to indirect land-use change, waste definitions, and negative emissions.

Opportunities for improvement:

Divergent regulatory treatment of fuel sustainability and GHG emissions introduces complications for fuel procurement and business optimization. EU ETS, FuelEU Maritime, and potentially the IMO NZF apply different LCA methodologies and compliance penalty structures. As a result, the same fuel can deliver markedly different emissions savings or even be eligible under one framework but excluded in another due to feedstock type, geographic origin, or accounting rules. Harmonizing LCA methodologies and penalty structures across zero-emissions regulatory frameworks would reduce these uncertainties. Streamlining and improved alignment of existing and future regulations is highly desirable.

Step 2: Fuel quality testing

2-4 months

Purpose:

Fuel quality testing determines whether a new fuel meets baseline quality specifications and is compatible with conventional fossil-based marine fuels.

Key tasks or activities:

- **Conduct laboratory fuel analysis on physical and chemical properties:** the reference fuel quality standard for marine fuels is ISO 8217:2024, Products from petroleum, synthetic and renewable sources — Fuels (class F) — Specifications of marine fuels. Fuel ignition and combustion analysis (FIA and FCA), which is not included in ISO 8217, is often conducted at this stage to gain an initial understanding of the fuel's combustion performance.

In the absence of a dedicated specification for new fuels, it is common practice to assess their fitness for maritime use against ISO 8217:2024. ISO 8217 is a commercial standard rather than a mandatory regulatory requirement and becomes enforceable only when referenced in contracts or charterparties.

The standard sets out detailed analysis and testing methods to characterize a wide range of fuels, including hydrocarbons from petroleum crude oil, oil sands, and shale oil; synthetic hydrocarbons, renewable hydrocarbons, or hydrocarbons from recycled sources, with molecular structures that are indistinguishable from petroleum hydrocarbons; FAME; and blends of any of the above, where permitted.

Stakeholder roles:

- **Fuel producers or traders** ensure the new fuel's quality.
- **Shipowners and ship operators** are motivated to assess fuel quality, compatibility, and potential risks to the asset.
- **Analysis laboratories** act as third parties performing the necessary analysis.

Technical or operational requirements:

Analysis laboratories require only a few liters of fuel for quality testing and blending studies. However, it is essential that these samples are representative of the actual quality and composition intended for the vessel trial. Therefore, at this stage, fuel producers are usually expected to be able to supply larger volumes—in the range of 100 tonnes—with consistent quality. This ensures smoother trial execution and reduces the need to revisit earlier steps. To support efficient analysis procedures, samples should be clearly and accurately labelled with comprehensive technical data.

To support informed fuel adoption decisions and reduce operational risks, experts recommend testing additional parameters, such as corrosion potential, stability, and the presence of specific inorganic materials. This broader screening provides the technical basis for defining key trial parameters for fuel blends, including the choice of fossil fuel and blending ratios.

At this stage, blending and stability tests with different fossil fuels are essential to understand how the new fuel behaves in blends and how it may react with residual fuels remaining in the vessel's fuel system after changeover. Given the chemical diversity of fossil fuels fractions and the wide variability of very low sulfur fuel oil (VLSFO), experts advise testing blends across multiple fuel fractions and test VLSFOs sourced from various regions and suppliers.

Safety and environmental aspects, which fall outside the scope of ISO:8217, should also be assessed at this stage and reflected by the Material Safety Data Sheet (MSDS) for all relevant blends.

Time estimates

The process takes a couple of months. While fuel quality testing according to ISO 8217:2024 can be carried out in a few weeks, the sample preparation and documentation can take a few months

Cost estimates

The fuel quality testing cost can be in the range of a few thousand USD per sample.

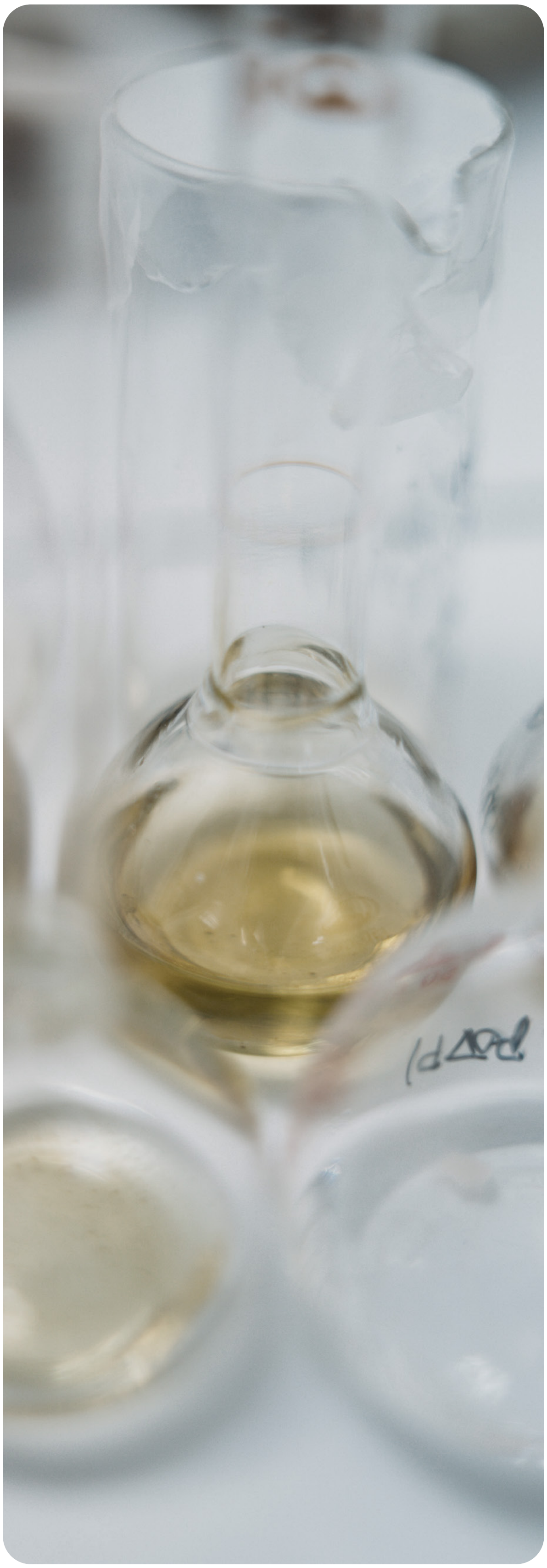
Risks and challenges:

Ongoing developments and incompatibilities for testing biofuels: Because new drop-in fuels can have a molecular composition entirely different from that of conventional fossil fuels, some testing methods originally designed for fossil fuels under ISO 8217:2024 are incompatible with biofuels. Understanding how new fuels may respond to established tests therefore requires deep expertise from analysis laboratories.

Fuel producers and test laboratories are also developing new testing methods. Methods developed by commercial enterprises are often protected by intellectual property rights and cannot be used commercially by third parties without a license.

Opportunities for improvement:

Good practice is to conduct fuel quality testing according to the most current ISO 8217 edition. However, implementation of new revisions of ISO 8217 often lags in practice. Fuel testing laboratories may continue using superseded versions of the standard due to the additional costs associated with updating testing equipment, employee training, and contractual requirements. In many cases, laboratories apply the ISO 8217 version specified by the requesting party, whose contracts may not be promptly updated following the release of a new revision. As a result, fuels are still frequently tested against ISO 8217 versions as old as 2005, creating uncertainty and potential delays when stakeholders expect results aligned with the latest standard.



Step 3: Fuel handling and combustion tests

2-12 months

Purpose:

These tests assess how the new fuel behaves during onboard storage, handling, and combustion, generating essential information on fuel performance but also insights to derisk a vessel trial by identifying potential deposit formation, instability, or engine component damage.

Key tasks or activities:

- Simulate onboard handling conditions using rig testing, high pressure and temperature tests, Alfa Laval spin tests, or equivalent stress tests.

- Conduct controlled combustion tests in downscaled stationary engines where the engine load is adjusted to test in accordance with ISO 8178 (Reciprocating internal combustion engines — Exhaust emission measurement). These tests examine injection, combustion, and emissions profiles for nitrogen oxides (NO_x), carbon monoxide (CO), and unburned hydrocarbons.

- Perform a nozzle imprint after testing to check for deposit formation or signs of wear.

- Assess erosion, corrosion, polymerization, and phase separation using recirculation in rig testing and high pressure/temperature trials to simulate harsh service conditions.

- Evaluate fuel behavior under onboard handling conditions, particularly its tendency to form sludge or undergo polymerization. The Alfa Laval spin test is used to deliberately “stress” the fuel by simulating these conditions.[4]

- Conduct compatibility tests to assess mixing ability, phase separation, and a blend’s polymerization tendency.

Is dilution the solution?

Compatibility is not yet well understood from a chemical point of view, and compatibility tests have shown non-linear, counterintuitive results. Notably, certain blends of bio-oils and conventional bunker fuels demonstrate improved compatibility at higher bio-oil blending ratios than at lower ratios.

Stakeholder roles:

- **Fuel producers or traders** ensure the new fuel’s quality.

- **Shipowners and ship operators** may provide financial support for the tests, motivated to assess fuel quality, compatibility, and potential risks to the asset.

- **Engine test centers** act as third parties performing the necessary analysis.

Technical or operational requirements:

To ensure meaningful preparation for a vessel trial, the fuel tested at this stage should closely match the composition and quality of the fuel intended for onboard testing.

Time estimates

Fuel handling and combustion tests depend on the availability of fuel testing facilities, with current waiting times exceeding one year of in certain cases. The actual tests only take a couple of weeks, including data treatment and reporting.

Cost estimates

Fuel handling and combustion tests cost in the tens of thousands USD.

Risks and challenges:

Global testing capacity is limited and the cost of tests can be high: Access to engine research centers is subject to long waiting times—often more than one year—due to the limited availability of stationary engines that are representative of marine applications.

While stationary four-stroke engines, which approximate a vessel's A/E, are more common, testing still requires 200–500 liters of fuel. These volumes represent a resource burden that limits parallel testing. Stationary two-stroke engines are far scarcer and require substantially larger fuel volumes—on the order of 10,000–80,000 liters—drastically increasing both costs and logistical complexity.

Non-standardized testing procedures across centers make comparisons difficult: Fuel handling and fuel combustion test centers integrate standard tests with methods developed in-house. Standardized methods to assess critical parameters such as corrosivity under high-temperature and high-pressure conditions, long-term fuel stability, and material compatibility with engine sealing components are lacking.

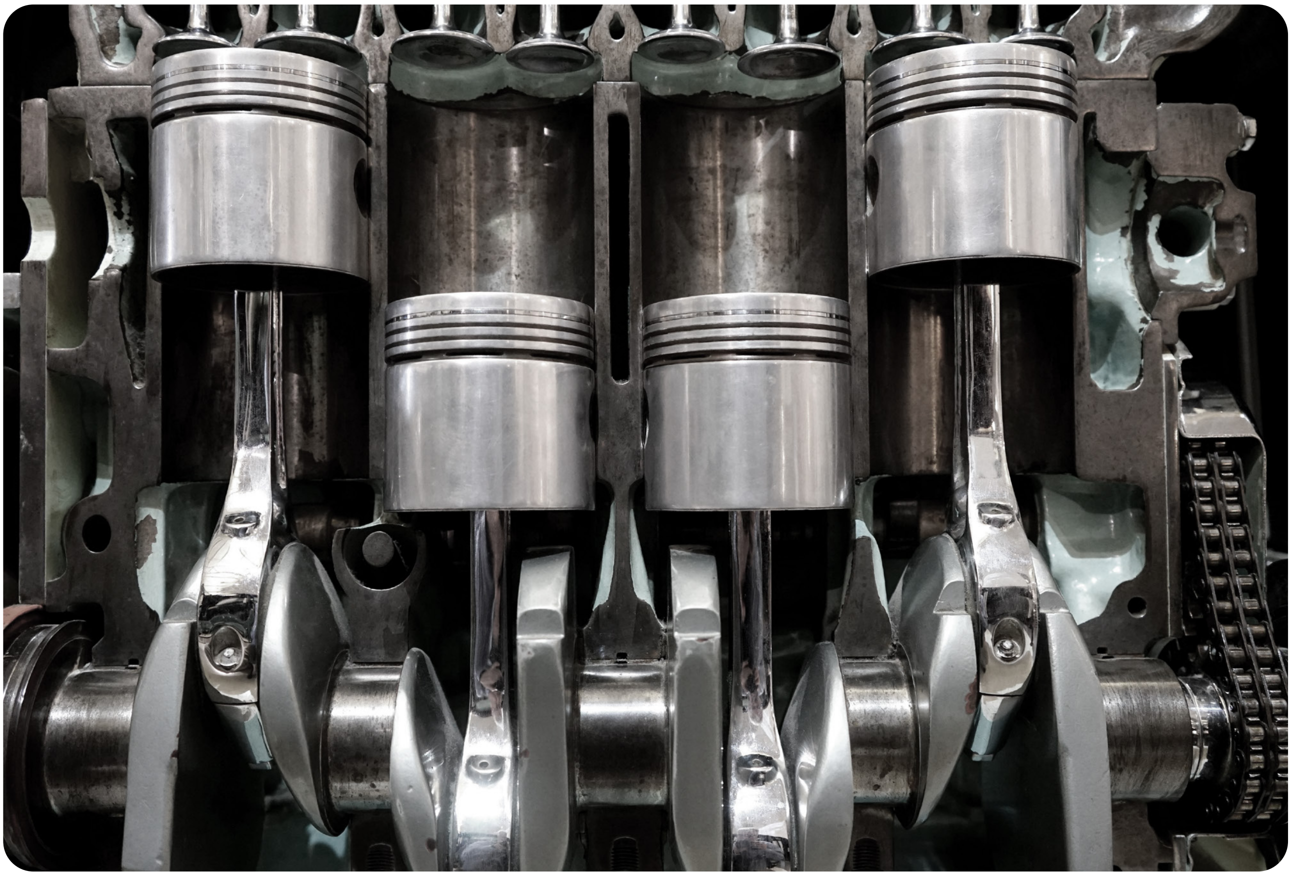
Lack of methods to assess compatibility of new fuels with conventional fuels: Uncertainties are introduced by changes in the composition of residual fuels resulting from desulfurization, which creates less stable bunker oils. Fuel instability increases further when certain biofuels are introduced because compositional mismatch between blends causes liquid-liquid separation, apart from asphaltenic phase separation.

Opportunities for improvement:

Three key opportunities for improvement have been identified in the testing phase: expanding testing capacity, improving alignment between testing approaches and OEM requirements, and increasing consistency across parallel tests.

First, insufficient testing capacity could be addressed through collaboration agreements with universities and private testing facilities.

Second, as test types are often non-standardized and results may not meet OEM expectations, OEMs should be involved early in planning fuel handling systems and combustion tests and granted access to test results.



Step 4: Vessel selection, risk assesment, and safety management

2-4 months

Purpose:

To select a suitable vessel for the trial and ensure safety and regulatory compliance. This step includes preparing the required technical documentation and risk assessment; engaging the technical manager, OEMs, classification society, and flag state; and securing the flag state's approval.

Key tasks or activities:

- **Identify a vessel for the trial**; a decision contingent upon several factors, including:
  - **Selection of an appropriate bunkering port**, tentatively selected by the ship operator and trader, depending on the fuel delivery logistics at the port and by the routes of interest to the operator.
  - **Alignment of the fuel supply schedule** with the vessel's trading route, which limits the pool of eligible ships.
  - **Consideration of engine warranties,** which generally remain valid only when fuels conform to OEM specifications, with a typical coverage of one year. Consequently, shipowners are often cautious about utilizing off-specification biofuels during this period to avoid the risk of invalidating their warranty coverage.
  - **Assessment of onboard equipment** that may be required for the trial, for example, availability of per-engine emissions monitoring equipment or fuel segregation systems.
  - **Designation of the engine for the trial,** with trials on unknown new fuels typically starting on an A/E, as its redundancy makes the test safer than using the M/E. Trials on M/E are generally undertaken only once sufficient experience with the new fuel has been gained.
  - **Clarification of charterparty requirements** related to the use of new fuels, including agreements on trial costs and any necessary retrofits. These costs typically fall to operators when they are the requesting party.
- Assess risks and manage safety:
  - **Classification societies review** the ship's technical characteristics, such as equipment, operations, safety, and environmental impact risk. This review involves technical managers and potentially OEMs working to identify safety concerns and recommend risk-mitigating interventions. Examples of such actions could include equipment replacement or retrofit, new measurement devices, training and instructions for the crew, or changes in operation management.
  - **OEMs evaluate fuel behavior and performance** in engines and other components of the fuel system either by relying on the results from stationary engine investigations conducted by the fuel producer or by carrying out their own investigations. Once sufficient confidence has been established, OEMs may issue a 'supporting letter,' indicating that the new fuel presents low risks and/or providing instructions to mitigate identified risks. When the engine manufacturer operates under a license, it is advisable to consult and involve the engine designer at an early stage.
  - **Shipowner and/or ship operator conduct a risk assessment** in collaboration with key stakeholders—including the classification society, technical managers and superintendents, and the vessel captain—to develop a risk mitigation plan.

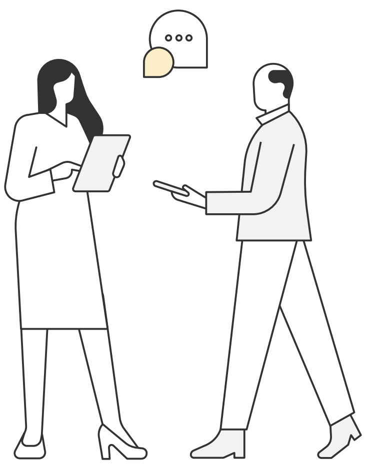
- Receive approvals for trial from the flag state, insurer, and shipowner:

  - A “dispensation” or “exemption” letter or certificate from flag states is required to test a specified amount of a new fuel on a given vessel. To issue such approval, flag states may require extensive preliminary investigations related to safety management, as described above. Dispensations are generally granted subject to defined conditions, including a limited validity period, a specified testing program, and restrictions on where testing may take place, often limiting trials to operations on the high seas. Documentation requirements for approval vary across flag states.

  - Insurance coverage to protect the ship (H&M), third parties, and the environment (P&I) is required by shipowners and flag states to protect assets and operations during the trial. The insurer does not approve the fuel itself but focuses on safe onboard operations. Typically, insurers rely on classification societies and OEMs to support the vessel trial. The owners are expected to do their own due diligence, inform the crew about the product received, and provide guidelines and risk management procedures.

Stakeholder roles:

- Shipowners or operators are motivated to test the fuel on board a vessel to assess fuel quality, compatibility, and potential risks to the asset. They identify the candidate vessel for the trial, approve onboard fuel testing, and start the process of engaging with relevant parties to receive the necessary approvals.



- Fuel producers or traders provide all documentation related to fuel quality, safety, handling guidelines, and sustainability certifications.

- OEMs evaluate fuel operational safety related to engine performance and durability, and may issue a supporting letter endorsing the vessel trial.

- Classification societies assess onboard fuel use risks, including due diligence on risk mitigation procedures.

- Flag states approve new fuel use in compliance with national and international regulations on voyage and crew safety, and environmental protection.

- Insurers assure against loss of asset values, H&M, damage to third parties and the environment, and P&I.

- Technical managers and superintendents carry out risk assessments.

Technical or operational requirements:

Selecting the ship for a vessel trial is a complex coordination challenge. On the supply side, securing sufficient fuel volumes can be a major hurdle—especially for research products. This fuel must often be transported across multiple countries to reach a suitable port. Timelines for transit, permits, and port-side fuel management approvals are difficult to predict for new products. Amid these uncertainties, the ship operator must align the vessel arrival with fuel delivery. Failure to sync fuel readiness with the ship's arrival can result in onerous port fees and penalties for overstaying at berth.

Once the vessel is identified, the ship operator initiates the risk mitigation and seeks approval. Typically, the documentation required includes:

- A certificate from the fuel supplier that confirms compliance with an approved voluntary certification system; this document justifies the trial’s necessity.

- Fuel specification and safety data: the analysis of fuel and blends per ISO 8217 and additional parameters as described in Step 2 and a comprehensive MSDS.

- The results from stationary engine tests as described in Step 3.

- Technical risk assessment: comprising Hazard Identification (HAZID) and/or Hazard and Operability (HAZOP) involving multiple stakeholders. This assessment focuses on engine compatibility, fuel system modifications, crew training requirements, and specialized emergency response (firefighting/spill containment), ultimately delivering the trial's Safety Management Plan.

- An engine-specific supporting letter from the engine manufacturer might be required.

- Onboard testing and fuel management protocol: a detailed plan for monitoring fuel consumption that includes a contingency strategy. This ensures sufficient conventional fuel always remains available to allow an immediate switch back to standard operations should Insurance of the ship for damages to H&M and/or damages against third parties (P&I).

- An exemption certificate issued by the flag state.

Time estimates

This process takes a couple of months. The time to obtain the exemption letter and the port's approval ranges from a few weeks to months, depending on the experience with the fuel of the stakeholders involved (flag state, class society, OEMs, port, and others).

Cost estimates

The cost of the vessel selection, risk assessment, and safety plan can be a few thousand USD for the technical manager's services. Notably, the costs of the trial and any retrofit often fall on the operator when they are the requesting party indicated in the charterparty.

Risks and challenges:

Delays in OEM involvement and assessment introduce potential knock-on effects for the vessel trials phase later. OEMs are often engaged only after preliminary testing at engine test centers and may require additional validation before issuing supporting letters based on third-party results. The OEM's assessment is thorough and resource-intensive, and can introduce bottlenecks in the process, particularly given the capacity constraints at test centers.

Missing the planned bunkering window: The trial may have to wait until the vessel calls at the same port again, which could take months.

Opportunities for improvement:

Improving alignment and technical information sharing across stakeholders presents a clear opportunity to simplify the process. Currently, requirements are not fully harmonized across shipowners, flag states, insurers, and technical managers. This lack of alignment makes it difficult to prepare a consistent set of data and often leads to duplicate reporting, where the same data must be submitted in multiple formats to satisfy different stakeholders. This challenge is amplified by the ongoing evolution of classification society rules as they are updated based on operational experience.

Greater coordination could demystify the process for shipowners new to biofuel trials, reducing hesitation regarding the deployment of their vessels for testing of new fuels. Enhanced information flows would also assist insurers, who currently rarely receive feedback on trial outcomes; access to these results, alongside environmental impact assessments, would build technical confidence and enable a more responsive risk assessment. Establishing a knowledge-sharing platform to disseminate trial outcomes, risk management strategies, and operational lessons could be an avenue to reduce uncertainty, build confidence among first-time adopters, and support broader uptake of new fuels.

Step 5: Operational preparation for vessel trial

3-6 months

Purpose:

Coordinate all logistical activities needed to deliver the new fuel from the production site to the designated bunkering location, blend it with fossil fuels (if required), store it, and bunker it in alignment with the vessel's operational schedule.

Key tasks or activities:

- Transport the new fuel from the production facility to the bunkering location via road, rail, or sea, depending on proximity, infrastructure, and volume.

- Accurately plan bunkering operations, including required infrastructure at the terminal.

- Blend the new fuel with a fossil fraction, if required.

- Obtain port authority permitting.

- Prepare the ship and the crew for the trial.

Stakeholder roles:

- Fuel producers or traders are responsible for arranging transport of the fuel to the port and for providing fuel documentation such as certificate of quality, MSDS, and the Proof of Sustainability (PoS).

- Terminal operators manage the handling, storage, and potentially the blending of the fuel within port facilities.

- Port authorities approve and oversee bunkering operations within their jurisdiction.

- Bunker suppliers deliver the fuel either by truck at berth or via barge at anchorage. They may also supply the fossil fuel fraction if blending is required. They prepare and deliver the bunker delivery note to the vessel.

- Shipowners or operators coordinate vessel readiness and ensure alignment between the vessel's voyage and the scheduled bunkering.

- Technical managers support the vessel in parallel by ensuring crew readiness and the availability of spare parts and other trial-specific equipment.

- Crew prepare the vessel's fuel tanks and systems to receive the new fuel, ensure the safe execution of the bunkering operation, and manage the onboard handling.

Technical or operational requirements:

Special consideration should be given to fuel transport documentation, customs clearance, import or export regulations, and fuel classification (e.g., if the fuel is considered hazardous or non-conventional) under national and international law.

The physical bunker supplier seeks approval from the port authority to handle and deliver the fuel within the port.

The technical management ensures the vessel is operationally ready for the trial. This includes preparing the necessary equipment on board (e.g., cleaning tanks and lines, installing exhaust gas monitoring equipment, procuring spare parts for high-wear components, and verification of specialized spill sorbents). Furthermore, technical management facilitates the deployment of relevant personnel like technical superintendents or OEM technicians and fuel supplier representatives. These preparations help ensure that data related to fuel performance, emissions, and machinery impact can be captured accurately and in real time.

Time estimates

This process takes a couple of months and can vary significantly depending on logistics readiness. In some cases, it may even require establishing the logistics from the ground up.

Cost estimates

The cost of vessel trial preparation includes:

- Fuel: the price per tonne of fuel.
- Logistics and bunkering: these vary widely depending on fuel volume, transport arrangements, and terminal or storage size and availability, but represent a small contribution to the total.
- Vessel preparation and modification: if the ship needs retrofitting, the costs are typically in the mid-five-figure range for fuel supply system and measurement equipment.

Risks and challenges:

Stakeholder coordination and small-scale fuel blending: Although preparing for the vessel trial may appear straightforward, it often involves significant complexity due to the number of stakeholders involved and the need to establish ad-hoc operations for the small fuel volumes typical of demonstration trials. Blending new fuels with fossil fractions is particularly challenging at these scales. As conventional storage and blending infrastructure is designed for much larger volumes, accurate dosing and mixing becomes more difficult.

Logistical complexity is further influenced by bunkering arrangements: Truck-to-ship bunkering at berth can increase port charges and berth occupancy time, while vessel-to-vessel bunkering at anchorage introduces additional coordination challenges related to weather, scheduling, and safety. Costs and operational complexity can vary substantially depending on whether the vessel is taking on the trial fuel during scheduled bunkering operations or if it must deviate from its commercial route to receive it. Vessel trial coordination is even more challenging in tramp shipping, where limited visibility of future vessel schedules makes advance planning of trials particularly difficult.

Opportunities for improvement:

It is essential to thoroughly plan the vessel trip in advance, assess the risks, and account for potential delays.

Step 6: Vessel trial

2-4 months

Purpose:

Evaluate the fuel under operational conditions, testing engine performance across various loads, emissions, operational safety, and system interactions including the M/E and/or A/E, purifiers, pumps, filters, and fuel lines.

Key tasks or activities:

- Collect performance data against baselines by operating on the fuel during routine vessel activities across a range of engine loads. Data collection typically covers engine and equipment performance including fuel consumption and efficiency, cylinder pressure and temperatures, exhaust temperatures, and filter and separator performance. Visual inspections of engine components are usually carried out to detect signs of wear, deposits, or corrosion. To enable meaningful comparisons, baseline data is also collected using conventional fuels, including under controlled engine loads.

- Assess the properties and operational behavior of the new fuel by monitoring changes in key characteristics—such as oxidation stability, sediment formation, and phase separation—before and after fuel purification throughout the storage period.

- Evaluate combustion performance and compliance with MARPOL Annex VI. Where emissions are to be measured, they are quantified using an analyzer capable of detecting exhaust gas components such as nitric oxide, nitrogen dioxide, sulfur dioxide, carbon monoxide, carbon dioxide, hydrocarbons, and oxygen. Data should be captured as close as practical to 25%, 50%, 75%, and 100% engine load, acknowledging that real-life operational conditions may constrain precision. Portable flue gas analyzers have proven practical for these tests.

In accordance with the Unified Interpretation to MARPOL Annex VI, regulation 18.3, the use of biofuels, synthetic fuels, and blends containing these fuels does not require NO_x emissions measurements, provided they can be used without changes to the engine's NO_x-critical components, settings, or operating values as specified in the engine's approved Technical File. This interpretation was developed to facilitate alternative fuels use within the existing certification framework, if the engine remains in its approved configuration.

Stakeholder roles:

- Shipowners or operators lead the vessel trial by developing a detailed plan specifying when and how the fuel should be consumed, which operational and fuel parameters should be monitored, and which onboard and external testing protocols should be followed.

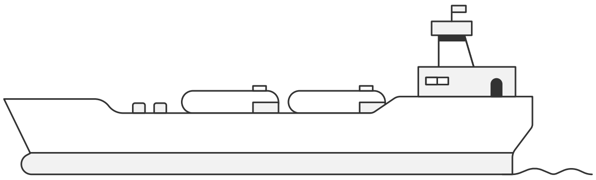
- Technical managers ensure that the vessel's crew is adequately informed and trained for the trial. The technical manager works with the shipowner or operator to implement the fuel consumption strategy and coordinate communication with the crew.

- The crew operates the vessel using the new fuel in accordance with the trial plan, monitor fuel and machinery performance, onboard sampling, and record operational data and observations.

- Fuel producers or traders produce and supply the fuel according to agreed specifications and provide the associated fuel documentation.

- OEMs, when directly involved in the trial, assess the fuel's operational impact on equipment.

- Analysis laboratories act as third parties analyzing the fuel samples received from the vessel.



Technical or operational requirements:

Before the trial, a switchover plan is prepared, including clear guidelines on which fossil fuels should be circulated through the fuel system prior to introducing the new fuel. Ensuring compatibility of the new fuel or blend with existing fossil fuels helps prevent issues such as fuel instability, filter clogging, or sludge formation during the transition to the new fuel.

The trial typically begins only once the analysis on the bunkered fuel is available and confirms that the fuel specifications match those anticipated and contractually agreed with the supplier. The PoS is required by a shipowner or operator to demonstrate that the new fuel qualifies for emissions reduction. The PoS includes key information such as the type of product, type of raw material, country of origin, name of the fuel supplier, the supplier's certificate number, the recipient (i.e., the shipowner), the GHG savings from the new fuel, and its emissions intensity. Delivery of a PoS can take 30–45 days from the fuel delivery date, potentially delaying subsequent verification steps, including regulatory reporting or compliance validation.

During a vessel trial, especially when testing a new fuel for the first time, it is common practice to have dedicated technical personnel joining the vessel for the full or partial duration of the trial. This can include a technical specialist from the shipowner or operator, technical superintendent or technical manager, fuel expert from the fuel producer or trader, or a technical specialist from an OEM or class society.

Fuel samples are typically collected at different stages over the entire trial duration and before and after purification to assess fuel stability and compatibility. Crew engagement plays a central role in a successful trial execution. As the crew directly manages onboard fuel changeovers, records operational data, and handles collection and labeling of samples, ensuring they are thoroughly briefed on trial objectives is essential to the process.

Time estimates

The duration of the vessel trials ranges from a few weeks to months, depending on the bunkered fuel volume and if it's consumed only on an A/E or the M/E as well.

Moreover, a vessel trial should be conducted over an extended period to accurately assess the properties and operational behavior of a new fuel. A long-duration trial is generally needed to generate meaningful insights into the fuel's performance, stability, and impact on onboard systems.

Cost estimates

The cost of the vessel trial may comprise:

- Onboard technical support, which is in the tens of thousands USD, depending on the days needed for the specialist to be present.
- The cost of route deviations to allow specialists to embark and disembark, which may also cost tens of thousands USD, depending on the extent of the route deviation.

Risks and challenges:

To mitigate the consequences of unexpected engine behavior, it is always advisable to carry out fuel switchover in open waters rather than the port or congested areas, where the vessel may need to perform delicate or prompt maneuvering.

Trial protocols are not standardized across the industry. Shipowners and operators tend to develop their own procedures based on risk tolerance, operational constraints, and acceptance criteria, resulting in varying approaches to testing and data collection and reducing comparability across trials.

Opportunities for improvement:

Strengthening feedback loops represents a clear opportunity to improve the effectiveness of fuel trials and accelerate learning across stakeholders. Where appropriate, systematic sharing of results with the broader maritime ecosystem would expand collective knowledge and support wider rollout of new fuels.

Step 7: Commercialization and standardization

Years

Purpose:

Enable the fuel to transition from pilot use to market-wide adoption by establishing shared standards, scaling supply chains, and developing supporting infrastructure through comprehensive trials demonstrating operational success across a diverse range of fuel applications.

Key tasks or activities:

- Typically involves repeating steps 2 to 6 as needed: Fuel quality tests (Step 2) and fuel handling and combustion tests (Step 3) should be repeated when information on new blends is needed: for example, with a different fossil blend stock or a different blending ratio. Steps 4, 5, and 6 are repeated if the trial is on a new ship with different fuel systems and equipment changes.

Stakeholder roles:

- All stakeholders in the ecosystem.

Technical or operational requirements:

Time estimates

Commercialization and standardization of new drop-in fuels take several years and results from joint industrial efforts rather than single company trials.

Cost estimates

Engine and vessel trials required to support standardization can cost several million USD across the involved parties of the supply chain, driven by the need to accumulate operating hours across diverse engines and onboard fuel systems, test different blending ratios, and assess compatibility and stability with various fossil fuels or biofuels.

Risks and challenges:

Testing duplication can occur when fuel quality and combustion data remain proprietary to the party that funded the initial research. Even if a specific fuel blend has been thoroughly validated by a shipowner, the results are often proprietary, which may require subsequent shipowners to repeat lengthy laboratory stages (Steps 2 and 3) simply because they do not have access to existing data. When fuel producers or traders retain proprietary ownership of test results, trials for known blends can proceed directly to Step 4.

The gap between adoption urgency and time for standards development remains a key challenge. Developing new fuel standards typically requires several years to accumulate sufficient real-world operational data. Moreover, ISO standards development is governed by predefined stages set within fixed 18-, 24-, or 36-month tracks, requiring working groups to adhere to established timelines. By way of illustration, even with decades of road-sector experience, it took the maritime industry more than ten years—from the first vessel trials in 2012—to fully integrate FAME into fuel standards, enabling the use of 100% FAME, which was achieved with ISO8217:2024. While such time frames are necessary to establish reliable and widely accepted standards, the absence of recognized fuel-quality specifications in the early stages of adoption can hinder safe and efficient adoption of new fuels.

Asset value protection is sometimes incompatible with knowledge sharing. While some insurers have established platforms and fora to exchange trial-related knowledge, the effectiveness of these mechanisms is limited by incomplete data, as insurers often receive information on unsuccessful trials but seldom on successful ones. Shipowners, particularly those chartering their vessels, may be cautious to share negative test outcomes due to perceived loss of asset value from the charterer's perspective.

Opportunities for improvement:

Accelerating standardization presents key opportunities to support the adoption of new fuels despite technical complexity and long development timelines. To mitigate the delays inherent in formal standardization, technical bodies such as the Conseil International des Machines à Combustion (CIMAC) could issue interim guidelines and fuel quality recommendations while ISO standards are under development, provided that sufficient data and operational input are made available. Early engagement of CIMAC expert groups could enable a more agile pre-standardization approach that complements the more protracted ISO process. This is particularly relevant for chemically complex fuels, such as pyrolysis oils, where stakeholders note that standardization will be especially challenging due to high variability of the fuels, depending upon sourcing.

Vessel trials are expensive and time-consuming. Ship operators are interested in shipowners having updated knowledge, so they would be more open to allowing for inclusion of new fuels in charterparty agreements. Some stakeholders are already sharing knowledge by engaging in CIMAC and ISO working groups. Some ship operators would be ready to share data, if they also could share the risk. Some operators are willing to share non-commercial insights from trials, and insurers and technical managers note that access to high-level trial outcomes, rather than commercial details, would support better service to the next ship. Improving technical knowledge-sharing is again key to support faster accumulation of industry experience and enable technical experts develop robust quality standards at a pace exceeding current practice.

In support of this, MMMCZCS has developed the Fuel Technology Collaboration Platform, an open platform for sharing operational, non-confidential insights on fuel technologies across industry stakeholders. Building on experience with currently deployed drop-in biofuels, the platform aims to reduce operational risks and accelerate the adoption of low-emission fuels through shared learnings and best practices.

05 Practical insight into the drop-in fuel adoption process

The preceding sections examined the industry's collective experience in adopting drop-in fuels. To provide greater granularity and a practical perspective, NORDEN, MASH Makes, and TotalEnergies have shared their experiences and lessons learned from real-world applications. The case studies presented in the next section illustrate the drop-in fuel adoption process in practice.

5.1 NORDEN vessel trial with MASH Makes pyrolysis biofuel

NORDEN is a Danish shipowner and operator in the dry cargo and product tanker markets. MASH Makes is an Indo-Danish biofuel and carbon removal company applying pyrolysis to convert agricultural residues, such as cashew press cake, into biochar and bio-oil, the latter to be used as marine biofuel product.

In 2024, the two companies conducted a joint vessel trial on a NORDEN vessel, consuming 60 tonnes of a MASH Makes B20 blend. The fuel comprised 20% upgraded pyrolysis bio-oil from cashew nut press cake in VLSFO and was tested on an A/E over more than 600 operating hours during an East Asia–Brazil roundtrip. Prior to the trial, the biofuel's quality, miscibility, and stability with fossil fuels were extensively assessed, and the B20 blend's combustion performance was tested in a land-based stationary engine.

The A/E trial found that the engine performance and emissions were on par with conventional marine fuels and minimal to no impact on engine components was observed within the accumulated operating hours.

The biofuel adoption process in practice

In relation to the first step of the drop-in fuel adoption process, shipowners and operators typically require fuel sustainability certification and access to large fuel volumes with consistent quality when preparing for a vessel trial. At the time of the A/E trial, these conditions were only partially met because parts of the process were still under development and the unit had not yet obtained certification from a voluntary scheme. As a result, no emissions reductions were claimed in connection with the A/E trial. Nevertheless, the trial was conducted to generate valuable technical insights to support the fuel's future commercialization.

During the second step, the fuel was characterized against ISO 8217 and additional fuel tests were conducted to fully assess the biofuel's specific properties not covered by the standard. Beyond this, the work included blending tests of MASH Makes' biofuel with various fossil fuels to assess compatibility and stability, and stress testing with customized high pressure and temperature tests that simulated onboard storage, handling, and fuel injection system. One significant challenge of this step was the lack of standardized and widely accepted methods to screen new fuel behavior during onboard storage and handling. A further practical challenge concerned sourcing and purchasing small quantities (liters) of marine gas oil (MGO) and VLSFO for the blending test, because these are typically traded in much larger volumes.

For the fuel handling and combustion tests usually done in the third step, stationary engine testing was performed using a single-cylinder, 4-stroke diesel engine with common rail injection at the FVTR test center in Rostock, Germany. Consistent with the challenges noted in the previous step, the limited availability of small volumes of VLSFO caused the project to rely on one source for the fuel from a local refinery at a significantly higher cost than typical bunker prices. Additionally, VLSFO quality can exhibit significant variability due to differences in crude oil sources, refinery configurations, and blending strategies. These variations affect key properties such as viscosity, density, aromatic content, catalyst fines concentration, and overall fuel stability, and it would have been advisable to conduct compatibility testing against various VLSFO samples.

The fourth step involves vessel selection, risk assessment, and safety management. In this case, the criteria for vessel selection included having full control of the asset and operations, with a vessel that could operate independently on conventional fuel on the M/E and the two A/Es not involved in the B20 trial. This is why a NORDEN-owned vessel equipped with two separate sets of settling and service tanks was selected. To improve planning, a vessel with more frequent port calls in Singapore was selected. During a scheduled five-year dry dock in spring 2024, modifications on the A/Es fuel supply lines were made such that one of the three A/Es of the vessel could run in isolation. This helped de-risk this first-of-its-kind B20 fuel test during commercial vessel operations. Furthermore, additional flowmeters for fuel consumption measurement were installed on the dedicated A/E and a sampling point was created on the exhaust pipe for exhaust gas measurements. The modifications needed approval by class society in coordination with NORDEN's technical team and the vessel's technical manager.

The NORDEN–MASH Makes experience in the fifth step of the process highlights a range of operational and coordination challenges. Transporting the biofuel from the production site in India to Singapore required multimodal shipment in an ISO tank container, including truck transport to a container port and onward sea transport to Singapore for the blending and bunkering. Operational challenges of this phase were compounded by regulatory considerations about export and import rules: new fuels may not yet be recognized under internationally standardized naming conventions, transport codes, or regulatory categories, and identifying the correct classification and applicable restrictions to international shipment can be challenging. Furthermore, identifying a licensed fuel supplier in Singapore capable of sourcing VLSFO, performing the blend, and supplying the fuel to the vessel proved complex, as it involved coordination among multiple parties, including the VLSFO trader, tank provider, and licensed bunker supplier. The small volumes typical of demonstration trials further complicated blending and bunkering, as they necessitated ad hoc operations that deviated from standard procedures, increased costs, and required blending in ISO tanks rather than shore tanks (which were too large). Bunkering was conducted as a truck-to-ship operation, requiring berth availability suitable for a Capesize vessel without disrupting its commercial schedule. To prevent costly idle time, logistical synchronization was essential to ensure that all spare parts and calibrated equipment were available and that technical personnel were mobilized and ready for deployment in strict alignment with the vessel's departure schedule.

Planning was further complicated by the vessel's operation in the tramp shipping market, which limited long term visibility over routes and schedules. This necessitated dynamic coordination between biofuel delivery logistics and the vessel's commercial transit through Singapore. Finally, the available trial window was constrained by NORDEN's fleet strategy, as the selected vessel was subsequently sold with delivery scheduled for March 2025, limiting the period for executing the trial.

Collaboration and adherence to best practice in data collection and monitoring are key to a successful vessel trial, which is the sixth step in the process. The captain, officers, and engineers were all well informed about the trial and established a good and direct line of communication to support fuel consumption and measurements. Prior to and throughout the trial, machinery was inspected, with baseline measurements collected using onboard fossil fuels. Following the switchover to the B20 blend, A/E performance was monitored at various loads in accordance with ISO 8178, while fuel samples were taken on board to assess compositional variations and the effects of onboard purification. While it only took a couple of days to receive the analysis from the drip sample taken during bunkering, it took a few weeks to receive results for the samples collected on board after purification, as these had to be landed ashore at the next convenient port. In this regard, it is advisable to consider the time between sample collection and availability of results to manage the timeline appropriately.

In a similar collaborative manner, results from the trial were presented and discussed by NORDEN, MASH Makes, and FVTR, who was also involved in assessing the status of the fuel injection equipment landed ashore post-trial. Technical details of this vessel trial were divulgated to the wider maritime ecosystem in a 2025 CIMAC publication, 'Qualification of Pyrolysis Oil from Cashew Nut Shell Press Cake as Marine Biofuel,' to ensure that the vessel trial outcomes reach the wider maritime ecosystem beyond those involved in the trial.[6]

A NORDEN employee measures intake air temperature and relative humidity at the turbocharger for ISO 8178 and NO_x Technical Code calculations.

5.2 TotalEnergies vessel trial with Cashew Waste Biofuel

As part of its commitment to market-leading decarbonization solutions, TotalEnergies partnered with a vessel charterer to validate a new alternative fuel designed to reduce the carbon footprint of maritime operations. Following this agreement, a vessel trial was conducted with an upgraded and proprietary biofuel derived of cashew nut shell liquid (CNSL). This upgraded product was branded Cashew Waste Biofuel (CWB) to emphasize the enhanced properties of the blend achieved through TotalEnergies' proprietary formulation expertise, including the selection and dosing of additives. The vessel trial was based on a 10% CWB (B10) with VLSFO blend and conducted from Northwest Europe to South America, totaling 2,500 running hours across several engines. This included: 1,500 hours equally divided across three A/Es and 1,000 hours split between two M/Es. The 10% blend was selected because laboratory tests demonstrated this ratio to be the most technically challenging. By selecting this blend, the trial aimed to evaluate the suitability and operational reliability of the enhanced biofuel under the most severe conditions.

The CWB adoption process in practice

TotalEnergies faced market-related uncertainties at the outset of the process, underscoring the importance of carefully conducting the market research step. At the time of the initial discussions between TotalEnergies and its partner, Louis Dreyfus Company (LDC), the charterer, multiple ship operators had already reported operational issues associated with CNSL. These reports originated from other market participants and are not related to the present vessel trial. Investigations revealed that certain fuel suppliers had mixed unsuitable grades of CNSL with conventional fuel. These incidents created industry-wide skepticism complicating the client's decision to proceed. Ultimately, the project was approved due to the confidence rebuilt through successful and extensive experimentation detailed in the next sections.

A significant challenge in step 2 was the wide variability in CNSL supply quality, which fluctuated based on geographic origin, extraction and processing methods (e.g., degumming). Consequently, substantial laboratory work was required to characterize and compare batches. This was further compounded by the absence of a dedicated analysis standard; while ISO 8217:2024 provides a useful reference, its scope is limited to bio-components such as FAME and HVO that comply with their respective specifications, and does not extend to other bio-derived fuels such as CNSL. As a result, a significant knowledge gap remains in evaluating their suitability for marine applications.

To overcome the issue of fluctuating CNSL quality, TotalEnergies' research and development team first defined a narrow specification for acceptable CNSL supplies. They then derived target characteristics to be met and rebranded these high-quality CNSL as CWB with uniform and controlled properties. Establishing this consistent fuel profile enabled the team to streamline subsequent development stages, significantly reducing the time and resources required for the remaining steps of the process. As a trade-off, it narrowed the pool of CNSL grades and suppliers currently able to meet TotalEnergies' specification.

In developing CWB, TotalEnergies addressed two main challenges. The first was the definition of comprehensive technical specifications for CWB. This required the development of new test methods, including a dedicated fouling test to assess polymerization propensity at the injection nozzle.

The second challenge is related to CWB's compatibility with VLSFO, which itself exhibits significant variability in nature, ranging from highly paraffinic to highly aromatic. To address this, TotalEnergies developed CWB to be largely independent of VLSFO composition. This achievement eliminated the need for extensive testing across various fossil fuel grades and helped de-risk marine operations.

Throughout the fuel handling and combustion tests described in the third step, the main challenge was accessing engine test benches, and the testing costs were significant. By developing CWB specifications that ensured compatibility with VLSFO across different grades and fuel characteristics, TotalEnergies was able to limit the scope of the required testing. This helped alleviate both capacity and cost constraints at this stage.

During vessel selection, risk assessment, and safety management—the fourth step in the process—LDC selected a ship with a built-in fuel segregation system to avoid any vessel modifications. To further mitigate risks and strengthen the validity of the results, two sister ships with identical configuration participated in the trial allowing the generation of two independent data sets under comparable operating conditions. On each vessel, one tank was filled with a B10 CWB blend in VLSFO for the trial on the open sea, while another tank was filled with conventional MGO for use in Sulfur Emission Control Area (SECA) zones, as a backup fuel, and for maneuvering. The segregation system enabled switching between fuels, allowing operations on MGO when required. On top of these measures, additional equipment spare parts were taken on board in case of material issue during the trial. The selection of the vessel route was based on commercial needs from LDC, availability of the shipowner's ship, and port readiness to store a CWB blend.

In line with the fifth step of the drop-in fuel adoption process, TotalEnergies' experience highlights that operational preparation for vessel trials is shaped by differing risk assessments, logistical constraints, and cost considerations, alongside opportunities to simplify approvals through targeted choices. Logistics presented a valuable area for development, as CWB is a new alternative marine fuel that currently lacks standardized customs-handling procedures. As a result, coordinating fuel delivery for blending and bunkering, as well as managing customs requirements, required careful attention. Storage time constraints added further complexity, as it is generally recommended to minimize the onboard storage duration of VLSFO/biofuel blends compared to VLSFO.[7,8] These restrictions may be relaxed for CWB in the future, as laboratory tests demonstrate that CWB enhances overall stability of its blends with both VLSFO or marine distillate. Operational decisions also carried cost implications because the vessel would normally operate on VLSFO outside SECA zones and bunkering additional MGO as backup fuel increased costs. At the same time, several practices helped facilitate the process, including the careful selection of a vessel with suitable configuration and availability, which earned classification society support without technical modifications, thereby reducing cost, time, and safety risks.

Good communication between TotalEnergies' technical teams and the vessel's crew was a key contributor to the success of this trial in the sixth step. Crew awareness and commitment were crucial for daily monitoring of key engine components, routine sampling of fuel and lubricants, management of the large number of samples and datasets on board, and ensuring their safe shipment to France for subsequent laboratory analyses.

The success of one vessel trial represents an important step forward, yet it does not, in itself, constitute a definitive pathway to approval. At present, the industry has not yet converged on universally accepted success criteria for indicators such as blend stability, engine performance, and emissions levels. This ongoing lack of harmonized benchmarks continues to be a central challenge, influencing both the pace of adoption and the scalability of commercialization for emerging fuels.

When it comes to the final stage of commercialization and standardization, most shipowners require evidence that the fuel has been tested on a vessel for 3-6 months before signing a commercial agreement to purchase alternative fuels. Encouraged by the success of the CWB trial and to address the lack of standardization, TotalEnergies is supporting Concawe's Special Task Force 29 Marine Fuels in drafting the Guidelines for the technical assessment of the suitability of new material in the production of marine fuels.

06 Conclusion

Drop-in fuels present a promising pathway to decarbonize shipping in the near-term. However, adoption of new drop-in fuels is challenged by the complexity of stakeholder involvement. While shipowners ultimately carry the operational and asset risk, the process depends on timely involvement of fuel producers, OEMs, classification societies, insurers, flag states, and port authorities, among others. In addition, long timelines are common due to a combination of limited testing availability, difficult coordination of a trial in a commercial vessel, and the need for repeated testing before full validation for commercial use. Streamlining the adoption process of new fuels can help mobilize drop-in fuels in near-term decarbonization. Key priorities include greater alignment of sustainability and LCA methodologies across regulatory frameworks, earlier and clearer engagement with OEMs and class societies, expanded testing capacity, knowledge sharing, and interim guidance while formal standards are under development. While the steps outlined in this report provide a structured overview, the practical adoption of new drop-in fuels often varies in timing, sequence, and stakeholder involvement, reflecting differences in fuel properties, vessel systems, and operational contexts.

A key contribution of this research is its end-to-end, experience-based mapping of the adoption process, grounded in real vessel trials, which clarifies where time, cost, and risk concentrate, and where targeted action can most effectively accelerate the uptake of new drop-in fuels. This development can be further supported with new research and cooperation across the maritime and fuel value chain. MMMCZCS will continue to provide analytical insights and share knowledge, leveraging its expertise and network to support maritime stakeholders in navigating the transition to decarbonization.

07 Project team

This document was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners, who contributed in a research capacity under the supervision and direction of MMMCZCS. Contributors marked with an asterisk (*) were seconded to the MMMCZCS from their home organization. We would like to extend a special thanks to all external and internal contributors to this project.

Lead authors: Aisha Matayeva (Maersk)*, Federica Conti (NORDEN)*, Roberta Cenni (MMMCZCS)

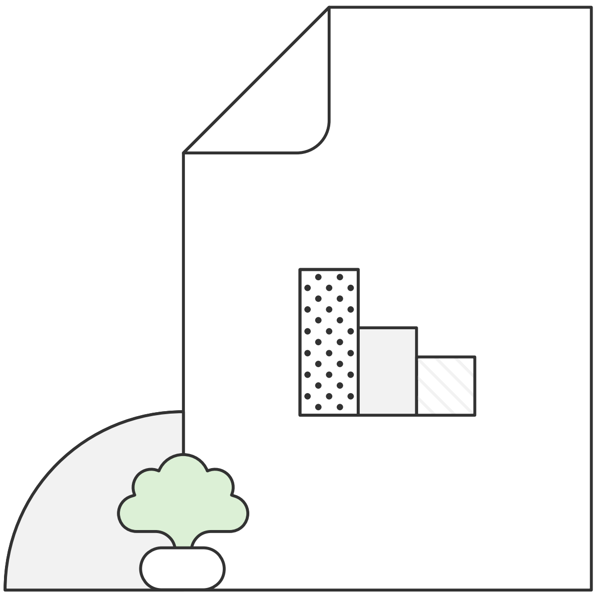
Contributing authors: Kylian Fournis (TotalEnergies)*, María Cristina Londoño (MMMCZCS)

For the knowledge contributed to the mapping study, we would like to acknowledge: ABS, Alfa Laval, Bernhard Schulte, Bunker Holding, Cargill, the Danish Maritime Authority, Equinor, Everllence, FincoEnergies, FVTR, Gard, GreenfuelHub, Lloyd's Register, Maersk, MASH Makes, the Maritime and Port Authority of Singapore (MPA), NORDEN, NorthStandard, Skuld, Stolt Tankers, TotalEnergies, VeriFuel, V.Group, Wärtsilä, and WinGD

Reviewers: Estela Vázquez Esmerode (MMMCZCS), Mira Bergem (MMMCZCS), Dax Van Diepen (Maersk Oil Trading), Julia Svensson (Everllence), Johannes Schürmann (FincoEnergies)

Editor: Jazelyn Rivas Rosende (MMMCZCS)

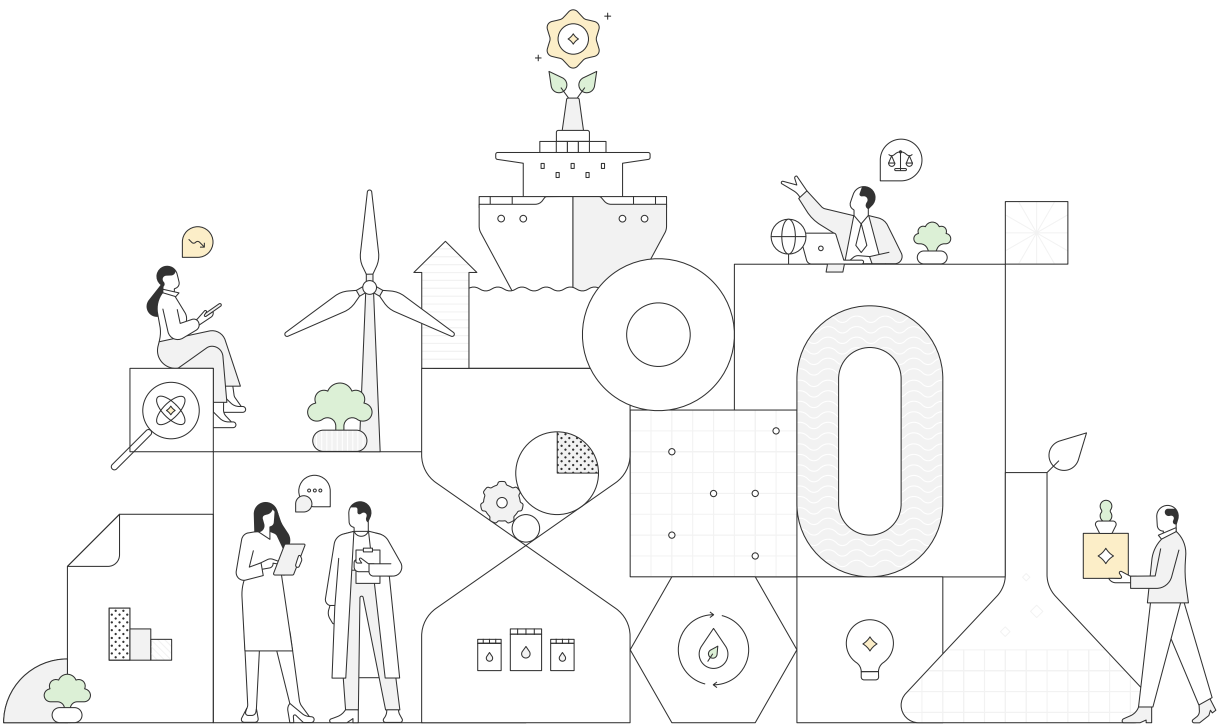
Design: Julia Maria Garbowska (MMMCZCS), Spring CC



Abbreviations

A/E	Auxiliary engine
B10, B20, or B100	10%, 20%, or 100% biofuel
CIMAC	Conseil International des Machines à Combustion
CNSL	Cashew nutshell liquid
CO	Carbon monoxide
CWB	Cashew waste biofuel
DoC	Document of Compliance
EU ETS	European Union Emissions Trading System
FAME	Fatty acid methyl esters, known as biodiesel
FOGs	Fats, oils, and greases
HAZID	Hazard identification study
HAZOP	Hazard and operability study
HVO	Hydrotreated vegetable oils, known as renewable diesel
H&M	Hull & machinery
IEA	International Energy Agency
IMO	International Maritime Organization
ISCC	International Sustainability & Carbon Certification
ISO	International Organization for Standardization
GHG	Greenhouse gas
LCA	Life cycle assessment
MGO	Marine gas oil
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping

MSDS	Material Safety Data Sheet
MTOE	Million tonnes of oil equivalent
M/E	Main engine
NO_x	Nitrogen oxides
NZF	Net-Zero Framework
OEM	Original equipment manufacturer
PoS	Proof of Sustainability
P&I	Protection & indemnity
RSB	Roundtable on Sustainable Biomaterials
SECA	Sulfur Emission Control Area
USD	United States dollar
VLSFO	Very low-sulfur fuel oil



References

1 Conference of the Parties to the Convention on Biological Diversity. Kunming-Montreal Global Biodiversity Framework. 2022.

2 Food and Agriculture Organization of the United Nations (FAO), International Fund for Agricultural Development (IFAD), UNICEF, World Food Programme (WFP) and World Health Organization (WHO). The State of Food Security and Nutrition in the World 2025 – Addressing high food price inflation for food security and nutrition. 2025. DOI: 10.4060/cd6008en

3 International Maritime Organization (IMO). MEPC 82/6/38 Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2023). 2024.

4 Ballard, D., de Witte, R., Muhammad, U. The fuel oil spin test: a method to help fuel users to predict sludge issues at the fuel oil separator. Conseil International des Machines à Combustion (CIMAC). 30th CIMAC World Congress, paper 014. 2023.

5 Westmoreland, K. Understanding certification, carbon metrics, and quality control in marine biofuels. WorldFuel. 2026.

6 Seidl-Zelenka J., Andersen J.B., Bank R., Chakravarty K.H., Conti F., Røjel H., Qualification of pyrolysis oil from cashew nut shell press cake as marine biofuel. CIMAC. 31st CIMAC World Congress, paper 021. 2025.

7 Conseil International des Machines à Combustion (CIMAC). CIMAC Guideline: Marine fuels containing FAME; a guideline for shipowners & operators. 2024.

8 CIMAC. CIMAC Guideline: Overview and interpretation of total sediment test results in the context of ISO 8217:2024. 2024.

Visit our website for more

www.zerocarbonshipping.com

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping